International Journal of Recent Engineering Research and Development (IJRERD)
ISSN: 2455-8761
www.ijrerd.com || Volume 06 – Issue 02 || February 2021 || PP. 14-29

The Design of a Sustainable Fruit and Vegetable Waste Network: Food Security and Public Health Leverage

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Abstract: In this paper, the fruit and vegetable waste (FVW) treatment alternatives are evaluated from a sustainability point of view. Using FVW characteristics as input data, we estimate the sustainable benefits such as energy utilization and GHG emission reduction for each potential food waste processing technique. Additionally, the sustainable benefits of reverse logistics of FVW are quantified based upon geographic distance and valorization characteristics.We formulate the FVW network framework as a strategic weighted goal programming model that aims to minimize total FVW management costs and impact on public health while maximizing nutrition value and satisfying emissions and energy use constraints. Given the recent regulations of the commercial food material disposal ban, we test the efficiency of the proposed framework by designing a sustainable FVW treatment network for the state of Massachusetts.This study provides case studies based on real-life data and generates multiple scenarios to better analyze the results and select the best recovery options from a sustainability perspective.The paper contributes to the assessment of the FVW recovery alternatives by expanding the system boundary and presenting additional key performance measures of sustainability. By utilizing the FVW network model, policymakers can achieve the best sustainable strategies for FVW management.

Keywords: Sustainability, Fruit and vegetable waste, Carbon emissions, Network design.

1. Introduction

Sustainability is improving living standards not only for current society but also for future generations. It aims to balance the economic, environmental, and social impact of implementing supply chain goals in the long term. It incorporates objectives wider than just efficient and profitable production and consumption including socially fair and environmentally friendly products [1]. In the US, the food sector meets internal food security while providing support to the national economy. One important step in the journey of food products from farm to fork is the transportation and all related logistical processes to deliver food to the consumer. Improving the efficiency of these processes begin with designing a Food Supply Chain (FSC) network that considers the design of processing and distribution centers, the management of the cold chain, and the design of reverse logistics network [2]. These recent changes in FSC management goals have led to the development of the trending concept: Sustainable Food Supply Chain Management (SFSCM). As a result, new key performance indicators are developing that can capture the integrated triple bottom line of sustainability in which profit, people, and planet are working as drivers of the supply chain decision-making process [1]. The sustainability of the food supply chain is facing so many challenges. First, food insecurity presents in different parts of the world. In India for example, about 24% of families have days with no food at all. At the same time, it is estimated that one-third of global food production is wasted per year. food production processes consume more than 10% of the total US energy budget, about 80% of fresh water in the US, and about 50% of U.S lands. However, more than 50% of all produced food is wasted before or after reaching consumers. This is estimated to cause a loss of more than $165 billion, 25% of fresh water, and huge yearly losses of energy, lands, and other resources [3]. As new challenges have emerged such as climate change, fair trade, food waste, and food security, all different actors in the food industry should consider ways to produce, process, distribute and consume food more sustainably without compromising costs. Food industry stakeholders should develop decision-making models and set up standards and technologies that address the development of SFSCM [2].

A related issue to the huge amount of wasted food is the increasing rates of global food insecurity. The United Nations' Food and Agriculture Organization (FAO) defines food security as the ability of all people, at all times, to have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life. The FAO estimated that more than 820 million people are undernourished in developing countries. Even in developed countries, about 15.7 million people are considered undernourished. Therefore, developing global policies and strategies for food waste prevention and recovery would be an effective sustainable approach towards addressing the food security issue [4]. However, studies that addressed such issues and associated complexities are still insufficient [5].

By examining the existing body of literature in the area of food waste management and recovery from a sustainability perspective, we notice that studies are insufficient and limited in terms of the lack of novel framework, subjective methodologies, or data-based results. The Availability-Surplus-Recoverability-Waste (ASRW) strategy developed by exploring 30 food supply chain case studies is limited to the derived results of these studies and cannot be utilized for the development of sustainable food systems in general [5]. Similarly, other studies drafted practical approaches from managerial propositions by investigating the causes of food waste in 15 commodities. However, such case-based methodologies would produce biased results that lack the generalization of data-based approaches [6]. Other attempts to identify the effectiveness of the food waste recycling activities are based on comparative studies by considering regulatory variation in developed and developing countries. Such case studies are dependent on the geographic peculiarities and can only be valid within the region from which the information is derived [7]. On the other hand, the framework of the food waste hierarchy approach is implied to prioritize food waste options. The priority in this approach is to work on food waste prevention, followed by directing food waste to human use, then animal feeding and composting, then comes the energy recovery from food waste, and lastly landfilling when all these options are exhausted. Although such a framework can consolidate the route through which the food waste stream could follow, it does not consider other important sustainability criteria to balance between those options. Also, this approach does not provide a methodology to implement food waste policies in practice [8]. Further, the food waste streamline can be observed in all stages of the food supply chain from farm to fork through production and distribution. However, relevant research studies only considered either the upper stream of food waste from farming and manufacturing or the lower stream from retailing and household and very limited studies on the simultaneous food waste throughout all stages of the food supply chain. Besides, such studies are interview-based foody waste policies that involve subjective bias and generalized results could not be derived [9]. Furthermore, studies aiming to develop efficient food waste management systems ignored developing data-based approaches that consider as many factors as possible such as carbon emissions and energy efficiency.

Therefore, our objective in this research is to overcome the limited approaches in the existing literature by proposing a novel comprehensive framework and a data-driven mathematical methodology that provide generalized and objective results and develop the sustainability of food waste management throughout all the stages of the food supply chain. As such, we will study the closed-loop food supply chain sustainability in terms of food waste management that reduce its economic and environmental impact [10]. The system boundaries include food waste resulted from farming, processing, packaging, warehousing, and distribution along with different disposal options to mitigate the food waste impact on sustainability. The model framework includes both local operational decisions and global strategic decisions.

1. The first local decision is selecting the best food waste valorization options based on economic, environmental, and social conditions including energy use and Greenhouse Gas (GHG) emissions.
2. The global scaled decision includes network design and food waste distribution to and from valorization centers in a sustainable design context.

To this purpose, the framework address reducing food waste impact on sustainability by incorporating a food waste network model that optimizes economic and environmental tradeoffs.

2. Literature Review

Considering reverse material flow in the design of the SFSC network has been growing recently due to today's governmental regulations, customers' requirements, environmental concerns, and economic advantages [11]. However, the research on closed-loop supply network design models in the food industry is very limited [12]. Lee and Tongarlak (2016) derived a retailer's optimal order policy under by-product synergy (BPS) that valorizes food waste from the main processes in the food supply chain to a user input onto other secondary processes. Implementation of these BPS policies showed that food waste decreases when demand uncertainty and the tax benefit from the donation are low. Further, food donation can be induced by tax credit and disposal fees [13]. Banasik et al. (2017) proposed a multi-objective model to optimize economic and environmental goals and investigate alternative recycling technologies organic matters for closing the loop in the mushroom supply chain. The study found that implementing recycling technologies could increase the total profit of the mushroom chain by 11%, while the environmental indicator could improve by 28% [14]. Sgarbossa and Russo (2017) developed a new sustainable closed-loop supply chain (CLSC) model for best resource recovery and waste reduction practices, energy efficiency, and improved social development in the meat processing industry. By implementing the new model, the profitability index showed the viability of recovery plants, reduced global environmental impact, and new skilled positions that improved firm reputation in the social context [12].

Garrone (2014) developed a food waste management strategy called Availability-Surplus-Recoverability-Waste (ASRW) in the context of the sustainable food supply chain. The study conducted 30 expletory case studies and presented three case studies to demonstrate the implementation of the proposed model [5]. Mena et al. (2014) investigated a multi-tier supply network of 15 food commodities in the UK to identify the underlining causes of food waste that lead to managerial propositions. These propositions trigger practical approaches to mitigate the economic, environmental, and social impact of food waste [6]. Mirabella et al. (2014) provided a literature review on the recycling of solid and liquid waste from the food processing industry. The study presented the main uses of the derived resources and highlighted applications in the nutraceutical and pharmaceutical industry [15]. Papargyropoulou et al. (2014) proposed a framework to identify food waste treatment options and priorities these options according to sustainability criteria by applying the waste hierarchy approach. The framework showed that the prevention of food waste is the most appealing sustainable option, then human use option, followed by recycling food waste into animal feed [8]. Thi et al. (2015) examined food waste management systems in developing countries in comparison to developed countries in terms of recycling activities, related regulations, and treatment technologies. The study provided a case study of Taiwanese food waste management system as a typical model for developing countries to follow [7]. Gruber et al. (2016) explored societal, regulatory, and systematic factors that lead to food waste in the retail and wholesale sector by conducting interviews with store managers. Based on these factors, the study derived public policy strategies for managing food waste [9]. Balaji and Arshinder (2016) studied casual factors of food waste and interactions among them in emerging markets such as India by utilizing total interpretive structural modeling (TISM) and interviews with experts in the food industry. Findings showed that causes of food waste could be represented by 16 factors including lack of harvesting technology and increase of intermediate stages of the FSC [16]. Thyberg and Tonjes (2016) explored food waste drivers on the residential, institutional, and commercial levels in the US. Moreover, the study examined the impact of the food system modernization on food waste generation for the aim of developing a sustainable policy approach for effective food waste management [17].

By analyzing the research area of the food waste sustainable recovery modeling, we observe the necessity to extend the conventional limited frameworks to the SFSCM including the network design of the sustainable food waste management. The limitations in the current research studies including but not limited to the absence of the sustainability parameters that estimate the economic, environmental, and social aspects of food waste management. In particular, there is no research analyzing the energy efficiency of the food waste recovery process. Second, there is no consideration of the various food waste valorization technologies and recovery options. Also, studies are limited to internal use of the food waste in a specific stage of the food supply chain and there is no analysis of the integrated recovery of the food waste both internally and to external supply chains [13]. The implementation of encountered research is specific to certain food waste categories such as citrus or mushroom and cannot be generalized to the generic sustainable food waste management. Some research even does not consider food waste itself at all. Instead, it is only limited to the organic growing medium which is a very small portion of the wasted food amount [14]. Also, most of the research analysis is based on analytical approaches that do not consider the balance between the conflicting objectives of sustainability, to the contrary of the quantitative modeling approaches.

Consequently, we propose a comprehensive framework for sustainable food waste recovery modeling that investigates the optimal configuration of the economic, environmental, social, and energy efficiency parameters. We adopt a quantitative modeling methodology to assess various food waste valorization alternatives based on the suggested sustainability criteria. The developed model is implemented in the case study of the Massachusetts food waste management system and results are verified by realistic data.

3. Research Methodology

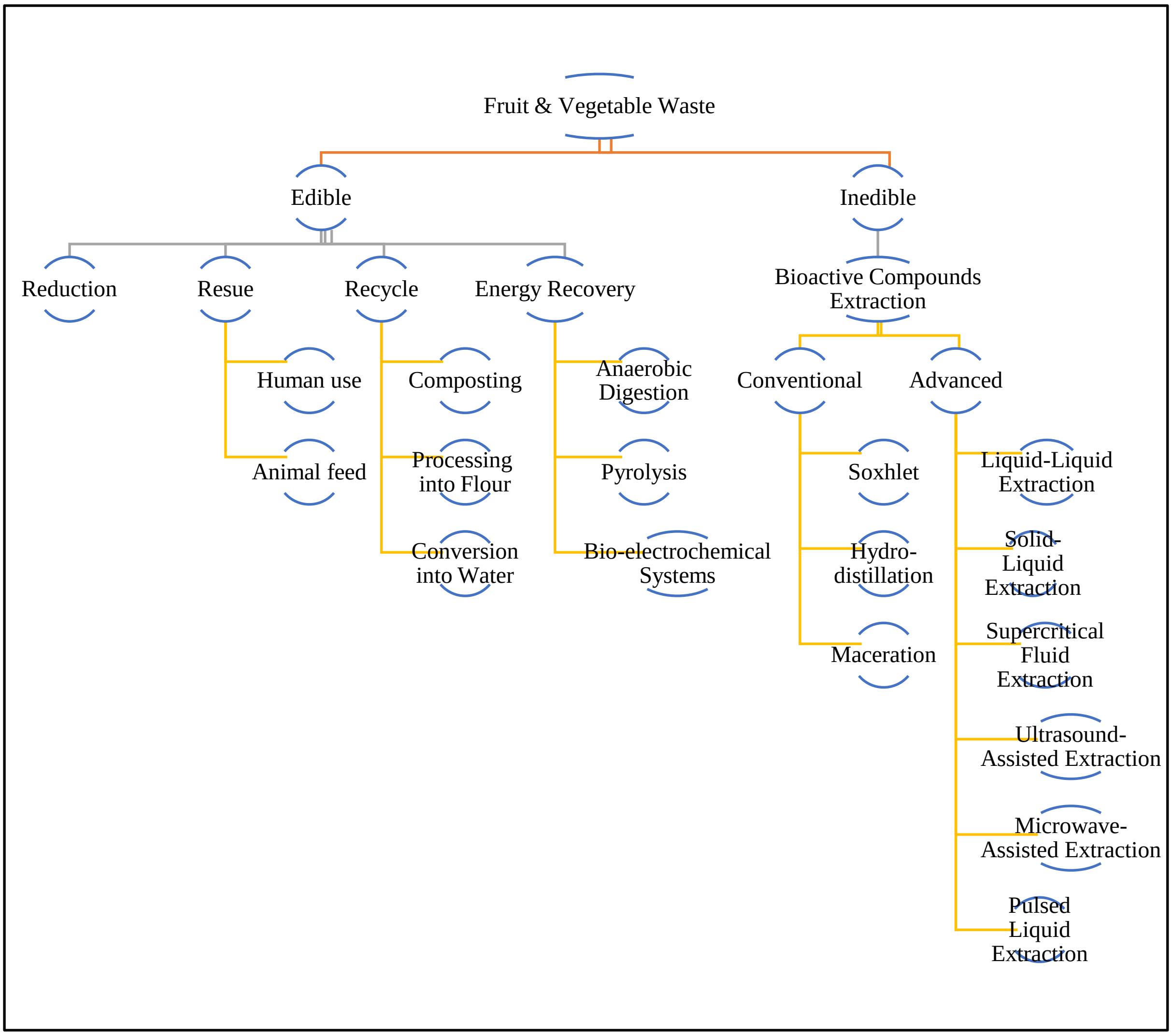
Addressing the FVW reduction issue in the context of sustainable food systems requires a multidisciplinary approach to identify the intersection between valorization techniques, reverse supply chains, ecological, and social issues [18]. Implementing the proposed approach of the FVW network framework can be achieved through the following steps:

1. Defining the sustainable system boundaries
2. Performing FVW assessment
3. Analyzing FVW sustainable valorization benefits
4. Solving the FVW network model

3.1 The Sustainable system boundaries

The first step in developing the FVW reduction framework is to identify the characteristics of the wasted fruit and vegetables accurately. Determining the best valorization option of FVW depends on the condition of the food in terms of type and quality, quantity, packaging characteristics, the source at which the waste occurred, energy and water use, and GHG emissions. These characteristics can be used to identify the system boundaries of FVW reduction. There are several different types of FVW including avoidable, non-avoidable, raw, and processed. Accordingly, each type of FVW has certain shelf life properties and temperature control requirements.

The quantity of FVW can be expressed in kg per capita per year or kcal per capita per day. The FVW may occur at any stage of the food supply chain from farm to fork. The distances between these sources and between the proposed valorization center locations are required to study the process of FVW reduction with tradeoffs between economic, environmental, and social costs [19]. Moreover, reverse logistics parameters include locations of both suppliers and consumers, capacities, and transportation costs, and environmental properties such as energy use and GHG emissions [20]. The FVW reduction framework utilizes food waste and the parameters of reverse logistics as inputs for the FVW network model.



Furthermore, the food waste hierarchy framework can be utilized to evaluate the sustainability impact of different FVW treatment options. Papargyropoulou et al. (2014) proposed a framework to identify food waste treatment options and priorities these options according to sustainability criteria by applying the waste hierarchy

Figure 1: Sustainable Alternatives of The FVW Management

approach [8]. The framework showed that the prevention of food waste is the most appealing sustainable option, then the human use option, recycling food waste into animal feed or by composting processes, followed by energy recovery [8]. The least favorable option according to this framework is the disposal of food waste into landfills due to the negative economic and environmental impact of this process.

3.2 Fruit and vegetable waste valorization assessment

In this step, the FVW valorization alternatives are evaluated from a sustainability point of view. These alternatives include Human use by donations or selling at the secondary market, recycling by preparing for animal feed or composting, and resource recovery by technologies such as anaerobic digestion. Each of these alternatives has a different impact on sustainability and a specific alternative or a combination of two or more could lead to the highest level of sustainable food waste reduction. Including reverse logistics, modeling will ensure optimal utilization of the wasted food by minimizing the traveled distance. Organic material recycling can be defined as the recovery of waste materials after a major modification of their characteristics [21]. As such, the recycling of FVW has great potential output due to the high water and low protein content. Recycling strategies are divided into the whole FVW mass recycling that includes composting, conversion into the water, and processing into flour. The second recycling strategy is compound extraction. Next, we present and conduct a comparative analysis of different sustainable alternatives of FVW management. The reduction, reuse, recycling of the edible FVW, and the bioactive compounds extractions of the inedible FVW will be within the scope of this research, (see figure 1).

3.2.1 Humanitarian Relief

Food surplus is avoidable food waste that is edible and can be used for human consumption under normal circumstances [8]. Hunger-relief organizations collect food surplus by cooperating with nodes of the SFSC and distribute the collected food to donation centers such as food banks, food cooperatives, and community kitchens. More than 10% of U.S. households who are affected by food insecurity receive nutritional assistance from federal programs such as Supplemental Nutrition Assistance Program (SNAP) and/or from charitable organizations such as food pantries. To encounter household and community food insecurity, the utilization of food surplus appeared to be an efficient practice to improve food access to the vulnerable. Moreover, the UK government suggested that food surplus redistribution is a potential strategy in the context of sustainable food systems for reducing food waste and generating social, environmental, and economic benefits for the food industry [22].

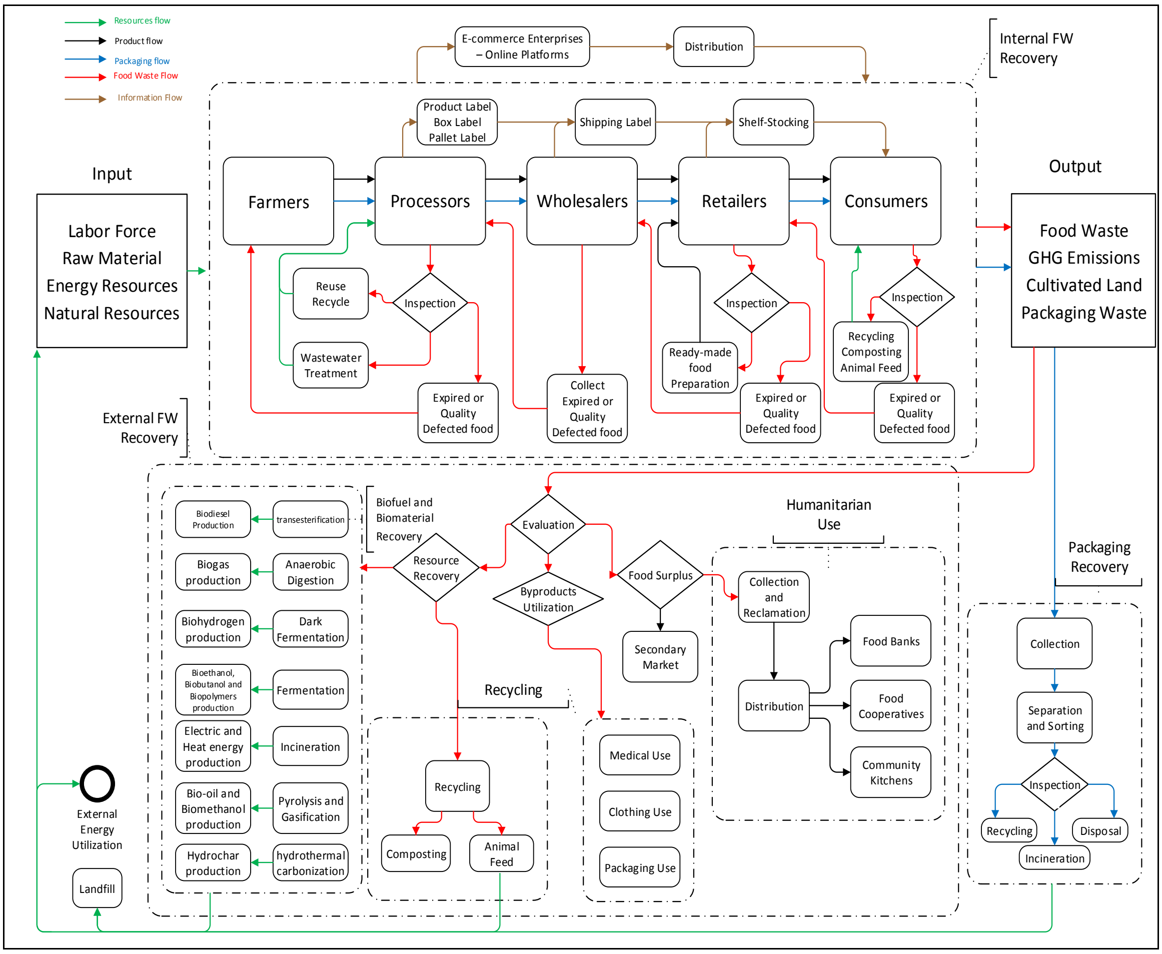


Figure 2: The Internal and external food waste valorization alternatives

3.2.2 Anaerobic Digestion

Anaerobic digestion for biogas production (methane-rich gas) is a well-established technology perfectly suited for food waste management. This technology can be applied to almost all types of biodegradable substrates as source-separated organic fraction of municipal solid waste, agricultural or industrial food waste, and food manufacturing residues. The inputs to this process constitute food waste or any organic matter, energy, and water. The outputs include biogas that could be utilized for digester energy use, effluent, and digestate [23].

3.2.3 Pyrolysis

Pyrolysis is a process that converts organic material into bio-oil, biochar, and other volatile matter by thermochemical decomposition. The process is applied by moving the biomass at a controlled rate through a horizontal tubular kiln at a temperature of around 400 ^{0} C. Applications of this technique include power generation, fuel production, soil amendment, and carbon mitigation strategies [24].

3.2.4 Microwave-assisted extraction

The use of microwaves which are a non-contact heat source in the microwave-assisted extraction technique (MAE) provides more effective heating and transfer of energy to extract several compounds such as antioxidants, flavorings, and essential oils. The MAE is flourishing, safe, and allows access to high temperatures that enable reduced reaction time and increased total yield with or without the use of any solvents [25].

3.2.5 Ultrasound-assisted extraction

The cavitation phenomenon produced by ultrasound-assisted extraction (UAE) has a mass transfer effect on plant cell walls that leads to the release of natural compounds. UAE is a versatile, flexible, and easy to use the method that requires low initial investment compared with other extraction techniques. The process of extraction using this technique involves two phases. First, the diffusion phase through the cell wall and then the rinsing phase where the cell content is rinsed after breaking the walls. The process can be applied directly or indirectly. The direct application provides 100 times higher intensity while water is used to transfer waves in the indirect application. Various biomaterials have been extracted using the UAE such as essential oils, proteins, dyes, and polysaccharides. The temperature, pressure, frequency, and sonication time are all factors that impact the yield of the UAE method [25].

3.2.6 Conversion into Water

Pure water can be obtained from FVW by applying the hyper-acceleration of aerobic decomposition. This technique utilizes the activity of naturally occurring microorganisms. When the environmental conditions are tightly controlled, this process is characterized by enhanced degradation capabilities. Companies, supermarkets, and restaurants have already applied patented systems to convert FVW into water [21].

3.3 Analyzing food waste sustainable valorization benefits

Input data of different system factors are collected and analyzed to quantify the benefit of valorizing the FVW by a specific potential technique. A sustainable benefit model can be utilized to determine the FVW reduction potentials using input data within the system boundaries. Such models use FVW characteristic data to estimate sustainable benefits such as energy reduction and GHG emission reduction. Additionally, the sustainable benefits of reverse logistics of FVW are quantified based upon geographic distance, valorization characteristics, and technologies for collection, storage, and distribution. By identifying inputs, outputs, and externalities associated with the sustainable FVW reduction system, the following sets, and parameters for the food waste network problem are generated as shown in **Table 1**.

Table 1: Sets and parameters for the FVW network problem

Sets	
g	1,…, G Food Waste (FW) generators
r	$1, \ldots, R$ FW recovery sites

$\nu \in \mathcal{V}$	(Humanitarian Relief (HR), Secondary Market (SM), Animal Feed (AF), Composting (CO), By-Product Production (BP), Anaerobic Digestion (AD), Transesterification (TR), Incineration (IN), Pyrolysis and Gasification (PG), Hydrothermal Carbonization (HC), Landfill (LA))
Parameters	
d_{gr}	distance between FW generator g and recovery site r(mile)
tc_{grv}	transportation cost between generator g and valorization option ν at recovery site $r(\$/ton - mile)$
CO_{2rv}	carbon emissions/absorption resulting from establishing valorization option ν in the recovery site r(ton CO_2eq/ton)
pCO_{2v}	carbon emission resulting from processing FW by option ν(ton CO_2eq/ton)
tCO_{2grv}	carbon emissions resulting from transport between generator g and option ν in site r(ton CO_2eq/ ton − mile)
w_{rv}	energy required to establish option ν in site r ($kwh\ /ton$)
pw_v	energy required to process FW with option ν ($kwh\ /\ ton$)
tw_{grv}	energy required for transport between generator g and option ν(kwh /ton − mile)
sw_{rv}	human toxicity resulted by establishing option v in site r (CTU /ton)
psw_v	human toxicity resulted by processing FW with option v (CTU /ton)
tsw_{grv}	Human toxicity resulted by transporting FW between generator g and option v in site r (CTU /ton)
fs_{rv}	nutrition value resulted by establishing option v in site r ($kcal$ /ton)
pfs_v	nutrition value resulted by processing FW with option v ($kcal$ /ton)
tfs_{grv}	nutrition value resulted by transporting FW between generator g and option v in site r ($kcal$ /ton)
db_r	development budget allocated for site r($)
fc_v	fixed cost to establish option ν($\$/ton$)
pc_{rv}	processing cost of FW by option ν in site r($\$/ton$)
cap_{rv}	capacity of processing facility v in site r (ton)
cp_{gv}	capacity of generator g (ton)allocated to option ν
cp_g	total capacity of generator g (ton)

ew_v	power generation resulted from FW treatment by option v(kwh /ton)
e_v	conversion factor for carbon emission associated with power generation ($tonCO_2eq/kwh$)
m_v	conversion factor for carbon emission associated with FW treatment ($tonCO_2\,eq/ton$)
q_v	the conversion factor for human toxicity associated with FW treatment (CTU/ton)
s_v	conversion factor for human toxicity associated with power generation (CTU/kwh)
u_v	the conversion factor for nutrition value associated with FW treatment ($Kcal/ton$)
n_v	conversion factor for nutrition value associated with power generation ($Kcal/kwh$)
fd_v	sustainability threshold for recovered FW by option v(ton)
w_i	preference weight for the ith goal
max $cost$	the numeric target level for the economic goal
max $toxin$	the numeric target level for the public health goal
min $nutrition$	the numeric target level for the food security goal
max_{LA}	maximum disposal limit of food waste (ton)

3.4 The fruit and vegetable waste network model

We formulate the FVW network framework as a strategic weighted goal programming model that aims to minimize total FVW management costs, maximize public health and food security while satisfying emissions and energy use constraints. The formulation is based on the following assumptions:

1. One year of FVW treatment with long term use of treatment options. This is because establishing treatment facilities requires substantial time and resources, which makes short term switching infeasible.
2. The FVW is assumed to be separated at the source and ready to be collected by the hauler.
3. The landfill does not involve gas recovery units
4. Assume expansion of existing FVW recycling facilities
5. Assume the life cycle of the treatment facility is 20 years

Given the sets and parameters in Table 1, the FVW network model is formulated as follows.

3.4.1 Decision Variables

Table 2: The model decision variables

x_{rv}	$\begin{cases}1, & if valorization option v is to be opened in site r\\ 0, & otherwise\end{cases}$
y_{grv}	FVW flow between generator g and recovery site r allocated to valorization option v (ton)
P_i	The positive deviational variable of the ith goal
N_i	The negative deviational variable of the ith goal

Table 2shows the decision variables of the FVW network model.

3.4.2 Objective function

$$\min a = w_1\left(\frac{P_1}{\max cost}\right) + w_2\left(\frac{P_2}{\max toxin}\right) + w_3\left(\frac{N_3}{\min nutrition}\right) \quad (1)$$

The objective function (1) combines the three goals of concern by weights to be determined based on the desired emphasis on specific goals.

3.4.3 The economic goal

$$\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} fc_v x_{rv} cap_{rv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} d_{gr}\, tc_{grv}\, y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} pc_{rv} y_{grv} + N_1 - P_1 = \max cost \quad (2)$$

The economic goal (2) minimizes the fixed, transportation, and processing cost of the FVW treatment. The fixed cost represents establishing treatment facilities. The transportation cost is related to the transporting of FVW by truck from generators to treatment facilities. The processing cost is associated with all activities of FVW treatment by the designated facilities.

3.4.4 The public health goal

$$\sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v=LA} q_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} psw_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} d_{gr}\, tsw_{grv}\, y_{grv} + \sum_{r=1}^{R}\sum_{v\in\mathcal{V}} sw_{rv} x_{rv}\, cap_{rv} - \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}-\{\mathrm{LA}\}} q_v y_{grv} - \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\{AD,TR,IN,PG,HC\}} s_v ew_v y_{grv} + N_2 - P_2 = \max toxin \quad (3)$$

The public health goal (3) aims to minimize the toxicity resulted from processing, transporting, and landfilling involved in the FVW processes.

3.4.5 The food security goal

$$\sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v=LA} u_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} pfs_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} d_{gr}\, tfs_{grv}\, y_{grv} + \sum_{r=1}^{R}\sum_{v\in\mathcal{V}} fs_{rv} x_{rv}\, cap_{rv} - \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}-\{\mathrm{LA}\}} u_v y_{grv} - \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\{AD,TR,IN,PG,HC\}} n_v ew_v y_{grv} + N_3 - P_3 = \min nutrition \quad (4)$$

The food security goal (4) aims to minimize the lost nutrition value resulted from processing, transporting, and landfilling involved in the FVW processes.

3.4.6 Demand fulfillment constraint

$$\sum_{g=1}^{G}\sum_{r=1}^{R} y_{grv} \geq fd_v \qquad \forall v \in \mathcal{V} \quad (5)$$

$$\sum_{r=1}^{R} y_{grv} \leq max_{LA} \qquad \forall g: 1,\dots,G, v: \mathrm{LA} \quad (6)$$

The set of constraints (5) guarantees that the demand of each FVW recovery product is met. Constraint (6) limits the FVW disposal amount to a maximum value set by regulators.

3.4.7 Capacity constraints

$$\sum_{g=1}^{G} y_{grv} \leq x_{rv} cap_{rv} \qquad \forall r: 1,\dots,R,\ v \in \mathcal{V} \quad (7)$$

$$\sum_{r=1}^{R} y_{grv} \leq cp_{gv} \qquad \forall g: 1,\dots,G,\ v \in \mathcal{V} \quad (8)$$

Constraints (7) and (8) limit the flow of FVW from generators to treatment sites per the processing capacity of treatment facilities and generators capacities allocated to each treatment facility, respectively.

3.4.8 Flow balance constrains

$$\sum_{r=1}^{R}\sum_{v\in V} y_{grv} = cp_g \qquad \forall g: 1,\dots,G \quad (9)$$

$$\sum_{r=1}^{R}\sum_{v\in V} x_{rv}\, cap_{rv} \geq \sum_{g=1}^{G} cp_g \quad (10)$$

Constraint (9) forces the amount of FVW flow within the system to be equal to the total capacity for each generator. Constraint (10) ensures the capacity of all FVW treatment facilities is at least as much as the total capacity of all generators.

3.4.9 Development budget constraint

$$\sum_{v \in V} fc_v x_{rv} cap_{rv} \le db_r \qquad \forall r: 1, \dots, R \tag{11}$$

Constraint (11) limits the fixed cost to establish treatment sites per the available budget for each site.

3.4.10 Emissions control constraint

$$\sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v=LA} m_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v \in \mathcal{V}} pCO_{2v} y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v \in \mathcal{V}} d_{gr}\, tCO_{2grv} y_{grv} + \sum_{r=1}^{R}\sum_{v \in \mathcal{V}} CO_{2rv} x_{rv} cap_{rv} \le \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v \in \mathcal{V}-\{\text{LA}\}} m_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v \in \{AD,TR,IN,PG,HC\}} e_v ew_v y_{grv} \tag{12}$$

Constraint (12) controls the net emissions resulting from the FVW treatment system. It ensures that emissions associated with establishing treatment facilities plus emissions from landfilling, processing, and transportation of FVW must either be offset by diverting FVW from disposal to landfill or FVW used for energy recovery.

3.4.11 Energy control constraint

$$\sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v \in \mathcal{V}} pw_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v \in \mathcal{V}} d_{gr}\, tw_{grv} y_{grv} + \sum_{r=1}^{R}\sum_{v \in \mathcal{V}} w_{rv} x_{rv} cap_{rv} \le \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v \in \{\text{AD,TR,IN,PG,HC}\}} ew_v y_{grv} \tag{13}$$

Like constraint (12), Constraint (13) ensures that the energy supply to the FVW treatment system is provided by the energy recovered from the FVW treatment activities.

$$x_{rv} \in \{0,1\}, \quad y_{grv}, P_i, N_j \ge 0 \qquad \forall r: 1, \dots, R, v \in \mathcal{V}, g: 1, \dots, G, i = 1,2,3, j = 1,2,3 \tag{14}$$

Finally, constraint (14) enforces binary values and non-negativity for the decision variables.

4. Designing the Food Waste Network in Massachusetts

We test the efficiency of the proposed framework by designing a sustainable FVW treatment network for the state of Massachusetts. The total amount of FVW in Massachusetts is estimated to be over four hundred tons generated from the commercial sector that includes food producers, retailers, restaurants, hospitals, and other institutions. Although the wasted food has the potential to be diverted for human use, recycling, energy recovery, and other FVW recycling technologies, most of the waste is disposed of in landfills. This practice is impacting the environment negatively by increasing GHG emissions from landfills [26]. As a result, the Massachusetts department of environmental protection (MassDEP) initiated a commercial food material disposal ban. The ban that took effect in 2014, limits the amount of commercial organic waste by businesses and institutions to a maximum of one ton per week. This regulation is considered as one of the agency's initiatives to achieve a 35% food waste diversion from disposal by 2020 [27]. We will focus on six processing options of food waste treatment based on the implementation feasibility of these options in the state of Massachusetts.

4.1 Data Collection and Analysis

Table 3 shows the average capacity for all FVW generators in Massachusetts to divert their food waste using six currently available processes. These processes are Humanitarian relief, anaerobic digestion, pyrolysis, MAE, UAE, and conversion into water or wet-systems. To comply with the ban, the capacity of disposal is limited to 240,000 tons of FVW.

Table 3: The capacity of FVW generators in Massachusetts

The total capacity of FVW for all generators cp_g (ton)	Capacity for FVW to be diverted by process vcp_{gv} (ton)						
	HR	AD	Pyrolysis	MAE	UAE	Wet-system	LA
400,000	280,000	360,000	360,000	320,000	320,000	320,000	400,000

We have collected emission, energy, and demand parameters data for each of the seven potential processes that could be selected for FVW treatment. Transportation cost for humanitarian relief is higher than other treatment processes as FVW need more temperature control equipment to be transported safely [23]. Carbon emissions cost is based on estimated emissions resulted from processing FVW by a particular process divided by the emissions social cost which is estimated to be 38$ per $tonCO_2eq$ [28]. We calculated the transportation emission and energy based on using truck mode [29]. Fixed costs include site preparation to expand processing activities and equipment purchases as shown in the 2017 analysis of organics diversion alternatives report. Processing cost includes operational costs, maintenance, and labor cost to process FVW per ton [30]. The energy required to process a ton of FVW by the MAE is the highest compared to other processing options, followed by the UAE. On the other hand, processing food waste for human use consumes the lowest energy rates [31]. The public health impact in terms of human toxicity is the highest from processing the FVW by landfilling while the human use of the FVW has the lowest impact [32]. Similarly, the landfill disposal option is contributing the most to the food insecurity by nutrition waste of more than 1.38E+6 kcal/ton [33]. On the other hand, wasted nutrition resulted from processing the FVW for human use is the least among other treatment options [34].

We deployed a conversion factor to calculate emissions, human toxicity, and wasted nutrition that is resulted from FVW disposal in Landfills. The data analysis is summarized as shown in**Table 4**. MassDEP has selected four sites for potential expansion to meet the expected increase in food waste diversion. We have derived the coordination of the average location of all generators in Massachusetts according to the 2017 analysis of organics diversion alternatives report. Accordingly, the distance from this central location to each potential processing site is calculated as shown in**Table 5**. Moreover, we derived the estimated budget allocated for each processing site from MassDEP relevant reports.

Table 4: Data analysis summary for the FVW network problem

Option ν	Off-site treatment options						On-site
	HR	AD	Pyrolysis	MAE	UAE	LA	Wet-system
tc_{grv}	0.915	0.5	0.5	0.5	0.5	0.5	0
CO_{2rv}	0.06	0.189	0.189	0.189	0.189	0.84	0.06
pCO_{2v}	0.01	0.159	0.046	95	15.6	5.6	0.01
tCO_{2grv}	0.03	0.01	0.01	0.01	0.01	0.0003	0
w_{rv}	123	330	330	330	330	180	123
pw_v	3.33	472.78	750	120000	41111.11	60	7.7
tw_{grv}	83.33	27.78	36.11	28	28	1.22	0
sw_{rv}	0.0467	7.9628	7.9628	7.9628	7.9628	0.0467	1.0316
psw_v	2.522E-02	2.524E+01	1.009E-01	1.143E+02	1.905E+01	2.522E-02	1.143E+02
tsw_{grv}	0.0880	0.7520	0.0974	0.0974	0.0974	0.0000	0.0974
fs_{rv}	5606.69	99553.68	99553.68	99553.68	99553.68	5606.69	84057.79
pfs_v	3.025E+03	2.297E+05	1.210E+04	1.129E+06	1.882E+05	3.025E+03	1.129E+06
tfs_{grv}	5280.874	7233.874	1013.956	1013.956	1013.956	0	1013.956
fc_v	75	90	90	90	90	50	22
pc_{rv}	16	33	33	33	33	3	70.3
ew_v	1938.89	605.56	3186.11	-	-	-	-
e_v	0.00034	0.00034	0.00034	-	-	-	-
m_v	1.02	1.02	1.02	1.02	1.02	1.02	1.02
q_v	37.4165	37.4165	37.4165	37.4165	37.4165	37.4165	37.4165
s_v	0.0534	0.0534	0.0534	0.0534	0.0534	0.0534	0.0534
u_v	369480.9	369480.9	369480.9	369480.9	369480.9	369480.9	369480.9
n_v	2602.12	2602.12	2602.12	2602.12	2602.12	2602.12	2602.12
$fd_v \times 1000$	40	10	10	10	10	10	-

4.2 Results

By implementing the collected data of different parameters, we run the FVW network model in Lingo and obtain an optimal solution in less than 0.01 s on a computer configured with an Intel Core 3.3 GHz processor and 8 GB of RAM. To compare the results, we make three different scenarios of the model. First, we put more weight on the cost objective which will show the economic perspective of the optimization model. Second, we explore the results of the equal weights for the three objectives. Lastly, the third scenario is to make the public health objective the priority, then the food security, and the lowest weight is given to the economic dimension. The results are summarized in**Table 6**. along with different KPIs to measure the sustainability impact of each scenario. The main KPIs include the cost of FVW treatment, net mitigated emissions, net energy use per ton of valorized food waste, the public health impact, the food security impact, and the food waste hierarchy impact. Figure 3 shows the results of the FVW network represented in the spider chart.

Table 5: Distance from generators to potential processing sites

Site r	Distance to generators d_{gr} (mile)	Development Budget db_r ($million$ $)
1	104.50	10.58
2	70.62	25.51
3	30.53	616.52
4	40.70	44.79

Table 6: Results and sustainability KPIs of the FW network model

	Scenario 1	Scenario 2	Scenario 3
Total Cost	$52,740,000.00	$56,457,000.00	$59,827,170.20
Food Treatment cost per ton	$131.85	$141.14	$149.57
Fixed Cost	$32,510,000.00	$34,270,000.00	$37,870,000.00
Fixed Cost Per ton	$81.28	$85.68	$94.68
Transportation Cost	$8,806,000.00	$6,759,000.00	$6,368,657.81
Transportation Cost per ton	$22.02	$16.90	$15.92
Processing Cost	$11,424,000.00	$15,428,000.00	$15,588,512.39
Processing Cost per ton	$28.56	$38.57	$38.97
Food Treatment Carbon Impact	0.00	0.00	0.00
Food Treatment Carbon Impact per ton	0.00	0.00	0.00
Food Energy Use impact	0.00	0.00	0.00
Food Energy Use impact per ton	0.00	0.00	0.00
Public Health impact	47475503.24	38519018.43	37412484.50
Public Health impact per ton	118.69	96.30	93.53
Food Security impact	-1768082878526.23	-1,314,035,589,466.71	-1,266,412,043,007.06
Food Security impact per ton	-4,420,207.20	-3,285,088.97	-3,166,030.11
Food waste hierarchy impact	86.50%	87.25%	87.01%

In the case of scenario one, the treatment cost is low and energy consumption and emissions constraints are satisfied. The total cost per ton reads $131.85 but the high human toxicity at 118.69 CTU/ton and the wasted nutritions of more than 4.4 million kcal/ton make this scenario less desirable from a sustainability perspective. On the other hand, the treatment cost has increased to $141.14 in scenario 2 as a result of diverting more food waste from disposal to landfill. However, besides the zero net emissions and energy use, this scenario achieved a reduction of human toxicity by %19 and increased the nutrition value by %26. Moreover, with just a 6% increase in the treatment cost compared to scenario 2, scenario 3 has achieved a reduction of the human toxicity to as low as 93.53 CTU/ton and increased nutrition value by 4%. However, this scenario has diverted more FVW from being used for human consumption. As a result, the food waste hierarchy impact achieved by this scenario is lower than scenario 2 but higher than scenario 1. Therefore, comparing all scenarios shows that planning and designing the FVW network model is vital to reach the balance between different parameters of the system and to better use of resources. These derived results are based on the data entered for the FVW characteristics and other parameters. In case of any changes to these data, the results will change accordingly. For example, if the FVW is not edible and contains a large number of contaminants, then energy recovery treatment options are more appropriate than human use. In this case, reaching the optimal balance between the conflicting goals of economic viability, public health, and food security is more challenging.

4.3 Discussion

Our study demonstrates a new approach to the sustainable modeling of the FVW recovery network. In particular, we built a quantitative multi-criteria evaluation of sustainable FVW treatment concerning economic, environmental, and social implications. The economic performance shows that shifting the FVW into the higher levels of the food waste hierarchy will result in moderate processing costs. Other studies in the literature that consider human use as a factor that contributes to food waste through the incentives of donation tax credits. In contrast, we assume that the human use of food waste is a contributing factor to sustainable development in the context of the food waste network and our results validate such assumption. Similar case studies in literature only considered the food waste to be recovered within the internal food supply chain which results in balancing profitability to the environmental performance of the recycling technologies. However, we extend this approach by considering the opportunity of food waste treatment in external supply chains which results in additional costs. Given this assumption, our model shows superior results by achieving energy self-sufficiency and 100% improvement in terms of environmental performance which is measured by the net carbon emissions.

The FVW network model is a valuable tool that policymakers, generators, and processors can use to determine the best sustainable FVW management. The model incorporates data about FVW to address the tradeoffs between the cost of treatment, environmental impact, resource utilization, and social impact derived from the food hierarchy framework. Moreover, the model largely depends on the advancement of FVW separation and treatment techniques. As these techniques improve, the treatment of FVW will be more efficient which will result in increased energy recovery, reduced emissions, and minimized treatment costs. The model metrics and KPIs enables decision-makers to manage the FVW treatment from a holistic sustainable perspective. First, the treatment cost KPI enables investors to make a cost-benefit analysis and determine the economic viability of different treatment options. Second, the treatment of emissions impact is crucial to comply with environmental policies relevant to climate change mitigation. Third, the energy use impact enables all stakeholders to cut back on fossil fuel dependency that has fluctuated prices and severe environmental impact. Fourth, the human toxicity indicator enables communities to leverage public health collectively. Moreover, the food security impact supports the best utilization of the FVW for the interest of the common good. Last, the food hierarchy impact adds more value to the society by allowing more food to be distributed to the most vulnerable sectors and amplify the public good consequently. Thus, by combining all these indicators in the FVW network model, policymakers can achieve the best sustainable strategies for FVW management.

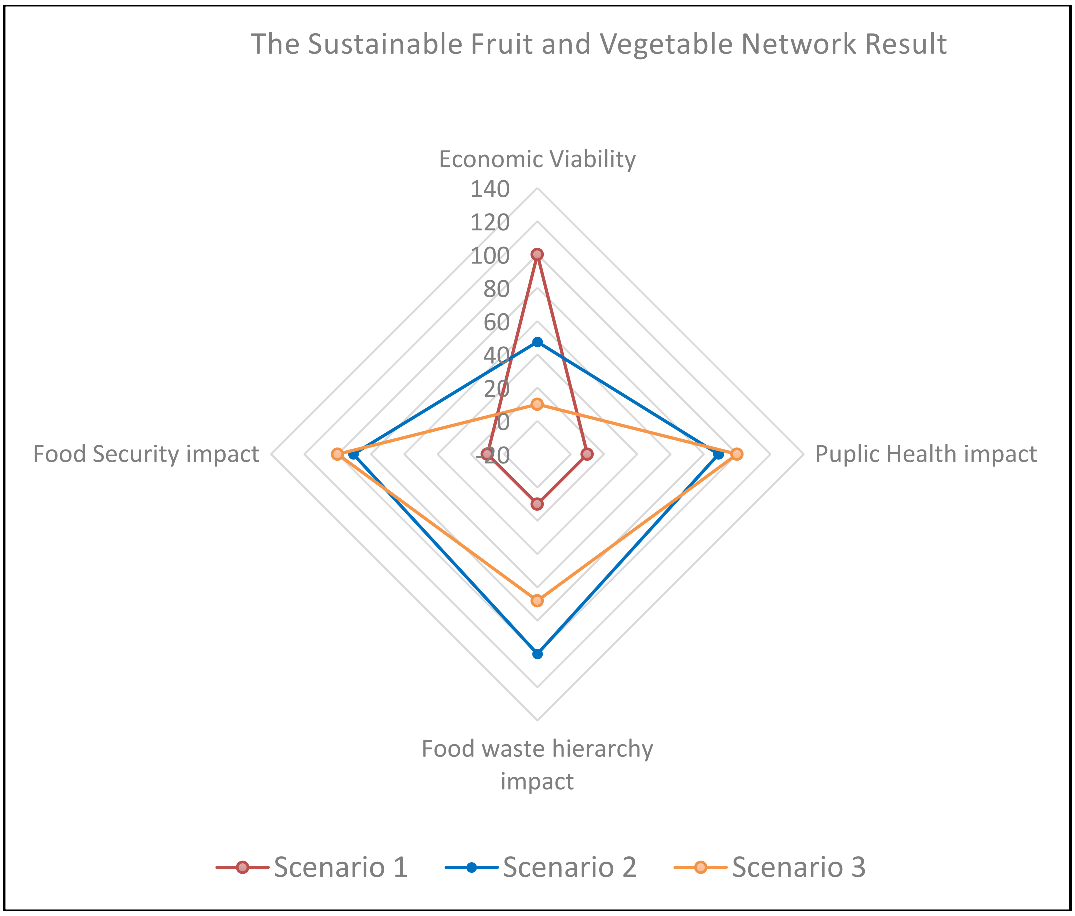


Figure 3: Spider chart of the FW network results

5. Conclusion

This paper proposed a novel quantitative FVW network model underpinned by a multi-dimensional approach that balances economic, environmental, social, and resource utilization goals. As such, the study transformed the analytical framework of food waste recovery hierarchy into a practical decision-making policy in the context of sustainable FVW networks. Further, the adopted research methodology incorporated uncovered aspects in the current literature in terms of considering FVW treatment both in the internal food supply chain and to external systems, simultaneously.

Our literature review indicates that there is a lack of research on the sustainable FVW network about issues such as considering the various FVW recovery options and technologies, optimizing the FVW recovery network, and inclusion of key sustainability parameters. For this purpose, we formulated the problem as a multi-criteria decision analysis model that minimizes total treatment cost, maximizes both the public health and food security benefits given energy use, carbon emissions, and other constraints imposed by different stakeholders of the sustainable FVW management system. Moreover, we derived a set of metrics that enables policymakers to move towards more sustainable FVW management. The model is implemented on designing the FVW network of the state of Massachusetts, USA. The results showed the potential of achieving higher sustainability performance of the FVW recovery process under budget constraints. Food producers, distributors, and consumers may utilize this model to tackle logistical issues of FVW recovery with a more efficient and sustainable structure.

This research can be further extended, and future work can be built on it in multiple directions. One could be to extend the KPIs to include more environmental measures such as air pollution impact or social measures such as employment rate impact. Another direction is to incorporate not only food waste but also packaging and other waste streams into the model to study the interdependency between all of them. Moreover, future research could be conducted by implementing different datasets to the model. The area of FVW prevention could also be investigated in terms of the efficiency of food distribution to consumers given food system resilient conditions. Finally, this research shows that there is a need to design FVW management models that address complex issues in the development of sustainable food systems.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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