

Combating food waste in the agricultural supply chain: A systematic review of supply chain optimization strategies and their sustainability benefits

Oluwakemi Betty Arowosegbe ^{1,*}, Catherine Ballali ², Kyei Richard Kofi ³, Mutolib Kehinde Adeshina ⁴, Jumoke Agbelusi ⁵ and Mohammad Awwal Adeshina ⁶

¹ *Supply Chain and Operations Management, Chicago, USA.*

² *Supply Chain and Operations Management, Boston, USA.*

³ *IT, Business Analyst, and Corporate Governance, McDaniel College, Westminster, Maryland, USA.*

⁴ *Construction Management, Ulster University, Belfast, United Kingdom.*

⁵ *Manufacturing operations and Supply Chain Management, Johannesburg, South Africa.*

⁶ *WP Carey School of Business, Arizona State University, USA.*

World Journal of Advanced Research and Reviews, 2024, 24(01), 122–140

Publication history: Received on 21 August 2024; revised on 28 September 2024; accepted on 30 September 2024

Article DOI: <https://doi.org/10.30574/wjarr.2024.24.1.3023>

Abstract

Food waste represents a significant global challenge, with approximately one-third of all food produced for human consumption lost or wasted annually, leading to severe environmental, economic, and social consequences. The issue not only exacerbates food insecurity but also contributes to greenhouse gas emissions, waste of resources, and economic losses estimated at over \$1 trillion each year. This paper aims to systematically review the causes of food waste across agricultural supply chains and explore effective supply chain optimization strategies to mitigate these losses. Through a comprehensive analysis, the paper identifies critical drivers of food waste, including post-harvest losses, inefficient processing, and aesthetic standards, while proposing technological innovations such as the Internet of Things (IoT), blockchain, and artificial intelligence (AI) as solutions to enhance supply chain efficiency. Furthermore, it evaluates policy frameworks that support waste reduction, highlighting the role of government incentives and regulations in promoting sustainable practices. The findings underscore the importance of reducing food waste not only for environmental sustainability but also for economic profitability, as optimizing supply chains can lead to substantial cost savings and increased revenue for businesses. Ultimately, the paper emphasizes the necessity for collaboration among stakeholders—including governments, industries, and non-profit organizations—to create systemic change and effectively combat food waste on a global scale. By fostering innovative practices and policies, we can pave the way for a more sustainable agricultural future, ultimately contributing to the alleviation of food insecurity and the enhancement of economic resilience.

Keywords: Food Waste; Agricultural Supply Chain; Sustainability; Optimization Strategies; Technological Innovations; Policy Frameworks

1. Introduction

1.1. Background of Food Waste

Food waste has emerged as a critical global issue, drawing attention due to its far-reaching implications for food security, environmental sustainability, and economic stability. Approximately 1.3 billion tons of food, which is about one-third of the total food produced for human consumption, is wasted annually (FAO, 2021). This staggering figure represents a loss of not only edible food but also the resources invested in its production, including water, land, and

* Corresponding author: Oluwakemi Betty Arowosegbe

energy. Moreover, the disposal of food waste contributes significantly to greenhouse gas emissions, with estimates indicating that food waste accounts for around 8-10% of global greenhouse gas emissions (IPCC, 2019).

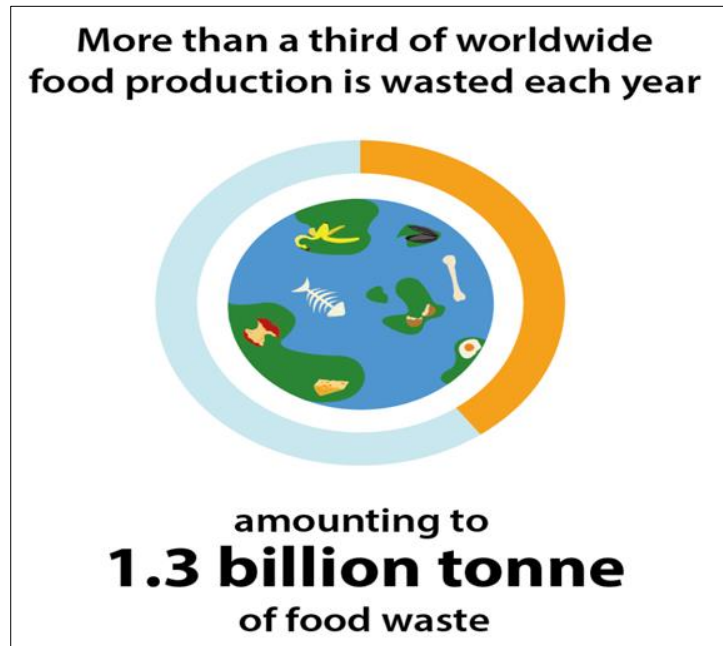


Figure 1 1.3 Billion Tonnes of Food Waste [1]

In agricultural supply chains, food waste occurs at various stages, including production, post-harvest handling, processing, transportation, and consumption. The Food and Agriculture Organization (FAO) reports that nearly 40% of food losses occur during the post-harvest and processing stages, where inefficiencies in handling and storage can lead to spoilage (FAO, 2019). Additionally, in developing countries, approximately 40% of food waste is attributed to inadequate infrastructure and poor management practices, while in developed nations, consumer behaviour and aesthetic standards are significant contributors (Garrone et al., 2014). This multifaceted issue highlights the urgent need for comprehensive strategies to combat food waste across agricultural supply chains. By addressing the root causes of food waste and implementing effective interventions, stakeholders can enhance food security, reduce environmental impacts, and improve economic outcomes for farmers and businesses alike.

1.2. Importance of Addressing Food Waste

Addressing food waste is critical for several interconnected reasons, primarily concerning food security, economic impact, and environmental sustainability. Food waste is a pressing issue, especially in the context of a growing global population projected to reach nearly 10 billion by 2050. With food insecurity affecting approximately 811 million people worldwide (FAO, 2023), reducing food waste can significantly enhance food availability and access. By diverting edible food that would otherwise be wasted to those in need, stakeholders can alleviate hunger and improve nutritional outcomes for vulnerable populations. Economically, food waste incurs substantial costs throughout the supply chain. According to the Food and Agriculture Organization (FAO), food loss and waste cost the global economy approximately \$940 billion annually (FAO, 2023). This figure encompasses the expenses associated with production, processing, transportation, and disposal of wasted food.

For farmers, waste translates to lost income and increased costs for production inputs, while consumers bear the financial burden of purchasing food that ultimately goes uneaten. By implementing effective food waste reduction strategies, businesses can realize significant cost savings and improve profitability. From an environmental perspective, food waste has a profound impact on natural resources and ecosystems. The production of food that is never consumed requires vast amounts of water, land, and energy, contributing to resource depletion and habitat destruction. Furthermore, food waste in landfills generates methane, a potent greenhouse gas that exacerbates climate change. It is estimated that if food waste were a country, it would rank as the third-largest emitter of greenhouse gases globally (FAO, 2019). Therefore, reducing food waste is not only an ethical imperative but also a vital component of achieving sustainability goals and mitigating climate change.



Figure 2 Impact of Food Waste [3]

1.3. Objectives of the Paper

This paper aims to comprehensively address the multifaceted issue of food waste within agricultural supply chains by systematically reviewing its causes and proposing effective optimization strategies. The first objective is to identify and analyse the key drivers of food waste at various stages of the agricultural supply chain, including production, post-harvest handling, processing, and distribution. By understanding these underlying causes, the paper seeks to highlight specific areas where intervention can significantly reduce food losses. This analysis will form the foundation for proposing tailored optimization strategies that can be employed to enhance efficiency and minimize waste. The second objective of this paper is to assess the sustainability benefits that arise from implementing these optimization strategies. This involves examining the environmental impacts of food waste reduction, such as decreased greenhouse gas emissions, conservation of water and energy resources, and the promotion of sustainable agricultural practices. By quantifying these benefits, the paper aims to provide a clear rationale for stakeholders to adopt food waste mitigation strategies not only for ethical reasons but also for achieving economic and environmental goals.

Furthermore, the paper will explore the existing policy frameworks that support food waste reduction initiatives. This includes evaluating government regulations, incentives for technology adoption, and the role of collaborative efforts among various stakeholders, such as governments, industries, and non-profit organizations. By examining these frameworks, the paper aims to identify gaps and opportunities for enhancing the effectiveness of policies designed to combat food waste. Ultimately, the objectives of this paper are to provide actionable insights that contribute to a more sustainable agricultural future while addressing the pressing challenges of food insecurity and resource depletion.

2. Causes of food waste

2.1. Overview of Food Waste Across Supply Chain Stages

The agricultural supply chain encompasses several critical stages: production, processing, distribution, and consumption. Each stage presents unique opportunities for food waste, contributing to the overall inefficiency of the system.

- **Production:** This initial stage involves growing crops and raising livestock. Food waste can occur due to overproduction, crop failures, and pests, resulting in substantial losses before the products even reach the market (Garrone et al., 2014).

- **Processing:** During processing, food is transformed into consumable products. Inefficient processing techniques, aesthetic standards, and handling errors can lead to significant waste, including by-products and discarded portions of fruits and vegetables (FAO, 2019).
- **Distribution:** This stage includes transportation and storage. Food waste arises from inadequate cold chain logistics, transportation delays, and spoilage during transit, often due to improper packaging or temperature fluctuations (Kumar et al., 2021).
- **Consumption:** Finally, at the consumer level, food waste results from purchasing excess food, poor meal planning, and inadequate storage practices, leading to uneaten food being discarded (Garrone et al., 2014).

By addressing food waste at each of these stages, stakeholders can enhance overall efficiency and sustainability within the agricultural supply chain.

2.2. Post-Harvest Losses

Post-harvest losses refer to the reduction in quantity or quality of agricultural products that occurs after harvesting and before consumption. During harvesting, losses can occur due to improper techniques, such as excessive force or delayed harvesting, which can damage crops and reduce their marketability. For example, bruising fruits or breaking stalks can lead to rapid deterioration (FAO, 2019).

Handling practices play a significant role in post-harvest losses. Inadequate storage facilities and poor management can result in spoilage due to pests, mold, or unfavourable environmental conditions, such as temperature and humidity fluctuations (Kumar et al., 2021). Additionally, improper transportation methods, including inadequate packaging, can lead to further losses as products are jostled and exposed to adverse conditions during transit. Collectively, these factors contribute to significant post-harvest losses, with estimates suggesting that approximately 14% of global food production is lost after harvest (FAO, 2021). Addressing these issues is crucial for improving food security and minimizing waste.

2.3. Inefficient Processing

Processing inefficiencies are significant contributors to food waste in the agricultural supply chain. These inefficiencies arise from various factors, including outdated technology, inadequate training of personnel, and lack of standardized procedures. For instance, many processing facilities rely on manual labour for sorting and grading produce, which can lead to inconsistencies and increased waste due to human error. Moreover, aesthetic standards imposed by retailers often result in the rejection of perfectly edible produce that does not meet specific visual criteria, leading to substantial losses (FAO, 2019). Additionally, inefficient processing methods can result in excessive by-products, such as peels and stems, which may not be utilized or repurposed effectively.

Furthermore, inadequate equipment maintenance and poor hygiene practices can lead to spoilage and contamination, compounding waste issues. Addressing these inefficiencies through modern technologies and better management practices is crucial for reducing food waste during processing stages.

2.4. Transportation Delays

Transportation delays significantly impact food waste in the agricultural supply chain by exacerbating spoilage and diminishing the quality of perishable goods. Various logistical challenges, such as traffic congestion, poor infrastructure, and insufficient cold chain management, can lead to prolonged transit times, which jeopardize the freshness of food products (Kumar et al., 2021). For instance, delays in delivering fruits and vegetables to markets can result in over-ripening or decay, rendering them unsellable. Furthermore, inadequate temperature control during transportation can cause critical losses, particularly for temperature-sensitive items like dairy, meat, and certain produce. According to the Food and Agriculture Organization (FAO), improper logistics can account for a significant portion of post-harvest losses, especially in regions with underdeveloped transportation networks (FAO, 2021).

Addressing these transportation challenges through improved infrastructure, better route planning, and enhanced cold chain logistics is essential for reducing food waste and ensuring food safety.

2.5. Inadequate Packaging

Packaging plays a crucial role in preventing spoilage and minimizing food waste throughout the agricultural supply chain. Effective packaging protects food products from physical damage, contamination, and environmental factors such as moisture, air, and light, all of which can accelerate spoilage. For instance, fruits and vegetables packaged in breathable materials can maintain freshness by allowing ethylene gas to escape while preventing moisture buildup, which can lead

to mould and decay (FAO, 2019). However, inadequate or improper packaging can significantly contribute to food waste. Poorly designed packages may not provide sufficient protection during transportation, resulting in bruising or spoilage. Additionally, packaging that does not effectively manage temperature can compromise the quality of perishable items, leading to early spoilage.

Investing in innovative packaging solutions, such as smart packaging that monitors freshness or modified atmosphere packaging, can help extend shelf life and reduce waste, ultimately benefiting both consumers and producers.

2.6. Cold Chain Failures

Cold chain failures pose significant risks to food safety and quality, leading to substantial food waste in the agricultural supply chain. The cold chain refers to a temperature-controlled supply chain designed to maintain the quality of perishable goods from production to consumption. Disruptions in this chain—such as equipment malfunctions, power outages, or logistical delays—can cause temperatures to rise, compromising the integrity of temperature-sensitive products like dairy, meat, and fresh produce (Kumar et al., 2021).

When these products are exposed to temperatures outside their optimal range, microbial growth accelerates, leading to spoilage and contamination. According to the Food and Agriculture Organization (FAO), improper temperature management throughout the cold chain can account for up to 50% of food waste in some regions (FAO, 2021). To mitigate these risks, it is essential to invest in reliable refrigeration systems, continuous temperature monitoring technologies, and robust contingency plans that ensure effective response to cold chain disruptions, thereby reducing food waste and enhancing food safety.

2.7. Overproduction

Overproduction in the agricultural sector often stems from mismatches between supply and demand, leading to significant food waste. Farmers may produce more than the market can absorb due to optimistic projections, lack of accurate demand forecasting, or market pressure to maximize yields. This surplus can occur in various scenarios, such as when there is an unexpected decrease in consumer demand, economic downturns, or changes in consumer preferences (Garrone et al., 2014).

When supply exceeds demand, perishable goods may go unsold, resulting in waste. Additionally, aesthetic standards imposed by retailers often lead to the rejection of perfectly edible produce that does not meet specific visual criteria, exacerbating the issue (FAO, 2019). Addressing overproduction requires improved market intelligence, effective communication between producers and retailers, and the adoption of demand-driven production strategies. By aligning production with actual consumer demand, the agricultural sector can minimize surplus and significantly reduce food waste.

2.8. Aesthetic Standards for Produce

Consumer expectations regarding the appearance of fruits and vegetables significantly impact food waste generation in the agricultural supply chain. Retailers often enforce strict aesthetic standards that prioritize uniformity, size, and colour, resulting in the rejection of perfectly edible produce that does not meet these criteria. According to the Food and Agriculture Organization (FAO), an estimated 20-30% of fruits and vegetables are discarded due to cosmetic imperfections (FAO, 2019).

This emphasis on aesthetics creates a disconnect between agricultural production and consumer expectations, leading to significant food waste. For instance, misshapen or slightly blemished produce may be deemed unsellable, even though they are nutritionally valuable and safe to consume. Addressing this issue requires educational campaigns to shift consumer perceptions and encourage acceptance of imperfect produce. By promoting the consumption of aesthetically diverse products, stakeholders can significantly reduce food waste while improving sustainability within the food system.

2.9. Summary of Causes

The causes of food waste in agricultural supply chains are multifaceted and interlinked, resulting from a combination of systemic inefficiencies and consumer behaviours. Key drivers include post-harvest losses due to improper handling and storage, which lead to spoilage before products reach consumers. Inefficient processing practices contribute to waste by generating excess by-products and rejecting aesthetically imperfect produce.

Transportation delays and inadequate packaging exacerbate spoilage risks, particularly for perishable items that require temperature control. Additionally, overproduction driven by supply-demand mismatches results in surplus products that often go unsold.

Consumer expectations regarding the aesthetic quality of produce further exacerbate food waste, as retailers often discard items that do not meet strict visual standards. Together, these factors highlight the need for comprehensive strategies aimed at optimizing the agricultural supply chain, improving efficiency, and fostering a cultural shift towards accepting diverse food products to mitigate food waste effectively.

3. Supply chain optimization strategies

3.1. Introduction to Supply Chain Optimization

Supply chain optimization refers to the systematic approach of enhancing various components of the supply chain to improve efficiency, reduce costs, and maximize value. In the context of food waste, optimizing supply chains is critical for minimizing losses at each stage, from production to consumption. By streamlining processes, improving coordination among stakeholders, and implementing best practices, organizations can effectively address inefficiencies that contribute to food waste. The importance of optimizing supply chains lies in its potential to enhance resource utilization and sustainability. Efficient supply chains not only reduce waste but also lower operational costs, leading to increased profitability for businesses (Cuthbertson & Piotrowicz, 2011). Furthermore, optimizing logistics and inventory management can ensure that food products are delivered in a timely manner, minimizing spoilage and ensuring freshness.

Moreover, as consumers increasingly prioritize sustainability, organizations that implement optimized supply chains are better positioned to meet market demands and regulatory expectations. This shift not only benefits individual companies but also contributes to broader environmental goals, including reducing greenhouse gas emissions associated with food waste. Ultimately, effective supply chain optimization serves as a key strategy for creating a more sustainable food system while enhancing economic viability.

3.2. Demand Forecasting

Demand forecasting is a crucial component of supply chain optimization, as it enables organizations to predict consumer demand accurately and adjust production and inventory levels accordingly. Accurate demand prediction helps minimize food waste by ensuring that the supply aligns closely with actual market needs. Various methods and technologies are employed to enhance demand forecasting accuracy. Traditional statistical methods, such as time series analysis and moving averages, are commonly used to identify patterns in historical sales data. These methods provide a foundational understanding of demand trends over time. However, they may not capture sudden market changes or shifts in consumer behaviour effectively.

Advanced technologies, including artificial intelligence (AI) and machine learning (ML), are increasingly utilized to improve demand forecasting. These technologies analyse vast amounts of data from multiple sources—such as sales transactions, weather patterns, and social media trends—to identify complex demand patterns and generate more accurate forecasts (Chong et al., 2017). Additionally, cloud-based solutions allow real-time data integration and collaboration among stakeholders, enabling a more responsive approach to demand changes. By leveraging these methods and technologies, businesses can optimize inventory levels, reduce overproduction, and ultimately decrease food waste in the supply chain.

3.3. Inventory Management

Effective inventory management is vital for reducing food waste in agricultural supply chains. By maintaining optimal inventory levels, organizations can ensure that perishable goods are sold before they spoil, thereby minimizing losses. Several strategies can enhance inventory control and improve overall efficiency. One key strategy is the implementation of just-in-time (JIT) inventory systems. JIT focuses on receiving goods only as they are needed in the production process, reducing the amount of stock held at any given time. This approach helps decrease spoilage and lowers storage costs, making it particularly beneficial for perishable items.

Another effective strategy is employing advanced inventory tracking technologies, such as RFID (Radio Frequency Identification) and barcode systems. These technologies enable real-time monitoring of inventory levels and product conditions, facilitating timely reordering and reducing the risk of overstocking (Akkerman et al., 2010). Moreover, utilizing inventory management software can streamline operations by automating processes such as demand

forecasting, order management, and stock replenishment. These tools can provide valuable insights into inventory performance, helping businesses make informed decisions. By adopting these inventory management strategies, organizations can enhance efficiency, reduce waste, and contribute to a more sustainable food supply chain.

3.4. Cold Chain Logistics

Cold chain logistics is essential for preserving the quality and safety of perishable food products throughout the supply chain. Maintaining a consistent temperature is critical in preventing spoilage, minimizing food waste, and ensuring consumer safety. Implementing best practices in cold chain logistics can significantly enhance efficiency and reduce losses. One fundamental practice is the use of temperature-controlled transport vehicles, equipped with refrigeration systems that maintain optimal temperatures for specific products. Regular monitoring of these temperature settings using IoT (Internet of Things) devices allows for real-time tracking and alerts if temperature deviations occur (Kumar et al., 2017).

Additionally, employing high-quality insulation and packaging materials is crucial to minimize temperature fluctuations during transit. Packaging solutions, such as thermal blankets and gel packs, help maintain temperature integrity, especially during prolonged transport or storage. Training personnel in proper handling techniques and temperature management is also vital. Ensuring that staff understands the importance of adhering to cold chain protocols helps mitigate risks associated with human error. Lastly, integrating technology for data logging and traceability can provide valuable insights into the cold chain's performance, allowing for continuous improvement and timely intervention when issues arise. By adhering to these best practices, stakeholders can effectively maintain the cold chain, significantly reducing food waste.

3.5. Just-in-Time (JIT) Inventory Systems

Just-in-Time (JIT) inventory systems are designed to minimize waste by aligning inventory levels closely with actual demand. This approach offers several benefits, particularly in reducing food waste and enhancing operational efficiency. One of the primary benefits of JIT is the significant reduction in holding costs associated with inventory storage. By receiving goods only as they are needed in the production process, businesses can lower storage expenses and minimize spoilage, especially for perishable items (Cohen et al., 2013). Additionally, JIT systems improve cash flow, as funds are not tied up in excess inventory, allowing for reinvestment in other areas of the business.

However, implementing JIT inventory systems also presents challenges. The reliance on precise demand forecasting makes organizations vulnerable to fluctuations in consumer behaviour and unexpected disruptions, such as supply chain delays or natural disasters. In such cases, businesses may face stockouts, leading to lost sales and potential customer dissatisfaction. Furthermore, maintaining effective supplier relationships is crucial for JIT success. Any disruption in the supply chain can jeopardize the entire operation, emphasizing the need for robust communication and contingency planning. Despite these challenges, when executed effectively, JIT inventory systems can significantly enhance sustainability and reduce food waste.

3.6. Circular Economy Approaches

Circular economy principles focus on minimizing waste and promoting the continual use of resources, contrasting with the traditional linear model of "take, make, dispose." In agriculture, these principles can be effectively applied to reduce food waste, enhance sustainability, and improve resource efficiency. One key aspect of circular economy approaches in agriculture is the concept of closing the loop in food production. This involves utilizing by-products and waste materials from one process as inputs for another, thereby reducing overall waste. For example, organic waste from food production can be composted to create nutrient-rich soil amendments, fostering healthier crops and reducing the need for chemical fertilizers (Ellen MacArthur Foundation, 2019).

Additionally, circular economy strategies promote sustainable farming practices such as crop rotation and agroecology, which enhance soil health and biodiversity while reducing dependence on external inputs. By focusing on resource recovery and reuse, these approaches not only minimize waste but also improve the resilience of agricultural systems. Implementing circular economy principles in agriculture requires collaboration among stakeholders, including farmers, businesses, and policymakers, to develop innovative solutions that maximize resource utilization and reduce environmental impact. By embracing these principles, the agricultural sector can contribute significantly to sustainability and food security.

3.7. Summary of Optimization Strategies

Optimization strategies play a critical role in mitigating food waste across the agricultural supply chain by addressing inefficiencies and enhancing resource management. Collectively, these strategies foster a more sustainable and efficient system that reduces losses from production to consumption. Demand forecasting techniques enable producers to align supply with actual market needs, significantly reducing overproduction and subsequent waste. Accurate inventory management, particularly through Just-in-Time (JIT) systems, ensures that perishable goods are sold before spoilage occurs, minimizing losses associated with excess stock.

Cold chain logistics are vital for maintaining the quality and safety of perishable items during transportation and storage. By implementing best practices in temperature control, organizations can prevent spoilage and ensure product freshness. Additionally, embracing circular economy principles allows for the recovery and reuse of agricultural by-products, further minimizing waste. This holistic approach not only addresses the root causes of food waste but also enhances economic efficiency by reducing costs associated with unsold inventory and waste disposal. Overall, the integration of these optimization strategies creates a more resilient agricultural supply chain that conserves resources, enhances food security, and contributes to environmental sustainability. By collectively focusing on efficiency and sustainability, these strategies can lead to substantial reductions in food waste while promoting long-term economic benefits.

4. Technological innovations

4.1. Role of Advanced Technologies

Advanced technologies are revolutionizing supply chains by enhancing visibility, efficiency, and responsiveness, ultimately contributing to significant reductions in food waste. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), and blockchain are transforming traditional supply chain processes, providing innovative solutions to persistent challenges.

The IoT facilitates real-time monitoring and data collection throughout the supply chain. Sensors and connected devices can track environmental conditions, such as temperature and humidity, ensuring optimal storage conditions for perishable goods. This capability allows for proactive interventions when deviations occur, reducing spoilage and waste (Kamble et al., 2020). Artificial intelligence and machine learning enhance demand forecasting accuracy by analysing vast datasets, identifying patterns, and predicting future trends. This enables businesses to make informed decisions regarding production, inventory management, and logistics. For instance, AI-driven analytics can optimize inventory levels, minimizing overproduction and ensuring that perishable items are sold before they expire.

Blockchain technology improves traceability and transparency within the supply chain. By creating an immutable record of transactions, stakeholders can verify the origin and journey of food products, ensuring compliance with safety standards and building consumer trust. This transparency can also facilitate quicker recalls in the event of safety concerns, thereby protecting public health and minimizing waste. Furthermore, smart packaging innovations, such as freshness indicators and active packaging, provide real-time information about the quality and safety of food products. These technologies empower consumers and businesses to make better decisions regarding food consumption and waste management. In summary, the integration of advanced technologies in supply chains not only enhances operational efficiency but also plays a crucial role in reducing food waste. By leveraging these innovations, stakeholders can create more sustainable and resilient supply chains that benefit both the economy and the environment.

4.2. Internet of Things (IoT)

The Internet of Things (IoT) is a transformative technology that enables real-time monitoring and data collection across various stages of the agricultural supply chain. By connecting devices and sensors to the internet, IoT facilitates seamless communication and data exchange, allowing stakeholders to make informed decisions that significantly reduce food waste and enhance operational efficiency. In agriculture, IoT devices can monitor environmental conditions such as temperature, humidity, and soil moisture. For example, smart sensors installed in storage facilities can continuously track temperature levels for perishable goods. If the temperature rises beyond the recommended threshold, alerts can be triggered, prompting immediate corrective actions. This real-time monitoring helps prevent spoilage and maintains product quality, thereby reducing waste (Kamble et al., 2020).

Furthermore, IoT can enhance traceability throughout the supply chain. By embedding RFID (Radio Frequency Identification) tags or QR codes in packaging, stakeholders can track the movement of products from farm to table. This level of transparency not only helps identify potential issues quickly but also fosters consumer trust by providing

information about the product's journey, including its origin and handling conditions. The data collected through IoT devices can be analysed using advanced analytics and machine learning algorithms. This analysis can reveal trends and patterns, allowing businesses to optimize inventory management and improve demand forecasting. For instance, retailers can analyse historical data on product sales to adjust their ordering processes, thereby minimizing overstock and waste. Additionally, IoT can facilitate better decision-making at all levels of the supply chain. By providing stakeholders with access to real-time data, they can respond promptly to changes in demand or supply disruptions, leading to a more agile and efficient system. In summary, the integration of IoT into the agricultural supply chain enhances real-time monitoring and data collection, significantly contributing to waste reduction, improved quality assurance, and increased operational efficiency.

4.3. Blockchain Technology

Blockchain technology is rapidly emerging as a pivotal tool for enhancing traceability and transparency in agricultural supply chains, particularly in efforts to reduce food waste. By providing a decentralized and immutable ledger, blockchain allows all stakeholders—producers, distributors, retailers, and consumers—to track and verify the entire journey of food products from farm to table. One of the primary advantages of blockchain is its ability to provide real-time visibility into the supply chain. Each transaction, whether it's the harvesting of crops, transportation, or storage, is recorded on the blockchain, creating a comprehensive and tamper-proof history of the product's journey. This transparency helps identify potential points of failure, enabling quick responses to issues such as spoilage or contamination (Kshetri, 2018). For instance, if a batch of produce is found to be contaminated, stakeholders can trace its origin and distribution path quickly, allowing for targeted recalls rather than broad, indiscriminate ones that can result in unnecessary waste.

Additionally, blockchain enhances trust among consumers by allowing them to access information about the products they purchase, including their origin, handling practices, and certifications. This information empowers consumers to make informed choices, fostering a culture of sustainability and reducing food waste by encouraging responsible consumption behaviours. Moreover, smart contracts on the blockchain can automate various processes, such as payments and compliance checks, further improving efficiency and reducing delays that can lead to spoilage. For example, a smart contract could automatically execute a payment to a farmer upon successful delivery of goods, ensuring timely transactions and minimizing disruptions. In summary, blockchain technology significantly enhances traceability and transparency in agricultural supply chains, facilitating better decision-making, reducing food waste, and fostering consumer confidence in the food they consume.

4.4. Artificial Intelligence (AI) and Machine Learning (ML)

Artificial Intelligence (AI) and Machine Learning (ML) are transforming agricultural supply chains by enhancing demand forecasting and waste analysis, ultimately contributing to the reduction of food waste. These technologies analyse vast amounts of data to identify patterns and trends, enabling stakeholders to make informed decisions that optimize resource allocation. In demand forecasting, AI and ML algorithms can process historical sales data, weather patterns, and consumer behaviour to predict future demand with remarkable accuracy. This capability allows producers and retailers to adjust their inventory levels accordingly, minimizing the risk of overproduction and spoilage. For example, a grocery store can utilize ML models to forecast demand for perishable items based on seasonal trends and local events, ensuring that products are stocked in appropriate quantities (Pérez-Ruiz et al., 2020).

Additionally, AI and ML can enhance waste analysis by identifying specific points in the supply chain where food waste occurs most frequently. By analysing data from various stages—such as processing, transportation, and retail—stakeholders can pinpoint inefficiencies and implement targeted interventions. For instance, predictive analytics can help anticipate spoilage rates in different conditions, allowing for better planning and adjustments to logistics and inventory management. In summary, AI and ML are invaluable tools for improving demand forecasting and waste analysis, leading to more efficient supply chains and significant reductions in food waste.

4.5. Smart Packaging

Smart packaging innovations are revolutionizing the agricultural supply chain by extending the shelf life of perishable goods and minimizing food waste. This technology incorporates advanced materials and sensors that actively monitor the condition of food products, ensuring they remain fresh and safe for consumption. One significant advancement in smart packaging is the use of active packaging, which can interact with the contents to enhance preservation. For example, oxygen scavengers and moisture absorbers are incorporated into packaging materials to reduce the levels of oxygen and moisture that promote spoilage. These elements help maintain optimal conditions for fresh produce, dairy, and meat products, thereby extending their shelf life (González et al., 2021).

Additionally, intelligent packaging equipped with sensors can provide real-time data about the freshness of the product. For instance, freshness indicators that change colour in response to microbial growth or spoilage can alert consumers and retailers about the quality of the food inside. This transparency helps in making informed decisions about consumption and reduces the likelihood of discarding food prematurely. Furthermore, QR codes and blockchain integration can be utilized within smart packaging to provide consumers with detailed information about the product's origin, handling history, and storage requirements, thus promoting better practices and reducing waste. In summary, smart packaging innovations play a critical role in prolonging the shelf life of perishable goods, enhancing food safety, and significantly reducing food waste in the supply chain.

4.6. Summary of Technological Innovations

Technological innovations in the agricultural supply chain play a crucial role in reducing food waste and enhancing sustainability. Key technologies, such as the Internet of Things (IoT), blockchain, artificial intelligence (AI), machine learning (ML), and smart packaging, collectively contribute to more efficient resource management and waste reduction. IoT devices facilitate real-time monitoring of environmental conditions, ensuring optimal storage and handling of perishable goods. This capability helps prevent spoilage and maintains product quality throughout the supply chain. Blockchain technology enhances traceability and transparency, enabling stakeholders to quickly identify and respond to issues such as contamination or spoilage, thus minimizing waste. AI and ML contribute significantly to demand forecasting and waste analysis. By accurately predicting consumer demand and identifying waste hotspots in the supply chain, these technologies enable better inventory management and resource allocation. This leads to reduced overproduction and waste.

Smart packaging innovations also play a vital role by extending the shelf life of products through active and intelligent packaging solutions. These technologies can signal freshness, allowing for informed decision-making by consumers and retailers, which ultimately reduces the likelihood of unnecessary food disposal. In summary, the integration of these technological innovations into the agricultural supply chain enhances efficiency, promotes sustainability, and significantly reduces food waste, addressing a critical global challenge.

5. Sustainability and economic benefits

5.1. Environmental Impacts of Food Waste

Food waste poses a significant threat to the environment, with far-reaching implications for greenhouse gas emissions, water usage, and resource depletion. When food is discarded, it does not simply disappear; it contributes to a range of environmental issues that exacerbate climate change and resource scarcity. One of the primary environmental concerns associated with food waste is the generation of greenhouse gases. Decomposing food in landfills produces methane, a potent greenhouse gas that is approximately 25 times more effective than carbon dioxide at trapping heat in the atmosphere over a 100-year period (IPCC, 2014). In fact, the Food and Agriculture Organization (FAO) estimates that food waste contributes around 8-10% of total global greenhouse gas emissions (FAO, 2013). Reducing food waste can therefore play a crucial role in mitigating climate change.

Moreover, the water footprint of food waste is substantial. It is estimated that around 1,800 cubic kilometers of water are wasted annually due to uneaten food (Mekonnen & Hoekstra, 2012). This wastage is particularly alarming considering the increasing global water scarcity and the fact that agriculture accounts for about 70% of global freshwater withdrawals. The resources used in growing, processing, and transporting food—such as land, energy, and labour—are also squandered when food is wasted, leading to further environmental degradation. Finally, food waste exacerbates resource depletion, as valuable agricultural inputs like fertilizers and pesticides are utilized to produce food that is ultimately discarded. This inefficiency places additional strain on ecosystems and natural resources, undermining efforts toward sustainable agriculture. In summary, the environmental impacts of food waste are profound, contributing to greenhouse gas emissions, excessive water usage, and the depletion of vital resources. Addressing food waste is imperative for fostering environmental sustainability and combating climate change.

5.2. Economic Benefits of Waste Reduction

Reducing food waste offers significant economic benefits for both businesses and consumers, leading to cost savings and enhanced profitability across the agricultural supply chain. By minimizing waste, stakeholders can achieve more efficient operations, which ultimately translates to financial advantages. For businesses, one of the most immediate benefits of waste reduction is the reduction in costs associated with waste disposal. When food is wasted, companies incur expenses related to production, transportation, storage, and disposal. By implementing strategies to minimize waste, businesses can lower these operational costs significantly. For example, adopting effective inventory

management practices and demand forecasting can help businesses avoid overproduction, thereby reducing the costs associated with unsold goods. According to a report by the FAO, if food waste were reduced by just 25%, it could save the food industry over \$400 billion annually (FAO, 2013).

Consumers also stand to gain economically from waste reduction efforts. Households that actively minimize food waste can save a substantial amount of money on grocery bills. Research indicates that the average household in developed countries wastes approximately 20-30% of the food they purchase, amounting to hundreds of dollars each year (Bennett et al., 2018). By being more mindful of purchasing habits and utilizing leftover food creatively, consumers can decrease their expenses and increase the value they derive from their food purchases. Furthermore, waste reduction contributes to enhanced sustainability, which can improve brand reputation and customer loyalty. Businesses that prioritize waste reduction often attract environmentally-conscious consumers, potentially leading to increased sales and market share. In summary, reducing food waste provides significant economic benefits by lowering costs for businesses and consumers, fostering more efficient supply chains, and enhancing overall sustainability within the food industry.

5.3. Case Examples of Sustainability Benefits

Numerous real-world examples illustrate the economic and environmental advantages of waste reduction in the agricultural supply chain, showcasing successful initiatives that have effectively addressed the food waste challenge. One notable case is that of Unilever, a multinational consumer goods company that has implemented comprehensive waste reduction strategies across its supply chain. Unilever set a target to halve its food waste from manufacturing to consumer level by 2025. By utilizing advanced analytics and better inventory management practices, the company reduced its food waste by 35% from 2016 to 2019, translating to significant cost savings estimated at €50 million annually. This initiative not only minimized waste but also bolstered Unilever's commitment to sustainability, appealing to eco-conscious consumers and enhancing brand loyalty (Unilever, 2020).

Another example is Kroger, one of the largest supermarket chains in the United States, which has adopted various strategies to tackle food waste. Kroger has implemented a program called "Zero Hunger | Zero Waste," aimed at eliminating food waste in its stores by 2025. Through improved inventory management, partnerships with food banks, and innovative use of technology for tracking perishables, Kroger has reported saving millions in operational costs while donating over 50 million meals annually. This not only supports food security in communities but also reduces the environmental impact associated with wasted food (Kroger, 2021). In agriculture, the Waste and Resources Action Programme (WRAP) in the UK has worked with farmers to reduce on-farm food waste. By implementing best practices for harvesting and storage, WRAP has helped farmers save over £200 million, highlighting the economic benefits of adopting sustainable practices. Additionally, this initiative has contributed to lower greenhouse gas emissions and enhanced soil health, demonstrating the interconnectedness of economic and environmental sustainability. These case examples underscore that implementing waste reduction strategies not only yields significant economic benefits but also promotes environmental sustainability, paving the way for a more resilient agricultural system.

5.4. Summary of Sustainability and Economic Impacts

Waste reduction strategies are not only crucial for addressing the global food waste crisis but also serve as a key driver for enhancing sustainability and profitability across the agricultural supply chain. By systematically implementing these strategies, stakeholders can achieve significant economic benefits while simultaneously contributing to environmental conservation. From an economic perspective, reducing food waste directly correlates with cost savings for businesses and consumers alike. Companies that optimize their supply chains—through methods such as improved demand forecasting, effective inventory management, and cold chain logistics—can significantly lower their operational costs and minimize waste disposal expenses. For instance, reducing food waste by just 25% could lead to potential savings of over \$400 billion annually for the food industry (FAO, 2013). For consumers, adopting practices to minimize household food waste can translate into substantial savings, as households waste about 20-30% of the food they purchase (Bennett et al., 2018).

On the sustainability front, waste reduction efforts contribute to mitigating climate change by decreasing greenhouse gas emissions associated with decomposing food in landfills. Moreover, these strategies promote the efficient use of natural resources, such as water and land, which are often squandered in the production of wasted food. The implementation of technologies such as the Internet of Things (IoT) and blockchain enhances supply chain transparency and efficiency, further supporting sustainability goals. Ultimately, the intersection of economic benefits and sustainability underscores the importance of collaboration among stakeholders—businesses, policymakers, and consumers alike. By prioritizing waste reduction, society can foster a more resilient agricultural system that not only ensures food security but also drives profitability and environmental stewardship. As awareness grows and initiatives

expand, the potential for transformative change within the agricultural sector becomes increasingly achievable, paving the way for a sustainable future.

6. Policy and regulatory frameworks

6.1. Role of Government and Regulatory Bodies

Governments and regulatory bodies play a critical role in addressing food waste through the development and implementation of policies and regulations that promote sustainable practices within the agricultural supply chain. These initiatives are essential for creating a comprehensive framework that encourages waste reduction at various levels, from production to consumption. One significant approach has been the introduction of food waste reduction targets and strategies. For example, the European Union has set ambitious goals to halve food waste by 2030 as part of its broader commitment to sustainable development and the circular economy. This includes the adoption of the Waste Framework Directive, which mandates that member states develop national waste prevention programs, thus promoting awareness and accountability in waste reduction efforts (European Commission, 2018). Additionally, governments have implemented legislation aimed at encouraging food donation and redistribution. For instance, France has enacted laws that require supermarkets to donate unsold food to charities, rather than discarding it. This policy not only helps reduce food waste but also addresses food insecurity, demonstrating how regulatory frameworks can simultaneously support social and environmental objectives (Fuchs, 2017).

Regulatory bodies also influence food waste management through funding and support for innovative technologies that enhance supply chain efficiency. By providing grants, tax incentives, or subsidies for the adoption of waste-reducing technologies, governments can encourage businesses to invest in practices that minimize waste. Moreover, public awareness campaigns, often spearheaded by government agencies, educate consumers on the importance of reducing food waste at home, further amplifying the impact of these policies. In summary, government and regulatory bodies are pivotal in shaping the landscape of food waste management. By establishing clear policies, encouraging innovation, and promoting collaboration among stakeholders, they create an enabling environment that fosters sustainable practices, ultimately leading to a more resilient agricultural system.

6.2. Incentives for Technology Adoption

Incentives for technology adoption play a crucial role in encouraging businesses and farmers to implement innovative solutions that can significantly reduce food waste across the agricultural supply chain. These incentives can be categorized into financial and non-financial types, each offering distinct advantages for stakeholders.

6.2.1. Financial Incentives

Financial incentives are among the most effective tools for driving technology adoption. Governments and regulatory bodies often provide grants, subsidies, and tax credits to encourage the implementation of waste-reducing technologies. For instance, many countries have established grant programs that offer funding to businesses investing in advanced technologies like the Internet of Things (IoT) for real-time monitoring or blockchain for enhanced traceability. These financial supports can cover a substantial portion of initial investments, making it economically viable for smaller businesses and farms to adopt costly but effective technologies. Additionally, low-interest loans and favourable financing options are available to support the purchase of equipment and software that enhance operational efficiency. Some regions also offer performance-based incentives, where businesses receive financial rewards based on their measurable contributions to reducing food waste or improving sustainability metrics.

6.2.2. Non-Financial Incentives

In addition to financial support, non-financial incentives play a vital role in promoting technology adoption. These include training programs and technical assistance that help businesses understand and effectively implement new technologies. Workshops, webinars, and hands-on training sessions can equip stakeholders with the necessary skills to operate and maintain advanced systems, ultimately leading to better waste management practices. Moreover, recognition programs, such as awards for sustainability and innovation, can motivate businesses to adopt cutting-edge technologies. Public acknowledgment can enhance a company's reputation and marketability, fostering a competitive advantage in an increasingly environmentally conscious marketplace. In conclusion, a combination of financial and non-financial incentives can significantly enhance the adoption of technologies aimed at reducing food waste, ultimately leading to more sustainable agricultural practices and improved economic outcomes for stakeholders.

6.3. Legislation Mandating Waste Reduction Practices

Legislation plays a vital role in promoting food waste reduction by establishing clear guidelines and responsibilities for various stakeholders in the food supply chain. Governments worldwide have recognized the urgency of addressing food waste and have enacted laws that mandate specific practices to minimize waste at different stages of production, processing, and consumption. One notable example is the French law passed in 2016, which prohibits supermarkets from discarding unsold food items. Instead, it requires them to donate this food to charities and food banks. This legislation not only helps to alleviate food insecurity but also actively encourages businesses to rethink their waste management strategies (Fuchs, 2017). By implementing such laws, France has set a precedent that many other nations are beginning to follow, emphasizing the importance of legislative action in food waste reduction.

In the United States, various states have adopted similar legislation, particularly in terms of food recovery and donation. For example, California's AB 1826 mandates that businesses generating a certain volume of organic waste implement composting or food recovery systems. This legislation aims to divert organic materials from landfills, thereby reducing greenhouse gas emissions and promoting resource recovery (California Department of Resources Recycling and Recovery, 2020). Moreover, the European Union's Waste Framework Directive encourages member states to create waste prevention strategies, including measures that specifically target food waste. This directive obliges countries to develop national waste prevention programs, which can include legal frameworks that require businesses to adopt waste-reducing practices. By mandating waste reduction practices through legislation, governments can establish accountability and drive systemic change within the food supply chain. Such laws not only create a regulatory environment conducive to innovation and collaboration but also foster public awareness and engagement around the critical issue of food waste.

6.4. Policies Promoting Sustainable Supply Chain Operations

The growing recognition of the environmental and economic impacts of food waste has led governments and organizations worldwide to implement policies that promote sustainable supply chain operations. These policies aim to enhance efficiency, reduce waste, and encourage responsible practices across the agricultural supply chain. One of the most effective frameworks is the European Union's Farm to Fork Strategy, part of the broader European Green Deal. This strategy emphasizes sustainability in food production, distribution, and consumption. It aims to reduce food waste at all levels by promoting practices such as sustainable sourcing, reducing overproduction, and improving food distribution logistics. The strategy sets specific targets, including halving per capita food waste at the retail and consumer levels by 2030, providing a clear and actionable framework for stakeholders (European Commission, 2020).

In the United States, the U.S. Department of Agriculture (USDA) and the Environmental Protection Agency (EPA) launched the U.S. Food Waste Challenge, which encourages businesses, communities, and individuals to reduce food waste. This initiative supports educational campaigns, provides resources for food recovery and donation, and facilitates partnerships among stakeholders to improve food waste management practices (USDA, 2019). Additionally, countries like Canada have implemented the Canada's Food Waste Reduction Strategy, which focuses on research and innovation, food rescue initiatives, and the establishment of a national food waste reduction target. This comprehensive approach aims to create a culture of waste reduction by engaging consumers, businesses, and governments in shared responsibility. These policies collectively emphasize the importance of collaboration among various stakeholders, including governments, industries, and non-profits, to foster a sustainable food supply chain. By providing clear frameworks and objectives, they encourage the adoption of best practices that minimize waste while enhancing economic and environmental sustainability.

6.5. Importance of Collaboration

Collaboration among stakeholders is essential for effectively combating food waste within agricultural supply chains. Food waste is a complex issue that involves multiple actors, including farmers, processors, distributors, retailers, and consumers. Each stage of the supply chain presents unique challenges that can contribute to waste, making it imperative that stakeholders work together to create systemic change. Partnerships between various entities—governments, non-profit organizations, industry players, and academic institutions—can drive innovative solutions and best practices for waste reduction. For instance, public-private partnerships can facilitate research and development of new technologies that enhance supply chain efficiency. When businesses collaborate with universities to explore cutting-edge solutions like artificial intelligence for demand forecasting, they can better predict consumer needs, reducing the likelihood of overproduction and subsequent waste (Chalak et al., 2021).

Additionally, collaboration fosters knowledge sharing and resource optimization. Stakeholders can exchange successful strategies and case studies, leading to the widespread adoption of effective practices across the industry. Non-profit

organizations often play a crucial role in connecting businesses with resources and training programs that can help implement waste reduction initiatives. For example, organizations focused on food recovery can partner with local businesses to streamline the donation process for surplus food, ensuring that it reaches those in need instead of going to waste (Feeding America, 2020). Furthermore, collaborative efforts can lead to the development of cohesive policy frameworks that encourage sustainability across the supply chain. By uniting various stakeholders, advocacy for favourable legislation and incentives can be more powerful and effective, amplifying the voices of those committed to reducing food waste. In summary, collaboration is critical for creating systemic change in food waste reduction. By working together, stakeholders can share knowledge, resources, and best practices, ultimately driving significant improvements in sustainability and efficiency across the agricultural supply chain.

7. Case studies and collaboration

7.1. Successful Initiatives from Developed Countries

Several developed countries have implemented innovative programs and strategies to combat food waste, demonstrating effective methods for reducing waste across agricultural supply chains. These initiatives often involve collaboration among governments, non-profits, and private enterprises, showcasing the importance of a collective approach. In Denmark, the Stop Wasting Food Movement has gained significant traction. This grassroots initiative was launched in 2008 and aims to raise awareness about food waste while encouraging individuals and businesses to take action. The movement includes campaigns that educate consumers on proper food storage and meal planning to minimize waste at the household level. Furthermore, the Danish government supports this initiative through policies that promote food donation and recycling, facilitating partnerships with food banks and charities to redistribute surplus food (Stop Wasting Food, 2021).

In France, the aforementioned law prohibiting supermarkets from wasting unsold food represents a landmark approach to food waste reduction. Enacted in 2016, this legislation mandates that supermarkets donate unsold food to charities rather than discarding it. The law has led to significant increases in food donations, providing critical support to food-insecure populations while reducing waste in landfills. This initiative has inspired similar legislative actions in other countries, emphasizing the role of government in combating food waste (Fuchs, 2017). The United Kingdom has also made strides through its Waste and Resources Action Programme (WRAP). This initiative focuses on reducing food waste through extensive research, public education campaigns, and partnerships with retailers. WRAP's "Love Food Hate Waste" campaign has successfully raised awareness about food waste and encouraged consumers to adopt practices that minimize waste at home, contributing to a significant reduction in household food waste since its inception (WRAP, 2020). These successful initiatives from developed countries highlight the potential for impactful strategies to combat food waste through collaboration, legislation, and public engagement.

7.2. Successful Initiatives from Developing Countries

In developing countries, the challenges associated with food waste are often exacerbated by limited infrastructure, economic constraints, and varying cultural practices. However, innovative initiatives have emerged that address these unique challenges while promoting sustainability and reducing food waste. In India, the Food Recovery Network has made significant strides in reducing food waste through community engagement and technology. This initiative connects surplus food from restaurants, weddings, and events with local food banks and shelters. Utilizing mobile applications, volunteers can quickly coordinate food pickups and deliveries, ensuring that excess food reaches those in need rather than being discarded. This model not only helps alleviate hunger but also raises awareness about food waste and its environmental impacts (Ghosh, 2019).

Kenya faces substantial post-harvest losses due to inadequate storage facilities and transportation infrastructure. To address this, the Kenyan government and various NGOs have introduced programs that promote the use of improved storage technologies, such as hermetic storage bags. These bags protect grains from pests and moisture, significantly extending their shelf life and reducing spoilage. By educating farmers about these technologies, the initiative has effectively minimized food waste and enhanced food security for rural communities (Karanja et al., 2020). In Brazil, the National Food Waste and Loss Prevention Strategy involves various stakeholders, including farmers, retailers, and consumers, in a collaborative approach to waste reduction. This initiative emphasizes education on food preservation and best practices for consumption. For example, the strategy has implemented community workshops that teach proper food handling and storage techniques, directly addressing the cultural practices that contribute to food waste in the region (FAO, 2019). These initiatives exemplify how developing countries can leverage local resources, community engagement, and innovative technologies to tackle food waste while addressing unique challenges, thereby promoting food security and sustainability.

7.3. Role of Collaboration

Collaboration among government entities, industry stakeholders, and non-governmental organizations (NGOs) is vital in addressing the complex issue of food waste across agricultural supply chains. Each partner brings unique strengths and resources that, when combined, create a more robust and effective approach to combating food waste. Governments play a crucial role in setting regulatory frameworks and policies that incentivize food waste reduction. By creating legislation that mandates waste reduction practices and providing financial support for technology adoption, governments can drive significant change. For example, initiatives that promote food donation and recycling can create an environment conducive to collaboration between various stakeholders. Furthermore, government-funded programs can facilitate research and development, allowing for innovation in waste reduction strategies (Garrone et al., 2014).

Industry stakeholders, including food producers, distributors, and retailers, are on the front lines of food waste generation. Their participation is essential in implementing best practices and technological solutions. Collaboration with NGOs can enhance these efforts by providing expertise in community engagement and awareness-raising campaigns. For instance, partnerships with NGOs can facilitate education programs that inform consumers about the implications of food waste and encourage responsible consumption behaviours (Stangherlin et al., 2019). NGOs often serve as intermediaries, bridging the gap between governments and industries. They can mobilize community resources, advocate for policy changes, and drive public awareness campaigns. Their grassroots efforts can lead to meaningful changes in local practices, fostering a culture of sustainability and responsibility towards food waste (Harrison et al., 2019). In conclusion, effective collaboration among governments, industries, and NGOs is essential for developing and implementing comprehensive food waste reduction strategies. By leveraging their respective strengths, these partnerships can create systemic changes that lead to significant reductions in food waste, ultimately contributing to food security and environmental sustainability.

7.4. Summary of Case Studies

Examining successful initiatives aimed at reducing food waste across various contexts provides valuable insights and lessons that can inform future strategies. One notable case is the Food Recovery Network in the United States, which connects food donors with local nonprofits to redistribute surplus food. A key takeaway from this initiative is the power of leveraging existing community networks and technology to efficiently address food waste while alleviating hunger. The use of mobile apps for coordinating food donations not only increases efficiency but also engages volunteers and fosters a sense of community responsibility (Ghosh, 2019). In Kenya, the adoption of hermetic storage bags significantly reduced post-harvest losses among farmers. The primary lesson learned from this initiative is the importance of empowering local communities with practical tools and education. By providing farmers with effective storage solutions and training on their use, the initiative demonstrated how simple technological innovations can lead to substantial reductions in food waste and improvements in food security (Karanja et al., 2020).

Brazil's National Food Waste and Loss Prevention Strategy highlights the effectiveness of a multi-stakeholder approach in combating food waste. By involving various parties—including government agencies, private sector players, and NGOs—the initiative illustrated that collaboration fosters a more comprehensive understanding of the issue and promotes accountability. This case underscores the necessity of a unified approach to policy and community engagement to drive systemic change (FAO, 2023). In summary, these case studies collectively emphasize the importance of community engagement, technology adoption, and multi-stakeholder collaboration in effectively addressing food waste. They provide valuable lessons on the need for localized solutions, the role of education in empowering individuals, and the effectiveness of partnerships in creating sustainable systems that mitigate food waste.

8. Conclusion and recommendations

8.1. Summary of Key Findings

This systematic review has highlighted the pervasive issue of food waste across agricultural supply chains and the critical need for effective mitigation strategies. The analysis began by addressing the causes of food waste, identifying key drivers such as post-harvest losses, inefficient processing, transportation delays, inadequate packaging, cold chain failures, overproduction, and stringent aesthetic standards for produce. These factors collectively contribute to significant losses at various stages of the supply chain, underscoring the complexity of the problem. To combat these issues, the paper emphasized the importance of supply chain optimization strategies. Techniques such as demand forecasting, effective inventory management, cold chain logistics, just-in-time (JIT) systems, and circular economy approaches were explored. These strategies aim to enhance resource efficiency, minimize surplus production, and reduce spoilage, thereby contributing to food waste reduction.

The role of technological innovations was also a key focus, highlighting advancements such as the Internet of Things (IoT), blockchain technology, artificial intelligence (AI), machine learning (ML), and smart packaging. These technologies provide enhanced visibility and traceability within the supply chain, improving operational efficiency and aiding in waste reduction efforts. Additionally, the paper discussed the sustainability and economic benefits of reducing food waste. Effective waste mitigation strategies can lead to significant reductions in greenhouse gas emissions, conserve vital resources such as water and energy, and generate cost savings for businesses and consumers alike. Lastly, the review emphasized the importance of policy frameworks and collaborative efforts among stakeholders. Governments, industries, and NGOs must work together to create systemic changes that support sustainable practices and drive collective action towards food waste reduction. Overall, the findings underscore that addressing food waste is not only essential for improving food security but also for fostering environmental sustainability and economic resilience.

8.2. Recommendations for Stakeholders

To effectively combat food waste across agricultural supply chains, various stakeholders—farmers, businesses, policymakers, and consumers—must take proactive and collaborative steps.

- **For Farmers:** Implementing better post-harvest practices is crucial. Farmers should adopt advanced storage techniques, such as hermetic storage bags and climate-controlled facilities, to reduce spoilage. Additionally, participating in training programs that focus on sustainable agricultural practices and waste reduction can enhance their productivity and profitability. Collaborating with local cooperatives can also facilitate knowledge sharing and resource pooling, enabling them to better manage surplus production.
- **For Businesses:** Companies in the supply chain should invest in technology that enhances visibility and traceability. Utilizing IoT devices and blockchain technology can help monitor the freshness of products and optimize logistics, minimizing waste due to spoilage. Additionally, businesses should adopt just-in-time inventory systems to align supply with actual demand, thereby reducing overproduction. Training employees on waste reduction practices can also foster a culture of sustainability within organizations.
- **For Policymakers:** Governments should create supportive regulatory frameworks that incentivize waste reduction initiatives. This includes offering financial incentives for businesses that adopt sustainable practices and funding research on innovative waste reduction technologies. Policymakers should also mandate food waste audits for large businesses to encourage transparency and accountability.
- **For Consumers:** Raising awareness about the impact of food waste is essential. Consumers should be educated on the importance of mindful purchasing and proper food storage techniques. Encouraging the adoption of "ugly" fruits and vegetables can help combat aesthetic standards that lead to waste. Participating in community food recovery programs can also facilitate the redistribution of surplus food to those in need.

In conclusion, a multi-faceted approach that involves collaboration among all stakeholders is essential for reducing food waste effectively. By implementing these recommendations, each group can contribute to a more sustainable and resilient food system.

8.3. Future Research Directions

Future research on food waste and supply chain optimization is crucial to developing more effective strategies and solutions for this pervasive issue. Here are several key areas for exploration:

- **Advanced Technologies and Innovations:** While this paper highlighted the role of technologies like IoT and blockchain, further research is needed to evaluate the long-term impacts of these technologies on food waste reduction. Investigating the cost-benefit analyses of implementing these technologies in various contexts can provide valuable insights into their feasibility and scalability.
- **Behavioural Insights:** Understanding consumer behaviour is vital for addressing food waste at the consumption stage. Future research should focus on the psychological and social factors that influence purchasing decisions and food handling practices. Studies examining effective communication strategies for raising awareness about food waste and encouraging responsible consumer behaviour could offer practical solutions.
- **Policy Effectiveness:** There is a need for comprehensive evaluations of existing policies aimed at reducing food waste. Research could explore the effectiveness of different legislative approaches and incentives across various regions and sectors. Understanding the role of public-private partnerships in fostering collaboration and driving systemic change would also be beneficial.

- **Circular Economy Models:** Further investigation into the application of circular economy principles in agriculture can provide insights into innovative practices that minimize waste. Research could focus on case studies that demonstrate successful circular economy initiatives and their scalability.
- **Regional Differences:** Food waste issues and solutions can vary significantly across regions. Future studies should examine local contexts and cultural factors influencing food waste and explore tailored solutions that consider geographical and socioeconomic differences.
- **Impact Assessments:** Research assessing the environmental and economic impacts of food waste reduction strategies over time can provide a comprehensive understanding of their effectiveness. Longitudinal studies that track the outcomes of specific interventions would be particularly valuable.

By focusing on these areas, future research can contribute significantly to the ongoing efforts to combat food waste, enhance supply chain optimization, and promote sustainability in the agricultural sector.

8.4. Final Thoughts

Addressing the global challenge of food waste requires a concerted effort that emphasizes collaboration and innovation across all sectors of the agricultural supply chain. Food waste not only undermines food security but also poses significant economic and environmental challenges. Therefore, fostering a culture of cooperation among farmers, businesses, policymakers, and consumers is essential for developing comprehensive strategies that effectively reduce waste.

Collaboration is paramount; it brings together diverse stakeholders to share knowledge, resources, and best practices. By forming partnerships, stakeholders can create synergies that amplify their impact. For instance, businesses can collaborate with local farmers to ensure that surplus produce is redirected to food banks or other community resources, rather than being discarded. Similarly, public-private partnerships can help drive technological advancements and policy changes that support waste reduction initiatives.

Innovation plays a critical role in this endeavour. The rapid advancement of technologies, such as IoT, blockchain, and AI, provides unprecedented opportunities to enhance supply chain transparency, traceability, and efficiency. These innovations can help stakeholders monitor food quality in real-time, optimize logistics, and ultimately minimize waste. However, innovation must be coupled with a commitment to sustainability, ensuring that new technologies and practices align with broader environmental goals.

As we confront the complexities of food waste, it is imperative to recognize that no single entity can solve this issue in isolation. The path forward involves harnessing the collective strengths of all stakeholders to create systemic change. By prioritizing collaboration and fostering a spirit of innovation, we can build resilient food systems that not only reduce waste but also contribute to sustainable development, economic growth, and improved food security for all. The time to act is now, as the global community must unite to combat food waste and secure a more sustainable future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

- [1] FAO. (2019). The State of Food and Agriculture 2019: Moving Forward on Food Loss and Waste Reduction. Food and Agriculture Organization of the United Nations.
- [2] FAO. (2023). The State of Food Security and Nutrition in the World 2023. Food and Agriculture Organization of the United Nations.
- [3] Garrone, P., Melacini, M., & Perego, A. (2014). An empirical investigation of food waste in the food supply chain. *Waste Management*, 34(6), 1428-1436.
- [4] Kumar, P., Singh, S. P., & Pal, P. (2021). An analysis of food waste in the supply chain: Issues and strategies. *Sustainability*, 13(9), 4875.
- [5] IPCC. (2019). Climate Change and Land. Intergovernmental Panel on Climate Change.

- [6] California Department of Resources Recycling and Recovery. (2020). Organic Waste Reduction Regulations: Assembly Bill 1826.
- [7] Fuchs, C. (2017). Reducing Food Waste: The Role of Policy in Addressing the Food Waste Crisis.
- [8] European Commission. (2020). Farm to Fork Strategy: For a Fair, Healthy and Environmentally-Friendly Food System.
- [9] USDA. (2019). U.S. Food Waste Challenge: A Strategy for Reducing Food Waste in America.
- [10] Cuthbertson, R., & Piotrowicz, W. (2011). Performance measurement in supply chain management: A review. *International Journal of Logistics Management*, 22(3), 293-303.
- [11] Chong, A. Y.-L., Lo, C. K. Y., & Weng, X. (2017). The role of big data analytics in supply chain management: A review. *International Journal of Production Economics*, 193, 130-143.
- [12] Akkerman, R., Farahani, R. Z., & Grunow, M. (2010). Fulfilling consumers' demand while reducing food waste: A review of food supply chain management. *Waste Management*, 30(2), 100-114.
- [13] Kumar, S., Singh, P., & Kumar, A. (2017). A comprehensive review of cold chain logistics: A case of perishable food products. *Journal of Food Science and Technology*, 54(3), 522-534.
- [14] Cohen, L., & Roussel, J. (2013). *Strategic Supply Chain Management: The Five Core Disciplines for Top Performance*. McGraw-Hill.
- [15] Ellen MacArthur Foundation. (2019). *Completing the Picture: How the Circular Economy Tackles Climate Change*. Retrieved from Ellen MacArthur Foundation.
- [16] Kamble, S. S., Gunasekaran, A., & Sharma, R. (2020). A framework for the implementation of Industry 4.0 in the food supply chain. *International Journal of Production Economics*, 219, 116-129.
- [17] Kshetri, N. (2018). Blockchain's roles in strengthening cybersecurity and privacy. In *Blockchain for Business* (pp. 3-22). Springer, Cham.
- [18] Pérez-Ruiz, M., Eguía, E., & González-Torre, P. (2020). A machine learning approach for demand forecasting in fresh food supply chains. *Sustainability*, 12(11), 4589.
- [19] González, A., Pantoja, L., & Soto, E. (2021). Active and intelligent packaging for food applications: A review. *Food Packaging and Shelf Life*, 28, 100673.
- [20] Food and Agriculture Organization (FAO). (2013). *Food Wastage Footprint: Impacts on Natural Resources*.
- [21] Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Mitigation of Climate Change*.
- [22] Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems*, 15(3), 401-415.
- [23] Bennett, A. E., et al. (2018). Estimating the Value of Food Waste Reduction in the United States: A Review of the Literature.
- [24] Kroger. (2021). *Kroger's Zero Hunger | Zero Waste Foundation*.
- [25] Unilever. (2020). *Sustainable Living: Progress Report*.
- [26] Waste and Resources Action Programme (WRAP). (2021). *Food Waste Prevention: Insights from the WRAP*.
- [27] European Commission. (2018). *A European Strategy for Plastics in a Circular Economy*.
- [28] FAO. (2014). *Innovative Solutions for Reducing Food Waste*.
- [29] United Nations Environment Programme (UNEP). (2021). *Food Waste Index Report 2021*.
- [30] Chalak, A., Abou-Zeid, M., & Alhajji, M. (2021). *Innovation in Food Waste Management: Technology and Best Practices*.
- [31] Feeding America. (2020). *The Role of Food Recovery in Reducing Food Waste: A Guide for Food Banks*.
- [32] Stop Wasting Food. (2021). *About the Stop Wasting Food Movement*.
- [33] WRAP. (2020). *Love Food Hate Waste: Campaign Impact Report*.
- [34] Ghosh, P. (2019). *Reducing Food Waste in India: Innovative Approaches to Food Recovery*.

- [35] Karanja, A., Okello, J., & Nyangweso, P. (2020). Post-Harvest Losses in Kenya: A Study on Causes and Interventions.
- [36] Garrone, P., Melacini, M., & Dallari, F. (2014). The Role of Collaboration in Food Waste Reduction: The Case of the Italian Food Supply Chain.
- [37] Harrison, A., Sweeney, M., & Eves, A. (2019). The Role of NGOs in Reducing Food Waste: Strategies and Initiatives.
- [38] Stangherlin, I., Mena, C., & Williams, H. (2019). The Role of Stakeholders in Food Waste Management: A Multi-Stakeholder Perspective