Carbon Emissions and Energy Balance in the Design of a Sustainable Food Waste Network Model

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Abstract

In this paper, the food waste valorization alternatives are evaluated from a sustainability point of view. Using food waste 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 food waste are quantified based upon geographic distance and valorization characteristics. We formulate the food waste network framework as a strategic linear programming (LP) model that aims to minimize total food waste management cost while 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 food waste treatment network for the state of Massachusetts. Results show that with a marginal increase in the treatment cost of food waste, the model has achieved zero net emissions, zero net energy use, and a competitive overall sustainability impact. Thus, by utilizing the food waste network model, policymakers can achieve the best sustainable strategies for the food waste management.

Keywords

Sustainability, Food waste, Carbon emissions, Network design

1 INTRODUCTION

We will study the closed-loop food supply chain sustainability in terms of food waste management that reduce its economic and environmental impact (Pochampally et al. 2008). 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 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 (Fadhel and Gupta 2019). However, the research on closed-loop supply network design models in the food industry is very limited (Sgarbossa and Russo 2017). 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 food supply chain to a useful 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 ca be induced by tax credit and disposal fee (Lee and Tongarlak 2016). 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% (Banasik et al. 2017). Sgarbossa and Russo (2017) developed a new sustainable closed-loop supply chain (CLSC) models 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 (Sgarbossa and Russo 2017).

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 of food waste prevention and recovery would be an effective sustainable approach towards addressing the food security issue (Fadhel et al. 2017). However, studies that addressed such issues and associated complexities are still insufficient (Garrone et al. 2014). 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 (Garrone et al. 2014). Mena et al. (2014) investigated multi-tier supply network of 15 food commodities in the UK to identify the underlining causes of food waste that leads to managerial propositions. Theses propositions trigger practical approaches to mitigate the economic, environmental, and social impact of food waste (Mena et al. 2014). 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 (Mirabella et al. 2014). 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 prevention of food waste is the most appealing sustainable option, then human use option, followed by recycling food waste into animal feed (Papargyropoulou et al. 2014). Thi et al. (2015) examined food waste management systems in developing countries with 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 (Thi et al. 2015). 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 (Gruber et al. 2016). 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 (M and K 2016). 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 (Thyberg and Tonjes 2016).

3 THE FOOD WASTE NETWORK FRAMEWORK

Addressing the food waste 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 (Alqahtani et al. 2019). Implementing the proposed approach can be achieved through the following steps:

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

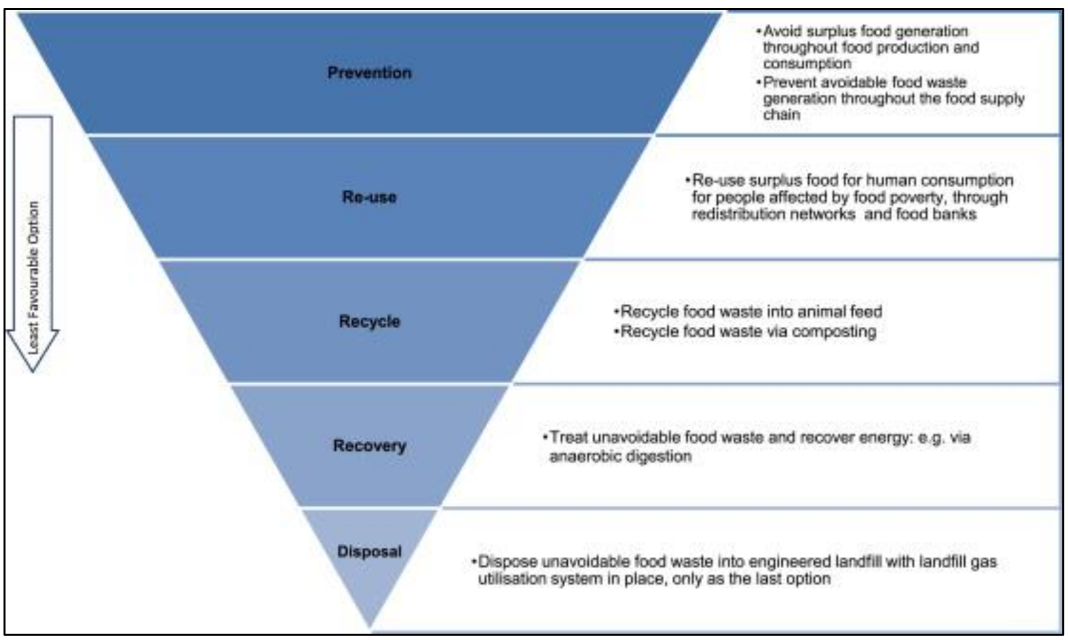

Figure 1. The Food Waste Hierarchy

3.1 THE SUSTAINABLE SYSTEM BOUNDARIES

The first step in developing the food waste reduction framework is to identify the characteristics of the wasted food accurately. Determining the best valorization option of food waste 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 food waste reduction. There are several different types of food waste including avoidable, non-avoidable, raw, processed, surplus food, and food waste. Accordingly, each type of food waste has certain shelf life properties and temperature control requirements. The quantity of food waste can be expressed in kg per capita per year or kcal per capita per day. The food waste 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 food waste reduction with tradeoffs between economic, environmental, and social costs (Gungor and Gupta 1999).

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 (Gupta 2016). The food waste reduction framework utilizes the food waste and reverse logistics parameters as inputs for the food waste network model.

Furthermore, the food waste hierarchy framework can be utilized to evaluate the sustainability impact of different food waste treatment options (See Figure 1). 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 (Papargyropoulou et al. 2014). The framework showed that prevention of food waste is the most appealing sustainable option, then human use option, next is recycling food waste into animal feed or by composting processes, followed by energy recovery (Papargyropoulou et al. 2014). The least favorable option according to this framework is the disposal of food waste into landfill due to the negative economic and environmental impact of this process.

3.2 FOOD WASTE VALORIZATION ASSESSMENT

In this step, the food waste 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 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. Figure 2 illustrates the different food waste valorization alternatives along with food waste and resources flows both within the internal FSC and in the external sustainable food system. We will focus on four processing options of food waste treatment based on the implementation feasibility of these options in the state of Massachusetts.

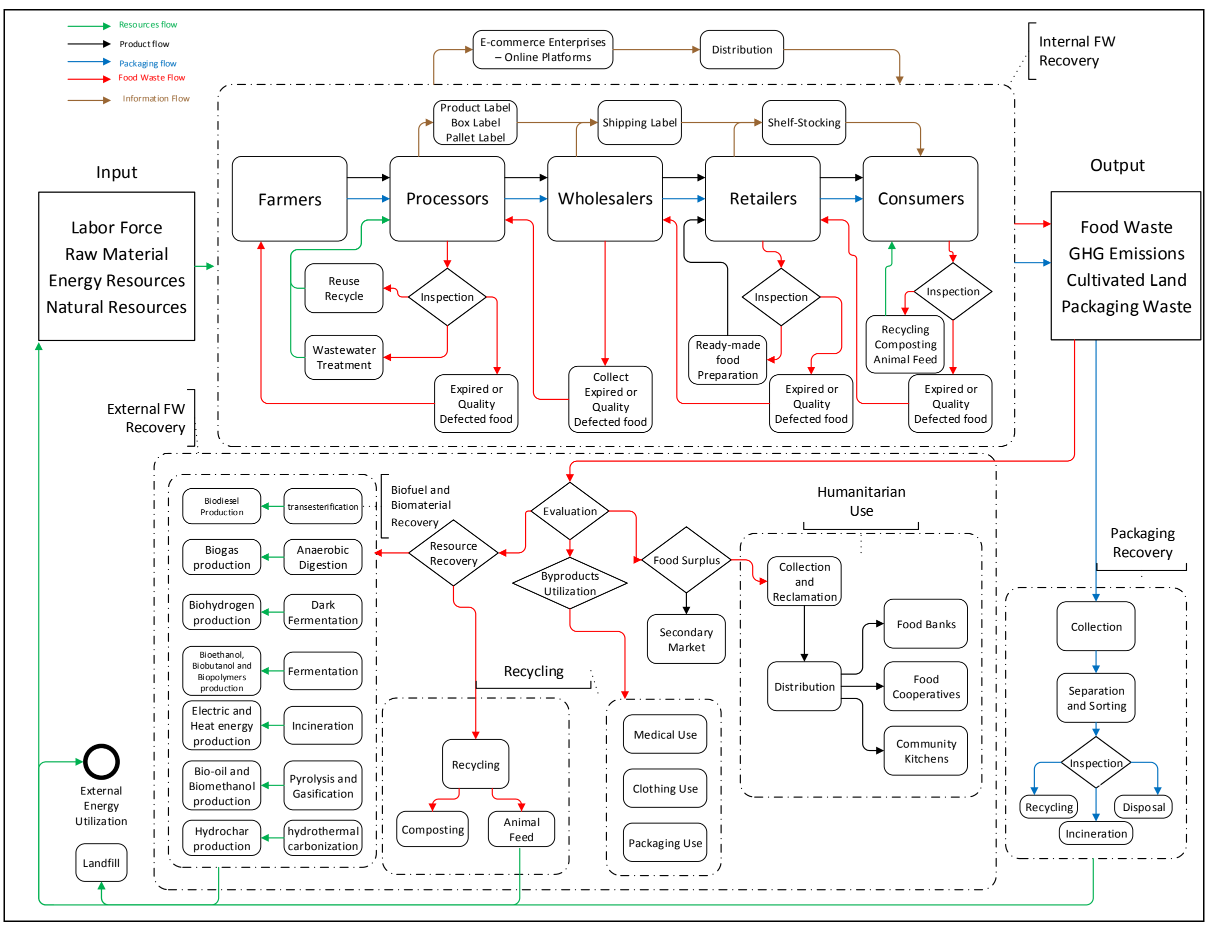

Figure 2. The Internal and external food waste valorization alternatives

3.2.1 Humanitarian Relief

Food surplus is avoidable food waste that is edible and can be used for human consumption under normal circumstances (Papargyropoulou et al. 2014). 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 (Midgley 2014).

3.2.2 Animal Feed

One processing technology of interest is to convert food waste to animal feed. Organic input to this process is exposed to initial inspection to remove large contaminants, then ground, run through additional contaminants removal, followed by dehydration or milling for mixing with other nutrients (DSM Environmental Services 2017).

3.2.3 Composting

FW often contains high concentrations of easily degradable organic substances such as sugars, starches, lipids, and proteins, thus it is suitable to be disposed of by composting (Chang and Hsu, 2008; Kumar et al., 2010). The inputs of the composting process include water, organic matter, and air while the outputs are carbon dioxide and compost that is used as fertilizer and soil enhancer. Although composting is not a new waste disposal method, the characteristics of food waste such as moisture content, nutrient content, and particle size still bring a unique challenge to the researchers, since the basic knowledge of FW composting is inadequate for supporting successful processes with high efficiency. Other important factors that influence the quality of the compost include temperature, aeration rate, and pH levels (Kocher 2018).

3.2.4 Anaerobic Digestion

Anaerobic digestion for biogas production (methane-rich gas) is a well-established technology perfectly suited for food waste management. This technology that 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 (Kocher 2018).

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 food waste by a specific potential technique. A sustainable benefit model can be utilized to determine the food waste reduction potentials using input data within the system boundaries. Such models use food waste characteristic data to estimate sustainable benefits such as energy reduction and GHG emission reduction. Additionally, the sustainable benefits of reverse logistics of food waste 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 food waste 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 food waste network problem

Sets	
g	1,…, G Food Waste (FW) generators
r	$1, \dots, R$ 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 recovery site r (ton CO_2 eq/ton)
pCO_{2v}	carbon emission resulting from processing FW by option ν (ton CO_2 eq/ton)
tCO_{2grv}	carbon emissions resulting from transport between generator g and option ν in site r (ton CO_2 eq/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)
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$)
cap_{rv}	capacity of processing facility v in site r (ton)
cp_{gv}	capacity of generator g (ton) allocated to option ν
cp_g	total capacity of generator g (ton)
ew_v	power generation resulted from FW treatment by option ν (kwh /ton)
e_v	conversion factor for carbon emission associated with power generation ($ton\ CO_2\ eq/kwh$)
m_v	conversion factor for carbon emission associated with FW treatment ($ton\ CO_2\ eq/ton$)
fd_v	sustainability threshold for recovered FW by option ν (ton)
max_{LA}	maximum disposal limit of food waste (ton)

3.4 THE FOOD WASTE NETWORK MODEL

We formulate the food waste network framework as a strategic linear programming (LP) model that aims to minimize total food waste management cost while satisfying emissions and energy use constraints. The formulation is based on the following assumptions:

1. A one-year period of food waste 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 food waste 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 food waste recycling facilities
5. Assume the life cycle of the treatment facility is 20 years

Given the sets and parameters in Table 1, the food waste 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}	FW flow between generator g and recovery site r allocated to valorization option v (ton)

Table 2 shows the decision variables of the food waste network model.

3.4.2 Objective function

$$\min \sum_{r=1}^{R}\sum_{v\in\mathcal{V}} fc_v x_{rv} cap_{rv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} d_{gr} tc_{grv} y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} pc_{rv} y_{grv} \quad (1)$$

The objective function (1) minimizes the fixed, transportation, and processing cost of the food waste treatment. The fixed cost represents establishing treatment facilities. The transportation cost is related to transporting food waste by truck from generators to treatment facilities. The processing cost associated with all activities of food waste treatment by the designated facilities.

3.4.3 Demand fulfillment constraint

$$\sum_{g=1}^{G}\sum_{r=1}^{R} y_{grv} \ge fd_v \qquad \forall v \in \mathcal{V} \quad (2)$$

$$\sum_{r=1}^{R} y_{grv} \le max_{LA} \qquad \forall g: 1,\dots,G, v: \text{LA} \quad (3)$$

The set of constraints (2) guarantee that the demand of each food waste recovery product is met. Constraint (3) limits the food waste disposal amount to a maximum value set by regulators.

3.4.4 Capacity constraints

$$\sum_{g=1}^{G} y_{grv} \le x_{rv} cap_{rv} \qquad \forall r: 1,\dots,R,\ v \in \mathcal{V} \quad (4)$$

$$\sum_{r=1}^{R} y_{grv} \le cp_{gv} \qquad \forall g: 1,\dots,G, v \in \mathcal{V} \quad (5)$$

Constraints (4) and (5) limits the flow of food waste from generators to treatment sites in accordance with the processing capacity of treatment facilities and generators capacities allocated to each treatment facility, respectively.

3.4.5 Flow balance constrains

$$\sum_{r=1}^{R}\sum_{v\in V} y_{grv} = cp_g \qquad \forall g: 1,\dots,G \quad (6)$$

$$\sum_{r=1}^{R}\sum_{v\in V} x_{rv}\, cap_{rv} \ge \sum_{g=1}^{G} cp_g \quad (7)$$

Constraint (6) force the amount of food waste flow within the system to be equal to the total capacity for each generator. Constraint (7) ensures the capacity of all food waste treatment facilities is at least as much as the total capacity of all generators.

3.4.6 Development budget constraint

$$\sum_{v\in V} fc_v x_{rv} cap_{rv} \le db_r \qquad \forall r: 1,\dots,R \quad (8)$$

Constraint (8) limits the fixed cost to establish treatment sites in accordance with the available budget for each site.

3.4.7 Emissions control constraint

$$\sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v=LA} m_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} pCO_{2v} y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} d_{gr} tCO_{2grv} y_{grv} + \sum_{r=1}^{R}\sum_{v\in\mathcal{V}} CO_{2rv} x_{rv} cap_{rv} \le \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}-\{\text{LA}\}} m_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\{\text{AD,TR,IN,PG,HC}\}} e_v ew_v y_{grv} \quad (9)$$

Constraint (9) control the net emissions resulting from the food waste treatment system. It ensures that emissions associated with establishing treatment facilities plus emissions from landfilling, processing, and transportation of food waste must either be offset by diverting food waste from disposal to landfill or food waste used for energy recovery.

3.4.8 Energy control constraint

$$\sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} pw_v y_{grv} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\mathcal{V}} d_{gr} tw_{grv} y_{grv} + \sum_{r=1}^{R}\sum_{v\in\mathcal{V}} w_{rv} x_{rv} cap_{rv} \le \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{v\in\{\text{AD,TR,IN,PG,HC}\}} ew_v y_{grv} \quad (10)$$

Like constraint (9), Constraint (10) ensures that the energy supply to the food waste treatment system is provided by the energy recovered from the food waste treatment activities.

$$x_{rv} \in \{0,1\},\ y_{grv} \ge 0 \qquad \forall r: 1,\dots,R, v \in \mathcal{V}, g: 1,\dots,G \quad (11)$$

Finally, constraint (11) 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 food waste treatment network for the state of Massachusetts. The total amount of food waste in Massachusetts is estimated to be over one million tons generated from the commercial sector that include food producers, retailers, restaurants, hospitals, and other institutions. Although the wasted food has the potential to be diverted for human use, recycling, or energy recovery, most of the waste is disposed of in landfills. This practice is impacting the environment negatively by increasing GHG emissions from landfills (Ilgin and Gupta 2010). 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 (Gerlat 2014). Table 3 shows the average capacity for all food waste generators in Massachusetts to divert their food waste using four currently available processes. These processes are Human use, animal feed, composting, and anaerobic digestion. To comply with the ban, the capacity of disposal is limited to 600,000 ton of food waste.

Table 3. The capacity of FW generators in Massachusetts

The total capacity of FW for all generators cp_g (ton)	Capacity for Food Waste to be diverted by process ν cp_{gv} (ton)				
	HR	AF	CO	AD	LA
1,000,000	400,000	700,000	700,000	800,000	1,000,000

We have collected emission, energy, and demand parameters data for each of the five potential processes that could be selected for food waste treatment. Transportation cost for humanitarian relief is higher than other treatment processes as food need more temperature control equipment to be transported safely (Kocher 2018). Carbon emissions cost is based on estimated emissions resulted from processing food waste by a particular process divided by the emissions social cost which is estimated to be 38$ per $ton\ CO_2\ eq$ (Industrial Economics 2017). We calculated the transportation emission and energy based on using truck mode (Weber and Matthews 2008). Fixed costs include site preparation to expand processing activities and equipment purchases (DSM Environmental Services 2017). Processing cost includes operational costs, maintenance, and labor cost to process food waste per ton (DSM Environmental Services 2017). The energy required to process a ton of food waste by composting is the highest compared to other processing options. On the other hand, processing food waste by landfill disposal consumes the lowest energy rates (Salemdeeb et al. 2017). We deployed conversion factor to calculate emissions resulted by food waste disposal in Landfill. 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 (DSM Environmental Services 2017). 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 FW network problem

Option ν	tc_{grv}	CO_{2rv}	pCO_{2v}	tCO_{2grv}	w_{rv}	pw_v	tw_{grv}	fc_v	pc_{rv}	ew_v	e_v	m_v	$fd_v \times 1000$
HR	0.915	0.06	0.02	0.0003	123	141	1.22	75	16	-	-	1.02	150
AF	0.5	0.27	0.09	0.0003	450	133.6	1.22	75	18	-	-	1.02	100
CO	0.5	0.6	0.2	0.0003	435	145	1.22	80	8.4	-	-	1.02	100
AD	0.5	0.189	0.063	0.0003	330	110	1.22	90	33	550	3.4E-04	1.02	50
LA	0.5	0.84	5.6	0.0003	180	60	1.22	50	3	-	-	1.02	-

By implemented the collected data of different parameters, we run the food waste network model in Lingo and obtain an optimal solution in less than 0.1 s on a computer configured with Intel Core 3.3 GHz processor and 8 GB of RAM. To compare the results, we make four different scenarios of the model. First, we make no restrictions either on the net emissions of GHG nor on the net power consumption of the system. This is achieved by relaxing constraints 9 and 10, which will show the purely economic perspective of the optimization model. Second, we employ constraint 9 that require offset of the resulted emissions by a sustainable treatment of the food waste. Lastly, the third scenario is to make the food system self-sufficient in terms of energy in addition to mitigating the resulted emissions. This is achieved by enforcing both constraints 9 and 10. 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 food waste treatment, net mitigated emissions, net energy use per ton of valorized food waste, and the food waste hierarchy impact.

Table 5. Distance from generators to potential processing sites

Site r	Distance to generators d_{gr} (mile)	Development Budget db_r ($million$ \$)
1	65.50	28.50
2	82.60	67.00
3	22.60	71.75
4	39.70	44.25

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

	Scenario 1	Scenario 2	Scenario 3
Total Cost	\$ 88,294,350.00	\$ 114,264,400.00	\$ 118,579,400.00
Food Treatment cost per ton	\$ 88.29	\$ 114.26	\$ 118.58
Fixed Cost	\$ 62,500,000.00	\$ 80,250,000.00	\$ 82,000,000.00
Fixed Cost Per ton	\$ 62.50	\$ 80.25	\$ 82.00
Transportation Cost	\$ 16,554,350.00	\$ 17,634,350.00	\$ 16,989,350.00
Transportation Cost per ton	\$ 16.55	\$ 17.63	\$ 16.99
Processing Cost	\$ 9,240,000.00	\$ 16,380,000.00	\$ 19,590,000.00
Processing Cost per ton	\$ 9.24	\$ 16.38	\$ 19.59
Food Treatment Carbon Impact	3221346.09	0.00	0.00
Food Treatment Carbon Impact per ton	3.22	0.00	0.00
Food Energy Use impact	103650974	64716872	0.00
Food Energy Use impact per ton	103.65	64.72	0.00
Food waste hierarchy impact	44.05%	80.71%	75.71%

In the case of scenario one, the treatment cost is low, but energy consumption and emissions are relatively high. The total cost per ton reads \$88.29 but emitting 3.22 $ton\, CO_2\, eq/ton$ and consuming energy equivalent to 103.65 $kwh\ /ton$. On the other hand, the treatment cost has increased to \$114.26 in scenario 2 as a result of diverting more food waste from disposal to landfill. However, this scenario achieved zero net emissions and recovery of energy that reduce energy consumption by %38. Moreover, with just a 3.8% increase in the treatment cost compared to scenario 2, scenario 3 has achieved zero net emissions and zero net energy use. However, this scenario has treated more food waste by anaerobic digestion and diverted from human use. As a result, the score for food waste hierarchy is lower than scenario 2 but higher than scenario 1. Therefore, comparing all scenarios shows that planning and designing the food waste 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 food waste characteristics and other parameters. In case of any changes to these data, the results will change accordingly. For example, if the food waste is not edible and contains a large amount of contaminates, then energy recovery treatment options are more appropriate than human use or animal feed. In this case, achieving zero net emissions and zero net energy use would be more easily and less costly.

The food waste network model is a valuable tool that policymakers, generators, and processors can use to determine the best sustainable food waste management. The model incorporates data about food waste 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 food waste separation and treatment techniques. As these techniques improve, the treatment of food waste 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 food waste 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 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. 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 food waste network model, policymakers can achieve the best sustainable strategies for food waste management.

5 Conclusion

This paper proposed a food waste network model underpinned by a multi-dimensional approach that balance between economic, environmental, and resource utilization goals. For this purpose, we formulated the problem as a linear programming model that minimizes total treatment cost given constraints imposed by different stakeholders of the sustainable food waste management system. Moreover, we derived a set of metrics that enables policymakers to move towards a more sustainable food waste management. 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 public health impact and employment rate impact. Another direction is to incorporate not only food waste but also packaging and other waste streams to the model to study the interdependency between all of them. Moreover, future research could be conducted by implementing different dataset to the model. For example, Saudi Arabia has an ambitious realization called vision 2030 that aims for economic development by diversifying income resources and empowering all sectors of the Saudi society. This model could be applied using data relevant to Saudi Arabia to develop a sustainable food waste management that contributes to the Saudi vision 2030. Finally, this research shows that there is a need to design food waste management models that address complex issues in the development of sustainable food systems.

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