Food Loss and Waste Management in the U.S. Frozen Fruits and Vegetables Supply Chain

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Abstract

Frozen fruits and vegetables (FrFV) are valued for their convenience and longer shelf life compared to fresh produce. While consumers and retailers discard far less FrFV than fresh ones, significant food loss and waste (LW) still occurs at various stages of the supply chain (SC). This review examines existing food LW management strategies' applicability, scalability, and estimated benefits when implemented in the U.S. FrFV SC. Despite the lack of LW management recommendations specific for FrFV SC stakeholders, best-fit strategies to deal with FrFV LW are recommended by analyzing recent literature, company reports of food LW management projects in other food industries, and food LW data in parallel industries (e.g., frozen foods industry). Strategies to reduce food LW have been proven to create renewable electricity, mitigate CO_2 emissions, lower costs, and be converted into organic fertilizers. The most effective and beneficial solutions to address FrFV LW identified in this review are optimizing manufacturing lines, creating secondary channels for selling imperfect and surplus products, producing value-added products from produce byproducts, and expanding buyer specifications.

Key Terms: Frozen Fruits and Vegetables, Supply Chain, Loss and Waste Management, Sustainability, Environmental and Economic Benefits

1. Introduction

It is estimated that annual food loss and waste (LW) around the world amounts to about 1.3 billion tons[1], costing the global economy over US$900 billion[2]. In the U.S. alone, 73.9 million tons of food were lost or wasted in 2023, resulting in approximately $382 billion spent on growing, processing, and transporting food that was never consumed[3]. As a result, Americans waste about 2% of total energy, more than 25% of freshwater supplies, and 31% of cropland[4].

This paper combines the Food and Agriculture Organization's (FAO) definition of food loss and food waste, which encompasses any decrease in food mass that occurs at any stage of the supply chain (SC), from farmers to consumers[5 6].

In recent years, frozen fruits and vegetables (FrFV) have been promoted as a way to reduce food waste, particularly at the consumer level, while also making healthy eating more convenient. At the consumer level, the waste rate for frozen vegetables is estimated to be nearly four times lower than that of fresh vegetables, while the waste rate for frozen fruits is more than ten times lower than that of fresh fruits[7].

Although FrFV significantly reduces consumer waste compared to their fresh counterparts, substantial LW still occurs across the pre-consumer steps of the SC. FrFV are estimated to account for up to 2.5% of the United States' food LW by weight and up to 1% of financial losses related to it.

Reducing and repurposing LW is crucial for any food SC business, as it can help address food insecurity, generate renewable energy, create job opportunities, support a circular economy, reduce greenhouse gas emissions, mitigate environmental impacts, lower costs, and decrease financial losses[8].

Within the FrFV SC, LW management strategies can be applied at all stages of the value chain, from farms all the way to retailers, and may focus either on reducing LW generation or repurposing it for other uses. The strategies with the highest estimated benefits from new projects, in addition to those already underway, are concentrated at the farm and manufacturing levels.

Despite the lack of information specific to LW in the FrFV SC, LW management strategies with the highest estimated return on investment when applied to the FrFV SC are identified and analyzed in this paper. Given the limited publicly available data for monitoring and managing FrFV LW, stakeholders must conduct further research and analysis specific to their own contexts before undertaking trial or large-scale implementations.

2. Methods

This study employed both quantitative and qualitative methods to examine the causes of food LW within the U.S. FrFV SC and to evaluate potential strategies to reduce or repurpose such losses, emphasizing those with the highest return on investment for industry stakeholders.

2.1 Literature Review Methodology

Articles and studies were collected from both open-access and organization-restricted platforms. Keywords used in the search included combinations of terms such as "food waste management," "frozen fruits and vegetables," "frozen food," and "supply chain waste management." Reports from the American Frozen Food Institute (AFFI) provided general information and identified major companies in the FrFV industry. Findings from company reports were cross-referenced with peer-reviewed studies or independent publications whenever possible to reduce potential bias.

Sources were included if they provided information on one or more of the following: (a) where or why losses or waste occurred within the FrFV SC; (b) strategies currently used to repurpose food LW, or (c) strategies aimed at reducing the generation of LW in the first place. Data from articles and studies not directly focused on the U.S. FrFV industry were still included if the processes examined were comparable to those in the FrFV SC. For instance, studies on food LW management during crop harvesting were incorporated because harvesting is also a key stage in the FrFV SC.

2.2 Datasets and Analysis Methodology

To complement the qualitative findings, quantitative data providing information on the magnitude, financial value, carbon footprint, and water wasted from food LW across different stages of the U.S. food industry was collected, with emphasis on fresh and frozen produce, and frozen foods. This data was used to project FrFV LW numbers assuming the share of other sectors, such as frozen foods and fresh produce, made up by FrFV is similar to the share of LW in these sectors made up by FrFV LW.

From the ReFED Insights Engine, estimated U.S. produce and frozen food LW across producers, manufacturers, and retailers data was gathered using 4 different metrics: food waste tons, dollar value of LW, CO2 emissions and wastewater. Additionally, the estimated benefits from implementing different solutions to reduce produce and frozen food LW were also gathered from the ReFED Insights Engine.

From USDA data, total U.S. production volumes were collected for fruits and vegetables, in raw, processed, and frozen forms. These figures allowed the calculation of the share of total produce and the share of processed produce represented by FrFV.

From AFFI, sales data for FrFV and for all frozen food products were obtained, to enable estimation of its share within the frozen food retail category.

2.2.1 Data Processing and Ratio Development

Three key multipliers were developed to translate general produce or frozen food LW data into U.S. FrFV-specific estimates:

1. FrFV share of total fruits and vegetables production:

$$Multiplier\ 1 = \frac{frozen\ fruits\ (lbs) + frozen\ vegetables\ (lbs)}{total\ fruits\ (lbs) + total\ vegetables\ (lbs)}$$

2. FrFV share of processed fruits and vegetable production

$$Multiplier\ 2 = \frac{frozen\ fruits\ (lbs) + frozen\ vegetables\ (lbs)}{processed\ fruits\ (lbs) + processed\ vegetables\ (lbs)}$$

3. FrFV share of frozen food sales

$$Multiplier\ 3 = \frac{sales\ of\ FrFV}{sales\ of\ all\ frozen\ foods}$$

2.2.2 Problem Quantification:

FrFV-specific LW estimates for each SC stage were obtained by multiplying ReFED's general produce or frozen food LW estimates by the relevant multiplier. The same procedure was applied to LW tonnage, financial value, CO_2e emissions, and wastewater:

$$FrFV\ LW\ at\ Producers = U.S.\ produce\ LW\ at\ producers \times Multiplier\ 1$$

$$FrFV\ LW\ at\ Manufacturing = U.S.\ produce\ LW\ at\ manufacturing \times Multiplier\ 2$$

$$FrFV\ LW\ at\ Retail = U.S.\ frozen\ food\ LW\ at\ retail \times Multiplier\ 3$$

2.2.3 Destinations of waste:

Estimates of the current destinations of surplus food in each SC stage were collected from ReFED as percentages of total U.S. surplus food for each stage. These percentages were then applied to previously calculated estimations of food LW at each FrFV SC stage to arrive at FrFV LW food tons that are currently not repurposed.

2.2.4 Potential Gains from Solutions:

To estimate the potential benefits of waste-reduction strategies within the FrFV sector, ReFED's projections for each solution were adjusted using the same multipliers. For example, the potential tonnage reduction for a given solution at the production stage was multiplied by Multiplier 1, at manufacturing by Multiplier 2, and at retail by Multiplier 3. This process was repeated for the financial, CO_2e, and wastewater impact estimates, which ensured consistency across all metrics.

2.2.5 Selection of the most effective and beneficial solutions:

To identify the solutions with the highest benefits across the four relevant metrics to this review: food tonnage, financial gain or loss, water use, and CO_2 emissions, each FrFV LW solution's estimated gains were normalized to create a score for each solution in each metric. The solution with the highest recovery in a metric received the highest score, while the lowest received the lowest score.

Each metric was then weighted according to the contribution of FrFV LW to the total U.S. surplus food problem when measured in that metric. For example, because FrFV LW accounts for 2.5% of national food waste tonnage but only 1% of the financial value lost, the food tonnage metric received greater weight.

By multiplying normalized scores by these weights and summing them, a "Utility Score" was obtained for each solution. Solutions were then ranked from highest to lowest Utility Score.

3. Results

3.1 Challenges and Opportunities: Multiple SC Steps

Food LW recycling offers significant environmental, social, and economic benefits. It creates jobs, reduces greenhouse gas emissions, lowers disposal costs, and supports sustainable circular economies[8]. In the case of fruit and vegetable LW, it can be repurposed into a wide range of products, from renewable energy to food ingredients.

Fruits and vegetables LW can be used for animal feed and composting; converted into biofertilizers; used for renewable energy; and ingredients for functional foods[9]. Banana waste, for example, is a good source of natural bioactive compounds used for animal feed and feedstock for bioenergy, while leafy vegetable waste can be processed into compost useful to increase soil fertility and future production[9].

Additionally, fruits and vegetables LW is rich in starch, a type of carbohydrate that can be used as a substrate for microbial growth in order to produce bioenergy at a low cost; polyphenols, a compound that prevents oxidation in fruits, can be used as a substitute for synthetic preservatives in the food industry; and their natural pigments can be used to produce natural food colorants[9].

Among the many different existing strategies and techniques for repurposing food, LW, incineration, although effective, is not considered an acceptable way to reduce solid waste due to its emitting high amounts of toxic gases[9 10]. Conversely, the main effective and sustainable energy-conversion techniques for food LW are Anaerobic Digestion (AD), Ethanol Fermentation (EF), and Hydrothermal Carbonization (HTC). Because both fresh and frozen fruits and vegetables have a high moisture content, HTC is often considered the most suitable option[10]. However, when the goal is upcycling for nutritional purposes, this same moisture content becomes a limitation. To address this, the dry matter must be increased through thermal processes. Pasteurization and low-temperature processing have been proposed, but only low-temperature processing is capable of inactivating microorganisms and enzymes, while avoiding the degradation of heat-labile components, which preserves the nutritional quality of the waste[9]. In addition to thermal treatments, studies suggest that optimal pre-treatment also requires a physical step, such as grinding the waste, prior to applying thermal processes. This combination improves the efficiency of later recycling or energy conversion[8].

Government participation is also key in reducing food LW. Effective regulations and subsidy schemes for driving infrastructure development have been reported to reduce post-harvest LW. For example, tax benefits can help the establishment of appropriate infrastructure, which is linked to reduced transportation time for perishable products and enhanced market efficiency[11]. In the U.S. specifically, government participation occurs at all levels–national, state, and local. At the federal level, two major initiatives are the Food Recovery Challenge (FRC) and the Food Waste Challenge (FWC). Through the FRC, the U.S. Environmental Protection Agency (EPA) provides tools, resources, and support to help participants establish baselines, set reduction objectives, and track progress–which includes connecting participants with solutions providers. The FWC serves as a platform for food industry participants and solution providers to share activities that reduce, recover, and recycle food LW[4]. These EPA reports highlight several success cases relevant to the FrFV SC, including Weis Markets' successful selling of lower-quality products for lower prices, and HelloFresh's application of warehouse management software to reduce food LW at the source[12].

3.2 Challenges and Opportunities: Farm (pre- and post-harvest)

The farm stage, both pre- and post-harvest, marks the point where food LW first emerges, with problems at this level impacting the entire SC. FrFV represents 11-13% of the U.S. Farms production of fresh produce[13], and losses at farms account for around 24% of total LW in the U.S.[3] Losses stem from natural, human, and market-driven factors. Addressing them requires both strategies that reduce LW generation at the source and approaches that repurpose unavoidable LW.

One of the most common causes for LW at farms is not meeting buyers' quality standards[4]. These rejected batches can be used for processing, animal feed, compost, or energy production[4 14].

Other significant sources of LW at this level include overproduction[15 16]; damage from diseases, pests, weather, and mechanized harvesting techniques; edible crops left unharvested due to diminishing return on investment (ROI); food safety scares among producers due to potential contamination; and improper handling at the farm[17].

Many solutions have been proposed to reduce and recycle LW at this SC stage. Frequently recommended repurposing strategies are using leftover crops as fertilizer or animal feeding; practicing farm-level food recovery, such as donation to non-profit organizations, and expanding secondary markets for items not meeting standards[4]. For LW generation reduction, commonly effective solutions are improving agricultural infrastructure, technological skills, and farmers' knowledge; and building collaboration with manufacturers, retailers, and other organizations[4].

Temperature mismanagement also contributes to the generation of fruits and vegetables LW at farms. Very high temperatures cause burning and scalding on most fruits, and very low temperatures cause fruit freezing and cell rupture, compromising their appearance[18]. Pre-harvest techniques such as canopy management, irrigation, and greenhouse cultivation help balance temperature during ripening[18]. In post-harvest storage, improper temperature and relative moisture cause fungal infections, resulting in damage or complete loss of the crop[18]. Correct application of fungicides before and after harvest is therefore essential[18].

Other common sources of fruits and vegetables LW between harvesting and processing processes are mechanical damage, lack of skilled workers, biological disorders, and cross-contamination from damaged crops[14]. Removing damaged or decayed produce early helps reduce risks of cross-contamination[14].

Lastly, a majority of the US farms' surplus food is never harvested (82%), primarily because of overproduction, resulting in a total loss of planting investments. As far as repurposing, the most common destination is animal feed production (10%)[3].

3.3 Challenges and Opportunities: Transportation to processing facilities

The transportation stage serves as a crucial link between farms and processing facilities, where inefficiencies lead to food LW. Damage during handling and transit, inadequate temperature control, and long distances between production and processing sites are among the main contributors to losses at this step. To address these, improvements in packaging, cold-chain management, and facility location are some of the strategies commonly proposed to reduce LW and preserve product quality before reaching processing facilities.

Mechanical damage, a significant cause of L&W at farms, is also a primary cause of LW during the transportation stage, and the likelihood increases when transportation pallets get damaged[19]. Therefore, Returnable Plastic Crates (RPCs) are recommended, as they can reduce mechanical damage, potentially reducing LW generation by 95%, and can be reused for years[19].

LW generated by inadequate temperature control prior to freezing can be reduced by ensuring consistent use of properly refrigerated vehicles[14]. In addition, both locating processing facilities closer to farms[11], and only storing compatible commodities together[14] are suggested to reduce LW caused by long pre-freezing transit distances and the chain of intermediaries. Compatibility of fruits and vegetables is based on factors such as temperature and humidity requirements, ethylene production and sensitivity, and tolerance to controlled-atmosphere conditions[14].

Lastly, different types of active packaging have been used to delay spoilage, reduce microbial growth, and maintain overall product quality. Some examples include moisture pads to reduce water condensation and microbial growth during transport; ethylene absorbers to slow ripening of climacteric fruits; and oxygen absorbers to limit oxidation[19].

3.4 Challenges and Opportunities: Processing and Freezing

The processing stage is a pivotal step in the FrFV SC, where raw agricultural products are transformed into frozen goods, and also where major losses happen. This is the stage where LW is most effectively repurposed. However, there is still a significant potential to further reduce its generation and increase the amount of LW that gets repurposed.

Trimming by-products and temperature mismanagement account for a meaningful share of LW, alongside issues related to quality standards and handling practices. Addressing these challenges requires a combination of LW reduction and repurposing approaches.

Trimming waste represents a major part of the LW produced in the processing stage of all food SCs, especially fruits and vegetables. It is estimated that fruits and vegetables yield between 25% and 30% of non-edible products, in some cases reaching up to 50%–75% of fresh weight. For instance, the banana industry produces >57.6 million metric tons of banana peels annually, contributing to about 40% of the total fresh weight of bananas[4 15]. In addition to trimming residuals, wastewater is another concern because high water usage and dirt or debris present in water at the end of processing or cleaning contribute to the negative environmental impacts associated with this SC stage[15].

Current repurposing technologies can recover 40-50% of the dietary-fiber-rich residual seeds to transform them into high-fiber ingredients in the food industry[9], and use waste from vegetables not meeting final pre-freezing quality inspection for production of bakery products that have received positive consumer feedback[20].

Several companies reported causes of LW at processing stages to be similar to those in farming and transportation stages: not meeting quality or appearance standards; food safety concerns; damaged product; and insufficient coordination throughout the SC[4]. Employee training, rapid pre-cooling[14], and proper upkeep of facilities and storage conditions[15] help reduce LW at this SC stage.

Smart packaging solutions, such as RFID packaging and the use of Time-Temperature Indicators (TTIs), are practical solutions to reduce LW resulting from temperature mismanagement. These technologies allow monitoring temperature, humidity, and shelf life across pallets, and temperature abuse during frozen transport/storage, facilitating identification of the cause of LW generation in a specific SC[19].

Modified Atmosphere Packaging (MAP), a relatively low-cost packaging technology, allows natural fruit respiration by replacing O_2 with CO_2, slows pre-freezing respiration and microbial growth; therefore, spoilage takes longer and final products are more nutritious and flavorful[21]. Additionally, gas indicators can be applied to MAP to ensure its effectiveness by detecting any O_2 /CO_2 leaks[19].

Overall, manufacturing produces the lowest share of LW that is not repurposed. Over 65% of the U.S. food LW generated during this SC step is either used to produce animal feed or is applied to the soil to increase its fertility[3].

3.5 Challenges and Opportunities: Frozen Storage

The frozen storage stage is required for maintaining the quality and safety of FrFV products, with cold chain management, including precise temperature and humidity control, being the primary factor in preventing losses. LW at this stage is often caused by temperature abuse, improper humidity, insufficient storage capacity, and inefficient handling practices. Solutions focus on robust monitoring systems, proper warehouse management, and overall infrastructure improvements.

The most important postharvest requirements and treatments to avoid losses are those related to the cold chain, temperature-controlled chain designed to maintain the quality and integrity of temperature-sensitive products, especially holding temperature and relative humidity[22]. For this reason, systematic service of warehouses is highly recommended to maintain good storage conditions[15].

LW in this SC step is also caused by insufficient storage and packaging facilities[17], and overall inefficiencies in storage[4]. Reducing inefficiencies comes mainly from ensuring correct preparation of loading, and security of shipment and unloading[15].

Although ice crystals are not a direct source of LW, they reduce product quality and may contribute to consumer rejection. Therefore, freezing products quickly is recommended as faster freezing produces smaller crystals when compared to slower freezing, which reduces textural and visual defects[23].

3.6 Challenges and Opportunities: Frozen Transport to Distributors and Retailers

The transportation of FrFV to retailers and distributors is a SC stage where product quality can deteriorate rapidly if cold chain requirements are not strictly maintained. Similar to transportation to processing facilities, LW at this stage is driven by temperature inconsistencies, overloading of vehicles, and procedural inefficiencies. To mitigate these risks, strategies such as smart packaging for real-time monitoring, optimized vehicle loading, and carefully planned delivery routes can be employed. In addition to preserving product quality, these measures can also reduce energy consumption and associated CO_2 emissions, aligning both LW reduction and sustainability goals.

Efficient shipment is key to ensuring the quality of frozen foods, as products usually begin to thaw after two days in transit[24]. In addition, inconsistencies in temperature, procedures, and more throughout the cold chain can increase the LW of products[19]. Smart packaging technologies recommended for previous stages, such as RFID systems and TTIs, also allow monitoring temperature inconsistencies and other relevant metrics during the frozen transport stage.

Reduction of LW and CO_2 emissions from vehicle overloading can be achieved by using lighter packages and optimizing truck load. Focusing on reducing traction energy by delivering larger orders to major clients first in the delivery tour has been shown to reduce CO_2 emissions at a higher rate than improving vehicles' refrigeration systems' efficiency[25].

3.7 Challenges and Opportunities: Wholesalers and Retailers

The distribution center and retail stage is the final step before frozen fruits and vegetables reach consumers, where accurate demand forecasting can be important to minimize losses. Compared to earlier stages, losses here are generally lower. For instance, frozen foods LW make up less than 0.5% of total U.S. food LW[3], and FrFV represents less than 20% of the market of frozen foods[26]. Nonetheless, unpredictable consumer demand leads to overstocking and overproduction. To address these challenges, strategies such as collaborative demand planning with other SC stakeholders and discounting slightly damaged products are strategies that may also be applied to the FrFV retail sector to improve both LW reduction and SC efficiency.

Frozen fruits are purchased less frequently, causing difficulties in forecasting demand and increased risk of overstocking[26]. Although overstocking is undesirable in most stores, especially those with limited frozen storage space, if stored at -18ºC or below, FrFV can maintain its best quality for up to 12 months and is safe for consumption indefinitely[27]. Despite its long shelf life, FrFV sales remain heavily dependent on promotions, which account for 24% of total sales[26].

In order to address the overproduction and overstocking caused by unpredictable demand, studies recommend analyzing item-level demand and forecasting in collaboration with other SC stakeholders[4, 15]. Such collaborations also allow sellers to have a dynamic linkage with farmers, helping to enhance demand visibility, reduce shortages and excess supply, and lower price fluctuations[11]. In addition to forecasting improvements, in-store discount shelves for slightly damaged but still edible products are efficient in reducing LW[4].

Finally, it is estimated that over 30% of the food LW from retailers is not repurposed. Most of the repurposed volume is either donated, used for composting, or turned into animal feed[3].

3.8 Industry Projects Review

In recent years, many companies have worked to improve sustainability by redirecting LW toward profitable uses. Reported strategies include upcycling fruits and vegetables byproducts, optimizing production and storage processes, and producing renewable energy through anaerobic digestion[28, 29].

Yumchop UK, a frozen ready-to-eat meals company, reduced losses from temperature abuse and humidity mismanagement by adopting IoT-based real-time monitoring. Sensors connected to cloud analytics and alert systems enabled the company to act quickly on deviations, making IoT a key tool in its waste reduction strategy[23].

Conagra's Birds Eye brand, which holds nearly 25% of the frozen vegetable market share[26], reports that over 90% of its solid waste was diverted to recycling and animal feed in 2024[30]. Conagra also placed its Waseca, MN, processing facility close to farm fields, minimizing the time from harvest to freezing and reducing losses in transit[31].

Dole, representing just under 10% of the FrFV U.S. market[26], has invested in both upcycling and resource efficiency. The company partnered with Fruit Leather Rotterdam to repurpose rejected mangoes into clothing fiber and mango seeds into oil and soap[32]. It also reuses treated water in production, applies wastewater in fertilizers, and produces renewable energy through anaerobic digestion[28].

Green Giant, the second-largest frozen vegetable brand in the U.S.[26], has upcycled byproducts from its canned pineapple operations. Pineapple stems are processed for enzymes used in pharmaceuticals, skins are directed to livestock feed, and core fiber and liquid waste are converted into plastics[29]. The company also invests in anaerobic digestion for renewable energy production[29].

Barnana, founded in 2012, pioneered snack products made from bananas and plantains that were too ripe for the fresh market. With an estimated annual revenue of up to $15 million[33], Barnana demonstrates how small companies can scale an upcycling model into a profitable business[34].

Greencore, a convenience foods manufacturer, partnered with stakeholders across the sandwich SC to implement 17 projects aimed at reducing food LW by 1,700 tonnes. The process began by focusing on high-volume product lines and analyzing the causes of LW generation. From there, project ideas were brainstormed and prioritized based on estimated benefits, required effort, process complexity, and scalability. The most promising initiatives, those offering the highest impact with the least effort, were first trialed to validate their potential. Finally, results were presented to SC partners, who collaborated with Greencore to decide which projects to adopt at scale[35].

3.9 Estimates of the most beneficial solutions

Frozen fruits and vegetables (FrFV) account for approximately 2.5% of the total U.S. food LW by weight, yet only 1% of the total financial losses associated with it. In contrast, the environmental impacts of FrFV LW are proportionally smaller, representing 0.5% of food waste-related CO_2 emissions and 0.6% of wasted water resources.

Table 1. Estimated annual FrFV LW segmented by SC stage. Measurements in terms of food waste tons, net financial impact, metric tons of CO_2 emissions, and gallons of water wasted.

SC Stage	Food Tons	Dollars Lost	Metric Tons of CO_2 emissions	Gallons of Water
Producer	1.8M (90%)	$1.54B (38%)	361.4K (29%)	63.2B (62.7%)
Manufacturing	218.8K (10%)	$ 2.32B (58%)	776.5K (63%)	32.3B (32.1%)
Retail	12.5K (<1%)	$159M (4%)	88.5K (7%)	5.2B (5.2%)
FrFV Total	2M(100%)	$ 4M (100%)	1.23M (100%)	100.7B (100%)

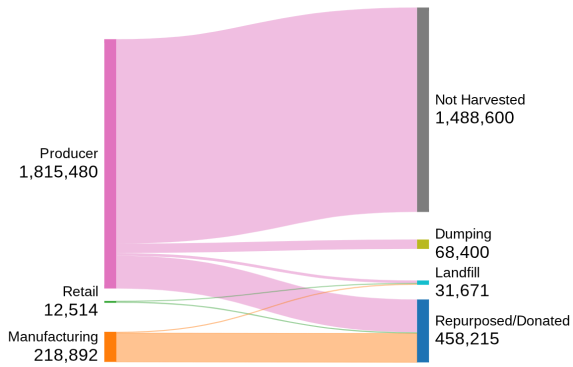

Figure 1. Estimated FrFV LW destinations divided by SC stage.

An estimated 78.2% of food LW generated throughout the FrFV SC is not repurposed, with most left unharvested. Only a very small share of this unutilized LW, less than 1% (0.8%), originates from the manufacturing and retail stages. Additionally, the higher in the value-chain, the more costly every food waste ton becomes, and a majority of the financial losses and CO_2 emissions resulting from FrFV LW come from the manufacturing stage.

The solutions with the most added benefit—financial, social, and environmental—compared to the current situation are optimizing production lines, selling imperfect and surplus produce through secondary channels, utilizing produce byproducts, and buyers expanding their quality specifications.

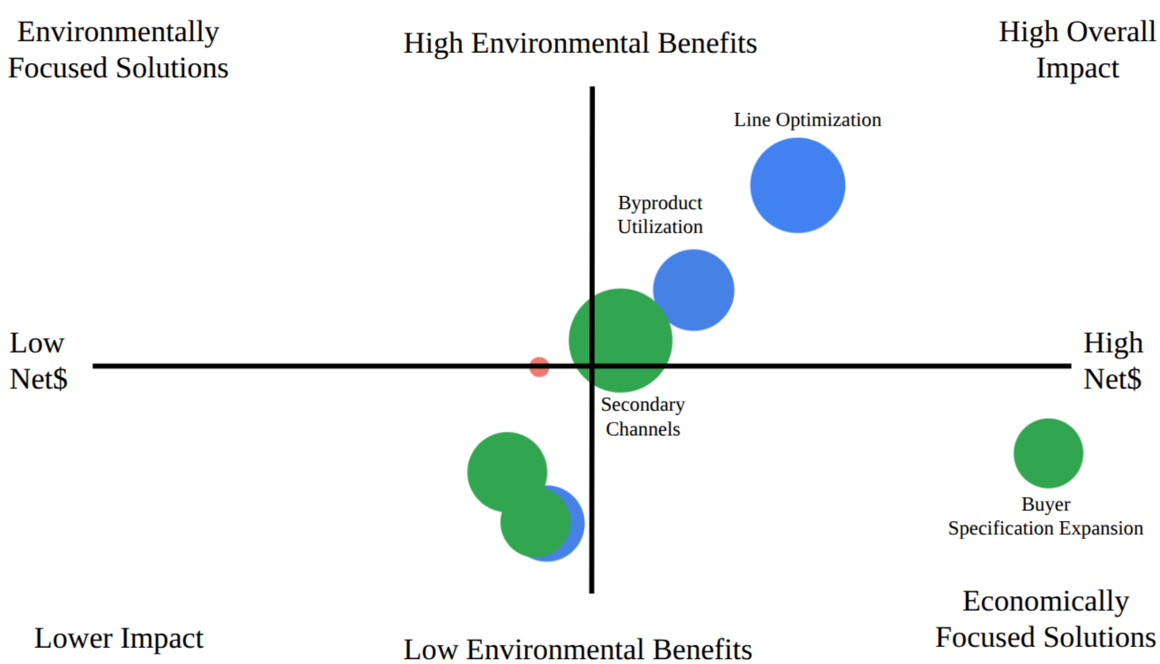

Figure 2. Comparison of FrFV LW management strategies. Solutions plotted by their estimated annual environmental benefits (vertical axis) and annual net financial benefits (horizontal axis). Bubble size represents the tons of food waste potentially saved.

Optimization of production lines targets reducing the generation of LW by identifying flaws in the manufacturing system design, modifying production schedules to minimize changeovers, and optimizing equipment operating conditions. Optimizing operations at the processing stage is associated with the most significant estimated reduction in wastewater and CO_2 emissions coming from FrFV LW. The main challenge in implementing this solution across the industry lies in the variability of processes among different processing facilities.

Selling imperfect and surplus produce through secondary channels has the objective of reducing food LW by selling overproduced fruits and vegetables, or those that don't meet all the quality and appearance standards, but are still safe to consume, directly to consumers. Furthermore, it is the solution with the highest potential to reduce food waste tonnage. Nevertheless, some sellers express concern that offering lower-grade products could harm their brand image, while farmers worry about the need to adapt logistics to meet higher demand and manage products of varying quality[3].

Unlike the others, utilization of produce byproducts is an LW repurposing strategy, meaning it focuses on using food LW for new purposes instead of trying to reduce its generation. Byproduct utilization consists of turning unused and underutilized produce, or parts of it, into a value-added product designed for human consumption. Implementing this solution can be challenging, as upcycled products may be significantly more expensive than conventional ones, and it may require collecting waste from multiple locations and ensuring proper storage to prevent damage.

Finally, expansion of buyers' quality specifications consists of buyers, manufacturers, and retailers, in this case, buying slightly more varied produce that would not normally meet strict quality standards, such as bananas considered too ripe or tomatoes that are not perfectly red, from producers. Additionally, it is the solution linked with the highest estimated financial gains from its implementation. The challenges associated with its implementation are similar to those of "imperfect and surplus produce channels," as sellers fear potential impacts on brand image from offering lower-quality products, and farmers are concerned about adapting logistics to meet higher demand and handle products of varying quality.

Lastly, many solutions to reduce or repurpose FrFV LW at the retail level are among the top returns in dollar gained per ton of food LW saved (5 of the top 10 analysed) because this is the stage where each food ton wasted is worth the most.

4. Discussion

While producers account for the majority of discarded volume, manufacturing also emerges as a stage with great financial and environmental consequences. In this section, FrFV LW estimates are examined in relation to their implications for industry stakeholders, with particular attention to the scalability and effectiveness of LW management strategies with the greatest estimated benefits.

The discrepancy between FrFV LW's share of U.S. food LW when measured across different metrics suggests that, while FrFV contributes to the overall economic burden of food LW, its role in the physical volume of discarded food is more substantial. When using environmental indicators such as wastewater and CO_2 emissions, the share of FrFV LW is even smaller. This highlights the importance of evaluating FrFV LW across multiple dimensions, while also recognizing that reductions in waste tonnage and financial losses carry greater weight than environmental factors.

None of the four most beneficial solutions to reduce or repurpose FrFV LW is implemented primarily by retailers or wholesalers. Although LW at this stage represents the greatest financial losses per ton wasted, and therefore the highest financial gains per ton saved, most retail-level interventions are either already widely in place or lack scalability, given the almost insignificant share of LW that occurs at this stage compared with earlier points in the SC.

The recommended solutions at the producer level that lead to significant benefits, such as buyer specification expansion and selling imperfect and surplus produce, do so in part because of their great scalability, as this stage is responsible for an estimated 90% of total FrFV LW volume and over 99% of the volume that is not already being repurposed.

Top manufacturing solutions have much higher benefits per ton of food LW saved than those at the producer level because the higher in the value chain, the more costly LW becomes. Although the FrFV LW in tons at this stage is much lower than at the farm level, causing scalability to be lower, it is still relatively significant (10%). As a result, the food waste, financial, and environmental recovery potential across the entire FrFV manufacturing stage is comparable to that of successful farm-level LW management solutions.

Out of the most beneficial FrFV LW management strategies, using produce byproduct is the only one focused solely on repurposing, instead of reducing, LW. Its potential success can be attributed to the high yields, up to 75% percent in some cases, of non-edible products from fruits and vegetables, such as skins and stems, which makes this solution have a high scalability in the FrFV at an industry-wide level. Since most of these non-edible products are high in dietary fiber, it is highly recommended that they are processed and used as ingredients for high fiber foods, such as low-carbohydrate breads and other health industry processed foods. However, these discarded parts can also be used in other upcycling processes, which will differ according to each commodity. Vegetable waste, for example, can be used in the production of bakery products.

Additionally, byproduct utilization can also be done by solutions providers, which helps ensure a constant supply of discarded produce to be repurposed and optimizes LW processing investments due to these companies being able to gather disposed fruits and vegetables, or parts of them, from multiple FrFV SC stakeholders. This kind of partnership can be facilitated by U.S. government initiatives already in place, such as the FRC, which helps FrFV SC companies partner with solutions providers that best fit their needs.

Based on implementations of byproduct utilization already done by companies, and feasible projects mentioned in literature and tests, it could be applied for two different causes of LW in the FrFV SC: trimming waste, such as fruit stems, seeds and skins; and produce that don't meet quality standards, even when standards allow for imperfect, but still edible fruits and vegetables. Processing LW from both sources at a single facility could increase the return on implementation efforts, though it would also require greater overall effort due to the logistical challenges of collecting waste from multiple locations. An alternative possibility of effort optimization when applying this solution to FrFV LW is using freezing facilities to also freeze LW, as part of the freeze and thaw pretreatment method recommended for later recycling.

Regarding optimizing production lines, proper implementation will result in fewer products being discarded due to mechanical damage, temperature mismanagement, and overall factory inefficiencies. Consequently, resources are used more efficiently, which leads to this solution being considered the most environmentally beneficial, as it is associated with the highest reduction in both wastewater and CO_2 emissions. Because the manufacturing level is responsible for the contribution of over 30% of wastewater and the majority of CO_2 emissions resulting from FrFV LW, it is logical that optimizing production lines significantly reduces both these metrics. Additionally, processing stage stakeholders must analyze where inefficiencies are present in their own facilities. When not sure where to start looking for unoptimized processes, it is recommended that the preparation of loading and security of shipment and unloading be analyzed. The likelihood of benefiting from improving one of these two processes is high, as correcting these is among the most common strategies mentioned in the literature to address overall inefficiencies at these stages.

Buyer specification expansion and selling imperfect and surplus produce through secondary channels may go side by side when managing FrFV LW. Manufacturers can buy more imperfect produce from farmers, process it, and sell it at lower prices than perfect produce, since discounted shelves are an effective way to market imperfect products. Additionally, FrFV manufacturers could partner with farmers to buy surplus produce resulting from overproduction at lower prices. By processing these into frozen products, what would have been wasted at farms becomes a profitable product. The freezing process prevents imperfect produce from further quality deterioration or becoming inedible, which can help alleviate sellers' concerns about product acceptability to consumers. Although FrFV can retain its quality much longer than fresh produce (up to 12 months) consumer satisfaction may decline if sales of FrFV processed over a year before being sold become significant, leading some stores to sell these products on promotion and, consequently, achieve lower profits. However, before applying this, manufacturers, alongside retailers and other SC participants, must attempt to forecast product demand. The U.S. government's FWC program can be a useful tool to use shared knowledge to facilitate FrFV SC participants to forecast demand and understand consumer acceptance levels for lower quality products.

To effectively implement this, partnerships between different SC stakeholders are necessary, as imperfect produce would likely have to be sold for a lower price at every stage of the chain, from farmers to processors, and from processors to retailers. Manufacturers must also examine how to charge less for imperfect produce that goes through the same processing as 'perfect' ones while still remaining profitable.

5. Conclusion

Reducing FrFV LW is not only an environmental and social goal but also a business opportunity. The findings of this research demonstrate that proper FrFV LW management can simultaneously create economic and environmental value through lower costs, reduced emissions, and the development of new product opportunities. Among the most effective solutions identified,such as manufacturing line optimization, selling imperfect and surplus produce through secondary channels, byproduct utilization, and expansion of buyers' specifications, each offers a pathway for recovering resources and profiting from it.

Although the FrFV sector already generates relatively low levels of LW compared to other food categories, its pre-consumer stages still represent significant opportunities for improvement. The success of LW reduction strategies, therefore, depends on coordination among all SC participants. Collaboration between producers, manufacturers, distributors, and retailers is necessary to scale solutions. Furthermore, government incentives can accelerate progress by strengthening data-driven infrastructure for LW reduction and repurposing.

Future research done by FrFV SC stakeholders should focus on testing these solutions' impact specific to their business and industry sub-sectors. Further exploration of consumer acceptance toward products derived from imperfect or upcycled produce would also provide valuable insight into market feasibility and demand for these products. Ultimately, successful FrFV LW management offers sustainability and profitability while transforming an environmental and social challenge into an opportunity for innovation within the food SC.

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