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Sustainable Food and Agriculture Production: Reducing Food Waste through Technological Advancements and Assessing Its Economic Impact

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Abstract: The food waste (FW) is a widespread and persistent concern that has substantial environmental, social, and economic consequences. This study addresses the intricate relationship among sustainable food production, technological innovation, and the imperative to reduce FW, analyzing the entire food supply chain from production to consumption to identify key points where waste occurs. The potential of developing technologies is evaluated to induce substantial transformations. The study elucidates how precision agriculture, smart packaging, blockchain, artificial intelligence, and consumer-centric apps can transform food systems through a comprehensive assessment of literature and case studies. Challenges, opportunities, and future research directions are comprehensively discussed, emphasizing the need for collaborative, multi-stakeholder approaches to achieve a sustainable and waste-conscious food future.

Keywords: Agriculture; Food waste; Innovative solutions; Sustainable food production; Precision

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1. Introduction

Food waste (FW) is a multifaceted problem that encompasses the discarding or loss of edible food, and it has far-reaching consequences. Annually, approximately one billion tons of food are lost or wasted, which accounts for around 33% of the total amount produced for human consumption [1, 2]. This significant statistic emphasizes the need to prioritize the reduction of FW as a vital aspect of sustainable food production.

The ecological ramifications of FW are immense [3]. The activity in question has a damaging impact on the quality of water, the release of gases that contribute to the greenhouse effect, the destruction of forests, and the reduction of biodiversity [4]. In addition, discarded food also signifies a substantial squandering of resources such as water, land, labor, and energy [2, 5].

Parfitt et al. [6] executed a study investigating customer attitudes and behavior on FW. The results suggest that insufficient knowledge, ambiguity regarding date labeling, and excessive buying are significant variables that contribute to FW at the household level [7, 8]. By implementing targeted strategies, such as instructional programs and simplified date labeling, it is possible to significantly reduce FW among consumers [9].

Several research have also explored the capacity of technical improvements to tackle the issue of FW. Abiri et al. [10] investigated the application of Internet of Things (IoT) sensors and data analytics for monitoring food quality and forecasting shelf life. This technology allows retailers to enhance inventory management and minimize FW. Blockchain technology has been suggested as a means to improve traceability and transparency in the food supply chain. This allows stakeholders to easily detect and tackle the causes of FW [11].

In addition to the negative impact on the environment, FW has significant social and economic consequences. In a global context when millions of people experience food insecurity, the act of discarding edible food is ethically condemnable. Moreover, there are significant economic losses that occur across the entire supply chain, spanning from farmers to retailers to consumers. These losses have been documented by FAO [2] and Agyemang et al. [12].

The advancement of technology offers a glimmer of hope in the fight against FW. New technology has the potential to revolutionize the production, preparation, distribution, and consumption of food. This can lead to the adoption of more efficient, sustainable, and waste-conscious methods [13].

The substantial quantity of garbage has significant ramifications for the environment, as it contributes to the emission of greenhouse gases (GHG), pollution of water bodies, destruction of forests, and loss of biodiversity [4]. Furthermore, FW intensifies the problem of food poverty and leads to economic losses, especially in developing nations with limited resources.

The factors contributing to FW are multifaceted and differ among various geographical areas and stages of the food distribution process [4, 14]. Insufficient storage facilities, weak transportation infrastructure, and limited market access are common causes of food loss in underdeveloped nations. FW is more common in industrialized countries at the retail and consumer stages due to excessive purchasing, uncertainty regarding "best before" dates, and a lack of understanding of the importance of food [15–17].

Technological improvements provide viable options to tackle the issue of FW [18]. Blockchain, artificial intelligence (AI), IoT, and drones are innovative technologies that have the capacity to transform the food supply chain by enhancing efficiency, transparency, and traceability [19]. These technologies have the potential to improve inventory management, optimize transportation routes, and facilitate communication among stakeholders, resulting in a reduction in FW and the creation of a more sustainable food system.

This study would significantly benefit from a more explicit articulation of the research questions and a more precise identification of the research gap, emphasizing that sustainable food and agricultural production can only be realized through technological advancements, alongside economic benefits and a reduction in FW.

This study encompasses five primary features. The first of these is the global FW crisis in the main title. The global crisis of FW in the main title includes factors contributing to FW, environmental impacts of FW, trends in FW, and social and economic impacts. The second main heading consists of technological interventions to reduce FW. The main heading of technological interventions for reducing FW consists of the food industry and precision agriculture, smart packaging, blockchain technology, AI and machine learning (ML) for FW, and subheadings of applications for direct use by consumers. The third main heading is the challenges and barriers to implementation and is examined under the subheadings of cost and affordability, lack of infrastructure and connectivity, data security and privacy issues, and consumer acceptance and behavior change. The final section, opportunities and future directions, focuses on future collaboration between public and private organizations and financial contributions to research and development.

This study investigates the many phases of the food supply chain, identifies significant causes of waste, and assesses the potential for innovative technology to bring about significant changes [16, 20]. The study recommends a comprehensive knowledge of the intricate relationship between technology, sustainability, and the decrease of FW by combining research findings, case studies, and expert insights [21]. This study aims to thoroughly investigate sustainable food production and novel strategies for minimizing FW using technological improvements.

2. Methodology of the Study

This study delineates its methodology, encompassing study design, data collecting, and analytical approaches, while elucidating how these elements are substantiated by existing literature.

Study design: This study employed a mixed methods approach, incorporating both qualitative and quantitative analyses. It initially examined and delineated worldwide issues in FW, focusing on prevention strategies for sustainability, potential solutions, and future actions.

Data collection: In this study, data was gathered following the aforementioned methodology, with analyses conducted by systematically reviewing the literature. This study involved identifying global FW crises, technological interventions to mitigate FW, challenges and barriers to implementation, as well as opportunities and future directions based on specified topics and criteria.

Analytical techniques: This study elucidates analytical approaches, namely thematic analysis and comparative analysis, with citations from the literature. Analytical methods, including thematic analysis and comparative analysis, utilized in synthesizing data from literature and case studies are identified and presented.

3. FW: A Global Crisis

Prior to exploring technological remedies, it is crucial to comprehend the scale and intricacy of the issue of FW [22]. The next phase offers an in-depth evaluation of the reasons, consequences, and present patterns in FW [21, 23, 24].

3.1 Factors Contributing to FW

FW accumulates at every stage of the supply chain due to multiple variables. Insufficient infrastructure, limited technological availability, and poor transportation networks in underdeveloped nations frequently result in losses during production, postharvest handling, and storage [2, 25]. FW due to over-purchasing and uncertainty about issues such as sell-by dates and aesthetic preferences is more prevalent at the retail and consumer level in developed countries [15].

In Figure 1, the regional food losses can be evaluated for 2021 year. According to these food loss rates [%], the most food is lost in Africa and the least in North America and Europe.

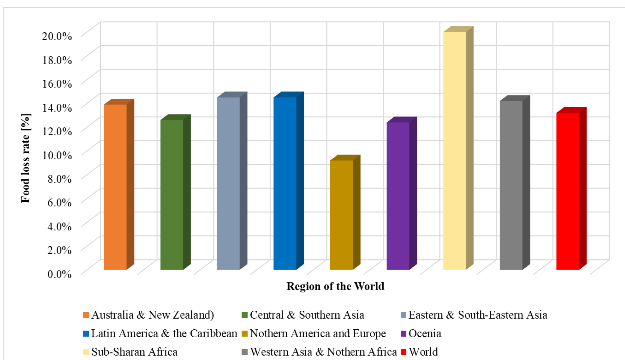

Figure 1. Regional food losses for 2021 year [26].

Table 1 demonstrates the primary factors contributing to FW at various levels of the supply chain, which are the point of the manufacture, the postharvest handling, the processing, the distribution, the retail, and the consumption. In addition, these points can be divided into many subtitles of the sources subjects as follows respectively; the pests and diseases, the adverse weather conditions, the inefficient harvesting techniques [2], the lack of access to markets, and the overproduction [27] for the point of the manufacture sources, the adequate storage facilities, the poor transportation infrastructure, the lack of processing facilities [28], inefficient packaging [29], and the improper temperature control [27] for the point of the postharvest handling sources, the inefficient processing techniques, the overproduction, the quality standards that lead to the rejection of edible food, and the product damage during processing [27] for the point of the processing sources, the poor inventory management, the inadequate transportation and refrigeration, the long distances between production and consumption centers, the damage during transportation [27], and the inefficient logistics [30] for the point of the distribution sources, the overstocking, the inappropriate storage conditions, the marketing and promotions [27], the consumer behavior (buying more than needed) [31], the confusion over date labels, and the emphasis on aesthetic appearance [29] for the point of the retail sources, the large portion sizes, the over-preparation of food, the discarding leftovers [32], the lack of awareness about FW [30], the cultural norms that discourage eating leftovers [33], the impulse buying [34], and the mismatch between household size and food packaging [29] for the point of the consumption sources.

3.2 FW's Environmental Impact

The environmental impact of FW, which are complex and extensive, results in the squandering of resources used in its production, such as water, land, energy, fertilizers, and pesticides. This wasteful use of resources intensifies environmental pressures, leading to climate change, deforestation, water scarcity, and loss of biodiversity. In addition, the process of breaking down food in landfills results in the emission of methane (CH_4), a powerful GHG that contributes to the phenomenon of climate change [30].

In Figure 2, when FW is disposed of in landfills, it breaks down without oxygen, producing CH_4, is a potent GHG that has 28 times the global warming potential of carbon dioxide (CO_2) over a span of around a century [30]. The cumulative effect of CH_4 gas emissions from FW in landfills is responsible for causing climate change.

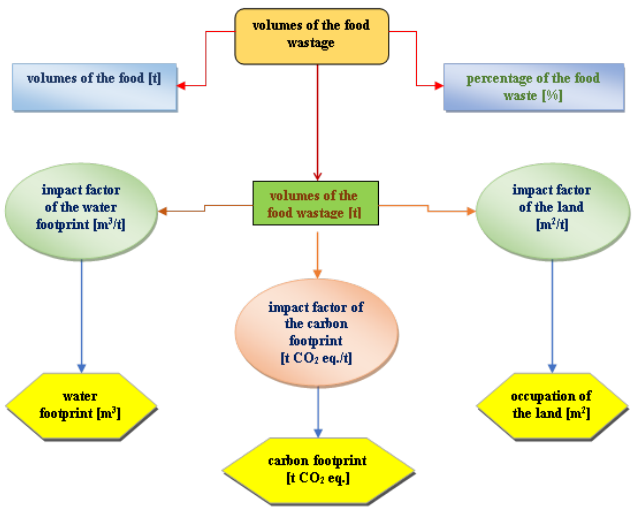

Figure 2. The impact of FW on the environment [30].

Table 2 demonstrates the greenhouse gas (GHG) emissions from some of the FW, which can be given as food category (beef herd, lamb & mutton, beef dairy herd, farmed prawns, cheese, pig meat, poultry meat, and eggs). According to these gas emission results, beef herd has the highest emission as carbon dioxide equivalents (CO_2 eq) with 99.48 [kg CO_2-eq], while potatoes have the lowest emission with 0.46 [kg CO_2-eq] [35]. According to Table 2, it is beneficial to present certain definitions and information. A GHG is a gas that increases the temperature of the atmosphere by absorbing and emitting radiant energy. It absorbs the radiation emitted by the Earth and prevents the heat from escaping into space. CO_2 is widely recognized as the most prominent GHG, although there are other significant ones such as CH_4, nitrous oxide, and even water vapor. The primary driver of global climate change is the release of anthropogenic GHGs resulting from activities such as burning fossil fuels, industrial processes, and agricultural practices. These GHGs collectively represent the total emissions contributing to climate change. Typically, these measurements are expressed as CO_2 eq, which consider the warming potential of individual molecules of various gases. The CO_2 is a prominent GHG. In order to standardize the measurement of GHGs, each gas is assigned

Table 1. Primary factors contributing to FW at various levels of the supply chain [2, 27–34].

Point	Sources
manufacture	pests and diseases, adverse weather conditions, inefficient harvesting techniques [2], lack of access to markets, overproduction [27]
postharvest handling	inadequate storage facilities, poor transportation infrastructure, lack of processing facilities [28], inefficient packaging [29], improper temperature control [27]
processing	inefficient processing techniques, overproduction, quality standards that lead to the rejection of edible food, product damage during processing [27]
distribution	poor inventory management, inadequate transportation and refrigeration, long distances between production and consumption centers, damage during transportation [27], inefficient logistics [30]
retail	Overstocking, inappropriate storage conditions, marketing and promotions [27], consumer behavior (buying more than needed) [31], confusion over date labels, emphasis on aesthetic appearance [29]
consumption	large portion sizes, over-preparation of food, discarding leftovers [32], lack of awareness about FW [31], cultural norms that discourage eating leftovers [33], impulse buying [34], mismatch between household size and food packaging [29]

a global warming potential (GWP) value, which allows for comparison with the warming effect of the CO_2. GWP quantifies the extent to which a gas contributes to global warming in relation to CO_2, which is given a specific GWP value. If a gas has a GWP of 10, then 1 kg of that gas has a warming effect that is 10 times greater than 1 kg of CO_2, whose equivalents are determined by multiplying the amount of each gas by its corresponding CO_2 eq value [36].

Table 3 presents some of estimated GHG emissions per kg of FW [kg CO_2-eq], which are indicated as food category (beef, lamb & mutton, dairy products, pig meat, poultry meat, cereals, and vegetables & fruits). According to these estimated GHG emissions per kg of wasted food, beef has the highest emission at 26.5 [kg CO_2-eq], while vegetables & fruits have the lowest emission at 1.0 [kg CO_2-eq] [30].

The production of FW involves significant water consumption. An estimated 250 km3 of water are used each year to produce food that is ultimately wasted. The figure illustrates that the volume of FW is three times greater than that of Lake Geneva, emphasizing the significant water usage associated with FW [30].

Moreover, the utilization of land for cultivating crops or raising livestock that are not consumed results in a substantial depletion of fertile land. Deforestation, caused by the expansion of agricultural land to meet elevating food demands, considerably triggers climate change and the loss of biodiversity.

3.3 Trends in FW

The problem persists and, in some areas, is even getting worse [23]. This is despite the fact that there is a growing awareness of the issue and initiatives to address it. There has been an increase in the amount of food that has been lost or wasted at various stages as a result of the COVID-19 pandemic, which has further disrupted supply chains. However, there are also encouraging patterns, such as an increase in initiatives aimed at reducing FW, the implementation of technological remedies, and the growing consciousness among consumers [37, 38].

3.4 Social and Economic Impact

As a result of FW, the problem of food insecurity is made worse, as a large number of people all over the world do not have sufficient access to sufficient quantities of nutrient-rich food to survive [2]. There will be significant financial repercussions as a result of FW, which will have an effect on agricultural producers, sellers, and buyers. It was reported by the Food and Agriculture Organization of the United Nations in 2013 that the annual global economic value of FW is approximately one tril-

Table 2. GHG emissions from some of the FW[35, 36].

Food Category	GHG Emissions per kg of Food Wastage	Food Category	GHG Emissions per kg of Food Wastage
beef herd	99.48	rice	4.45
lamb & mutton	39.72	milk	3.15
beef dairy herd	33.30	tomatoes	2.09
farmed prawns	26.87	maize	1.70
cheese	23.88	wheat & rye	1.57
pig meat	12.31	peas	0.98
poultry meat	9.87	bananas	0.86
eggs	4.67	potatoes	0.46

Table 3. Estimated GHG emissions for some of the FW[30].

Food Category	Estimated GHG Emissions per kg of Food Wastage
beef	26.5
lamb & mutton	22.9
dairy products	9.0
pig meat	7.5
poultry meat	4.5
cereals	3.7
vegetables & fruits	1.0

lion dollars. According to Sheahan and Barrett[28], the economic and social repercussions due to the loss and waste of food in Sub-Saharan Africa are relatively significant.

4. Technological Interventions for Reducing FW

Technological advancements are crucial in addressing the FW challenge. The different cutting-edge strategies utilize technology to reduce food loss and waste throughout the entire supply chain. Blockchain technology provides a decentralized and unchangeable record that can monitor the movement of food products across the supply chain[39]. Blockchain can help retailers identify products nearing their expiration dates and implement targeted discounts or donations to prevent waste[40]. Furthermore, blockchain technology has the capability to authenticate and trace the source of food products, thereby minimizing the potential for deception and guaranteeing the safety of the food supply[39].

AI algorithms have the capability to examine extensive quantities of data in order to detect patterns and trends in the production, distribution, and consumption of food. By employing ML, AI can predict demand, optimize inventory levels, and identify potential sources of FW. AI-powered platforms possess the capacity to analyze historical sales data, weather patterns, and consumer behavior to accurately forecast demand. This guarantees the production and distribution of an ideal amount of food, resulting in a decrease in waste[40].

IoT devices, like sensors and RFID tags, can be placed in food products or packaging to track different factors such as temperature, humidity, and location. The real-time data can be sent to a central platform for analysis, ensuring that food is stored and transported in the best possible conditions to reduce the chances of spoilage and waste[39]. Internet of Things (IoT) sensors have the capability to notify retailers in the event of a refrigerator malfunction, allowing them to promptly address the issue and prevent any food wastage[40]. Moreover, the Internet of Things (IoT) can enhance efficient inventory management by monitoring the movement of products and their expiration dates. This enables retailers to implement focused promotional campaigns or donations to prevent wastage[40].

By enhancing transportation and logistics, drones have the potential to bring about significant changes in the industry that supplies food. By reducing the need for lengthy transportation routes and minimizing the amount of food that spoils while in transit, unmanned aerial vehicles (UAVs) can be utilized to transport food to areas that are underserved or remote. Furthermore, the utilization of drones that are fitted with sensors makes it possible to monitor the health of crops and to identify areas in which there may be a decrease in yield. This gives farmers the ability to take the necessary actions and prevent any potential crop failure that may occur during the production phase [41, 42].

4.1 Food Industry and Precision Agriculture

Precision agriculture, as defined by Sishodia et al. [41], and Zhang et al. [42], Balasubramanian et al. [43], encompasses various technologies that empower farmers to optimize resource utilization, enhance crop productivity, and minimize post-harvest losses. Table 4 employs sensors, global positioning system (GPS) technology, drones, and data analytics to provide farmers with up-to-date information on soil conditions, crop health, and weather patterns. The provision of information enables farmers to make informed decisions regarding irrigation, fertilization, and pest management, leading to reduced losses and increased efficiency [44].

Table 4. The utilization of precision agriculture technologies and their implementation in reducing fertilizer and water usage.

Technology	Application in the Reduction of FW
Data Analytics	By analyzing data collected from various sources such as sensors and drones, patterns, trends, and anomalies can be identified. This allows for making decisions based on data, which in turn helps optimize resource utilization and reduce waste [45].
Drones	Aerial imaging is used to monitor crops, detect diseases, and estimate yields. This helps in implementing specific interventions and reduces the requirement for widespread use of pesticides and fertilizers [46].
GPS	The process involves cartography of agricultural plots, identification of regions with subpar crop production, enhancement of irrigation and fertilization techniques, and implementation of precise harvesting methods [46].
Robotics and Automation	By automating tasks such as planting, weeding, and harvesting, agricultural processes can be made more efficient, labor costs can be reduced, and crop damage can be minimized [47].
Sensors	The process of monitoring soil moisture, nutrient levels, crop growth, and pest infestations allows for timely interventions to prevent losses in agricultural production [46].
Variable Rate Technology	Implementing site-specific management techniques, such as adjusting the application rates of fertilizers, pesticides, and water according to the specific requirements of different sections within a field, in order to maximize resource efficiency and minimize wastage [48, 49].

4.2 Smart Packaging

Smart packaging utilizes technology to improve the longevity, security, and excellence of food products. The system includes sensors, indicators, and data communication capabilities to monitor the state of the food and deliver real-time information to producers, retailers, and consumers. Intelligent packaging integrates sensors and indicators to monitor the state of food products and offer up-to-date information on their freshness and quality. This technology has the potential to increase the amount of time that food can be stored without spoiling, decrease the amount of food that goes to waste, and provide both retailers and consumers with the necessary information to make educated choices about when to consume the food [50]. In Table 5, the smart packaging technologies and their applications in FW reduction can be defined by technologies, which are Time-Temperature Indicators (TTIs), Gas Indicators, Radio Frequency Identification (RFID) Tags, Quick Response (QR) Codes, Active Packaging, and Intelligent Packaging. Figure 3 illustrates the various categories of smart packaging based on active and intelligent techniques [50–53].

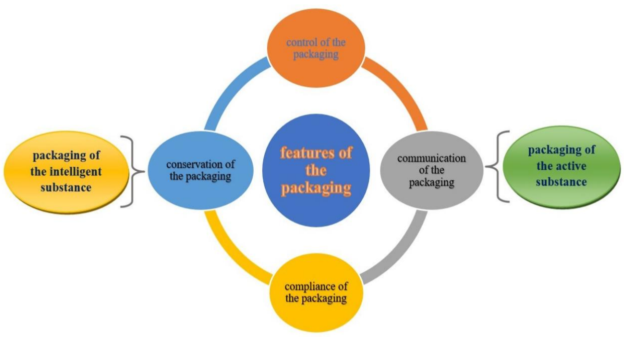

Figure 3. Categories of smart packaging [50–53].

4.3 Blockchain Technology

Blockchain, a distributed and unchangeable digital record, provides unparalleled ability to track and disclose information in the food distribution network. Blockchain technology has the ability to improve food safety, decrease fraudulent activities, and quickly identify contaminated products by keeping a record of every transaction and movement of food items. This, in

Table 5. Smart packaging technologies and their applications in FW reduction.

Technology	Application in FW Reduction
Time-Temperature Indicators (TTIs)	Track the temperature records of a product to ascertain whether it has been subjected to temperatures that could potentially undermine its quality or safety [54].
Gas Indicators	Identify the existence of gases, such as oxygen or carbon dioxide, which serve as indicators of food spoilage or decay [55].
Radio Frequency Identification (RFID) Tags	Enable the monitoring and tracing of products across the entire supply chain, simplifying inventory management, guaranteeing the authenticity of products, and facilitating specific recalls [56].
Quick Response (QR) Codes	Provide consumers with comprehensive information regarding the product's source, constituents, and nutritional composition, enabling them to make well-informed choices [51, 57].
Active Packaging	Engages with the food or its surroundings in order to preserve its quality and prolong its shelf life, such as by using oxygen scavengers and moisture absorbers [55].
Intelligent Packaging	Utilizes sensors and communication technologies to oversee the state of the food and deliver immediate updates to consumers, such as freshness indicators that alter their color as the food deteriorates [53].

turn, helps to minimize waste [58]. Blockchain technology provides a clear and reliable method for monitoring food products at every stage of the supply chain. Blockchain technology can enhance traceability, improve food safety, and reduce losses caused by fraud and contamination by accurately recording every transaction and movement of food items [39]. Figure 4 depicts the incorporation of blockchain technology into the food supply chain, showcasing the sequential flow of provider, producer, process, distribution, retailer, and consumer [39, 59, 60].

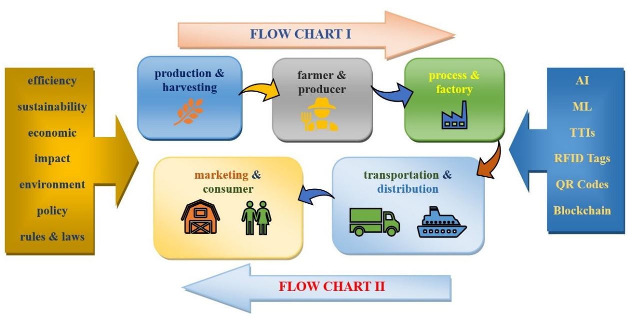

Figure 4. The implementation of blockchain technology in the food supply chain.

4.4 AI and ML for the FW

AI and ML are transforming different facets of the food system. AI algorithms have the capability to analyze large quantities of data in order to improve demand forecasting, inventory management, and supply chain logistics. ML models have the capability to forecast food spoilage, allowing retailers to offer discounts on items before they reach their expiration date, thereby minimizing waste. The provided data can be utilized to enhance inventory management, forecast demand, and minimize wastage by synchronizing supply with demand. In Figure 5, AI domains (sectors) can be classified by reasoning, language, learning, perception, problem and solution as the focus of intelligence [61].

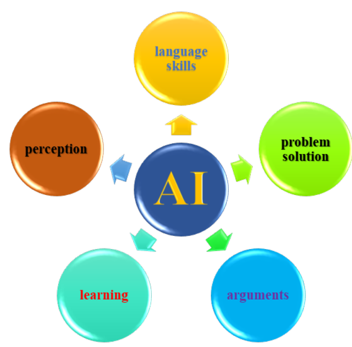

Figure 5. AI of FW for sustainability [61].

4.5 Applications Designed for Direct Use by Consumers

Enabling consumers is a vital component of reducing FW. Consumer-oriented applications, such as mobile applications and online platforms, are utilizing technology to offer information, tools, and incentives for minimizing FW at home. These applications provide functionalities such as recommending recipes based on leftover ingredients, platforms for sharing food, and discounts on products that are about to expire. Mobile applications and online platforms have the ability to empower consumers to minimize FW. Mobile applications that offer recipes for unused ingredients, facilitate the connection between consumers and excess food, and provide discounts on products that are close to their expiration date can promote the adoption of more environmentally-friendly food consumption habits [10, 62, 63].

5. Problems and Obstacles to Implementing

Introducing innovative technologies to reduce FW is not without difficulties. The financial constraints associated with implementing technology can hinder the advancement of small-scale farmers and businesses [44]. Furthermore, it is essential to establish uniform procedures for gathering and exchanging data to guarantee compatibility among various platforms and technologies [40]. Notwithstanding these challenges, the opportunities are substantial. The food system can be significantly improved by technological advancements, leading to increased efficiency, sustainability, and resilience. Through the utilization of technology, it is possible to diminish FW, preserve resources, and guarantee food security for future generations [43, 64].

5.1 Cost and Affordability

Many technological solutions, such as precision agriculture equipment and smart packaging, can be expensive, making them inaccessible to small-scale farmers and businesses in developing countries. Precision agriculture equipment and smart packaging can be expensive, limiting access for smallholders. One of the biggest challenges when implementing technological solutions can be their cost, especially for small-scale farmers and businesses in developing nations. Individuals with limited financial resources are often unable to afford precision agriculture equipment, sensors, and smart packaging due to their high cost [65–68]. In Table 6, the focus area can be divided as the precision agriculture technologies, AI and ML technologies, and the financial barriers to adoption for the cost and affordability barriers to technology adoption.

Table 6. Cost and affordability barriers to technology adoption.

Focus Area	Key Findings	Region/Context
Precision Agriculture Technologies	Highlights the financial difficulties encountered by small-scale farmers when implementing expensive precision agriculture technologies [69–71].	Global
AI and ML Technologies	Explores the need for affordable AI and ML solutions for food industry small and medium enterprises [72–75].	Global
Financial Barriers to Adoption	Emphasizes the significance of financial incentives and support mechanisms in promoting the adoption of technology in developing nations [23, 76–78].	Developing Countries

5.2 Lack of Infrastructure and Connectivity

The implementation of technologies like blockchain and AI often requires reliable internet connectivity and digital infrastructure, which may be lacking in certain regions, particularly in rural areas [79–81]. In Table 7, the focus area can be divided as the digital divide, and the blockchain technology for the infrastructure and connectivity barriers to technology adoption. The key findings of the digital divide can be summarized as the unequal distribution of internet access and digital technologies across different regions of the world [82–85]. The key discoveries of the blockchain technology can be summarized as the examination of the challenges associated with implementing blockchain technology in regions with insufficient internet access and infrastructure [40, 81, 86–88].

5.3 Data Security and Privacy Issues

Security and privacy of data are vulnerabilities that arise from the gathering and dissemination of data within the food supply chain. Stringent protocols and regulations are necessary to guarantee responsible data handling and safeguard sensitive information [13, 89–96]. With the increasing prevalence of technologies such as blockchain and AI, it is of utmost importance to prioritize the responsible and secure management of sensitive data [97, 98]. In Table 8, the data security and pri-

Table 7. Infrastructure and connectivity barriers to technology adoption.

Focus Area	Key Findings	Region/Context
Digital Divide	Highlights the disparity in internet access and availability of digital technologies across various global regions [82–85].	Global
Blockchain Technology	Explores the difficulties of adopting blockchain technology in areas with inadequate internet access and infrastructure [40, 81, 86–88].	Global

Table 8. Data security and privacy issues in technology adoption.

Focus Area	Key Findings	Region/Context
Blockchain Technology	Explores the possible privacy and security vulnerabilities linked to blockchain technology in the food industry [99–103].	Global
Data Protection Regulation	The European Union has established regulations to safeguard individual data, which have implications for the collection and sharing of data in the food supply chain [104–107].	European Union

vacy issues in technology adoption can be created by blockchain technology, and the data protection regulation.

5.4 Consumer acceptance and behavior change

Consumer views and conduct have a substantial impact on FW [108, 109]. Encouraging consumers to adopt new technologies and change their food consumption habits requires effective communication, education, and incentivization strategies [38, 110–112].

Table 9 indicates the consumer acceptance and behavior change barriers that can separate as the consumer behavior, the consumer education and engagement, and the consumer awareness and attitudes for the focus area.

Table 9. Consumer acceptance and behavior change barriers.

Focus Area	Key Findings	Region/Context
Consumer Behavior	Reviews consumer attitudes and behavior change interventions related to FW reduction [109, 113–116].	Global
Consumer Education and Engagement	Provides insights into consumer engagement strategies and campaigns aimed at reducing FW in the UK [38, 117–119].	United Kingdom (UK)
Consumer Awareness and Attitudes	Investigates the consumer awareness and attitudes toward FW in the US [31, 109, 118, 120, 121].	United States (US)

6. Opportunities and Future Directions

Despite the challenges, the opportunities for leveraging technology to reduce FW are immense. Further technological advancements, along with favorable policies and cooperative initiatives, have the potential to make substantial advancements in this field [122–125].

6.1 Collaborations between Public and Private Entities with the Future Way

Effective collaboration among governments, businesses, research institutions, and civil society organizations is essential for expanding the implementation of technological solutions and ensuring their fair distribution to future generations [23, 126–129].

Table 10 emphasizes the collaborations between public and private entities with the future way for FW reduction. The focus area can be categorized into three main components: reducing FW throughout the supply chain, preventing and reducing FW within the European Union, and rescuing and redistributing food. The key partners in the effort to reduce FW across the supply chain include grocery manufacturers, food marketing companies, and restaurants. In the European Union, the European Commission, EU Member States, and businesses are involved in preventing and reducing FW. Food banks, corporate partners, foundations, and governments are also important partners in the rescue and redistribution of food.

6.2 Financial Contributions to Research and Development

Sustained investment in research and development is crucial for promoting innovation and creating cost-

Table 10. Collaborations between public and private entities with the future way for FW reduction.

Focus Area	Outcomes	Key Partners
FW reduction across the supply chain	The implementation of consistent measurement and reporting practices for FW, along with industry cooperation and consumer education initiatives, have been highlighted in several studies [130–134].	grocery manufacturers, food marketing, restaurant
FW prevention and reduction in the EU	The EU is working on creating an action plan that focuses on developing and sharing knowledge, disseminating best practices, and engaging stakeholders. This initiative is supported by the studies conducted by Candeal et al. [135], Casonato et al. [136], Garcia Herrero et al. [137], and Vittuari et al. [138].	European Commission, EU Member States, businesses
Food rescue and redistribution	Operates in more than 40 countries, providing assistance to food banks, facilitating the distribution of excess food to individuals in need, and actively promoting policy reform [139–141].	food banks, corporate partners, foundations, governments

effective and easily accessible technologies to reduce FW [142–145]. A thorough action plan focusing the advancement of large-scale technologies with pilot applications should be undertaken as soon as possible in response to recent economic events in the regional and global contexts of FW. Both developed and developing countries should receive assistance and support from FW R&D. Decisions to mitigate FW linked to global research and development, as well as maintaining worldwide compliance, are expected to help resolve the FW issue.

7. Results and Discussions

This study includes many studies and reviews on sustainable food production and innovative solutions, and also presents many opportunities and competitive situations related to food. While technological advancements offer promising solutions to reduce FW, their successful implementation requires addressing several challenges as follows:

- Cost of Implementation: The cost of implementing these technologies, particularly in developing countries with limited resources, can be a significant barrier [144, 146, 147]. For instance, precision agriculture technologies require substantial upfront investments in equipment and training, which may be prohibitive for smallholder farmers.
- Lack of uniformity and interoperability: The lack of uniformity and interoperability between different technologies can hinder data sharing and collaboration between stakeholders [40, 148–150]. The result can be inefficiencies in the supply chain and a failure to realize the full potential of technology solutions.
- Privacy and security issues: Security and privacy issues are brought up by the gathering and exchange of data via these technologies [103, 151, 152]. Ensuring the responsible and secure handling of data is crucial for maintaining trust among stakeholders and preventing misuse of information. Despite these challenges, the opportunities for reducing FW through technological advancements are vast.
- Collaboration and Data Sharing: Stakeholders in the food supply chain can build a more open, effective, and sustainable food system by working together and exchanging data [23, 153, 154]. This may result in enhanced decision-making, increased coordination, and decreased waste throughout the process.
- Government Support: Providing incentives to businesses can play a crucial role in governments adopting these technologies and developing regulations that encourage FW reduction [144, 155]. This can include tax breaks, subsidies and other financial mechanisms to encourage investment in sustainable technologies.
- Business Opportunities: Businesses can leverage

these technologies to optimize their operations, reduce costs, and enhance their sustainability credentials[144]. The aforementioned can result in a mutually beneficial scenario where businesses reap financial gains while simultaneously making valuable contributions to a more sustainable food system.

- Consumer Empowerment: Consumers can also play a significant role by making informed choices, reducing FW at home, and supporting businesses that prioritize sustainability[156, 157]. This can create a positive feedback loop, where consumer demand drives further innovation and adoption of waste-reducing technologies.
- Strengths, Weakness, Opportunities, Threats (SWOT) analysis of FW state can be detailed in Figure 6[158–164]. The SWOT analysis presents the strengths, weaknesses, threats and opportunities of the FW in this study. Its major strength is that FW can be used as an energy fuel. The main weakness is the lack of access to sufficient food. Threats include wars and the world plunging into the greenhouse effect. The opportunity is that it will have an impact on the greening of the world by encouraging the development of agriculture and will also provide energy savings.

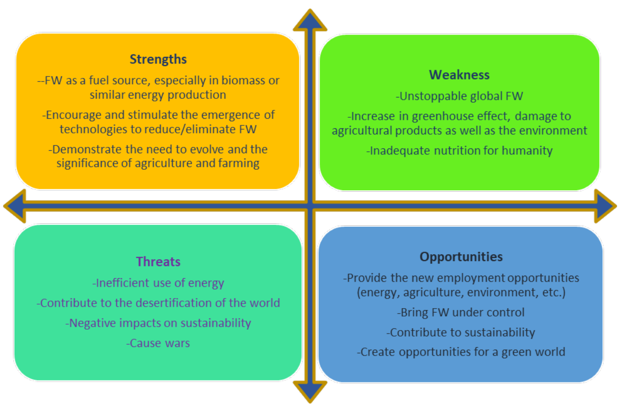

Figure 6. SWOT analysis of FW for sustainability.

Policymakers, sector practitioners, and consumers as stakeholders in the prevention of FW for sustainability are essential, and many factors need to be addressed. Globally, many countries, especially in Europe, are expected to give more weight to this issue. For a green world, it can only be successful if stakeholders are coordinated. It is essential to determine the analyses (such as SWOT and techno-economic analyses) by determining the lower and upper limits of each region by focusing on the FW issue on a country and regional basis.

It is known that the world population will be 8 billion in 2024[165]. 821 million (10.9%) of the world's population are hungry[165, 166], and the world population is projected to be around 10 billion by 2050[165, 167]. Unfortunately, the number of hungry people is expected to reach 2 billion, most of them in the global South. The demand for food (such as wheat) is a global shortage, considering the wars. In the future, it is expected that the countries with the largest populations will be the main drivers of the wheat market[165]. Supply and demand dynamics are equilibrated by mitigating FW; else, future periods would profoundly impact the planet on a global scale. Utilizing sophisticated technologies can mitigate both economic issues and hunger. Consequently, it is imperative to tackle the food waste issue internationally via an immediate action plan focused on sustainable food production and agricultural productivity. Some solutions and methods should be identified to make FW sustainable. Water wastage can be reduced with intelligent water farming technologies[168]. Waste minimization technologies should be applied as soon as possible with the aid of prediction using intelligent systems (AI, ML, etc.)[169]. Energy efficiency can be attained through food waste management and sustainable waste-to-energy generation[170]. Food safety and environmental sustainability can be enhanced by effective and efficient food waste management[171]. Furthermore, energy efficiency can be enhanced by utilizing industrial food waste as biodiesel[172]. Energy can be generated by enzymatic chemical processes employing several ways, and biogas can play a role in techno-economic and environmental analyses[173]. The biodigester is engineered to treat all decomposable waste and can generate a substantial proportion of biogas (CH_4), which is subsequently transformed into electrical and thermal energy[174]. Energy production from biogas (CH_4) also benefits the environment with its sustainable energy system. In this study, a global road map with the studies that need to be carried out with sustainability in FW is put forward by analyzing and comparing the studies in many different types of literature.

8. Conclusion

FWs are a worldwide emergency that has significant implications for the environment, society, and the economy. Technological advancements provide promising solutions to reduce food loss and waste throughout the supply chain. The adoption of precision agriculture, intelligent packaging, blockchain technology, artificial intelligence, and consumer-oriented applications has the potential to revolutionize the food system, making it more efficient, sustainable, and flexible.

Consequently, it is feasible to maintain equilibrium in supply and demand by averting FW; otherwise, future times will profoundly impact the planet on a global scale. Utilizing sophisticated technologies can mitigate both economic issues and hunger. Consequently, it is imperative to tackle the food waste issue internationally with an immediate action plan focused on sustainable food production and agricultural productivity.

Some solutions and methods should be identified to make FW sustainable. In the prevention of FW, after adjusting the working boundaries on a regional basis, it should be determined where integrated actions will be taken in the economic sense by uniting on a common denominator by dividing into developed, developing and underdeveloped regions. Coordination centers should be set up in line with the above analyses, and concrete steps should be taken towards food efficiency and sufficiency for the future by establishing common policies in agriculture and global agriculture. Overall, while challenges exist, the opportunities for leveraging technology to reduce FW are substantial. By tackling these obstacles and adopting cooperative methods, it can be fully exploited the capabilities of technology to establish a food system that is both sustainable and fair for everyone.

Nevertheless, the successful implementation of these technologies requires overcoming challenges related to costs, infrastructure, data privacy, and customer behavior. To maximize the efficacy of technology interventions against FW, it is essential to pursue joint efforts, form public-private partnerships, and sustain continuous investment in research and development. By employing technology and advocating for sustainable practices, we may advance toward a future where food is produced, distributed, and consumed responsibly, ensuring food security for all while minimizing environmental damage.

Author Contributions

The author contributed to the development and design of this study. O.O.T. conducted the material preparation, data collection, and analysis. O.O.T. authored the initial version of the manuscript and provided feedback on earlier iterations of the document. The author has thoroughly reviewed and endorsed the final manuscript. Conceptualization; Methodology; Formal analysis and investigation; Writing—original draft preparation; Writing—review and editing: O.O.T.

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Not applicable.

Informed Consent Statement

Not applicable.

Data Availability

The datasets produced in the current study are available from the corresponding author upon reasonable request.

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Conflict of Interest

The author stated that there is no conflict of interest for this study.

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