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Digital Technologies in Food Supply Chain Waste Management: A Case Study on Sustainable Practices in Smart Cities

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Abstract: This study explores how digital technologies and data analytics can transform urban waste management in smart cities by addressing systemic inefficiencies. Integrating perspectives from the Resource-Based View, Socio-Technical Systems Theory, Circular Economy Theory, and Institutional Theory, the research examines sustainability, operational efficiency, and resilience in extended supply chains. A case study of Company A and its demand-side supply chain with Retailer B highlights key drivers of waste, including overstocking, inventory mismanagement, and inefficiencies in transportation and promotional activities. Using a mixed-methods approach, the study combines quantitative analysis of operational data with advanced statistical techniques and machine learning models. Key data sources include inventory records, sales forecasts, promotional activities, waste logs, and IoT sensor data collected over a two-year period. Machine learning techniques were employed to uncover complex, non-linear relationships between waste drivers and waste generation. A waste-type-specific emissions framework was used to assess environmental impacts, while IoT-enabled optimization algorithms helped improve logistics efficiency and reduce waste collection costs. Our findings indicate that the adoption of IoT and AI technologies significantly reduced waste by enhancing inventory control, optimizing transportation, and improving supply chain coordination. These digital innovations also align with circular economy principles by minimizing resource consumption and emissions, contributing to broader sustainability and resilience goals in urban environments. The study underscores the importance of integrating digital solutions into waste management strategies to foster more sustainable and efficient urban supply chains. While the research is particularly relevant to the food production and retail sectors, it also provides valuable insights for policymakers, urban planners, and supply chain stakeholders. By bridging theoretical frameworks with practical applications, this study demonstrates the potential of digital technologies to drive sustainability and resilience in smart cities.

Keywords: smart cities; urban waste management; IoT and AI in supply chains; sustainability; circular economy

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1. Introduction

Smart cities represent a transformative approach to urban development, leveraging advanced digital technologies and data analytics to address the multifaceted challenges of urbanization, including waste management. As urban populations continue to grow, cities worldwide face escalating waste volumes, inefficient supply chains, and the environmental and economic consequences of unsustainable practices. Waste management is not merely a logistical issue; it is central to urban resilience, environmental sustainability, and economic efficiency. It also aligns with global sustainability goals, particularly the United Nations Sustainable Development Goals (SDGs), including SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production) [1]. These goals emphasize the need for cities to adopt sustainable waste management strategies that minimize environmental impact, reduce resource consumption, and enhance circular economy principles.

Despite increasing awareness of sustainable urban development, waste management remains a persistent challenge, exacerbated by rapid urbanization, inadequate infrastructure, and fragmented supply chains. Traditional waste management systems often lack real-time data integration and predictive analytics, leading to inefficiencies such as overproduction, mismanaged inventories, and excessive waste generation [2]. These inefficiencies are particularly evident in extended supply chains, which involve multiple stakeholders, including manufacturers, retailers, logistics providers, and consumers. Without effective coordination and technological intervention, supply chain disruptions can amplify waste levels, making waste reduction an increasingly complex task [3].

A sector that is particularly vulnerable to supply chain inefficiencies and waste is the food industry. Food waste is a significant challenge in urban supply chains, particularly in food manufacturing, retail, and logistics. It occurs at multiple stages, including production, transportation, and distribution, and is often driven by overproduction, inventory mismanagement, and demand forecasting inaccuracies [4]. At the production stage, food waste results from surplus stock, poor handling, and inadequate storage conditions, leading to spoilage [5]. At the transportation stage, mismanagement, delays, and improper temperature control further exacerbate the problem, particularly for perishable goods [6]. Additionally, misaligned promotions and inefficient logistics contribute to overstocking, resulting in significant waste as goods become unsellable due to timing mismatches between supply and demand [7]. These inefficiencies not only contribute to environmental degradation and financial losses but also jeopardize food security, highlighting the urgent need for systemic, technology-driven solutions.

1.1. Digital Technologies in Waste Management

Advancements in digital technologies have opened new avenues for addressing systemic inefficiencies in waste management. Emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and the blockchain have transformed the way urban supply chains operate, enabling more data-driven, predictive, and responsive waste management strategies [8]. AI-powered analytics facilitate precise demand forecasting and inventory optimization, reducing waste by aligning production volumes with actual consumption patterns. IoT-enabled devices provide real-time monitoring of waste levels, temperature conditions, and logistics tracking, ensuring that supply chain disruptions are detected and mitigated before they result in significant waste [9]. Blockchain technology enhances transparency and traceability, ensuring accountability across the supply chain and preventing fraudulent waste disposal practices.

The integration of these technologies aligns with key theoretical perspectives that support sustainable digital waste management. The Resource-Based View (RBV) highlights how firms can gain a competitive advantage by leveraging AI and the IoT for waste reduction and resource efficiency. The Socio-Technical Systems (STS) perspective emphasizes that technology adoption must be accompanied by organizational readiness and collaboration to maximize its impact. The circular economy (CE) framework reinforces the importance of waste prevention, resource recovery, and sustainable material flows, while Institutional Theory explains how regulatory frameworks and corporate policies influence the adoption of digital waste management strategies. These perspectives ensure a comprehensive understanding of how digital solutions can effectively reduce waste and enhance sustainability in urban food supply chains.

The adoption of AI, the IoT, and the blockchain in waste management strategies is particularly crucial for the food industry, where approximately one-third of all food produced—around 1.3 billion tonnes annually—is lost or wasted [4]. This not only represents a USD 940 billion economic loss but also contributes to 8–10% of global greenhouse gas emissions, making food waste a critical issue for sustainability efforts [10]. Within urban supply chains, inefficiencies such as misaligned promotional activities, inaccurate demand forecasting, and logistics mismanagement exacerbate this problem, further reinforcing the need for smarter, technology-enabled waste management solutions.

1.2. Research Focus and Contribution

This study examines the potential of digital technologies and data analytics in enhancing waste management practices within food supply chains in urban environments. While the broader discourse on smart cities and sustainable waste management often considers municipal waste management systems, this study focuses specifically on waste generation and reduction strategies within extended supply chains. Using a case study of Company A, a food manufacturing and logistics organization, and its supply chain with Retailer B, this research explores how AI-driven analytics, IoT-enabled tracking, and blockchain transparency can mitigate key waste drivers such as overproduction, inventory inefficiencies, and promotional misalignments.

While the findings contribute to broader discussions on urban sustainability and smart waste management, this study remains context-specific and is most applicable to food supply chain operations. By examining a real-world case study, this research provides practical insights into how digital tools can drive operational efficiencies, offering scalable solutions that may be adapted for wider industry applications. However, recognizing the sectoral focus of the study, the findings should not be generalized without considering contextual variations across different industries and urban environments.

1.3. Research Objectives

The key objectives of this study are as follows:

To identify the primary drivers of waste generation in extended urban food supply chains.

To analyze the role of digital technologies (AI, the IoT, and the blockchain) in mitigating waste and reducing emissions.

To propose actionable strategies for urban planners, policymakers, and supply chain managers to integrate data-driven solutions into smart waste management frameworks.

To contribute to the academic and practical understanding of sustainable urban supply chains by providing data-driven insights from a real-world case study.

By addressing these objectives, this study seeks to bridge the gap between theoretical insights and practical applications, offering a data-driven roadmap for cities, businesses, and policymakers looking to implement innovative, sustainable waste management practices. The findings contribute to both academic discourse and industry best practices, enabling smarter, data-driven approaches to urban resilience, supply chain optimization, and environmental sustainability.

2. Literature Review

Smart cities represent a transformative shift in urban development, leveraging digital technologies to enhance resource efficiency, sustainability, and operational effectiveness. Waste management remains a critical challenge in this transition, as rapid urbanization and industrial activities significantly increase the volume of waste generated. According to the World Bank (2022), global municipal solid waste production is expected to rise from 2.01 billion tonnes in 2016 to 3.40 billion tonnes by 2050, with a substantial portion originating from urban centers [11].

Traditional waste management approaches—reliant on static collection schedules, landfill dependency, and reactive interventions—are increasingly ineffective in addressing the complexities of modern urban waste. These methods fail to incorporate real-time data, leading to overstocking, inefficient collection, and mismanaged recycling efforts. To overcome these inefficiencies, smart waste management systems are integrating Artificial Intelligence (AI), the Internet of Things (IoT), and blockchain technologies, enabling predictive analytics, optimized logistics, and real-time waste monitoring.

Cities such as Barcelona, Amsterdam, and Singapore have successfully implemented IoT-enabled waste management solutions, which allow for the dynamic monitoring of waste levels, adaptive collection routes, and emission reductions [2]. This approach aligns with Industry 5.0, which advocates for human–machine collaboration and sustainable digital transformation to optimize waste reduction and resource efficiency [12].

The integration of digital technologies has fundamentally reshaped waste management by enabling real-time monitoring, predictive analytics, and resource optimization. For instance, Barcelona utilizes IoT-enabled smart bins that monitor waste levels and adjust collection schedules, leading to reduced operational costs and improved recycling rates. In Singapore, AI-driven demand forecasting optimizes logistics, minimizes waste generation, and enhances sustainability outcomes. Meanwhile, in Seoul, IoT sensors track waste levels in real-time, optimizing collection routes and reducing unnecessary emissions [7]. These examples demonstrate how digital technologies have been effectively integrated into waste management systems, offering valuable insights into their practical applications in urban settings. Through these technologies, cities are not only improving operational efficiency but also advancing sustainability and circular economy principles.

However, achieving effective waste reduction in urban environments requires a comprehensive understanding of the core drivers of waste generation across supply chains. Inefficiencies in stocking, inventory management, promotional activities, and logistics operations contribute significantly to waste accumulation. By addressing these inefficiencies through AI-driven forecasting, IoT-based real-time tracking, and blockchain transparency, significant reductions in waste can be achieved, leading to better supply chain coordination and enhanced sustainability efforts.

2.1. Stocking and Inventory Management

One of the most significant contributors to waste in urban supply chains is overstocking, particularly in the food, retail, and consumer goods industries. Overstock occurs when inventory levels exceed market demand, often due to inaccurate forecasting, supply chain inefficiencies, and misaligned production strategies. This surplus frequently leads to product expiration, disposal of unsold goods, and financial losses for businesses.

A key driver of overstocking is the reliance on static demand forecasting models that fail to account for market fluctuations, seasonal variations, and external disruptions such as economic downturns or unexpected consumer behavior shifts. Many businesses continue to use historical sales trends to predict demand, which does not always reflect real-time market dynamics, resulting in misalignment between supply and demand. Similarly, retailer-driven promotional strategies contribute significantly to overstocking. Aggressive marketing campaigns often artificially inflate short-term demand, prompting manufacturers to ramp up production. However, once the promotional period ends, the excess inventory remains unsold, eventually leading to waste. The absence of real-time inventory tracking further exacerbates this issue, as businesses lack visibility into actual stock movements, causing inefficiencies in stock rotation and increasing the likelihood of spoilage in the case of perishable goods.

The consequences of overstocking extend beyond economic losses. In industries such as food and pharmaceuticals, where expiration dates dictate product usability, excess inventory often results in significant waste disposal. The environmental footprint of this waste is substantial, contributing to landfill overuse, greenhouse gas emissions, and resource depletion [7]. Additionally, businesses suffering from persistent overstocking face increased storage costs, supply chain bottlenecks, and reduced profitability, making inventory mismanagement a central issue in waste reduction strategies.

To mitigate overstocking and its associated waste, AI-driven inventory management systems and IoT-enabled tracking technologies offer effective solutions. AI-powered forecasting models can analyze historical data, real-time sales patterns, and external variables such as weather conditions or economic indicators to generate dynamic demand predictions, ensuring production scales accurately with market needs. Unlike static models, machine learning algorithms continuously adapt to changes in demand, preventing unnecessary overproduction and reducing the risk of waste accumulation [5].

IoT-enabled smart inventory systems further enhance waste reduction efforts by providing real-time tracking and stock rotation automation. Smart sensors placed in warehouses or retail shelves can monitor product conditions, expiration dates, and stock levels, sending automated alerts when inventory levels exceed optimal thresholds. This allows businesses to take corrective actions such as redistributing excess stock, adjusting pricing strategies, or modifying procurement plans before products become waste. Companies such as Alibaba have successfully implemented AI-driven inventory optimization systems, reducing overall waste by 20%, demonstrating the practical impact of digital inventory management in real-world applications [13].

In addition to AI and the IoT, blockchain technology is playing an emerging role in inventory optimization by enhancing supply chain transparency and traceability. Blockchain-enabled tracking systems allow the real-time documentation of stock movements, reducing inefficiencies and ensuring that waste-related accountability is maintained across all stakeholders. This technology also facilitates supplier coordination, allowing businesses to adopt just-in-time (JIT) inventory models that minimize overproduction and enhance supply chain agility.

The integration of these digital solutions is crucial in making inventory management more sustainable and cost-effective. AI-driven forecasting ensures that production remains aligned with demand trends, while IoT-powered monitoring prevents product expiration and overstock accumulation. The blockchain adds an additional layer of transparency and accountability, ensuring that supply chain inefficiencies are minimized. These innovations collectively contribute to the wider objectives of smart waste management, making supply chains more adaptable, efficient, and environmentally responsible.

2.2. Promotional and Sales Activities

Promotional and sales activities are widely used to boost demand, increase market share, and optimize revenue. However, misaligned promotional strategies often result in overproduction, supply chain inefficiencies, and waste, especially in industries like food, fashion, and consumer goods, where short product life cycles and seasonal fluctuations exacerbate the issue [5].

A key problem is demand miscalculation, where promotions such as discounts or bulk-buy incentives lead to excess stock buildup. Once the promotion ends, unsold inventory, particularly perishable goods, is discarded, contributing to waste [13]. Additionally, multibuy offers encourage over-purchasing, increasing household waste as consumers fail to use all their items before expiration [2].

Promotions also generate environmental and operational inefficiencies. Overproduction increases resource consumption and emissions, while excess stock adds logistical burdens, requiring additional storage, redistribution, and disposal efforts [7].

To reduce waste, businesses are adopting AI-driven predictive analytics, real-time sales tracking, and IoT-enabled forecasting. AI can predict actual market responses, aligning production with demand and preventing overproduction [5]. IoT-enabled sales tracking offers real-time insights into stock movement, allowing for efficient adjustments to inventory and production levels. Retailers like Amazon and Walmart use these technologies to manage inventory and avoid overstocking [13]. The blockchain further enhances transparency, helping businesses track demand fluctuations and adjust production accordingly [2].

By integrating AI, the IoT, and the blockchain, businesses can optimize promotional strategies, ensuring they align with real-time demand and reduce waste. These technologies help companies minimize waste, improve resource efficiency, and promote supply chain sustainability.

2.3. Transportation and Logistics

Efficient transportation and logistics are essential for minimizing waste in urban supply chains, yet inefficiencies in routing, fleet management, and storage contribute significantly to waste generation. Poorly planned transportation schedules often result in underutilized vehicles, excessive fuel consumption, and increased carbon emissions. In industries such as food and pharmaceuticals, improper handling and storage conditions lead to spoilage and product loss, further exacerbating waste levels [2].

A major challenge in logistics waste reduction is rigid routing and scheduling, which fails to adapt to real-time traffic conditions, fluctuating demand, or supply chain disruptions. Traditional fleet management systems often rely on fixed schedules, leading to inefficient collection cycles, delays, and mismanaged deliveries. Additionally, poor warehouse handling and temperature fluctuations during transportation cause significant product deterioration, particularly for perishable goods [7].

To address these inefficiencies, IoT-enabled sensors, AI-driven route optimization, and blockchain-based tracking systems are being deployed across supply chains. IoT technology provides the real-time monitoring of temperature, humidity, and product conditions, enabling early detection of storage or handling issues before waste occurs. AI-powered logistics solutions improve dynamic route planning and fleet utilization, reducing fuel waste and operational costs. Blockchain integration enhances supply chain transparency, ensuring accountability in product handling and movement [6].

Companies like UPS and Amazon have successfully implemented AI-driven logistics systems, achieving significant reductions in emissions, transportation inefficiencies, and supply chain waste. By leveraging smart logistics solutions, businesses can transition from reactive waste management to proactive, data-driven decision-making, optimizing operational sustainability while reducing waste accumulation and environmental impact [13].

2.4. Role of Digital Technologies in Waste Management

Digital technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), and the blockchain, are transforming waste management by enhancing efficiency, transparency, and predictive capabilities throughout supply chains. Traditional waste systems often rely on reactive decision-making and inventory mismanagement, leading to overproduction and unnecessary waste. By integrating these digital tools, organizations can enable real-time monitoring, accurate forecasting, and improved waste tracking, minimizing inefficiencies and boosting sustainability outcomes [2].

AI-driven predictive analytics significantly improve demand forecasting and inventory optimization, helping businesses reduce surplus production. For example, companies like Alibaba have reduced food waste by 20% through AI-enabled planning [13]. IoT-enabled sensors offer real-time monitoring of stock levels and environmental conditions, preventing spoilage and improving inventory control [6]. Blockchain technology enhances supply chain transparency, reducing fraud and optimizing waste disposal. Walmart's blockchain traceability system, for instance, has resulted in a 31% reduction in food waste by improving tracking and handling practices [14].

While these technologies present significant potential for waste reduction, cost and scalability barriers remain, particularly for small businesses and developing cities. However, public–private partnerships and government incentives can facilitate wider adoption [9]. By shifting from reactive waste disposal to proactive waste prevention, digital tools are driving smarter, more sustainable supply chains and advancing circular economy principles, contributing to broader global sustainability goals.

Additionally, data-driven solutions empower urban planners, policymakers, and supply chain managers to make informed, strategic decisions that reduce waste and improve operational efficiency. IoT-enabled real-time monitoring is critical for tracking waste levels, inventory status, and environmental conditions, allowing for dynamic adjustments to waste collection and distribution processes. AI-driven analytics enhance decision-making by analyzing historical data, market trends, and environmental factors, enabling businesses to predict periods of high waste generation and adjust strategies accordingly [13].

Blockchain technology also plays a key role in enhancing transparency and accountability by providing secure, immutable records of waste movements and disposal practices. This ensures regulatory compliance and improves collaboration among stakeholders in urban waste systems [14]. By integrating these technologies, governments and businesses can transition from reactive waste disposal to proactive waste prevention, fostering more efficient, resilient, and sustainable urban waste systems [9].

Beyond storage and logistics, digital technologies offer innovative solutions for waste valorization and the integration of circular economy principles. AI- and IoT-enabled tracking systems allow for the real-time monitoring of waste streams, ensuring that waste is properly classified and directed to the most appropriate repurposing method. These technologies facilitate the following solutions:

AI-driven waste classification, which identifies the composition of food waste and determines whether it is best suited for biogas production, composting, or high-value processing.

IoT-enabled waste monitoring, where sensors track food spoilage and inventory turnover, enabling businesses to redirect surplus food before it becomes waste.

Blockchain technology for waste traceability, ensuring transparency in waste repurposing efforts and tracking waste materials from production to reuse.

By leveraging these technologies, organizations can shift from reactive waste disposal to proactive circular economy solutions, aligning waste management practices with broader sustainability goals.

2.5. Supply Chain Sustainability in Urban Waste Management

The effectiveness of waste management strategies in urban environments is closely tied to the management of extended supply chains. These supply chains span across multiple stages—manufacturing, transportation, storage, and consumption—each of which contributes to waste generation. A significant proportion of waste is produced during the production and distribution phases, often due to poor inventory management and inefficient logistics [15].

The key drivers of supply chain waste include overproduction, inventory misalignment, and promotional activities. Promotions, especially in the retail sector, often lead to overproduction, resulting in unsold goods that are ultimately discarded. This issue is particularly problematic for perishable goods in the food industry, where limited shelf lives and fluctuating demand exacerbate waste levels [5]. Addressing these drivers requires more accurate demand forecasting, real-time inventory tracking, and smarter promotional strategies that align production with actual consumption patterns.

A shift toward circular economy principles can significantly enhance supply chain sustainability by minimizing waste generation and maximizing resource efficiency. Practices such as recycling, upcycling, and the use of sustainable packaging not only reduce waste but also promote long-term sustainability. For instance, Unilever's circular supply chain model, which utilizes 100% recycled plastic in its products, has resulted in a 30% reduction in plastic waste [16]. These circular approaches create a closed-loop system, where waste is viewed as a resource to be reused, helping businesses align their operations with broader sustainability goals.

However, effective waste management in urban supply chains requires collaboration among various stakeholders, including manufacturers, distributors, consumers, and regulatory bodies. Clear communication, shared logistical systems, and coordinated efforts in production scheduling are essential for achieving sustainability goals. When stakeholders work together to streamline operations, waste reduction becomes more attainable [17].

Despite these opportunities, achieving supply chain sustainability is often hindered by conflicting priorities, lack of technological integration, and regulatory constraints. Addressing these challenges requires a multifaceted approach that incorporates policy interventions, technological innovations, and stakeholder collaboration to create resilient, sustainable urban supply chains.

Food Waste Diversity and Its Management Implications

Food waste in urban supply chains is diverse in its composition, requiring tailored handling and processing strategies. Organic waste, such as fresh produce and dairy, decomposes quickly, making it suitable for biogas production or composting. On the other hand, packaged food waste presents greater challenges due to the need to separate plastics, glass, and other materials before recycling. Processed food waste, including meats and prepared meals, can be repurposed through insect-based processing or fermentation, creating alternative protein sources or other value-added products.

Understanding the diversity of food waste is essential for optimizing waste handling strategies and ensuring that materials are diverted toward appropriate circular economy solutions. A data-driven approach to waste classification, supported by AI-powered analytics and IoT-based monitoring, enhances the efficiency of sorting, redistribution, and waste management efforts. This approach helps to reduce dependency on landfills while maximizing resource recovery, turning waste into valuable resources and advancing the principles of sustainability.

2.6. Theoretical Perspectives on Waste Management in Smart Cities

This study employs a combination of four interrelated theories—the Resource-Based View (RBV), Socio-Technical Systems (STS) Theory, Circular Economy (CE) Theory, and Institutional Theory—to develop a comprehensive theoretical framework. This integrated approach provides the foundation for exploring the complexities of waste management in smart cities, focusing on how digital technologies and data analytics can enhance sustainability and urban resilience. By synthesizing these theories, the study aims to examine the interplay between resources, social and technical systems, sustainability principles, and regulatory influences, offering a holistic lens to address the research objectives.

The Resource-Based View emphasizes that a competitive advantage arises from the strategic use of valuable, rare, inimitable, and non-substitutable resources [18]. In the context of smart waste management, this perspective highlights how urban stakeholders, such as municipalities, manufacturers, and supply chain operators, can leverage advanced digital technologies and organizational capabilities to achieve efficiency and sustainability. For instance, AI-driven demand forecasting tools and IoT-enabled waste tracking systems represent critical resources that enhance the responsiveness and precision of urban waste systems [2]. The RBV also explains disparities in the success of waste management initiatives across cities, which often depend on the availability and strategic deployment of these unique resources. By focusing on the identification and enhancement of technological and collaborative assets, the RBV provides a lens to understand the operational advantages of adopting smart waste management practices.

Complementing the RBV, Socio-Technical Systems Theory emphasizes the interplay between social and technical elements within a system, arguing that optimal outcomes are achieved when these components are harmonized [19]. This theory is particularly relevant in a smart city context, where the success of technological interventions depends on their alignment with stakeholder behaviors and societal dynamics. For example, the effective deployment of IoT-enabled waste management systems requires not only technological infrastructure but also public awareness, user-friendly interfaces, and stakeholder collaboration [7]. STS Theory ensures that the integration of technologies into waste systems addresses human and organizational barriers, such as resistance to change or lack of technical expertise. By focusing on the alignment between technical innovations and social practices, this theory underscores the importance of designing systems that are both technologically advanced and socially inclusive.

Circular Economy Theory, which promotes the transition from linear to circular resource flows, aligns directly with the sustainability goals of smart cities. This theory advocates for waste valorization practices such as recycling, composting, and waste-to-energy conversion, which minimize waste and maximize resource efficiency [20]. For instance, the use of anaerobic digestion systems to convert organic waste into biogas and compost illustrates how CE principles can be operationalized to address urban waste challenges [6]. In the context of extended supply chains, CE Theory provides a framework for integrating circular practices at every stage of production and consumption, fostering long-term environmental and economic sustainability. Furthermore, it highlights the role of innovation in designing sustainable packaging and production processes that reduce waste generation at the source. By embedding circularity into urban waste systems, CE Theory contributes to a systemic rethinking of how resources are managed in cities.

Institutional Theory adds another critical dimension to the framework by focusing on the influence of external pressures such as regulations, norms, and societal expectations on organizational behavior [21]. This theory is particularly pertinent to understanding how waste management practices in smart cities are shaped by regulatory frameworks and public policies. International agreements such as the Basel Convention and regional policies like the European Union's Waste Framework Directive compel stakeholders to adopt sustainable practices, including waste minimization and enhanced recyclability [22]. Institutional Theory also provides insight into how societal expectations and cultural factors influence the adoption of digital technologies in waste systems. For example, public demand for greater accountability and transparency has driven the use of the blockchain in tracking waste across supply chains, fostering trust and compliance [14]. By contextualizing technological and organizational strategies within broader institutional frameworks, this theory ensures that the analysis of waste management systems considers external drivers and constraints.

Together, these theories form a cohesive framework that addresses the multi-dimensional nature of smart waste management in urban contexts (Figure 1). The RBV highlights the strategic use of resources, while STS Theory ensures that technological advancements are aligned with human and organizational dynamics. CE Theory provides a sustainability-focused lens, emphasizing waste reduction and resource optimization, and Institutional Theory situates these strategies within regulatory and societal contexts. By integrating these perspectives, the theoretical framework enables a holistic analysis of the drivers, barriers, and outcomes of leveraging digital technologies in urban waste systems. This comprehensive approach not only aligns with the research objectives but also contributes to advancing academic and practical understandings of sustainable waste management in smart cities.

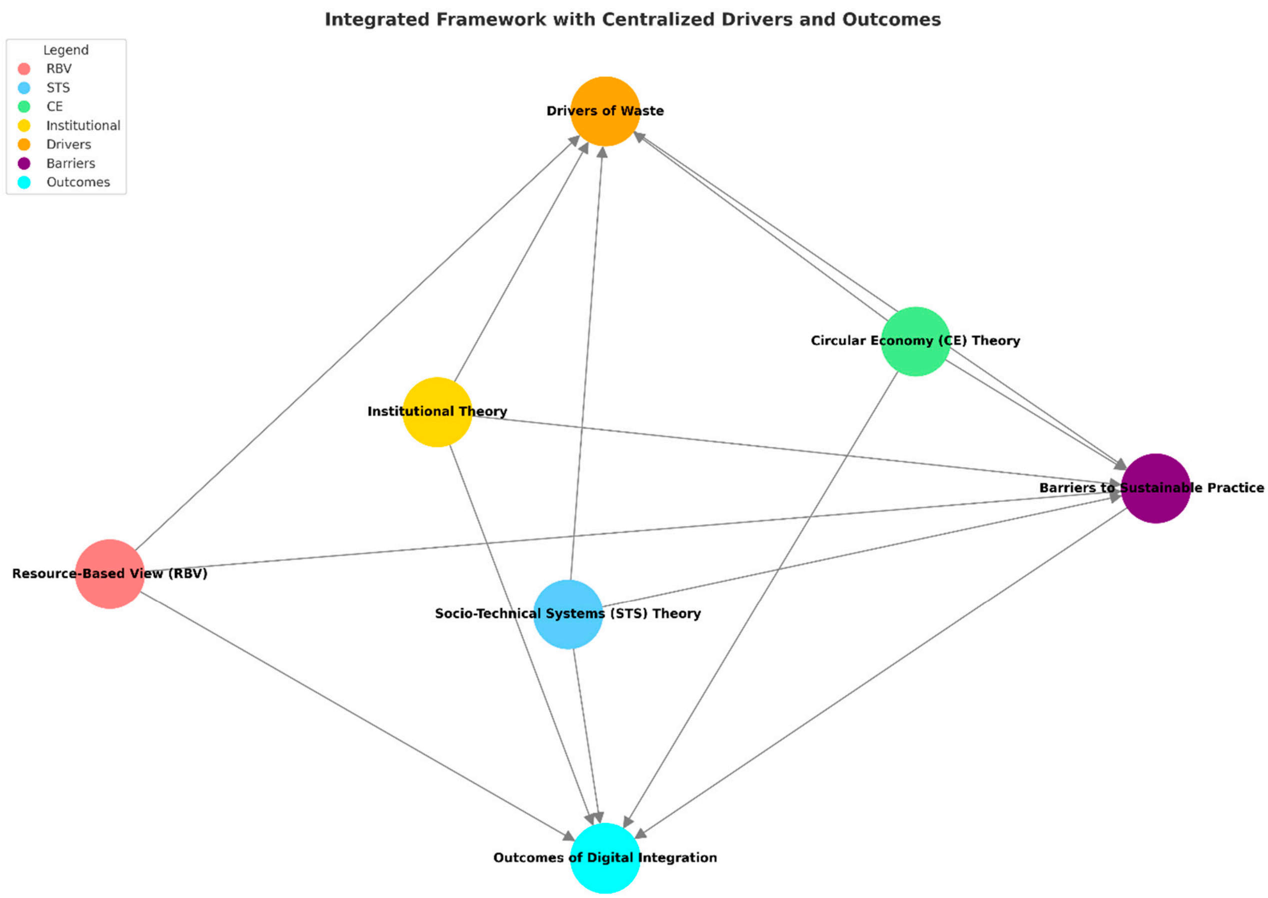

Figure 1. Proposed theoretical framework for smart waste management.

The diagram visually represents the integration of the four theories—the Resource-Based View (RBV), Socio-Technical Systems (STS) Theory, Circular Economy (CE) Theory, and Institutional Theory—into a cohesive framework. Each theory contributes to the "Integrated Framework," emphasizing their interconnected roles in addressing smart waste management challenges in urban contexts.

2.7. Digital Technologies for Emission Reduction in Urban Supply Chains

Urban waste systems are significant contributors to greenhouse gas (GHG) emissions, particularly methane from organic waste decomposing in landfills. According to the United Nations Environment Programme [10], food waste alone accounts for 8–10% of global

GHG emissions, making it a critical area for intervention. In smart cities, the application of digital technologies offers transformative potential for emission reduction across extended supply chains.

Artificial Intelligence (AI) and Internet of Things (IoT) technologies enable the precise tracking of waste generation and emissions at every stage of the supply chain. IoT-enabled sensors monitor the temperature and humidity of perishable goods in real time, reducing spoilage during storage and transportation [2]. Similarly, blockchain technology creates transparent, immutable records of waste movement, helping to identify emission hotspots and fostering accountability among stakeholders [14].

Furthermore, smart cities have begun to integrate waste management with other urban systems, such as energy and mobility. For instance, Amsterdam's waste-to-energy facilities not only reduce landfill dependency but also provide district heating for thousands of homes, demonstrating the potential of circular solutions to lower emissions while enhancing urban efficiency [7]. However, scaling such initiatives across cities remains challenging due to high initial investments and varying levels of technological adoption.

Despite these obstacles, the potential of digital technologies to revolutionize urban waste management and significantly reduce emissions cannot be overstated. These tools align with the broader sustainability objectives of smart cities, supporting the transition to low-carbon, resource-efficient urban systems.

3. Methodology

This study employs a quantitative approach to examine the transformative role of digital technologies and data analytics in urban waste management within smart cities. The research focuses on Company A, a UK-based food manufacturer, and Retailer B, a major UK retailer, providing a real-world application of smart waste management technologies. This case study enables a detailed analysis of how AI, the IoT, and data-driven decision-making impact waste reduction, operational efficiency, and supply chain sustainability.

The analysis was structured around key assumptions and system boundaries. It assumed that IoT sensor data and AI-generated insights were accurate and representative of typical operational conditions across different stages of the supply chain. Furthermore, it presumed that digital technologies were fully integrated into Company A's and Retailer B's infrastructure, without major adoption barriers or technical disruptions. The scope of the study was confined to three key supply chain stages: production, inventory management, and transportation.

A quantitative analysis was conducted on Company A and Retailer B's operational records spanning from January 2022 to December 2023. The dataset included the following:

- Inventory records, identifying overstocking trends and supply–demand mismatches.
- Sales forecasts and promotional activities, assessing their influence on surplus production and waste.
- Waste logs, documenting waste patterns across different supply chain stages.
- IoT sensor data, monitoring storage conditions and transportation efficiency.

By leveraging this dataset, the study applies a multi-method analytical framework, integrating statistical analysis, machine learning techniques (Gradient Boosting Regressor, Neural Networks), and optimization models. Machine learning models were utilized to identify non-linear relationships between operational inefficiencies and waste generation, while IoT-enabled algorithms optimized waste collection and transportation routes to enhance efficiency.

Given the increasing regulatory pressures and consumer demand for sustainable practices in the UK's urban food supply chain, this study provides data-driven insights into how digital transformation can drive waste reduction, sustainability, and supply chain optimization.

3.1. Advanced Statistical and Computational Methods

To rigorously examine waste drivers and their relationships to waste generation, this study employed a combination of emissions calculations, machine learning (ML), deep learning (DL), and optimization algorithms to derive predictive insights and enhance waste management strategies:

3.1.1. Emissions Calculation

The environmental impact of waste was quantified using the waste-type-specific method, as follows:

$$E = W \times EFE \tag{1}$$

where

- E: Total emissions (CO_2-equivalent emissions).
- W: Waste produced by type (e.g., tonnes, m^3).
- EFE: Emission factor for specific waste types (e.g., kg CO_2/tonne for cardboard or food waste).

This methodology quantified greenhouse gas (GHG) emissions based on the composition of waste materials, with each waste type (e.g., organic food waste, plastic, paper, or metal) assigned a specific emission factor (EF) to assess environmental impact. The results guided the selection of sustainable waste management strategies, prioritizing low-emission interventions.

3.1.2. Machine Learning (ML) Application

To predict waste generation and identify key contributing factors, this study employed two primary models: the Gradient Boosting Regressor (GBR) model and a Feedforward Neural Network (FNN).

The GBR model was selected due to its ability to capture non-linear relationships between multiple waste drivers, such as overstocking, inventory mismanagement, and transportation inefficiencies. GBR's feature importance analysis enhances interpretability, helping businesses pinpoint the most significant contributors to waste. Unlike simpler regression models (e.g., logistic regression), which assume linearity and are more suitable for classification tasks, GBR effectively models complex interactions in structured supply chain data.

The performance of the ML model was evaluated using the coefficient of determination (R^2), calculated as follows:

$$R^2 = 1 - \Sigma(yi - \hat{y}i)^2/\Sigma(yi - y^-)^2 \tag{2}$$

where

- yi: Actual waste values.
- $\hat{y}$i: Predicted waste values.
- y^-: Mean of actual waste values.

The GBR model achieved a high R^2 value of 0.87, indicating strong predictive accuracy in explaining variance in waste generation.

3.1.3. Deep Learning (DL) Application

A Feedforward Neural Network (FNN) was implemented to further enhance waste prediction accuracy by learning intricate non-linear dependencies between waste variables. Unlike more complex models such as transformers, which are optimized for sequential or natural language tasks, FNNs offer computational efficiency and stability for structured tabular data, making them well-suited for supply chain analytics. The controlled architecture of the FNN also ensures faster convergence and lower computational overhead compared to deep transformer-based architectures, which require extensive data preprocessing and fine-tuning.

- Architecture: The FNN consisted of two hidden layers with 64 and 32 neurons, each using ReLU activation to enhance learning efficiency. Dropout layers (20%) were incorporated to mitigate overfitting.
- Training Process: The model was trained over 100 epochs, using a batch size of 32 and the Adam optimizer for adaptive learning
- Evaluation: The DL model achieved an R2 value of 0.87 on the test dataset, which was comparable to the ML model but provided enhanced performance for non-linear relationships.

3.1.4. Optimization Algorithms

An IoT-enabled optimization model was implemented to minimize waste collection costs and enhance logistics efficiency. The optimization problem was formulated as follows:

$$min \sum_{i=1}^{n} c_i d_i$$

Subject to

$$\sum x_{ij} = 1,\ \forall \text{j} \tag{3}$$

This means that for **every** location jjj , exactly one vehicle iii must be assigned.

$$\sum x_{ij} \leq C,\ \forall \text{i}$$

This means that for **every** vehicle iii , the total number of assigned locations should not exceed its capacity CCC.

where

- C_i: Collection cost per waste unit.
- d_i: Distance traveled for waste collection.
- x_{ij}: Binary variable indicating waste collection from location j by vehicle i.
- C: Capacity constraints of collection vehicles.

This approach enabled the dynamic routing of waste collection vehicles, reducing redundant trips and improving operational efficiency.

3.2. Data Processing and Visualization

To ensure the accuracy, reliability, and interpretability of the data, several preprocessing steps were undertaken. Data cleaning was performed to handle missing values and remove duplicates, ensuring dataset integrity. Missing values were addressed using statistical imputation techniques, minimizing the risk of skewed analysis [23]. Additionally, outlier detection was carried out using the Interquartile Range (IQR) method, allowing for the identification and removal of extreme values that could distort the results. By refining the dataset, the study ensured that the models were trained on high-quality, representative data.

Following data cleaning, standardization was applied to improve model performance. Since machine learning and deep learning models are sensitive to differences in scale, features were normalized using z-score scaling, a technique that ensures all variables have a mean of zero and a standard deviation of one. This preprocessing step facilitated efficient model convergence and improved predictive accuracy.

Once the data were processed, various visualization techniques were employed to facilitate interpretation and enhance the communication of key insights. Feature importance rankings were generated to identify the most influential variables in waste generation. Furthermore, predictive performance graphs, including residual plots and performance curves, were used to evaluate model accuracy and validate results. In addition, trend analysis was conducted to explore correlations between waste generation patterns and operational inefficiencies, allowing for a deeper understanding of how different supply chain variables impact waste levels.

To enhance clarity and accessibility, the study utilized data visualization tools such as Matplotlib (3.8.2) and Seaborn (0.13.1) to create intuitive graphical representations of waste generation trends, feature importance rankings, and predictive model outputs. These visualizations played a crucial role in making complex findings more comprehensible for decision-makers, enabling the identification of key areas for intervention and optimization. By integrating advanced statistical analysis with effective data representation, this study provides a robust methodological foundation for improving waste management strategies in urban food supply chains.

3.3. Integrating Findings

By combining advanced statistical methods, machine learning, deep learning, and real-time IoT and blockchain data, this study provides a robust framework for understanding the role of digital technologies in sustainable waste management. The interdisciplinary methodological approach aligned with the study's aim to address the intersection of technology, sustainability, and urban resilience. The case study of Company A served as a practical lens to explore broader smart city applications, offering actionable insights for urban planners, policymakers, and supply chain managers.

4. Data Analysis and Findings

This section presents the refined findings derived from Company A's operational data, emphasizing the transformative impact of digital technologies on waste management. The results provide critical insights into key waste drivers, the role of advanced analytics in waste reduction, the environmental benefits of improved waste management, and the operational efficiencies gained within extended urban supply chains. These findings closely align with the study's research objectives and are substantiated by empirical data and relevant figures.

The analysis of Company A's production and inventory management records reveals that inefficiencies in forecasting and stock control significantly contribute to waste generation. Overstocking remains a persistent issue, with fluctuations in stock levels leading to frequent product disposal. Inaccurate demand predictions result in surplus production, which, coupled with mismanaged inventory rotation, causes perishable items to expire before reaching consumers. Data captured from IoT-enabled sensors provides real-time insights into inventory accumulation, highlighting patterns of waste emergence and opportunities for optimizing stock replenishment cycles. The integration of data-driven monitoring has demonstrated improvements in identifying waste trends and adjusting production accordingly, reducing inefficiencies that stem from overproduction.

Similarly, Retailer B's sales and promotional data illustrate the substantial impact of marketing activities on supply chain stability. Promotional campaigns often generate short-term spikes in demand, leading to overstocking as suppliers increase production in anticipation of sustained high sales volumes. However, as promotions end, sales frequently return to normal or decline, leaving excess inventory unsold. Forecasting discrepancies exacerbate this misalignment, disrupting coordination between production and retail operations. Retailer B's inventory records further demonstrate that significant volumes of unsold stock accumulate post-promotional-periods, reinforcing the necessity for real-time demand forecasting models that align promotional strategies with actual consumption patterns.

By integrating AI-driven predictive analytics, IoT-enabled monitoring, and data-driven decision-making, both Company A and Retailer B can address structural inefficiencies in supply chain operations. The findings demonstrate that adopting digital waste management strategies enables better inventory control, optimizes stock levels, and minimizes waste accumulation, ultimately enhancing sustainability in urban food supply chains.

4.1. Overview of Waste Generation in Extended Urban Supply Chains

The analysis of Company A's supply chain operations identified several key inefficiencies contributing to waste generation. Overstocking emerged as the most prominent driver, accounting for 35% of total waste, primarily due to static demand forecasting that failed to adapt to market fluctuations. Inventory mismanagement, which led to limited visibility and coordination failures across the supply chain, was the second-largest contributor (30%). Meanwhile, Retailer B's promotional activities were identified as a major factor, driving 20% of waste generation due to aggressive sales strategies that prioritized short-term revenue over sustainability. Additionally, transportation inefficiencies, including suboptimal routing and poor vehicle utilization, accounted for 15% of the total waste.

These findings highlight the systemic nature of waste generation in urban food supply chains, with misalignment between supply and demand creating cascading inefficiencies. Overstocking and inventory mismanagement at Company A's production facilities were directly linked to fluctuating promotional activities initiated by Retailer B, exacerbating waste generation and logistics inefficiencies. As shown in Figure 2, digital technologies led to significant reductions in waste for each of these drivers, addressing the core inefficiencies in the system.

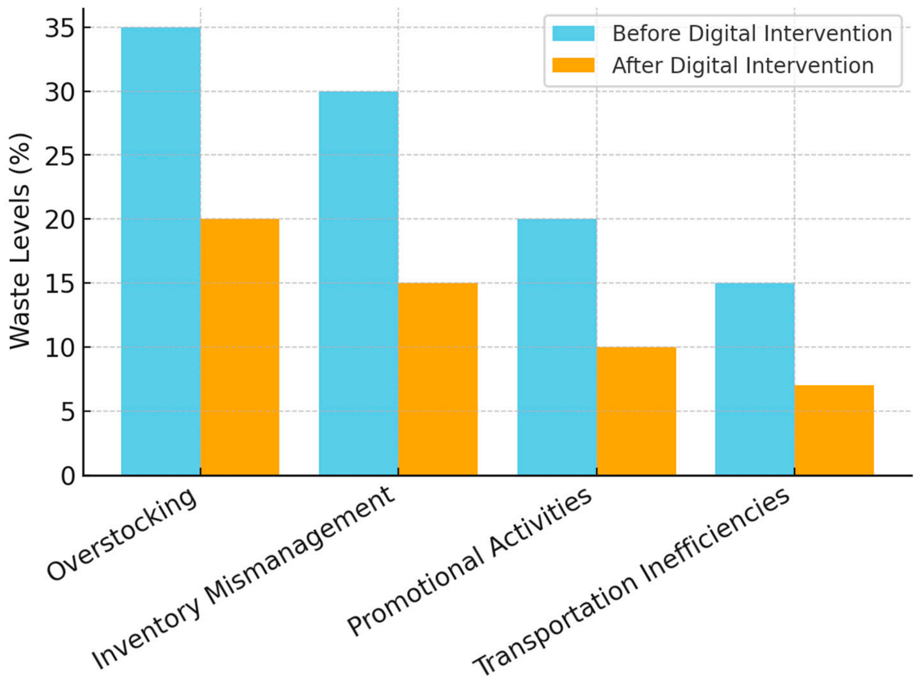

Figure 2. Distribution of waste by source, and reductions achieved.

4.2. Impact of Digital Technologies on Waste Reduction

The implementation of IoT and AI technologies led to substantial reductions in waste across all major categories, as depicted in Figure 3. Overstocking decreased by 43% due to the introduction of AI-enabled demand forecasting systems, which provided more accurate predictions of market demand and prevented surplus production. Inventory mismanagement saw a 50% improvement through IoT sensors that offered real-time visibility into stock levels, enabling dynamic adjustments to replenishment schedules. Promotional waste experienced the most dramatic reduction, dropping by 60%, as AI-driven analytics tailored promotional campaigns to specific consumer segments, minimizing overproduction. Transportation inefficiencies also decreased by 60%, with IoT-enabled route optimization systems streamlining vehicle utilization and reducing redundant trips.

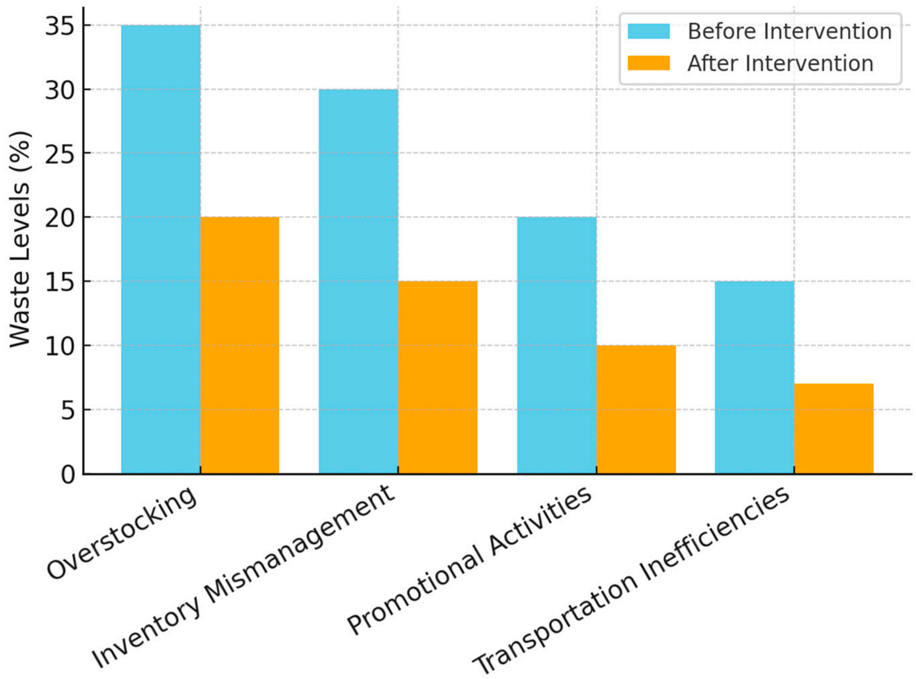

Figure 3. Comparative analysis of waste levels before and after digital intervention.

These results underscore the transformative potential of the IoT and AI in addressing inefficiencies in waste management. By enabling real-time monitoring and predictive capabilities, these technologies have not only reduced immediate waste but have also set the stage for long-term sustainability in urban supply chains.

4.3. Efficiency Gains in Waste Collection over Time

The integration of IoT-enabled waste collection systems yielded significant operational improvements over a four-week period. As shown in Figure 4, the system reduced redundant trips from 10 to 5 per week while increasing time savings from 10 to 15 h per week. These efficiencies were achieved by replacing static collection schedules with dynamic routing based on real-time data from IoT sensors installed in waste bins.

This dynamic routing allowed collection teams to prioritize high-need areas, reducing overflow incidents and improving resource allocation. The results highlight the effectiveness of real-time data in streamlining logistics and enhancing operational performance in waste management systems.

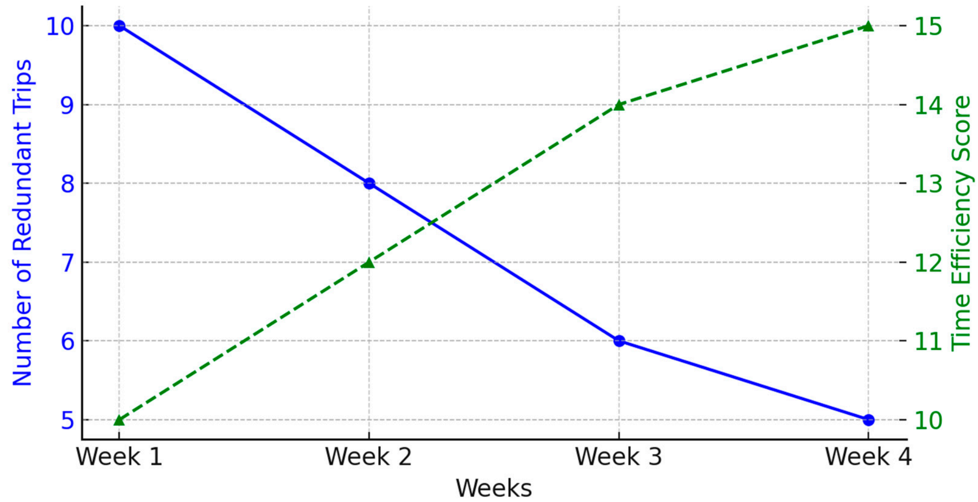

Figure 4. Weekly waste optimization using IoT.

4.4. Correlation Between Overstocking and Waste Generation

A strong positive correlation (r = 0.91) was observed between overstocking levels and waste generation, as illustrated in Figure 5. The analysis showed that increases in overstocking directly led to higher levels of waste, particularly in the case of perishable goods, where spoilage rates were significantly higher. A temporal lag of one to two weeks was identified, reflecting the time required for surplus inventory to transition into waste.

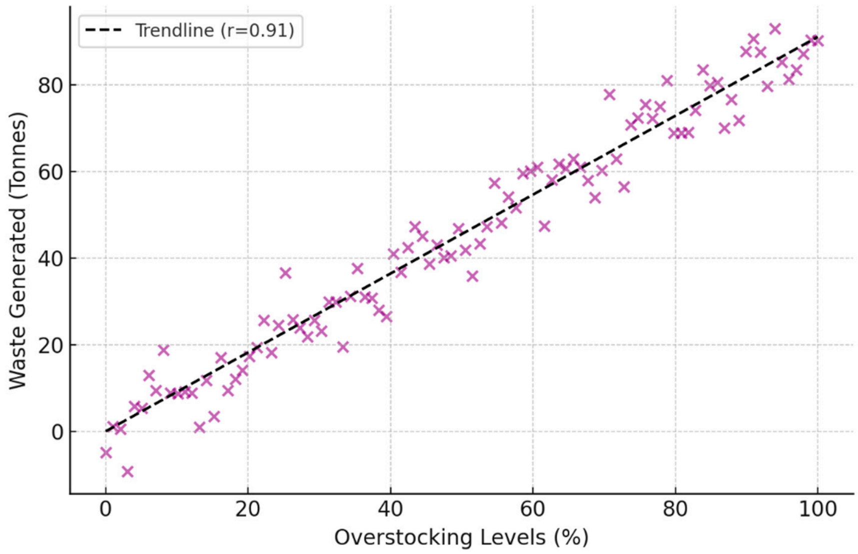

Figure 5. Correlation between overstocking and waste generation.

This relationship underscores the need for upstream interventions to mitigate overstocking and its downstream consequences. Predictive analytics and automated inventory management systems can address these inefficiencies by aligning stock levels more closely with actual demand, preventing the cascading effects that lead to waste.

4.5. Reduction in Carbon Emissions Through Optimized Collection

The environmental benefits from the IoT-enabled waste collection system are depicted in Figure 6, which compares carbon emissions before and after optimization. Fuel consumption decreased by 33%, driven by optimized routing that reduced travel distances. Transportation-related emissions dropped by 40%, reflecting the efficient utilization of vehicles. Operational emissions showed the most substantial improvement, with a

50% reduction due to the elimination of redundant processes and the better allocation of resources.

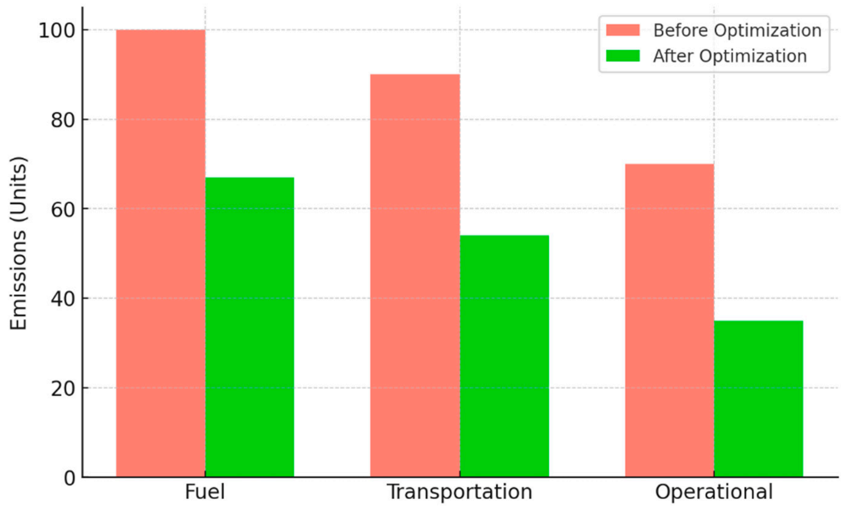

Figure 6. Reduction in carbon emissions through optimized collection.

These findings demonstrate the dual benefits of cost efficiency and environmental sustainability. By minimizing fuel usage and optimizing logistics, the IoT-enabled system contributes to broader sustainability objectives, such as reducing greenhouse gas emissions in alignment with the UN's Sustainable Development Goals.

4.6. Comparative Performance of Predictive Models

The performance of predictive models for waste generation was evaluated using R-squared ($R^2R^2R^2$) values, as shown in Figure 7. Traditional regression models achieved an $R^2R^2R^2$ value of 0.70, highlighting their limitations in capturing complex relationships between waste drivers. Gradient Boosting models improved accuracy significantly, achieving an $R^2R^2R^2$ value of 0.87. Deep learning models outperformed both, with an $R^2R^2R^2$ value of 0.91, demonstrating their ability to model non-linear interactions and intricate patterns in the data. This comparative analysis underscores the value of advanced AI techniques for waste prediction in complex and dynamic environments. The superior performance of the deep learning models highlights their potential to support data-driven decision-making in waste management.

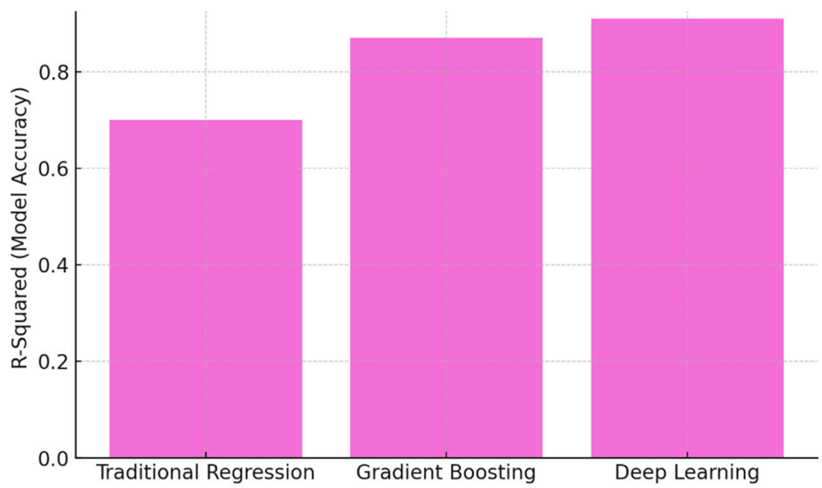

Figure 7. Predictive model accuracy for waste generation.

5. Discussion

The findings from the analysis of Company A's waste management systems offer invaluable insights into the transformative potential of digital technologies and data analytics in tackling urban waste challenges. By situating these findings within the theoretical frameworks of the Resource-Based View (RBV), Socio-Technical Systems (STS) Theory, Circular Economy (CE) Theory, and Institutional Theory, this discussion further enriches our understanding of how organizations can leverage digital innovation to improve sustainability, operational efficiency, and resilience.

The study demonstrates that the adoption of Artificial Intelligence (AI) and Internet of Things (IoT) technologies can substantially reduce waste in food supply chains by optimizing demand forecasting, inventory management, and logistics. However, since this research was based on a single case study within the food production sector, further research is needed to explore the applicability of these digital interventions across other industries and urban waste systems. Investigating how similar technological frameworks could be integrated into sectors such as construction or municipal waste management would provide deeper insights into the scalability and adaptability of these solutions.

5.1. Addressing Systemic Inefficiencies in Urban Supply Chains

Overstocking and inventory mismanagement emerged as the primary drivers of waste, contributing 35% and 30% to total waste generation, respectively. These inefficiencies reflect deeper systemic misalignments within supply chain operations. The RBV offers a valuable perspective in interpreting these findings, as it emphasizes the strategic importance of unique resources in gaining competitive advantage [18]. At Company A, the implementation of IoT sensors and AI-driven analytics proved to be valuable, rare, and inimitable changes, enabling the company to achieve a 43% reduction in overstocking and a 50% improvement in inventory management.

The cascading effects of inefficiencies, such as increased spoilage and storage costs due to overstocking, highlight the interconnected nature of supply chain operations. This resonates with STS Theory, which underscores the interdependence between technological tools and organizational practices [19]. While IoT sensors provided real-time visibility into inventory levels, their effectiveness depended on the organization's capacity to act on the data in a timely manner. The observed 1–2-week delay between overstocking and waste generation, as shown in Figure 5, highlights the need for adaptive decision-making processes that integrate both social and technical components seamlessly.

Seasonal Demand Fluctuations and Overcoming Challenges in Waste Reduction

The analysis reveals that overstocking remains a major driver of waste generation in food supply chains, particularly during seasonal demand fluctuations. Seasonal peaks, such as holiday periods and promotional campaigns, often lead to inaccurate demand forecasting, resulting in excess inventory and increased waste levels. AI-driven predictive analytics and real-time inventory tracking using IoT sensors can enable businesses to adjust production and supply chain strategies dynamically, reducing surplus stock and preventing unnecessary waste.

In less-developed cities and small businesses, implementing sophisticated AI and IoT solutions may present challenges due to financial constraints, infrastructure limitations, and a lack of digital expertise. However, alternative low-cost approaches—such as rule-based forecasting models, mobile inventory tracking applications, and cloud-based supply chain management systems—offer scalable solutions for waste reduction without requiring extensive technological investment. Additionally, collaborative platforms for resource-sharing among small retailers and suppliers can reduce procurement inefficiencies, ensuring that surplus stock is redistributed rather than wasted.

Comparing these findings to previous research on waste management technologies, our study aligns with prior models demonstrating the effectiveness of AI and the IoT in optimizing food supply chain sustainability [2,6]. However, unlike earlier studies that primarily focus on static predictive models, our results emphasize the importance of real-time digital interventions, highlighting how adaptive decision-making frameworks can significantly enhance waste reduction efforts in dynamic supply chain environments.

These findings reinforce the potential of data-driven waste management strategies while also highlighting the need for context-specific adaptation based on technological accessibility, financial capacity, and industry scale. By integrating flexible, real-time monitoring solutions, businesses across diverse economic landscapes can enhance supply chain efficiency and minimize waste generation.

5.2. The Role of Digital Technologies in Sustainability

The integration of IoT and AI technologies at Company A not only reduced waste but also generated significant environmental benefits, aligning with the principles of Circular Economy (CE) Theory. CE Theory emphasizes resource efficiency, waste minimization, and the transition from linear to circular resource flows [20]. The findings revealed that promotional waste and transportation inefficiencies were each reduced by 60%, as AI-driven analytics optimized promotional strategies and IoT-enabled systems streamlined logistics. These reductions, illustrated in Figure 3, emphasize the role of digital tools in fostering circular resource use by minimizing overproduction and optimizing transportation routes.

Additionally, the environmental benefits quantified in this study underscore the broader sustainability impacts of digital transformation. For instance, a 33% reduction in fuel consumption, a 40% decrease in transportation-related emissions, and a 50% reduction in operational emissions were achieved through optimized routing and improved resource allocation, as demonstrated in Figure 6. These outcomes support the core tenets of CE Theory, which advocate for reducing the environmental footprint of operations through closed-loop systems. Furthermore, the reductions in carbon emissions align with policy-driven goals such as the European Union's Waste Framework Directive, which mandates sustainable waste management practices [22]. This synergy between technological innovation and regulatory frameworks exemplifies Institutional Theory, which underscores the influence of external pressures on organizational behavior [21].

5.3. Operational Efficiencies and Urban Resilience

The operational efficiencies realized through IoT-enabled waste collection systems exemplify the practical application of Socio-Technical Systems (STS) Theory. By dynamically adjusting collection routes based on real-time data, Company A saved an average of 12 h per week, as illustrated in Figure 4. These efficiencies underscore the symbiotic relationship between technology and human decision-making, where IoT systems deliver actionable insights that optimize logistics and resource allocation. The capacity to adapt collection schedules in response to real-time conditions not only improves operational performance but also enhances urban resilience. As adaptive waste systems become increasingly capable of handling fluctuations in waste volumes and responding to emergencies, they contribute to the robustness of urban supply chains, enhancing their ability to withstand and recover from disruptions [24].

Beyond improving operational efficiency, the proposed system's responsiveness to external disruptors is essential for ensuring its long-term resilience. The integration of digital technologies, such as AI, the IoT, and the blockchain, enables real-time monitoring and predictive analytics, allowing the system to adjust dynamically to changing conditions [25]. However, in the event of force majeure events, such as natural disasters, supply chain disruptions, or economic crises, the system's agility would be tested. For instance, if an unforeseen logistical delay or production halt occurs, the system's ability to accurately forecast demand and adjust inventory or production schedules can help minimize the impact on waste generation. Moreover, IoT sensors can swiftly detect anomalies, enabling real-time adjustments to waste collection schedules or distribution routes. The effectiveness of these adjustments, however, depends on data availability, the degree of technology integration, and stakeholder coordination, highlighting the importance of collaboration and flexibility in mitigating the effects of such disruptions.

From a Resource-Based View (RBV) perspective, these operational efficiencies highlight the strategic value of IoT sensors as unique resources that enhance an organization's ability to respond dynamically to logistical challenges. However, the scalability of these systems remains a significant challenge, especially in cities with limited access to digital infrastructure. Institutional Theory emphasizes the critical role of policy frameworks in overcoming these barriers. It suggests that policy-driven incentives can promote technological adoption and foster collaboration among stakeholders. For example, policies promoting extended producer responsibility can incentivize organizations to adopt more sustainable practices, while international agreements such as the Basel Convention provide a global impetus for waste reduction and resource recovery.

In certain urban contexts, the implementation of smart waste management systems may encounter disruptions if the system cannot update routes dynamically due to external factors such as infrastructure limitations, severe weather conditions, or sudden fluctuations in waste volumes. These disruptions could lead to setbacks in operational efficiency, as previously planned routes may no longer be optimal. However, improvements in other criteria, such as real-time data processing and predictive analytics, may mitigate these challenges by enabling flexible adjustments that maintain system performance. Furthermore, the introduction of agile decision-making frameworks and real-time route adjustments could further enhance the system's responsiveness to such challenges, ensuring minimal disruption to waste management operations and reinforcing urban resilience.

5.4. Challenges of Scalability, Integration, and Model Stability

While digital technologies have transformed waste management at Company A, their scalability, integration, and stability remain key challenges. Socio-Technical Systems (STS) Theory highlights the need for alignment between digital tools and organizational practices [19], requiring substantial investments in infrastructure, workforce training, and capacity building [7]. In resource-limited settings, such investments pose barriers to adoption, restricting scalability.

Institutional Theory suggests that regulatory pressures shape adoption, with policies such as the UK's Waste and Resources Strategy, the EU Green Deal, and EPR policies creating compliance requirements that drive digital adoption [21,22]. However, inconsistent regulations introduce variability, affecting model stability and predictive accuracy [9]. Additionally, shifting consumer preferences for minimal packaging, organic sourcing, and food traceability alter waste patterns, requiring frequent recalibration of predictive models [4].

Addressing these challenges necessitates adaptive waste management frameworks that integrate regulatory flexibility, evolving consumer trends, and cost-effective implementation strategies.

5.4.1. Addressing Scalability and Implementation in Resource-Constrained Environments

AI-driven waste management solutions face significant adoption barriers in less-developed cities and small businesses, including digital infrastructure deficits, financial constraints, and weak regulatory enforcement [2]. Limited access to the IoT, cloud computing, and machine learning capabilities prevent real-time waste monitoring, while high costs make advanced digital solutions unaffordable [3,5].

A more pragmatic approach involves deploying low-cost AI models that operate on mobile devices rather than high-end cloud platforms [13]. Similarly, mobile-based waste tracking systems using QR codes or barcode scanning offer an accessible alternative to IoT-based monitoring [6]. Collaborative resource-sharing models, such as waste reduction cooperatives and pooled logistics, can enhance efficiency where infrastructure is weak [9]. Furthermore, public–private partnerships (PPPs) can provide financial support, ensuring that small businesses can access digital waste solutions without bearing the full cost [5].

5.4.2. Enhancing Model Stability in Dynamic Markets

Ensuring the long-term stability of AI-driven waste models requires adaptability to regulatory shifts, consumer trends, and market dynamics. Regulatory adaptation mechanisms can be embedded into AI models to track evolving policies and enable dynamic recalibration [21]. Using modular AI architectures, businesses can swiftly update compliance frameworks in response to new sustainability mandates [22].

To maintain consumer-driven accuracy, reinforcement learning can help AI models adjust predictions in real time based on changing market behaviors, such as increased demand for plant-based products or stricter transparency expectations [4]. Additionally, scenario-based forecasting models can simulate the impact of varying regulatory intensities and government interventions, enabling businesses to anticipate waste management challenges [9]. Collaboration with policymakers, industry stakeholders, and technology developers through regulatory sandboxes can further refine AI-driven waste prediction tools [17].

By integrating regulatory flexibility, consumer sensitivity analysis, and scenario forecasting, businesses can enhance the resilience and scalability of AI-driven waste models, ensuring they remain viable despite evolving market and policy conditions.

5.5. Spatial Considerations in Waste Management and Comparative Contexts

The effectiveness of digital waste management is shaped by urban infrastructure, regulatory enforcement, and socio-economic conditions [17]. In developed cities like London, Amsterdam, and Singapore, strong regulatory frameworks, digital infrastructure, and governmental support facilitate the seamless adoption of AI, the IoT, and blockchain-based waste tracking [9]. These cities benefit from high-speed connectivity, real-time waste monitoring, and AI-powered analytics, enhancing waste management efficiency.

Conversely, less-developed cities such as Jakarta, Lagos, and Dhaka face infrastructure deficits, inconsistent regulatory enforcement, and financial constraints [5]. Many lack centralized waste management policies, making AI-driven solutions less effective [17]. In these environments, mobile-based tracking systems, decentralized waste collection, and alternative financing models can improve adoption. Governments can facilitate policy incubation through public–private partnerships (PPPs) and introduce micro-financing schemes to support businesses investing in AI-driven waste solutions [14].

By tailoring digital waste management models to the specific infrastructure, regulatory, and financial realities of different urban settings, these solutions can be made more scalable, equitable, and effective across diverse environments [5].

6. Conclusions

This study examined the transformative role of digital technologies and data analytics in urban waste management, focusing on extended supply chains within smart cities. Through an in-depth analysis of Company A and its collaboration with Retailer B, the research demonstrated how integrating digital innovations, such as IoT, AI, and the blockchain, can enhance waste reduction efforts, optimize operational efficiency, and mitigate environmental impacts. By embedding these insights within a comprehensive theoretical framework, the study advances the understanding of systemic inefficiencies in urban supply chains while aligning with broader sustainability and resilience objectives.

The integration of digital waste management solutions was explored through the lens of the Resource-Based View, Socio-Technical Systems Theory, Circular Economy Theory, and Institutional Theory. The Resource-Based View highlights the strategic advantage of leveraging data-driven technologies to enhance waste management practices and create long-term value. Socio-Technical Systems Theory underscores the interplay between technological innovations and organizational decision-making, demonstrating the importance of aligning digital solutions with operational structures to ensure efficiency. Circular Economy Theory contextualizes the study within sustainability principles, emphasizing waste minimization and the shift towards closed-loop supply chains. Institutional Theory provides a regulatory perspective, illustrating how external pressures, such as governmental policies, environmental mandates, and industry regulations, shape the adoption of digital waste management solutions. Together, these theories contribute to a holistic understanding of how technology-driven interventions can reshape urban waste management.

From a practical perspective, the findings offer critical insights for urban planners, policymakers, and supply chain managers seeking to transition towards more sustainable and efficient waste management systems. The implementation of IoT-enabled sensors and AI-driven analytics demonstrated tangible benefits in improving inventory management, reducing unnecessary waste, and enhancing transportation efficiency. These improvements not only contribute to cost savings but also support environmental sustainability by reducing emissions and optimizing resource use. By shifting from reactive waste disposal strategies to proactive, data-driven waste prevention, organizations can achieve significant operational efficiencies while contributing to broader circular economy objectives.

Policymakers play a crucial role in fostering an enabling environment for digital waste management adoption. Regulatory incentives, industry standards, and public–private partnerships can help overcome barriers related to resource constraints, technological adoption, and system integration. Existing frameworks, such as the European Union's Waste Framework Directive and Extended Producer Responsibility policies, provide essential guidelines for promoting sustainable waste management practices. Additionally, international agreements such as the Basel Convention highlight the need for coordinated efforts to align waste reduction strategies with global sustainability goals. By strengthening policy support and encouraging cross-sector collaboration, governments and businesses can accelerate the transition towards digitally enabled waste management systems.

Despite this study's contributions, its findings are inherently context-specific and may not be directly generalizable to all industries or urban settings. The scalability of digital technologies in waste management depends on various factors, including infrastructure readiness, regulatory landscapes, and stakeholder cooperation. Further research is needed to assess how these technologies can be adapted across different sectors, such as retail, pharmaceuticals, and municipal waste systems, where waste generation dynamics may vary. Additionally, investigating the impact of regional differences in digital infrastructure and policy enforcement will provide a deeper understanding of the factors influencing successful implementation.

To build on the insights presented in this study, future research should explore emerging technologies, such as the blockchain, robotics, and machine learning models, which have the potential to enhance transparency, accountability, and resource recovery in waste management. Blockchain can improve traceability across supply chains, fostering trust and collaboration among stakeholders, while robotics can automate waste sorting and handling, further reducing inefficiencies. Longitudinal studies examining the sustained impact of digital tools on urban resilience and sustainability would also provide valuable empirical evidence to support policy development and practical implementation strategies.

By addressing these areas, future research can further refine and expand the integration of digital technologies in waste management, ensuring that cities and businesses adopt more efficient, resilient, and sustainable waste reduction strategies.

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References

1. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015.
2. Kamble, S.S.; Gunasekaran, A.; Dhone, N.C. Industry 4.0 and lean manufacturing practices for sustainable organizational performance in Indian manufacturing companies. *Int. J. Prod. Res.* **2020**, *58*, 1319–1337. [CrossRef]
3. Lipianina-Honcharenko, K.; Komar, M.; Osolinskyi, O.; Shymanskyi, V.; Havryliuk, M.; Semaniuk, V. Intelligent waste-volume management method in the smart city concept. *Smart Cities* **2024**, *7*, 78–98. [CrossRef]
4. FAO. *The State of Food and Agriculture: Moving Forward on Food Loss and Waste Reduction*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2019.
5. Brusset, X.; Teller, C. Supply chain capabilities, risks, and resilience. *Int. J. Prod. Econ.* **2017**, *184*, 59–68. [CrossRef]
6. Dora, M.; Kumar, M.; Gellynck, X. Digital technologies and waste management: A systematic review. *J. Clean. Prod.* **2022**, *332*, 130015.
7. Onyeaka, H.; Ezugwu, A.L.; Mba, M.O. Smart waste management technologies for urban cities. *Waste Manag.* **2023**, *152*, 14–24.
8. Alam, T. Metaverse of Things (MoT) applications for revolutionizing urban living in smart cities. *Smart Cities* **2024**, *7*, 2466–2494. [CrossRef]
9. Scholten, K.; Schilder, S. Supply chain resilience and the role of digital technology. *Int. J. Oper. Prod. Manag.* **2020**, *40*, 47–74.
10. UNEP. *Food Waste Index Report 2021*; United Nations Environment Programme: Nairobi, Kenya, 2021.
11. World Bank. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*; World Bank: Washington, DC, USA, 2022.
12. Fatorachian, H. The significance of Industry 5.0 in the globalization of supply chain management. *Eur. Econ. Lett.* **2023**, *13*, 872–885. [CrossRef]
13. Zhao, L.; Liu, Y.; Zhang, H. AI in retail: A case study of Alibaba's demand forecasting system. *J. Retail.* **2020**, *96*, 23–34.
14. Kamath, R. Food Traceability on Blockchain: Walmart's Pork and Mango Pilots with IBM. *J. Br. Blockchain Assoc.* **2018**, *1*, 3712. [CrossRef] [PubMed]
15. Fatorachian, H.; Kazemi, H. Impact of Industry 4.0 on Supply Chain Performance. *Prod. Plan. Control* **2021**, *32*, 63–81. [CrossRef]
16. Unilever. *Annual Sustainability Report 2022*; Unilever PLC: London, UK, 2022.
17. Govindan, K.; Soleimani, H.; Kannan, D. Reverse logistics and closed-loop supply chains. *Transp. Res. Part E Logist. Transp. Rev.* **2020**, *55*, 99–124.
18. Barney, J. Firm resources and sustained competitive advantage. *J. Manag.* **1991**, *17*, 99–120. [CrossRef]

19. Trist, E. *The Evolution of Socio-Technical Systems: A Conceptual Framework and an Action Research Program*; Ontario Quality of Working Life Center: Toronto, ON, Canada, 1981.
20. Ellen MacArthur Foundation. *Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition*; Ellen MacArthur Foundation: Cowes, UK, 2013.
21. DiMaggio, P.J.; Powell, W.W. The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *Am. Sociol. Rev.* **1983**, *48*, 147–160. [CrossRef]
22. European Union (EU). Waste Framework Directive (Directive 2008/98/EC). In *European Commission Environmental Policies*; European Union (EU): Brussels, Belgium, 2021.
23. Bryman, A. *Social Research Methods*, 5th ed.; Oxford University Press: Oxford, UK, 2016.
24. Meerow, S.; Newell, J.P.; Stults, M. Defining urban resilience: A review. *Landsc. Urban Plan.* **2016**, *147*, 38–49. [CrossRef]
25. Fatorachian, H. Sustainable Supply Chain Management and Industry 5.0. In *Eco-Innovation and Sustainable Development in Industry 5.0*; IGI Global: Hershey, PA, USA, 2024; pp. 172–197. [CrossRef]