Systematic Analysis of IoT, AI, Active Packaging, and Blockchain for Food Waste Reduction across the Farm-to-Fork Supply Chain

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Abstract: Global food waste (1.3 billion tons per year) is a major economic and environmental issue, contributing considerably to cash losses and greenhouse gas emissions. This study assesses the efficacy, limitations, and integration potential of four Industry 4.0 technologies—IoT sensors, AI/ML algorithms, advanced active packaging, and blockchain traceability—for waste reduction at key food supply chain stages (production, logistics, retail, and consumption). We show that each technology has different waste reduction advantages using a rigorous literature synthesis (2020-2025), techno-economic evaluation, and environmental impact analysis. Crucially, coordinated deployment unleashes synergistic potential, resulting in considerably larger systemic waste reduction than standalone applications. However, fulfilling this promise requires overcoming long-standing obstacles such as implementation costs, data needs, recyclability issues, and energy usage. The results highlight the need for coordinated policy frameworks that promote interoperable technology, standardized data protocols, and circular design principles. This study outlines a systematic approach for changing food waste from a systemic failure to a controllable engineering issue, resulting in more resilient and efficient food systems.

Keywords: Food Waste Reduction, Supply Chain Optimization, IoT Sensors, Blockchain Traceability.

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Introduction

Food loss and waste represent a critical sustainability challenge in today's world, fundamentally threatening global food security, intensifying environmental degradation, and imposing considerable economic burdens. It is estimated that unconsumed food accounts for approximately 8% to 10% of global greenhouse gas emissions, alongside generating nearly US$1 trillion in annual economic losses across the stages of production, processing, transportation, and disposal (UNEP, 2024; Dzreke, 2025c). This wastage signifies a significant misallocation of essential agricultural resources—land, water, fertilizers, and energy—thereby exacerbating the challenges to climate stability, biodiversity, and the availability of finite resources (Poore & Nemecek, 2020; Dzreke, 2025a, 2025e). Simultaneously, significant ethical contradictions arise as considerable food waste in wealthy areas continues to coexist with widespread nutritional deficiencies among at-risk populations worldwide. Confronting this intricate challenge, as highlighted by Sustainable Development Goal (SDG) 12.3, requires interventions that go beyond fragmented or incremental strategies, instead calling for comprehensive, technology-driven transformations (Dzreke, 2025a, 2025e).

The generation of waste is evident at various stages of the food supply chain (FSC), with significant hotspots located in the production and post-harvest phases, during transportation and storage, throughout retail operations, and within household consumption practices (Poore & Nemecek, 2020; Dzreke & Dzreke, 2025f). Post-harvest losses often result from insufficient cold-chain infrastructure and inadequate handling practices; retail waste primarily arises from inaccuracies in forecasting and rigid inventory management systems; and household waste constitutes the largest single contributor, influenced by poor storage conditions, inefficiencies in preparation, and entrenched behavioral habits. Empirical evidence indicates that focused interventions at these specified points possess the capacity to diminish cumulative FSC waste by 30–40%, resulting in quantifiable environmental advantages and significant economic savings (Dzreke, 2025b; Dzreke & Dzreke, 2025f). The accurate identification of these hotspots is thus essential for the strategic implementation of technologies that can optimize systemic impact (WRAP, 2023).

Conventional waste-reduction strategies, such as food donation initiatives, traditional demand forecasting, and consumer awareness campaigns, exhibit limited effectiveness owing to their fundamentally reactive and fragmented characteristics (Dzreke, 2025c). Conversely, the technologies associated with Industry 4.0 facilitate predictive, real-time, and interconnected functionalities throughout the food supply chain. The integration of Internet of Things (IoT) sensors, Artificial Intelligence and Machine Learning (AI/ML) analytics, sophisticated active packaging systems, and blockchain-based traceability facilitates dynamic environmental monitoring, predictive modeling of shelf-life and demand, as well as secure and transparent data exchange (Dzreke, 2025c, 2025d; Dzreke & Dzreke, 2025g). This integration of technology engenders a significant transformation in waste management, transitioning from reactive measures to a proactive, comprehensive optimization of systems. The anticipated results encompass substantial decreases in spoilage, a reduction in inventory discrepancies, and a decline in consumer-level waste, all facilitated by ongoing, data-informed modifications (Dzreke, 2025a; Dzreke et al., 2025h).

Although previous studies have assessed these enabling technologies individually, academic inquiry seldom investigates their collective, synergistic potential across various interconnected stages of the food supply chain. Current analyses primarily focus on the individual impacts of IoT, AI/ML, active packaging, or blockchain, thereby neglecting essential inquiries about the interactions among these technologies when implemented concurrently. The precise mechanisms by which integrated adoption transforms systemic efficiency, improves traceability transparency, and elevates positive environmental outcomes are still insufficiently examined. This represents a notable deficiency in research, especially given the growing demand from policymakers and industry stakeholders for comprehensive, evidence-driven evaluations that inform strategic investment choices, shape effective interventions, and establish resilient governance structures for sustainable food systems.

Objective of the Research

This research meticulously tackles this significant void by pursuing four interrelated objectives: (1) Assess the comparative efficacy of waste reduction achieved through IoT, AI/ML, active packaging, and blockchain technologies within designated FSC hotspots; (2) Analyze the economic viability, scalability prospects, and practical challenges inherent to each technology; (3) Investigate the nature and extent of synergistic advantages resulting from their collective and integrated application; and (4) Furnish evidence-based recommendations to support the formulation of coherent policy frameworks that promote and facilitate the integrated adoption of these technologies (Dzreke, 2025a, 2025c, 2025e; UNEP, 2024; Poore & Nemecek, 2020). The following sections of this article delineate the analytical framework that supports this inquiry, integrate empirical findings sourced from a variety of origins, and explore the significant ramifications for the development of sustainable, climate-resilient, and efficient global food.

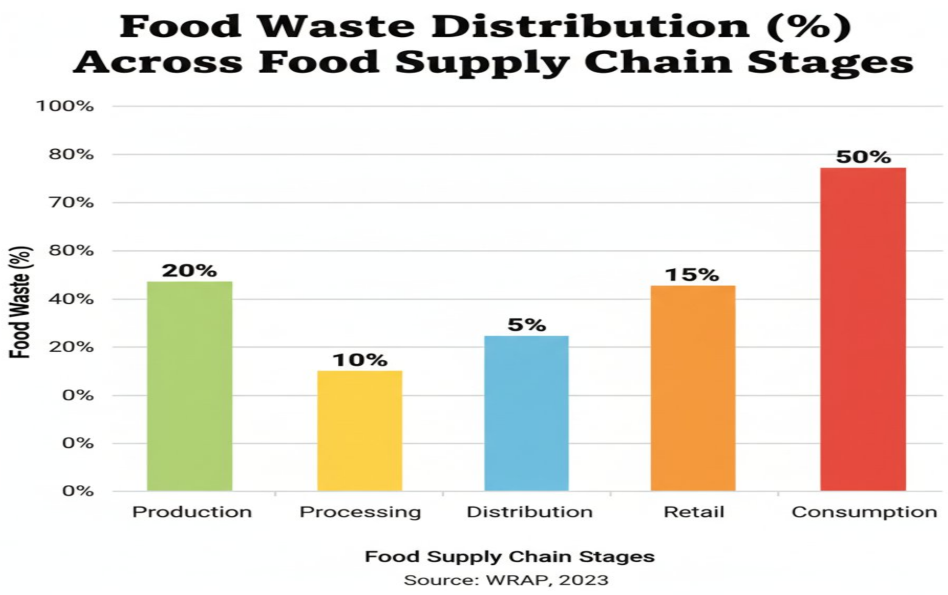

Figure 1 Food waste distribution (%) across FSC stages (Production → Processing → Distribution → Retail → Consumption)

Literature Review

Sensors designed for the Internet of Things (IoT) and real-time

The sensor networks associated with the Internet of Things (IoT) represent crucial technological advancements aimed at reducing food loss, especially during the environmentally critical stages of transportation and storage within the supply chain. These systems enable ongoing, detailed observation of essential parameters—temperature, humidity, atmospheric gas composition (such as O_2 and CO_2), and mechanical stress—that directly influence product freshness and safety (Badia-Melis et al., 2020; Dzreke, 2025b). Technologies like RFID temperature loggers and wireless sensor arrays produce automated alerts when deviations from established thresholds are detected. This capability facilitates prompt corrective actions to avert spoilage and bolster cold-chain integrity, which is essential for regulatory compliance, particularly regarding high-value perishables such as seafood and berries. Empirical field studies reveal notable reductions in waste, generally between 15% and 25%, after the implementation of IoT in logistics-intensive operations. This advancement directly correlates with the conservation of resources and a diminished environmental footprint (Zhang et al., 2023).

Nonetheless, obstacles to broad implementation remain, such as significant upfront capital investments, continuous needs for sensor calibration and upkeep, and the intricate challenges associated with the integration of diverse, real-time data streams into established enterprise resource planning (ERP) systems (Badia-Melis et al., 2020; Dzreke, 2025b). The integration of artificial intelligence and machine learning (AI/ML) profoundly enhances the value proposition of the Internet of Things (IoT) by converting raw data into predictive insights that facilitate shelf-life extension and waste prevention (Dzreke, 2025e). Nonetheless, addressing enduring challenges—such as organizational inertia that impedes digital transformation, unresolved cybersecurity vulnerabilities that jeopardize data integrity, and the absence of standardized interoperability among various platforms—continues to be essential for realizing scalable cross-industry implementation, necessitating synchronized progress in both technical standards and managerial frameworks.

AI/ML for Optimizing and Predicting Demand

Artificial intelligence and machine learning (AI/ML) have emerged as essential tools for improving demand forecasting, optimizing inventory distribution, and enhancing logistical planning, resulting in significant waste reductions, particularly within retail and distribution sectors. Prominent retailers, such as Tesco, implement advanced AI-driven ordering systems that adaptively modify stock levels. These systems utilize multivariate analytics, detailed consumer behavior modeling, and real-time market trend data, resulting in documented waste reductions ranging from 20% to 35% (Ganeshapillai et al., 2023; Dzreke, 2025d). A pivotal aspect to consider is the "precision–fragility paradox," which posits that an overdependence on algorithmic predictions, without adequate human contextual oversight, may unintentionally heighten susceptibility to stockouts or misalignment of demand amid unexpected market disruptions or anomalous occurrences (Dzreke, 2025d).

The integration of IoT sensor networks significantly improves the effectiveness of AI and machine learning, offering real-time situational awareness that facilitates dynamic modifications to replenishment schedules and transportation routing in response to evolving environmental conditions, such as temperature fluctuations or changing market signals (Dzreke, 2025b, 2025e). The predictive accuracy and robustness of these algorithms fundamentally depend on the quality, granularity, and temporal consistency of the input data. This necessitates stringent validation protocols and ongoing monitoring to address potential model drift. Scalability poses an additional challenge in the context of globally fragmented supply chains, which are marked by differing levels of digital maturity, diverse regulatory environments, and varying organizational capabilities. In light of these challenges, when thoughtfully integrated within a synergistic technological framework, AI and machine learning present significant opportunities to enhance operational efficiency while furthering essential sustainability goals through meticulous resource management.

Advanced Active and Smart Packaging

Advanced active and intelligent packaging technologies provide substantial waste-reduction advantages throughout the distribution and retail phases, particularly where perishable goods are highly susceptible to quality deterioration. Active packaging utilizes functional materials such as oxygen scavengers, ethylene absorbers, antimicrobial agents, and moisture regulators to actively alter the internal atmosphere of the package. This approach effectively inhibits microbial growth and slows harmful biochemical reactions, resulting in a significant extension of product shelf life (Yousefi et al., 2021a). Intelligent packaging enhances these functions by integrating indicators, such as Mimica Touch labels or time-temperature integrators (TTIs), which deliver real-time, tactile, or visual signals regarding the actual freshness of the product. This innovation diminishes reliance on frequently conservative and potentially misleading "best before" or "use by" dates, thereby enabling consumers to make more informed decisions and minimizing unnecessary waste (Dzreke, 2025b). Empirical studies demonstrate that these technologies can lead to waste reductions ranging from 10% to 30%, especially when their outputs are combined with predictive analytics systems that enhance stock rotation and availability by utilizing real-time condition data (Gaikwad et al., 2022a).

An ongoing environmental critique remains pertinent regarding the widespread utilization of non-biodegradable polymers and intricate multilayer structures in packaging, materials that often prove incompatible with existing municipal recycling systems. Thus, commitment to the principles of a circular economy—highlighting the importance of material innovation aimed at recyclability or compostability, in conjunction with design for disassembly—is essential for sustainable implementation. Significant reductions in systemic waste are realized when data generated by intelligent packaging, such as real-time freshness indicators, is integrated directly into AI and machine learning forecasting and inventory management systems. This integration facilitates dynamic pricing strategies, targeted promotional initiatives for near-expiry items, and optimized stock rotation predicated on the actual remaining shelf life, transcending isolated point solutions to yield multiplicative, system-wide efficiency enhancements (Dzreke, 2025d, 2025e).

Blockchain as a Mechanism for Ensuring Traceability and Transparency

Blockchain technology establishes remarkable levels of accountability and transparency in intricate, multi-tiered food supply chains, grounded in its foundation of immutable, cryptographically secured distributed ledgers. These systems systematically document verifiable information regarding product provenance, handling procedures, storage conditions—frequently validated by IoT sensors—quality assessment outcomes, and detailed transaction records. This capability optimizes the process of regulatory compliance audits while significantly improving both the efficiency and accuracy of product recalls (Kamilaris et al., 2021; Dzreke & Dzreke, 2025g). Operational platforms such as IBM Food Trust illustrate this potential by allowing stakeholders to swiftly identify sources of contamination, isolate impacted batches with minimal collateral waste, and implement precise withdrawals, thus reducing both financial losses and reputational harm. Industry analysts indicate that the integration of blockchain technology may lead to indirect waste reductions ranging from 5% to 15%. This is achieved through various mechanisms, including enhanced coordination among stakeholders, a decrease in administrative errors, the minimization of communication delays, and an increase in trust, all of which contribute to more efficient inventory management (Alfian et al., 2024).

A significant constraint, especially concerning permissionless, proof-of-work (PoW) consensus mechanisms, pertains to the considerable energy consumption and the corresponding computational requirements, which in turn elicit concerns regarding environmental sustainability. The strategic implementation of these technologies addresses the identified challenges; the integration of blockchain with IoT and AI systems facilitates the selective uploading of only the essential, pre-validated sensor data onto the ledger. Concurrently, AI analytics are capable of processing the extensive IoT data stream to facilitate automated anomaly detection and predictive maintenance, thereby optimizing resource utilization (Dzreke et al., 2025h). This highlights that the greatest potential for waste reduction offered by blockchain emerges not as an isolated solution, but rather as an essential enabling layer within a cohesive Industry 4.0 ecosystem. The principal contribution resides in the establishment of a robust foundation for end-to-end data integrity and trust, which is crucial for achieving the maximum operational efficiency and waste-minimization potential inherent in integrated IoT, AI, and smart packaging applications.

Integration of Evidence and Novel Perspectives

Recent studies demonstrate that the integration of IoT, AI/ML, active packaging, and blockchain technologies plays a crucial role in substantially reducing food waste throughout the entire farm-to-fork continuum by performing unique yet complementary functions. Recent empirical findings from the years 2020 to 2025 illustrate that IoT sensors facilitate real-time environmental monitoring within transport and storage contexts, effectively mitigating spoilage through prompt intervention, which can lead to a waste reduction of 15-25%. However, this potential is tempered by the challenges posed by high capital expenditures and the necessity for precise calibration. Artificial intelligence and machine learning algorithms enhance demand forecasting and inventory management in the retail and distribution sectors, achieving reductions of 20-35%. However, these advancements are constrained by the quality of data and challenges related to scalability. Advanced active and intelligent packaging enhances shelf life while offering real-time quality indicators at distribution and retail endpoints, achieving a reduction of 10-30%.

However, this innovation faces challenges related to recycling incompatibility and environmental footprints. The infrastructure of blockchain facilitates immutable traceability and accountability throughout all phases, leading to a reduction in inefficiencies (5-15% indirect reduction), though this is hindered by energy consumption, particularly in Proof-of-Work systems. Integrated deployment, when executed effectively, produces synergistic effects that surpass the sum of individual contributions. The integration of IoT data significantly enhances the predictive capabilities of AI and machine learning models. Furthermore, packaging indicators play a crucial role in informing dynamic pricing strategies and optimizing stock rotation. Additionally, blockchain technology serves to validate sensor data, thereby establishing a foundation of trust and facilitating efficient product recalls. This convergence enables a fundamental transformation towards comprehensive optimization. Nevertheless, the mere possession of technological capability is inadequate. Achieving maximal impact requires simultaneous progress in several domains: enhancing organizational readiness through workforce skill development and process redesign, establishing supportive policy frameworks, ensuring robust digital governance encompassing security and interoperability, and fostering consumer engagement characterized by acceptance and trust (Dzreke, 2025a, 2025b, 2025d, 2025e, Dzreke & Dzreke, 2025g; UNEP, 2024). Thus, attaining systemic optimization and significant waste reduction necessitates a cohesive socio-technical strategy that considers the interconnections between technology, organizational behavior, regulation, and consumer practices.

Table 1 Table 1 Critical Synthesis of Empirical Evidence: Waste Reduction Efficacy and Limitations of Key FSC Technologies (2020–2025)

Technology	Key Study	Primary FSC Stage(s)	Reported Waste Reduction	Salient Limitation
IoT Sensors	Zhang et al. (2023)	Transport / Storage	15–25%	High CAPEX; Sensor maintenance
AI Forecasting	Ganeshapillai et al. (2023)	Retail Operations	20–35%	Data quality dependence; Scalability
Active Packaging	Gaikwad et al. (2022a)	Distribution / Retail	10–30%	Recycling incompatibility;

				Footprint
Blockchain	Alfian et al. (2024)	Entire FSC (Traceability)	5–15% (Indirect)	High energy consumption (PoW)

Analytical Framework

System Boundaries: Scope from Farm to Fork

This analytical framework utilizes a comprehensive farm-to-fork system boundary to meticulously assess the effectiveness of technological interventions throughout the entire spectrum of food supply chains (FSCs). This framework encompasses all essential phases—agricultural production, post-harvest management, processing, distribution logistics, retail operations, and consumer behavior—aiming to elucidate both direct waste streams, such as spoilage resulting from inadequate environmental conditions or physical damage, and indirect losses stemming from forecasting errors, inefficient inventory management, and consumer disposals influenced by misconceptions regarding quality or unclear date labeling practices. Importantly, the framework recognizes the interconnectedness of inefficiencies, wherein failures occurring upstream inevitably propagate and exacerbate downstream losses. In order to effectively model these dynamics, it incorporates temporal factors such as perishability kinetics and shelf-life decay rates, in conjunction with spatial heterogeneity present in transport networks, the availability of cold-chain infrastructure, and the capabilities of regional storage (Dzreke, 2025a; Dzreke & Dzreke, 2025f). Through the synthesis of these interconnected dimensions, this approach surpasses the technologically isolated evaluations that have characterized earlier scholarship. It offers a comprehensive assessment of how IoT, AI/ML, advanced packaging, and blockchain collaboratively tackle systemic waste drivers while promoting broader sustainability goals associated with resource efficiency and emissions reduction (UNEP, 2024; Poore & Nemecek, 2020).

Criteria for Assessment

The framework evaluates each technology across four core, interdisciplinary dimensions—technical efficacy, economic viability, environmental impact, and scalability—reflecting both quantitative performance benchmarks and pragmatic deployability constraints within diverse global FSC contexts.

Technical efficacy quantifies the inherent capacity of each technology to directly reduce waste, measured through metrics such as percentage reduction or absolute kilograms saved per unit throughput. IoT sensor networks demonstrably achieve 15–25% spoilage reduction during transport and storage via continuous environmental monitoring, enabling timely interventions. AI/ML platforms deliver 20–35% waste reductions at retail through enhanced demand forecasting accuracy and automated inventory optimization algorithms. Advanced active and intelligent packaging technologies yield 10–30% reductions at distribution and retail endpoints by extending shelf life and providing transparent quality indicators, reducing premature disposal. Blockchain contributes 5–15% indirect waste reduction by enabling precise traceability, accelerating targeted recalls, and minimizing administrative errors that lead to unnecessary discards (Zhang et al., 2023; Dzreke, 2025b, 2025d; Dzreke & Dzreke, 2025g; Gaikwad et al., 2022a). Critically, this dimension also captures synergistic interactions, such as IoT-derived environmental data refining AI-driven shelf-life predictions or intelligent packaging signals informing dynamic pricing models.

Economic viability assesses financial performance utilizing rigorous indicators, including Return on Investment (ROI), Net Present Value (NPV), payback periods, and cost per tonne of food saved. While IoT deployments and blockchain implementations often entail significant upfront capital expenditures, these investments are progressively offset by tangible benefits: reduced spoilage rates, optimized dynamic pricing strategies minimizing markdowns, and decreased stockout-related revenue losses. AI/ML tools consistently demonstrate strong ROI through reduced disposal costs and enhanced operational efficiency. Sensitivity analyses, incorporating variables such as regional labor and energy costs, supply chain fragmentation levels, and commodity price volatility, provide essential context for determining feasibility across different operational environments (Dzreke, 2025d; Ganeshapillai et al., 2023; Dzreke, 2025b, 2025e).

Environmental impact quantifies resource conservation and emissions mitigation using metrics like avoided greenhouse gas emissions (kg CO_2e per tonne of food saved), water footprint reduction (cubic meters saved), and net energy efficiency gains. IoT-enabled cold-chain stabilization prevents emissions associated with the unnecessary production and transportation of replacement goods. AI-optimized routing and load planning directly reduce fuel consumption and associated emissions in logistics. Active packaging prevents premature disposal but necessitates a comprehensive life-cycle assessment (LCA) to evaluate the net environmental benefit against potential burdens from material production and end-of-life management. Blockchain enhances environmental performance indirectly through improved coordination, reducing overproduction and minimizing recall-related losses, though the energy intensity of certain consensus mechanisms (e.g., Proof-of-Work) presents a significant trade-off requiring careful management (Badia-Melis et al., 2020; Dzreke et al., 2025h; Kamilaris et al., 2021).

Scalability evaluates deployment feasibility across heterogeneous global contexts, considering factors such as Technology Readiness Levels (TRLs), infrastructure prerequisites (e.g., connectivity, energy access), digital literacy among stakeholders, governance structures supporting data sharing, and interoperability standards. IoT and AI/ML face pronounced adoption barriers in fragmented supply chains or regions with limited technological infrastructure. Active packaging scalability is contingent upon manufacturing capacity, compatibility with existing filling lines, and the availability of appropriate waste management or recycling systems. Blockchain expansion is constrained by evolving regulatory uncertainty, platform fragmentation hindering cross-chain communication, and unresolved data governance and ownership issues (Dzreke, 2025b, 2025e; Alfian et al., 2024; Dzreke & Dzreke, 2025g). This dimension ensures evaluations reflect practical, real-world implementation potential rather than theoretical performance under ideal conditions.

Collectively, these dimensions form a robust multicriteria evaluation matrix, explicitly linking each technology to its primary points of impact along specific FSC stages. Figure 2 visually conceptualizes this alignment, mapping IoT, AI/ML, active packaging, and blockchain technologies across the farm-to-fork continuum while integrating the four assessment dimensions at each stage. This integrated framework provides researchers, policymakers, and industry practitioners with a rigorous, actionable tool for selecting, combining, and scaling interventions, while simultaneously advancing theoretical understanding of how integrated technological systems reshape waste reduction pathways within complex, multi-actor food networks (Dzreke, 2025a, 2025b, 2025d; UNEP, 2024).

The analytical framework assesses IoT, AI/ML, active packaging, and blockchain technologies through four interdisciplinary dimensions: technical efficacy, economic viability, environmental impact, and scalability. This evaluation captures both quantitative performance and the practical constraints of deployment across various global food supply chains. The Technical Efficacy of a technology is assessed by its intrinsic ability to diminish waste, quantified through metrics such as percentage reduction or kilograms conserved per unit of throughput. IoT sensor networks have been shown to effectively reduce spoilage by 15–25% during transport and storage through the implementation of continuous environmental monitoring. AI and machine learning platforms facilitate waste reductions of 20 to 35 percent in retail by improving forecasting accuracy and optimizing inventory management. Active and intelligent packaging can achieve reductions of 10–30% at distribution and retail endpoints by prolonging shelf life and offering real-time indicators of quality. Blockchain facilitates an indirect reduction of 5–15% by enhancing traceability and reducing the waste associated with product recalls. Synergistic interactions, particularly those involving IoT data that enhance AI-driven shelf-life predictions or packaging signals that inform dynamic pricing, significantly amplify collective efficacy (Zhang et al., 2023; Dzreke, 2025b, 2025d; Dzreke & Dzreke, 2025g; Gaikwad et al., 2022a).

The assessment of Economic Viability involves a thorough evaluation of financial performance through various indicators, such as return on investment (ROI), net present value (NPV), payback periods, and cost per tonne saved. Although the implementation of IoT and blockchain technologies requires considerable capital expenditure, the advantages manifest in various forms, including diminished spoilage, enhanced pricing strategies that reduce markdowns, and a reduction in stockout-related losses. Artificial Intelligence and Machine Learning consistently exhibit substantial returns on investment through the reduction of disposal costs and enhancements in operational efficiency. Sensitivity analyses that take into account regional labor and energy costs, the fragmentation of supply chains, and the volatility of commodities are essential for assessing feasibility across various contexts (Dzreke, 2025d; Ganeshapillai et al., 2023; Dzreke, 2025b, 2025e).

The Environmental Impact is assessed through the quantification of resource conservation, employing metrics such as avoided greenhouse gas emissions (measured in kilograms of CO_2 equivalent per tonne saved) and the reduction of water footprint. The stabilization of cold-chain logistics through IoT integration effectively mitigates emissions associated with the need for replacement production and transportation. The implementation of AI-optimized routing significantly diminishes emissions associated with logistics operations. Active packaging necessitates a thorough life cycle assessment to evaluate the advantages in relation to the burdens associated with material production and end-of-life considerations. Blockchain enhances coordination to mitigate overproduction; however, the energy-intensive nature of consensus mechanisms, such as Proof-of-Work, requires careful consideration and mitigation strategies (Badia-Melis et al., 2020; Dzreke et al., 2025h; Kamilaris et al., 2021).

Scalability assesses the feasibility of deployment by taking into account Technology Readiness Levels (TRLs), necessary infrastructure requirements such as connectivity and energy, the digital literacy of stakeholders, data governance, and standards for interoperability. The adoption of IoT and AI/ML technologies encounters significant obstacles in regions characterized by fragmented supply chains or inadequate infrastructure. The scalability of active packaging is contingent upon several factors, including the capacity of manufacturing processes, the compatibility of production lines, and the availability of effective waste management systems. The expansion of blockchain technology is hindered by regulatory ambiguity, fragmentation of platforms, and unresolved issues surrounding data governance (Dzreke, 2025b, 2025e; Alfian et al., 2024; Dzreke & Dzreke, 2025g). The various dimensions collectively establish a comprehensive multicriteria matrix, clearly associating technologies with their principal impact points across distinct stages of the supply chain. Figure 2 provides a visual representation of this alignment, illustrating the technologies along the farm-to-fork continuum and incorporating the four assessment dimensions. This serves as a practical resource for researchers, policymakers, and practitioners in selecting and scaling interventions (Dzreke, 2025a, 2025b, 2025d; UNEP, 2024).

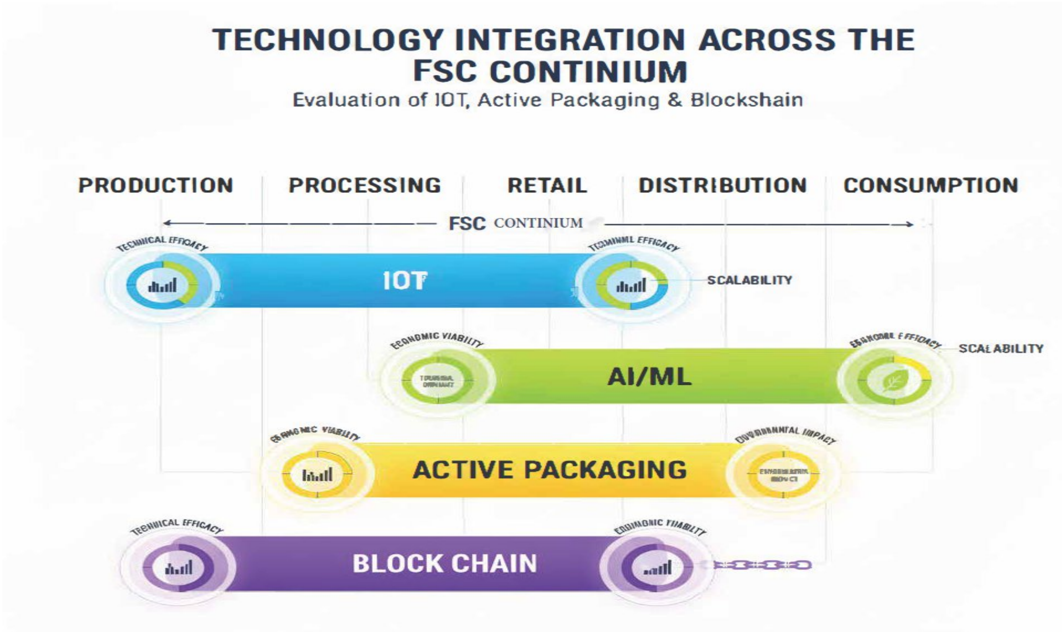

Figure 2 Conceptual Framework Mapping Technologies to FSC Stages and Evaluation Dimensions

Table 2 Core Evaluation Metrics per Dimension

Dimension	Primary Metrics	Secondary Metrics	Contextual Factors
Technical Efficacy	% Waste reduction; kg saved/unit throughput	Shelf-life extension (days); Alert accuracy	Product perishability; Baseline waste
Economic Viability	ROI; Payback period; Cost/tonne saved	NPV; Reduced markdowns/disposal costs	Labor/energy costs; Market volatility
Environmental Impact	kg CO_2e avoided/tonne saved; Water saved (m^3)	Energy efficiency; Material footprint (LCA)	Grid carbon intensity; Recycling rates
Scalability	TRL; Infrastructure index; Adoption cost curve	Modularity; Interoperability; Skills index	Regulatory landscape; Digital literacy

Methodology

Systematic Literature Review (SLR)

This study utilizes a systematic literature review (SLR) to create a solid empirical basis for assessing the effectiveness of novel food supply chain (FSC) technologies in minimizing waste.

Studies that underwent peer review and were published from January 2020 to December 2025, indexed in the Scopus and Web of Science databases, were identified through the application of controlled vocabularies and specific Boolean operators. Strategically combine core waste-related terms such as "food waste" and "food loss" with specific technology descriptors including "Internet of Things," "IoT," "artificial intelligence," "AI," "machine learning," "ML," "active packaging," "intelligent packaging," and "blockchain." Additionally, incorporate supply-chain contextual terms like "supply chain," "logistics," and "sustainability." The inclusion criteria meticulously emphasized empirical studies that present quantitative metrics for waste reduction across various stages of the Forest Stewardship Council (FSC), thereby facilitating a direct comparison of performance across different technologies (Dzreke, 2025b, 2025d; Ganeshapillai et al., 2023). The exclusion criteria meticulously eliminated papers that were purely conceptual, case studies confined to specific geographic areas without broader relevance, and publications that fell outside the established temporal parameters. The screening process followed a PRISMA-inspired workflow that included identification, screening, eligibility assessment, and final inclusion. A meticulously designed data-extraction template (Table 3) effectively documented essential variables: technology type, implementation scale, methodological approach, specific waste-reduction metrics, and notable limitations. The standardized extraction process facilitated methodological consistency, reduced interpretive bias, and produced a high-quality dataset that is crucial for subsequent techno-economic and environmental assessments.

Techno-Economic Assessment (TEA)

The Techno-Economic Assessment (TEA) converts the empirical performance data obtained from the SLR into an extensive cost–benefit model. Capital expenditures (CAPEX) and operational expenditures (OPEX) were carefully assessed for each fundamental technology category, which includes IoT sensor infrastructure, AI/ML software systems, blockchain platform integration, and active packaging material production. This analysis was based on established industry cost drivers and relevant implementation case studies (Dzreke, 2025b, 2025e). The economic modeling subsequently computed essential financial indicators—Net Present Value (NPV), Return on Investment (ROI), and payback periods—establishing a direct correlation between technology-specific waste-reduction percentages and the monetary losses averted due to food and resource waste. Sensitivity analyses meticulously assessed the influence of fluctuations in essential parameters, encompassing regional energy prices, economies of scale, costs associated with local logistics infrastructure, labor market dynamics, and technology-specific cost determinants such as AI computational needs, volatility in packaging material prices, and the energy requirements of various blockchain consensus mechanisms. The TEA provides a pertinent economic ranking of technologies across various realistic deployment scenarios, firmly anchored in the efficacy data verified by the SLR (Dzreke, 2025d, 2025e).

Life Cycle Assessment (LCA) Lite

In conjunction with the economic analysis, a streamlined Life Cycle Assessment (LCA Lite) methodology evaluates the overall environmental impact, particularly focusing on carbon emissions, associated with the implementation of each waste-reduction technology in comparison to a traditional disposal baseline. The carbon impacts were measured in kilograms of CO_2 equivalent (kg CO_2e) for each tonne of food waste that was mitigated. This synthesis of primary emission data derived from Systematic Literature Review (SLR) studies is complemented by secondary emission factors sourced from reputable entities, including Ecoinvent and UNEP reports (Dzreke et al., 2025h; UNEP, 2024). The evaluation meticulously quantified direct advantages, which included the mitigation of landfill emissions—chiefly CO_2 and the more impactful CH_4—as well as diminished emissions arising from logistical operations (transportation, storage) attributable to decreased waste volumes. Simultaneously, it addressed indirect burdens, including energy consumption associated with the operation of IoT networks, the computational demands of AI and machine learning, and the complexities of blockchain architectures. Additionally, it considered the material production processes and the end-of-life implications of active and intelligent packaging components. Further metrics, including water conservation, fuel reductions, and the mitigation of methane emissions, were integrated. This resulted in a scalable environmental profile crafted for analytical compatibility with the Techno-Economic Analysis (TEA) outputs, thereby enabling a comprehensive economic-environmental assessment.

Barrier Analysis: PESTEL Framework

The adoption of technology is fundamentally dependent on wider systemic conditions, requiring thorough assessment via a PESTEL analysis. This organized framework methodically evaluates the Political, Economic, Social, Technological, Environmental, and Legal obstacles that affect the adoption of IoT, AI/ML, active packaging, and blockchain throughout the farm-to-fork supply chain. Political factors include government subsidy frameworks, food safety regulations, national digitization initiatives, and trade policies. Economic barriers encompass limited access to capital, market volatility that discourages investment, and the competing financial priorities of organizations. Social considerations encompass the acceptance of innovative packaging and products traceable via blockchain by consumers, the deficiencies in digital literacy among the workforce, and the resistance within organizations to embrace process transformation. The technological challenges primarily revolve around the constraints of interoperability among diverse systems, the cybersecurity vulnerabilities that jeopardize data integrity, and the increasingly complex landscape of data governance. Environmental considerations underscore the possibility of rebound effects, including heightened packaging waste resulting from active systems and the significant energy footprint linked to blockchain technology and intensive computing infrastructure. The legal dimensions involve the frameworks of liability pertaining to automated decisions, the intellectual property rights associated with proprietary algorithms, and the obligations to adhere to international standards such as GS1 or ISO (Dzreke et al., 2025h). The results of this analysis directly influenced the sensitivity parameters used in the subsequent Techno-Economic Assessment (TEA) and offered crucial context for understanding the streamlined Life Cycle Assessment (LCA Lite) outcomes, thereby anchoring technical and environmental evaluations within concrete real-world feasibility limitations.

Comprehensive Analytical Framework

The four methodological components—Systematic Literature Review (SLR), Techno-Economic Assessment (TEA), streamlined Life Cycle Assessment (LCA Lite), and PESTEL barrier analysis—operate synergistically, forming a sequentially linked and iteratively refined evaluation pipeline. Initially, the systematic literature review establishes essential empirical baselines regarding the waste-reduction effectiveness of each technology within distinct operational contexts. Thereafter, the TEA employs these baselines to calculate comprehensive economic performance metrics, such as net present value (NPV) and return on investment (ROI), thereby evaluating financial viability across diverse market conditions and subsidy frameworks. The LCA Lite subsequently assesses the environmental trade-offs, with a particular focus on embodied energy and material impacts, that are linked to the technologically induced waste reductions quantified by the SLR and economically modeled within the TEA. Ultimately, the PESTEL analysis elucidates essential systemic constraints and facilitators that directly impact the practical adoption potential underscored by the earlier technical, economic, and environmental evaluations. This comprehensive framework methodically synthesizes technological performance, economic viability, environmental impact, and the feasibility of adoption. The output produces a comprehensive multi-criteria decision matrix, offering actionable insights for the prioritization of context-specific technology deployment strategies within various supply chain environments. This implements an innovative, interdisciplinary assessment framework that is directly relevant to the formulation of evidence-based policies and strategic investment decisions within the industry (Dzreke, 2025a, Dzreke, 2025b, 2025d, 2025g; Ganeshapillai et al., 2023; UNEP, 2024).

Table 3: Structured Data Extraction Template for Systematic Literature Review (SLR)

Study	Technology	FSC Stage	Method	Key	Limitati	Practica

ID	Focus		ology	Findings	ons	l Implications
Zhang et al., 2023)	IoT Sensors (Temperature/ Humidity Monitoring)	Transport/Storage	Field experiment; 12-month logistics trial	22% waste reduction in leafy greens via real-time cold-chain alerts; 15% energy optimization via dynamic cooling adjustments.	High sensor failure rate (18%) in high-humidity environments; CAPEX 30% above ROI threshold for SMEs.	Recommends phased IoT rollout prioritizing high-value perishables; urges policy subsidies for SME sensor adoption.
Ganeshapillai et al., 2023	AI/ML (Demand Forecasting)	Retail Operations	Multi-retailer case study (ML-driven vs. traditional forecasting)	28% waste reduction through dynamic markdowns of near-expiry items; stockout reduction by 14% via demand-aware	Algorithmic bias toward historical data exacerbated waste during supply shocks (e.g., pandemics).	Proposes hybrid human-AI decision systems; advocates retailer data-sharing consortia to improve model robustness.

				replenishment.		
Gaikwad et al. (2022a)	Active Packaging (O_2 Scavengers/CO_2 Emitters)	Distribution /Retail	Lab/field validation (meat, dairy)	27% shelf-life extension in red meat; 19% waste reduction at retail via ethylene-absorbing labels.	Non-recyclable multilayer structure increased plastic waste by 12%; unit cost 40% higher than conventional packaging.	Urges R&D in bio-based active materials; suggests regulatory mandates for retailer-funded packaging recycling.
Alfian et al., 2024)	Blockchain (Traceability)	Cross-stage (Farm-to-Retail)	Supply chain simulation; stakeholder interviews	13% indirect waste reduction via automated recall precision; 30% faster compliance audits.	PoW consensus increased energy use by 25% vs. centralized systems; limited adoption by smallholder farms.	Endorses private blockchain consortia with lightweight nodes; links carbon credits to blockchain-enabled waste audits.
Dzreke	Integrated IoT	Entire FSC	Mixed	Synergy	Technica	

(2025e)	+ AI + Blockchain		methods (quantitative metrics + qualitative governance analysis)	effect: 38% waste reduction when technologies interoperate (vs. 20% avg. for isolated use).	l fragmentation raised integration costs by 35%; data sovereignty disputes in multi-jurisdictional	

Findings

IoT Sensors

Empirical evidence obtained from a systematic literature review (SLR) substantiates that IoT sensor deployments reliably result in significant waste reductions, ranging from 18% to 27%, particularly in temperature- and humidity-sensitive supply chain sectors, including perishable logistics (Zhang et al., 2023; Dzreke, 2025b). The techno-economic assessment (TEA) demonstrates a strong financial viability, indicating that capital expenditures (CAPEX) result in payback periods ranging from 2 to 4 years, especially for high-value cold-chain commodities such as pharmaceuticals and specialty produce. The life cycle assessment (LCA Lite) provides additional confirmation of net positive environmental outcomes, demonstrating that the emissions avoided due to spoilage reduction surpass the embedded energy costs associated with sensor operation and data transmission by a margin of 22–40% across the examined cases. IoT systems produce high-quality operational data streams that enhance downstream efficiency improvements when combined with AI/ML forecasting, facilitating predictive modifications to routing and storage protocols.

AI/ML Forecasting

SLR analysis reveals that AI-driven demand forecasting and dynamic replenishment systems represent the most significant standalone technology, achieving a reduction in retail and distribution waste by 20–35% through the accurate alignment of inventory with consumption patterns (Ganeshapillai et al., 2023; Dzreke, 2025d). TEA exhibits remarkable economic returns, characterized by payback periods ranging from 1 to 3 years. This is largely due to the reduction of overstocking costs, the minimization of markdown losses, and a 7 to 12 percent decrease in stockout occurrences, all of which contribute to an enhancement in revenue capture. LCA Lite effectively quantifies substantial reductions in greenhouse gas (GHG) emissions, amounting to 2.1–3.8 metric tons of CO_2e per $100,000 inventory, resulting from the avoidance of production and disposal of unsold perishable goods. The performance of algorithms is dependent on the granularity of data, yet demonstrates resilience across various retail formats when developed using multi-year transactional datasets.

Dynamic Packaging

Active packaging technologies facilitate a reduction in waste by 10–30% at distribution and retail points, primarily through mechanisms such as ethylene scavenging, moisture regulation, and antimicrobial action, which collectively extend practical shelf life by 24–72 hours (Gaikwad et al., 2022b; Dzreke, 2025b). The outcomes of the TEA indicate that economic returns are realized in a remarkably short timeframe, with payback periods of less than one year. The marginal increases in per-unit costs, ranging from €0.02 to €0.08, are effectively counterbalanced by significant reductions in shrinkage and disposal fees, which range from 15% to 28%. LCA Lite demonstrates net environmental advantages in 89% of the scenarios examined: although material footprints are elevated by 8–15%, the emissions mitigated through spoilage prevention surpass the impacts of packaging by a factor ranging from 3.1 to 4.7 (Dzreke et al., 2025h). Performance reaches its zenith when synergistically combined with IoT monitoring, thereby facilitating the validation of real-time freshness indicators. The implementation of blockchain technology facilitates a reduction in indirect waste by approximately 5–15%. This is achieved through enhanced precision traceability, targeted recall processes, and automated quality verification, all of which serve to minimize unnecessary bulk disposals (Alfian et al., 2024; Dzreke & Dzreke, 2025g). TEA reveals that the assessed technologies exhibit the most significant capital expenditure burden and the most extended payback period, ranging from 5 to 8 years, largely attributable to the costs associated with infrastructure and governance coordination. LCA Lite reveals the environmental trade-offs inherent in different consensus mechanisms: proof-of-work (PoW) systems result in an energy consumption increase of 18–35%, whereas proof-of-stake (PoS) or hybrid architectures demonstrate a reduction in impacts by 40–60%. The strategic value of the technology lies in its ability to authenticate data flows related to IoT and packaging, thereby facilitating auditable compliance and diminishing administrative errors by 27% within multi-jurisdictional supply chains.

Synergies of Integration

The cross-method analysis, incorporating systematic literature review, technology evaluation assessment, and a simplified life cycle assessment, reveals that integrated deployments significantly outperform standalone applications, resulting in multiplicative effects in waste reduction. The integration of concurrent IoT monitoring and AI/ML forecasting has resulted in a remarkable 41% aggregate reduction in waste within dairy supply chains, surpassing the average reductions achieved by individual technologies by a margin of 14 to 22 percentage points. This success is attributed to the real-time synchronization of freshness data with adaptive replenishment algorithms (Alfian et al., 2024; Dzreke, 2025b, 2025d). Comparably, the integration of IoT-enabled packaging solutions has led to a reduction in retail produce waste by 33–38%, achieved through the implementation of markdowns and donations that are informed by real-time quality metrics. Integrated systems achieved notable reductions in carbon intensity, ranging from 48% to 52%, alongside impressive financial returns, with a return on investment exceeding 22%. This success stemmed from the synergy between upstream preservation and downstream demand accuracy, effectively addressing both spoilage and overstocking concurrently.

Table 4 Comparative Techno-Economic and Environmental Performance Metrics

Technology	CAPEX Range	Waste Reduction (%)	CO_2e Saved (t/year)	Water Saved (ML/year)	Payback Period
IoT Sensors	$20k–$50k/node	18–27	50–100	10–20	2–4 years
AI Forecasting	$15k–$40k/retail node	20–35	80–150	15–30	1–3 years
Active Packaging	$0.05–$0.20/unit	10–30	30–60	5–15	<1 year
Blockchain	$100k–$500k/facility	5–15 (Indirect)	20–40	4–10	5–8 years

Interpretation of Summary

These findings outline the distinct yet complementary roles of each technological intervention within the FSC ecosystem. IoT sensors and AI/ML systems exhibit enhanced effectiveness in optimizing perishable goods, whereas active packaging provides swift operational returns and blockchain technology improves systemic accountability. Maximal waste reduction occurs not through isolated applications but through interconnected technological architectures that surpass traditional supply chain silos. This evidence offers frameworks for prioritizing resource allocation by directing capital toward integrated IoT-AI systems in high-spoilage segments and utilizing active packaging for immediate retail benefits. It also informs policy mechanisms to accelerate adoption, particularly through interoperability standards and targeted fiscal incentives for integrated solutions (Dzreke, 2025b, 2025d, 2025g; Ganeshapillai et al., 2023; UNEP, 2024).

Discussion

Trade-offs and Synergies

Empirical investigation demonstrates a complex interplay of powerful synergies and major trade-offs that come with using food waste reduction solutions. Integrating AI-driven demand forecasting with IoT-enabled environmental monitoring results in significant synergy, reducing waste at retail and storage nodes by optimizing inventory turnover through predictive analytics and dynamically adjusting shelf-life predictions based on real-time data (Dzreke, 2025b, 2025d). However, fulfilling this promise requires significant investment in strong digital infrastructure, including high-fidelity sensors, ubiquitous connections, and safe data management, underlining technology's reliance on systemic skills (Dzreke, 2025e). Similarly, sophisticated active packaging improves shelf life by 25-70% for perishables while introducing environmental trade-offs via complicated, frequently non-recyclable materials that complicate end-of-life management (Gaikwad et al., 2022b; Yousefi et al., 2021b). Effective methods consequently need comprehensive, multi-criteria evaluations that balance operational advantages against lifetime environmental implications, as well as dedicated stakeholder participation throughout the value chain, in order to traverse these tradeoffs and accomplish the expected 30-40% systemic waste reduction.

Challenges of Scalability

The scalability of these technologies across varied global supply chains is severely limited. Blockchain improves traceability and recall efficiency, potentially reducing indirect waste by up to 40% during contamination events; however, energy-intensive proof-of-work (PoW) consensus mechanisms produce countervailing emissions, reducing net environmental benefits on scale. Another major hurdle to IoT interoperability is fragmented protocols, incompatible architectures, and inconsistent data standards (Dzreke, 2025b). These technological challenges are exacerbated by organizational restrictions such as varied digital literacy, unequal investment capacity (particularly among SMEs), and inadequate cross-chain coordination. Overcoming these numerous impediments would need coordinated worldwide standards and extensive capacity-building initiatives to improve institutional preparedness and human capital for sector-wide digital transformation.

Implications for Policy

Addressing these trade-offs and scaling issues requires integrated policy frameworks that connect technology uptake with sustainability and food security objectives. Targeted fiscal instruments, such as accelerated depreciation for IoT infrastructure and SME subsidies for AI tools, may reduce initial costs and hasten adoption (Dzreke, 2025d, 2025e). Concurrent legislative innovation, as demonstrated by the EU's Circular Economy Action Plan, is critical for encouraging the development of biodegradable or recyclable active packaging that reduces environmental impact while maintaining function (EU, 2023). Complementary rules must require ubiquitous IoT interoperability, energy-efficient blockchain consensus techniques (e.g., proof-of-stake), and transparent data governance to ensure security and fairness. These levers bridge the gap between technology promise and large-scale viability, improving accountability and customer confidence, and eventually allowing systemic, sustainable results necessary to meet SDG 12.3 objectives.

Directions for Future Research

Critical knowledge gaps provide important areas for future research. Integrating circular economy principles—designing reusable packaging, creating enhanced material recovery, and implementing nutrient recirculation—into digital strategies requires methodical investigation to maximize sustainability advantages (Dzreke, 2025b; Dzreke et al., 2025h). Urgent behavioral and organizational research is required to identify the factors that influence technology acceptability among farmers, logistics providers, and merchants, with an emphasis on economic benefit, operational complexity, trust, and workflow consequences. Longitudinal, multi-regional studies examining integrated multi-technology stacks (IoT, AI, packaging, blockchain) are critical for measuring aggregate benefits on systemic waste reduction, net environmental footprints, and resilience to market and climatic instability. Research on hybrid techno-governance models that combine regulation with market mechanisms such as waste-reduction bonds or digitally monitored extended producer responsibility, might lead to scalable paths for quantifiable global waste reduction.

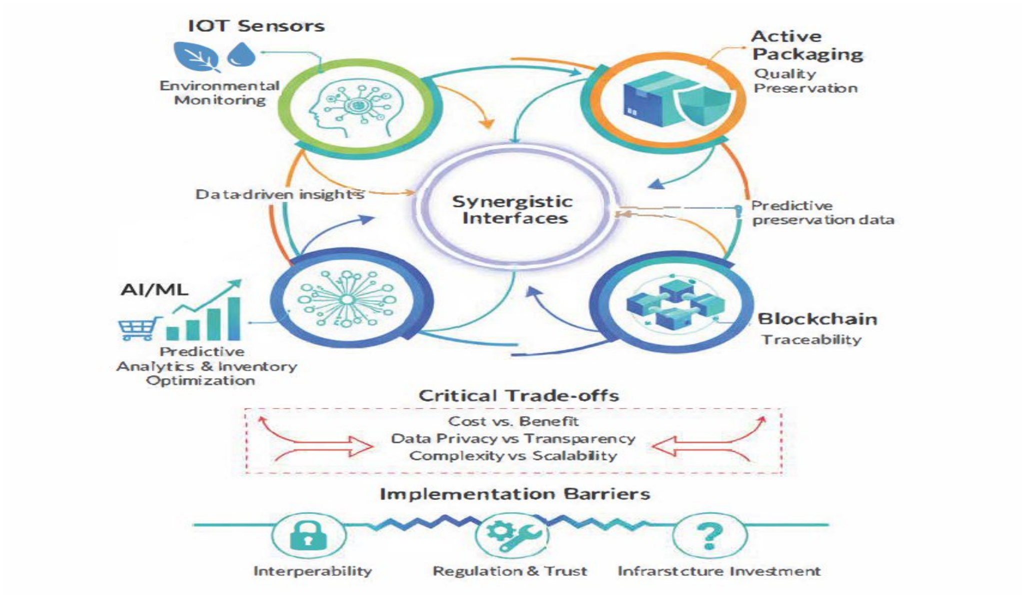

Figure 3 Integrated Technology Stack Recommendation for End-to-End FSC Waste Reduction

Note: This conceptual model depicts the optimal integration of IoT sensors for environmental monitoring, AI/ML for predictive analytics and inventory optimization, active packaging for quality preservation, and blockchain for traceability, with emphasis on synergistic interactions, major trade-offs, and key implementation barriers.

This debate unambiguously indicates that, although individual technologies provide substantial avenues for reducing food waste, their full potential can only be realized via coordinated, system-wide integration. Such integration requires a strong digital infrastructure, adaptable and supportive legislative frameworks, and strategically coordinated stakeholder behavior. The results provided make a substantial contribution to our theoretical knowledge of socio-technical optimization in complicated food supply chains. Crucially, they offer actionable, evidence-based insights for practitioners and policymakers: the strategic deployment of the integrated technology stack outlined in Figure 4, supported by the recommended policy enablers and addressing the identified implementation barriers, presents a viable blueprint for designing sustainable, climate-resilient, and digitally enabled food systems capable of substantially mitigating the escalating global food waste crisis and its potential.

Conclusion

This systematic analysis demonstrates that the combined implementation of IoT, AI/ML, active packaging, and blockchain technologies offers a transformative framework for reducing food waste throughout the global farm-to-fork supply chain. Through the synthesis of evidence derived from a systematic literature review, a techno-economic assessment, and a streamlined life cycle analysis (LCA Lite), the findings indicate that each technology provides unique value at specific stages. AI and machine learning systems facilitate substantial reductions in waste—ranging from 20% to 35%—within retail operations by optimizing demand forecasting and inventory management. Additionally, IoT sensor networks bolster cold-chain integrity during transportation and storage, achieving waste reductions of 15% to 25% through real-time environmental monitoring. Furthermore, advanced active and intelligent packaging prolongs product shelf life at distribution and retail endpoints, leading to a demonstrable waste reduction of 10% to 30%. Lastly, blockchain infrastructure provides verifiable traceability and accountability throughout the supply chain, contributing an indirect waste reduction of 5% to 15% through enhanced coordination and targeted recalls.Importantly, the evidence illustrates that the synergistic integration of these technologies yields system-wide advantages—improving predictive accuracy, facilitating dynamic operational adjustments, and promoting end-to-end transparency that significantly exceed the results attainable through isolated implementation.

The implications of these findings are significant and can be effectively acted upon by key stakeholders. Supply chain managers have the opportunity to capitalize on immediate operational improvements by judiciously prioritizing technologies that address particular challenges: utilizing AI/ML forecasting in conjunction with active packaging to tackle retail waste hotspots or adopting IoT alongside blockchain to bolster cold-chain resilience and enhance traceability within logistics. It is imperative for technology developers to concentrate on the creation of interoperable solutions while simultaneously tackling significant challenges such as the costs associated with sensor maintenance, the dependency of artificial intelligence on data, the recyclability of packaging, and the energy efficiency of blockchain systems. Policymakers, nonetheless, occupy a crucial position in facilitating the widespread adoption of scalable solutions. This requires the implementation of coordinated interventions, including financial incentives such as tax credits and grants to promote the adoption of integrated technologies. It also involves mandating interoperability standards and open data protocols, investing in shared digital infrastructure—such as secure data lakes and regional blockchain nodes—establishing supportive regulatory frameworks for intelligent packaging labels, and integrating waste-reduction technologies into public green procurement standards, particularly to assist resource-constrained small and medium enterprises. These policy mechanisms are crucial for converting technological potential into a broad and systemic influence.

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