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Interactions and tradeoffs for sustainability, equity, and resilience in wasted food models

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Abstract

Reducing wasted food has been identified as a key strategy to meet food security goals and attain human nutritional needs and food preferences in an equitable, sustainable, and resilient manner. Yet, mathematically modeling how reducing wasted food contributes to sustainability, equity, and resilience objectives, and the possible interactions and tradeoffs among these metrics, is limited by challenges to quantifying these characteristics. Using the process of convergent science, we develop a prototype wasted food model to evaluate how a set of common equity, sustainability, and resilience measures interact. We consider prevention (consumer education) and treatment (anaerobic digestion and composting) options for wasted food diversion from landfills. The model applies a convex nonlinear optimization to determine the allocation of wasted food to different management alternatives, optimizing for economic (net cost), sustainability (emissions reductions or energy savings), or equity (distribution of per-capita cost or emissions reduction impacts). The model developed in this research is available online as open-source code for others to replicate and build upon for future studies and analysis. Our findings illustrate that optimal wasted food management alternatives may vary when targeting different metrics and that strategies promoting cost-effectiveness may be in tension with sustainability or equity goals and vice versa. The implications of this study could be used by policy makers to evaluate how wasted food reduction measures will impact sustainability, equity, and resilience goals.

1. Introduction

Wasted food occurs when edible food that is safe and nutritious for human consumption is discarded along the entire food supply chain, from primary production to its end phase at the household consumer level (FAO 2013). Wasted food constitutes 22% of the municipal waste generated in the U.S. (U.S. EPA 2017) resulting in negative environmental and economic impacts (Muth *et al* 2019). Wasted food results in over 113 million metric tons of CO_2 emissions annually and costs the US economy about \$198 billion per year of which consumer waste accounts for \$124 billion (Venkat 2011). In addition to this, wasted food can also have an extended impact on air quality. Reducing wasted food could lower global air pollution by up to 3%, decrease anthropogenic NH_3 emissions by 16%, and reduce local $PM_{2.5}$ concentrations by up to 5 $\mu g\ m^{-3}$ (Guo *et al* 2023, Gatto and Chepeliev 2024) while also minimizing the risk of premature mortality and potentially saving 67,325 lives worldwide (Gatto and Chepeliev 2024).

Sustainable Development Goal 15 aims to halve per capita wasted food and loss which also supports other global goals related to food systems. Reducing wasted food saves environmental resources. For example, in the U.S., halving food loss and waste results in an estimated 8–10% reduction in environmental pressure (Read *et al* 2020).

The impact of wasted food on the environment is becoming even more evident as population increases, development grows, and the complexity of supply chains advances. Wasted food is now one of the world's most crucial issues (Warshawsky 2016). Wasted food is caused by multiple reasons throughout the supply chain, including over-production and over-supply product and packaging damage, handling at improper temperatures, and over-preparation (Gunders 2012). The causes of food loss and wasted food in medium/high-income countries mainly relate to consumer behavior as well as to a lack of coordination between different actors in the supply chain (FAO 2011).

There is a gap in integrated assessment when it comes to studying the socio-economic and environmental impacts of wasted food reduction (Shafiee-Jood and Cai 2016, Omolayo *et al* 2021), particularly when considering key concepts such as sustainability, equity, and resilience. The term sustainability refers to the ability to meet current needs without comprising future generations' ability to do the same (UN 1987, Tendall *et al* 2015). Equity involves ensuring fair distribution of resources and opportunities while resilience refers to a system's capacity to recover from disruptions and maintain its essential function (Bajželj *et al* 2020, Bozeman *et al* 2022). Our understanding of how reducing wasted food contributes to food system equity, sustainability, and resilience, and the possible interactions and tradeoffs among these measures is limited by data and conceptual challenges to quantifying these characteristics. First, there are empirical challenges related to the sparsity of available data, uncertainties, and inconsistencies in available data, and mismatches in political, spatial, and temporal resolution and coverage (Bozeman *et al* 2019, 2022). Typically, information is more reliable and readily available for the economic aspects of food production, transportation, and consumption, such as input prices, production, transportation costs, and consumer prices. However, information is often not available on the physical properties of wasted food, such as the quantity and quality of wasted food, and the spatio-temporal patterns of wasted food. Second, there is a wide variety of metrics and indicators for quantifying each objective of sustainability, equity, and resilience in food systems, making it difficult to compare across studies (Baker *et al* 2023). For example, sustainability can include economic, social, and/or environmental sustainability within food systems, and each of these has multiple dimensions. For example, environmental sustainability relates to nutrient, water, and carbon aspects, varying with the product, location, and time period. Third, in the context of food systems, processing, storing, transporting, and packing food for final consumption varies across production and is not standardized. Consequently, to study sustainability, resilience, and equity across systems requires manual assessment to select the study boundary and scope.

Studies have individually analyzed how the reduction of wasted food impacts various characteristics of the supply chain. Economic models analyze market responses (supply and consumption) to food loss and wasted food reductions (de Gorter *et al* 2021). The environmental impacts of reducing wasted food at each stage of the food supply chain are studied by evaluating indicators such as GHG emissions, eutrophication, and energy, water, and land use (Read *et al* 2020). Cristóbal *et al* (2018) developed a model that prioritizes wasted food prevention and management measures based on environmental impact criteria under a budget constraint. A few recent studies began to develop and apply various equity indicators to understand fair allocations of rescuing and redistributing wasted food among various emergency food organizations (Mahmoudi *et al* 2022, Rivera *et al* 2023). Although these studies examine various impacts of wasted food, they have a narrower focus on economic, environmental, and equity measures and lack analysis on other dimensions such as resilience and their tradeoffs across metrics. This study fills this knowledge gap by integrating sustainability, equity, and resilience metrics in a single quantitative framework. The model combines these metrics into a generalizable tool that can assess environmental, social, and economic impacts. Our study uses the process of convergent research to study the problem through deep integration of multiple disciplines and produce a prototype model that can have broad applicability (Ashton *et al* 2024). This study responds to the need for quantitative models that can combine multiple dimensions of sustainability, equity, and resilience, which have often been studied in isolation. Our study fills this gap by presenting a unified framework for modeling the interrelationship between these metrics in the context of wasted food reduction. Our approach overcomes the challenges associated with the diversity of metrics and indicators used to measure sustainability, equity, and resilience and overcomes the current literature gap that focuses on isolated aspects of wasted food reduction. This study integrates various objectives into a single model, enabling a more holistic assessment of the impacts of wasted food reduction and trade-offs among these objectives.

Food systems research covers sustainability, equity, and resilience, a broad range of concepts. These three measures are conceptually analyzed and integrated across the food supply chain. The first term, sustainability, is broadly defined as 'the capacity to achieve today's goals without compromising future capacity' (UN 1987, Tendall *et al* 2015). Sustainability involves advancing the well-being of people and the planet (Ramaswami *et al* 2018). It encompasses environmental impacts such as GHG emissions, eutrophication, ecological and human toxicity, land, water, and energy use (Cuéllar and Webber 2010, Kummu *et al* 2012, Klein and Whalley 2015, Sun et al 2018, Goossens et al 2019, Read et al 2020, de Gorter et al 2021, Naegler et al 2021, Larrea-Gallegos et al 2022), and socio-economic assessments (Venkat 2011, Klein and Whalley 2015, Ziolkowska 2017, Bozeman et al 2019, de Gorter et al 2021).

Assessing the sustainability effects of food waste is important due to the significant resources consumed in food production, including 20% of the national energy budget (Canning et al 2010) and 50% of freshwater withdrawals (Maupin et al 2014). Studies reveal that food loss and wasted food utilize about one-third of all resources in the U.S. food system (Birney et al 2017), resulting in the misuse of approximately 30 million acres of cropland, 4.2 trillion gallons of irrigation water, 780 million pounds of pesticides, and 1.8 billion pounds of nitrogen fertilizer. Moreover, the food supply chain contributes up to 15% of global GHG emissions (Pelletier et al 2011, FAO 2013). Food loss and waste can dramatically contribute to increased life cycle GHG emissions of food, where packaging materials and driving for shopping are important contributors (Qin and Horvath 2020). Additionally, the disposal of wasted food in landfills in the U.S. contributes to climate impacts through the emissions of carbon dioxide and methane (Bernstad and la Cour Jansen 2012, Bernstad Saraiva Schott et al 2016).

In many wasted food studies, environmental emissions impacts are considered the main sustainability measure (Usubiaga et al 2018, Goossens et al 2019, Read et al 2020, de Gorter et al 2021, Larrea-Gallegos et al 2022). Energy use is also another focus area when analyzing sustainability issues related to wasted food (Cuéllar and Webber 2010, Read et al 2020). Energy is embedded in wasted food as it is required for food's agricultural production, transportation, processing, and handling. As estimated by Cuéllar and Webber (2010), food handling, which includes food services, packaging, and residential energy consumption, is a major contributor to the total energy required for food production. The same authors estimated that wasted food in the US represented 2% of the country's energy consumption in 2017 (∼2030 trillion BTU) (Cuéllar and Webber 2010). Wasted food impacts on other resources such as freshwater, cropland, and fertilizer use are also covered (Kummu et al 2012, Sun et al 2018).

The second metric, equity, refers to social equity, in which 'power and material resources are shared so that people and communities can meet their needs, and live with security and dignity' (Allen 2010). Equity metrics are useful to measure the fairness of the distribution of resources and the environmental and socio-economic burdens across different population demographics (Bozeman et al 2022, Baker et al 2023). Equity has been measured in different social aspects. For instance, Mu et al (2023) assessed equity through various indicators that measure resource allocation and accessibility while Bozeman et al (2020) used environmental impacts (land, GHG emissions, and water impacts) resulting from food consumption by racial-ethnic groups (Black, White, and Latinx). In another study, Lee et al (2021) used residential proximity to biorefinery facilities to evaluate health risks associated with exposure to these facilities, finding that respiratory emergency department visit rates were higher among residents closer to biorefineries.

Resilience is the third metric considered in this study. This term is defined as 'the ability of the food system to withstand and to recover from shocks' (Bajželj et al 2020). Resilience can be broadly defined as the ability of a system to withstand or adapt to disturbances and to reorganize itself in ways that allow it to operate under new conditions (Tendall et al 2015). Specifically for food systems, Tendall et al (2015) define resilience as 'the capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances'. Resilience and sustainability are complementary concepts; sustainability is the measure of the system's performance, while resilience can be seen as a means to achieve it (Tendall et al 2015). In food systems, wasted food has short-term positive and negative linkages with stability, diversity, redundancy, flexibility, and adaptability of the system (e.g., through interventions that induce variability of supply and demand) and it undermines long-term resilience by aggravating ecosystem damage, (Bajželj et al 2020).

A comprehensive integration of sustainability, equity, and resilience into wasted food management models is crucial to address the multifaced impacts of various wasted food reduction alternatives. Targeting sustainability ensures long-term environmental benefits, while equity focused measures ensure fair and inclusive outcomes for all stakeholders. On the other hand, resilience emphasizes the ability of the system to adapt to shocks. By incorporating these metrics simultaneously into the decision-making process, trade-offs between environmental, social, and economic outcomes could be better analyzed. The model developed in this study achieves this by adopting flexible, quantitative modeling approaches that provide the links between these dimensions, allowing assessment of broader impacts. The model offers a generalized tool that quantifies the impacts wasted food reduction across the three dimensions.

Sustainability, equity, and resilience metrics are potentially deeply interconnected and can collectively impact the outcomes of wasted food reduction efforts. Sustainability focuses on minimizing environmental harm and resource use, equity ensures that the benefits and burdens of wasted food reduction are distributed fairly across all stakeholders, and resilience enables systems to adapt to disruptions. These dimensions may interact in complex ways as sustainability-focused approaches may unintentionally overlook social inequalities, while resilience strategies may not always account for long-term environmental goals. Understanding and managing these trade-offs, along with identifying synergies between sustainability, equity, and resilience, is crucial for developing effective, comprehensive models. This paper combines an overview of the scientific modeling literature on relevant metrics of sustainability, equity, and resilience with a quantitative approach to integrating these metrics into mathematical modeling. We show the relevance of quantitative modeling research in assessing the comprehensive impacts of wasted food reduction. Specifically, we present a set of equity, sustainability, and resilience metrics that have been adopted within food systems literature and illustrate their application and interrelationship within a prototype open-source model. We encourage the reader to refer to more formal review articles we have cited for a thorough elaboration of sustainability, equity, and resilience for wasted food. This paper is dedicated to providing a generalizable tool to measure sustainability, equity, and resilience. The study implements a unified framework and analyzes how decision-making will vary depending on the outcome variable of focus. Our goal is to provide a generalizable method to implement metrics of sustainability, equity, and resilience. We have thus not focused on detailed empirical data for wasted food, but more on generalizable functions and constraints that can be easily ported over for other models. The model provides a general assessment tool with multiple dimensions including cost, environmental, and social factors. We provide the model code implemented within a Python/Pyomo (Van Rossum and Drake 1995, Hart *et al* 2011) coding environment to serve as a resource for future work quantifying equity, sustainability, and resilience of food systems[8].

2. Methods

2.1. Prototype optimization model formulation

The prototype model developed in this paper is adopted from a techno-economic optimization model developed by Shahid and Hittinger (2021). This techno-economic model determines the most efficient allocation of commercial wasted food and manure across various waste treatment facilities, with the objective of minimizing system cost. Furthermore, the framework integrates economic and emissions assessment models for analyzing cost, energy generation potential, and emissions offsetting capacities.

The prototype model applies an optimization technique aimed at preventing wasted food through consumer education and allocation of wasted food to two types of management facilities: anaerobic digestion and composting (figure 1). Anaerobic digestion and composting are two common methods used for treating organic waste, including wasted food. Consumer education involves implementing wasted food reduction strategies through campaigns designed to raise public awareness. The model determines the optimal allocation of wasted food across different counties by targeting various decision criteria, namely economic, sustainability, and equity. The model balances the distribution of wasted food between education, anaerobic digestion, and composting facilities by considering regional variations in wasted food generation rates, transportation distance, and specific decision objectives. The framework derived the most effective distribution strategy based on minimizing cost, reducing environmental and energy use impacts, and equity promotion. In this study, we considered a baseline scenario in which 97% of the wasted food is directed to the landfill, with 3% diverted to composting (Industrial Economics, Incorporated 2017). This distribution reflects the predominant trend of wasted food being sent to landfills. The different measures applied to prevent and allocate wasted food to the treatment facilities are discussed in the following sections. Note that we have used generic functions for our prototype models allowing future researchers to substitute more relevant functions and data for their studies.

The generic representation of this prototype model was formulated to manage wasted food in three counties, Montgomery, Prince George's, and Baltimore counties, in state of Maryland. The corresponding volume of wasted food generated in each county and demographic characteristics is given in table 1 and table 2. County A generates the highest amount of wasted food, followed by County C and County B, reflecting distinct levels of consumption patterns, behaviors, and number of residents across these regions. The concept of population sub-groups is integrated within this framework to represent unique demographic profiles within each county (Bozeman *et al* 2020). These characteristics may include a diverse array of factors such as race, educational attainment, income levels, and socio-economic status. This disaggregation of population data is important to facilitate the analysis and evaluation of both the costs associated with managing wasted food and the potential impact of wasted food reduction initiatives across various sub-groups. By incorporating population sub-groups with different income levels, this model enables a high-level examination of how different segments of the population contribute to, and are affected by, wasted food management decisions.

2.1.1. Economic measures

Economic analysis is the first criterion examined to design the wasted food management system. The economic metric measures the cost-effectiveness of setting up prevention and treatment facilities in different counties.

[8] The code for the prototype model is available on: https://github.com/wastedfoodnsf/RECIPES/blob/main/Modeling_metrics_prototype_model.ipynb

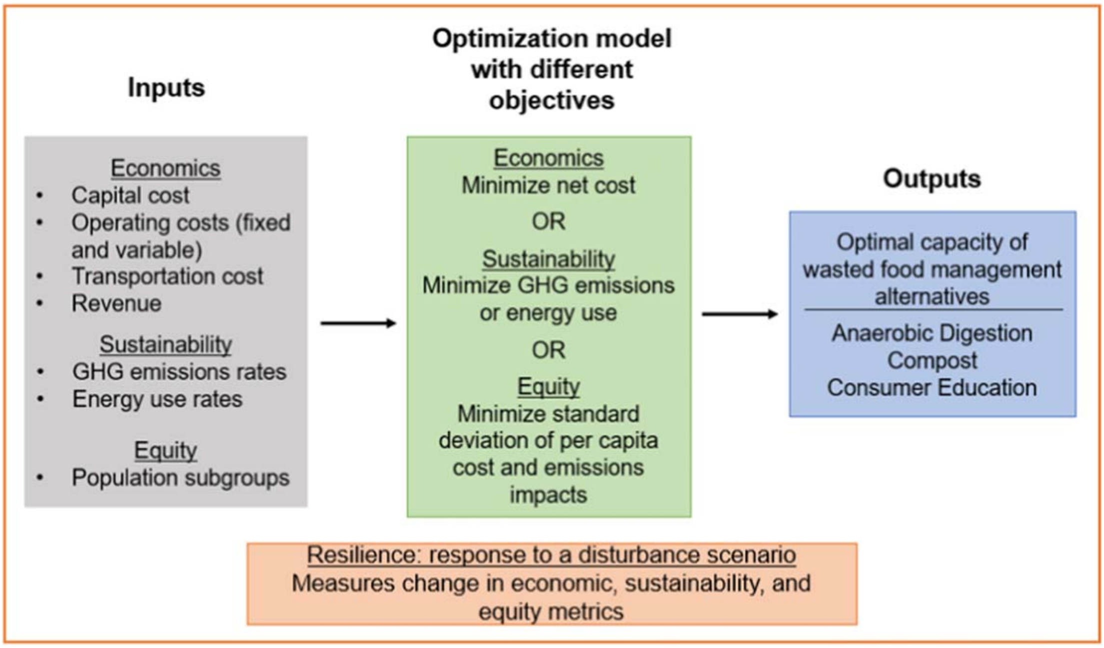

Figure 1. Optimization model that integrates sustainability, equity, and resilience measures to assess the impacts of wasted food management.

Table 1. Demographic characteristics of the three counties across various income levels. Share of wasted food represents the ratio of calories wasted to calories available (Lopez Barrera and Hertel 2021).

Counties	Total Population, millions	Population, %		
		Low income	Medium income	High income
Montgomery county - County A	1.06	18.2	51.8	30
Prince George's county - County B	0.967	22.9	60.6	16.5
Baltimore county - County C	0.854	27	59	14
Share of wasted food		0.08	0.19	0.31

Table 2. Amount of wasted food and hauling distance in the three counties.

	County A	County B	County C
Wasted food, ton/year	5,000	2,000	3,000
Hauling distance, miles	30	15	20

Economic costs are generated or avoided as a result of food sent to landfills, waste management (anaerobic digestion and food composting), and waste prevention (Martinez-Sanchez *et al* 2015, De Menna *et al* 2018). The economic assessment involves examining various cost and revenue components that are listed below. Costs are in U.S. dollars.

Capital costs: The capital cost function consists of linear and nonlinear components. The linear element for anaerobic digestion and compost facilities is adapted from the original model. The cost coefficient for consumer education is an estimate from ReFED. This paper suggests that consumer education campaigns could divert approximately 585 ktons of wasted food per year at a cost of $22 million annually (ReFED 2016). In this study, we add a nonlinear term to account for increasing marginal costs with capacity (equations (1)–(3)).

$$Capital\ cost_{i,\text{anaerobic digestion}} = 603x_i + \frac{1}{2}{x_i}^2 \tag{1}$$

$$Capital\ cost_{i,Compost} = 91x_i + \frac{1}{2}{x_i}^2 \tag{2}$$

Table 3. Indices and parameter values used in the prototype model. Costs and revenue rates are obtained from Shahid and Hittinger (2021).

x	Amount of wasted food, ton/year
i	County
j	Wasted food management alternative
k	Population subgroup
Transportation cost	\$0.25/ton-mile
Fixed cost rate	5%
Variable cost rate	0.55 c kWh^{-1} (anaerobic digestion) and \$20/ton (compost)
Revenue	5.5 c kWh^{-1} (anaerobic digestion) and \$35/ton (compost)

$$Capital\ cost_{i,Education} = 38x_i + x_i^2 \tag{3}$$

where x_i is the amount of wasted food in county i as shown in table 2.

Operating and maintenance costs (O&M): O&M costs constitute fixed and variable costs. For both anaerobic digestion and compost systems, fixed cost is assumed to be 5% of the total capital cost. Variable costs are 0.55 c kWh^{-1} and \$20/ton for anaerobic digestion and compost, respectively.

Transportation costs: The transportation cost assumes a rate of \$0.25/ton-mile in all three counties, accounting for wasted food and transportation distance. In this study, we consider a transportation distance of 30, 15, and 20 miles for Counties A, B, and C, respectively.

Revenue: Wasted food management activities such as anaerobic digestion or composting can generate revenue through by-product sales such as electricity, compost, or fertilizer. In this study, income is generated through electricity sales or compost sales for anaerobic digestion and composting facilities, respectively. We use a revenue factor of 5.5 c kWh^{-1} for anaerobic digestion and \$35/ton for composting.

Net cost: The economic metric is measured using net cost which is the aggregate of all cost components less the revenue in all three counties. The model determines the optimal wasted food allocation to different treatment alternatives with the goal of minimizing the *Net Cost* (equation 4).

$$Min.Net\ Cost = \sum_{i,j}(Capital\ cost_{i,j} + O\,\&\,Mcost_{i,j} + Transportation\quad cost_{i,j} - Revenue_{i,j}) \tag{4}$$

where i is the index of counties and j is the index of wasted food management alternative.

2.1.2. Sustainability measures

In this study, we consider sustainability metrics that are associated with environmental impacts and resource utilization intensity. Sustainability is measured through GHG emissions (Mt CO_2 eq/ton of wasted food) (Kim *et al* 2011, Venkat 2011, Usubiaga *et al* 2018) and energy use rates (million Btu/ton of wasted food) (Cuéllar and Webber 2010).

GHG Emissions: The emissions reduction potential of the various wasted food management alternatives is measured using the EPA WARM model (U.S. EPA 2016). This model quantifies climate change impacts using life cycle assessment and provides factors that reflect the offsets in response to the applied waste management decision. Total emissions are estimated in reference to a baseline scenario in which 97% of the wasted food is directed to the landfill and 3% to composting. The GHG emission rates (Mt CO_2eq/ton) used in the prototype model are given in table 3, where negative signs indicate emissions avoided. In our analysis, food waste prevention through consumer education campaigns was considered as a form of source reduction, aligning with the practice outlined in the EPA WARM tool. Although the WARM tool does not provide specific quantification for consumer education, the broader impact of reducing food demand is recognized as part of source reduction.

Energy Use: The amount of energy used or avoided when employing an alternative is estimated using the EPA WARM model (U.S. EPA 2016). The energy use factors (million Btu/ton) used in the prototype model are shown in table 4. Like the GHG emissions, the net energy use is compared with the reference baseline scenario.

The optimal wasted food allocation targeting the sustainability metrics is determined by solving the following two objectives respectively. For complete formulations, please refer to the Supplemental Information.

$$Min.Net\ emissions = \sum_{i,j} Baseline\ emissions_{i,j} - \sum_{i,j} Emissions\ avoided_{i,j} \tag{5}$$

$$Min.Net\ energy = \sum_{i,j} Baseline\ energy\ use_{i,j} - \sum_{i,j} Energy\ savings_{i,j} \tag{6}$$

Table 4. Emissions and energy use rates (U.S. EPA 2016), negative signs represent avoided emissions and energy savings.

	Anaerobic digestion	Composting	Education	Landfill
Emissions rate (Mt CO_2eq/ton)	−0.09	−0.12	−3.66	0.5
Energy use (million Btu/ton)	−0.36	0.73	−14.5	0

2.1.3. Equity measures

In this study, we use per-capita measures to normalize the GHG emissions reductions and government spending associated with wasted food management alternatives across three income levels: low, medium, and high (table 1). To account for the variability in wasted food generation patterns among households with different income levels, we factored in Share of Wasted Food (SWF) parameter, which represents the ratio of calories wasted to calories available (Lopez Barrera and Hertel 2021). This normalization allows us to determine how GHG emission reductions and government spending (cost) associated with implementing alternative management strategies are spread out across different demographic profiles.

$$Per\ capita\ GHG\ emissions\ reduction_{i,k} = \frac{GHG\ emissions\ reduction_i\ *\ SWF_k}{Income\ subgroup\ population_{i,k}} \quad (7)$$

$$Per\ capita\ cost_{i,k} = \frac{Total\ cost_i\ *\ SWF_k}{Income\ subgroup\ population_{i,k}} \quad (8)$$

for county i and income sub-group k.

Based on the per-capita values, optimization objectives are then chosen to analyze the wasted food models targeting equity. These problems are set up in the model with the goal of minimizing the standard deviation or distribution bias of the per-capita GHG emission reduction impacts and per-capita costs across the three population subgroups in three counties (Mu *et al* 2023).

2.1.4. Resilience

In this study, we simulate a scenario where all treatment facilities (anaerobic digestion and compost) in a specific location (County B) stop functioning, in which case wasted food is directed to the neighboring counties (Counties A and C). The model assesses the response to this disturbance (figure 2). The model assesses the

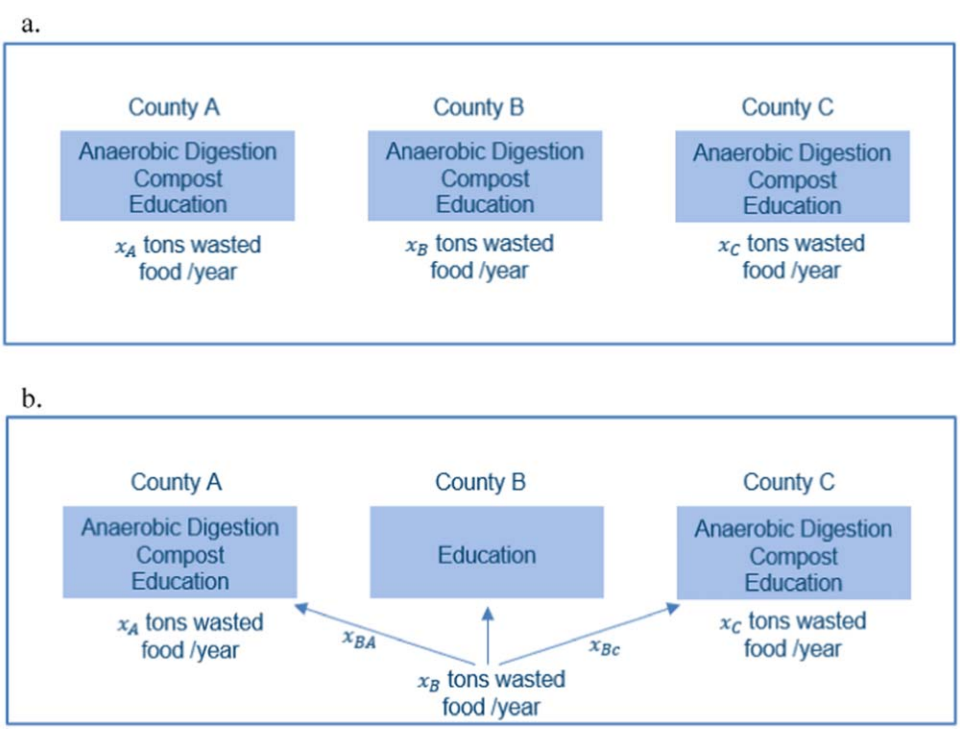

Figure 2. The prototype model considers three counties and various wasted food management alternatives: anaerobic digestion, compost, and consumer education. Model setup under normal operation (a). Model setup under resilience scenario that diverts portions of wasted food from County B to County A and County C due to disruptions in treatment facilities in County B (b).

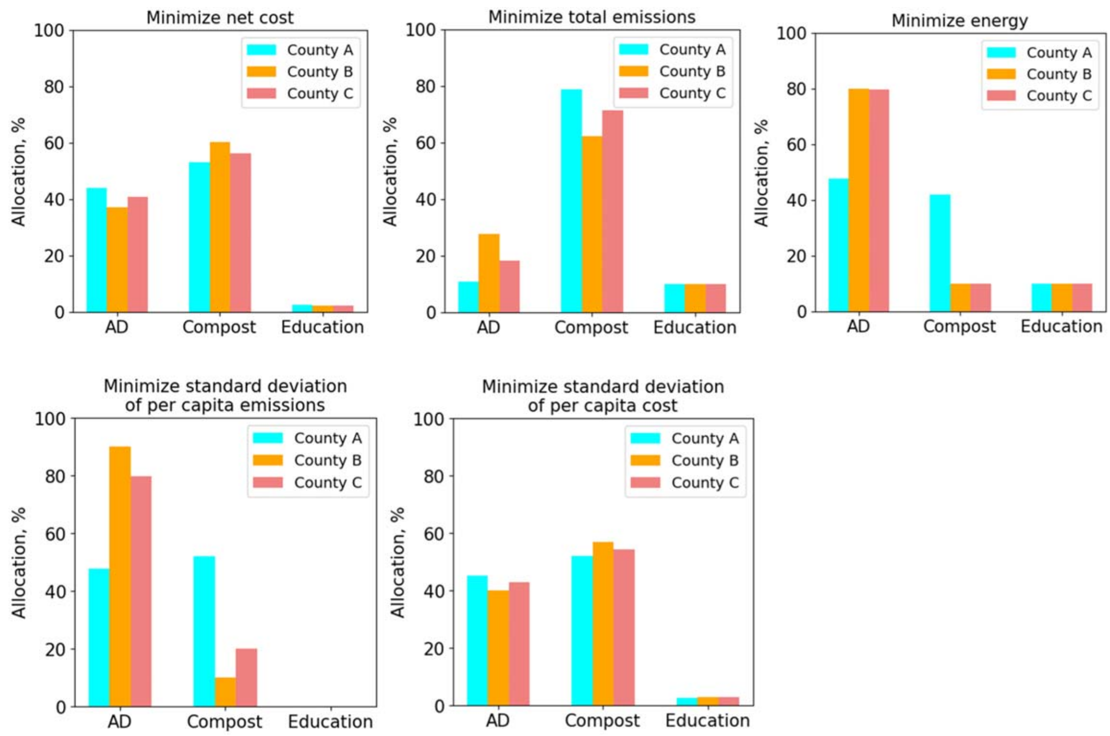

Figure 3. Variation in wasted food allocation across three wasted food management alternatives (i.e., anaerobic digestion (AD), compost, and education) in three counties. In each case, the model targets to optimize different economic, sustainability, and equity measures. More wasted food is directed to composting over anaerobic digestion facilities when minimizing GHG emissions while anaerobic digestion facilities are favored for minimizing energy use.

response to this disturbance. Resilience is measured through the change in GHG emissions, energy use, and costs after a disturbance scenario compared to before the disturbance. This metric provides insight into how the overall systems in the three counties adapt to a disturbance while maintaining the functionality of wasted food management. Resilience was measured by quantifying the changes in operating characteristics before the treatment facilities return to standard operation.

3. Results

The results of this study aim to capture the broader aspects for the quantitative analysis of wasted food management models and impacts on sustainability, equity, and resilience measures. Our model implements consumer education and sets up treatment facilities in three counties to prevent wasted food from going to landfills. The model results examine the effectiveness of wasted food interventions, focusing not only on economic aspects but also on promoting sustainability, equity, and resilience.

3.1. Optimal wasted food allocation

Minimizing net costs results in a slightly larger portion of wasted food channeled towards compost compared to anaerobic digestion facilities (figure 3). However, in minimizing emissions and energy use scenarios, the allocation of wasted food is based on the potential of the facility to reduce GHG emissions and energy consumption rates. Our findings illustrate that composting facilities have a greater capacity to offset GHG emissions compared to anaerobic digestion facilities (0.12 Mt GHG eq/ton versus 0.09 Mt GHG eq/ton). As a result, minimizing emissions results in 60% to 80% of the wasted food being processed through composting. On the other hand, anaerobic digesters exhibit lower energy consumption than composting processes, leading to a higher proportion of wasted food being managed through anaerobic digestion when the objective is to minimize energy use.

When seeking alternatives to minimize variation in per-capita GHG emissions and costs, we examined three income levels (low, medium, and high) to represent different demographic profiles. The model aiming to minimize variations in per-capita GHG emissions prioritizes the construction of larger-capacity anaerobic digestion facilities in counties with lower levels of wasted food and directs a higher ratio of wasted food to compost facilities in counties with high amounts of wasted food. This approach aims to leverage the high emissions offset capability of compost facilities to counterbalance emissions avoided in counties with lower

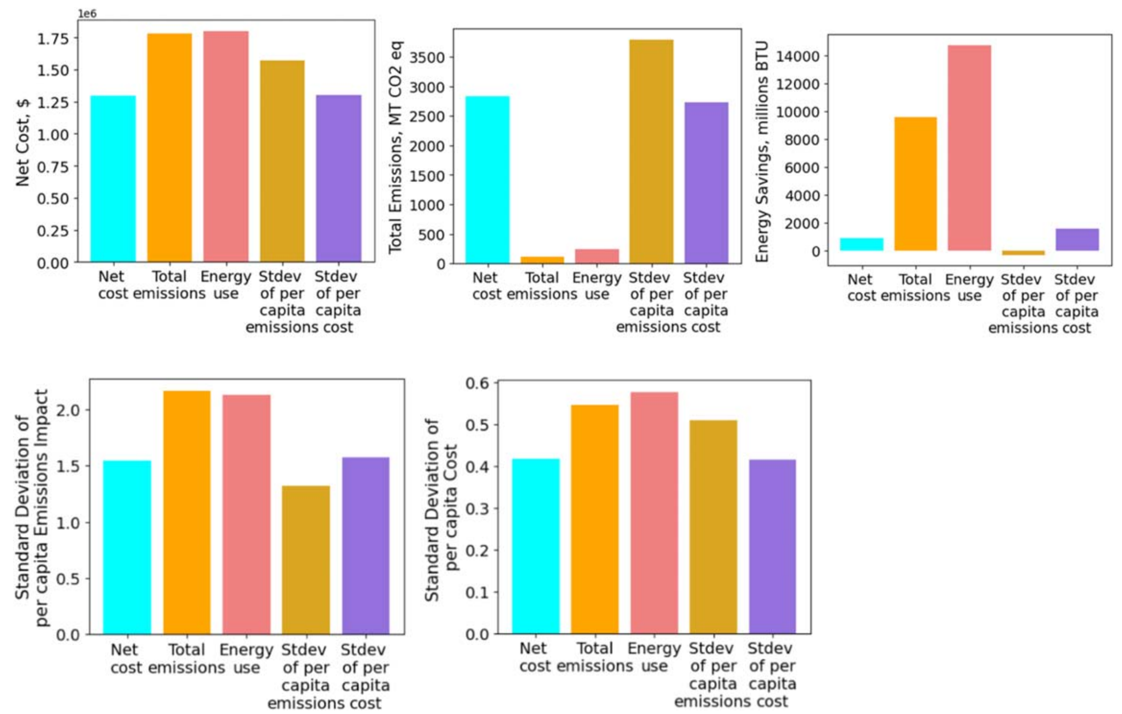

Figure 4. Variation in net cost, sustainability, and equity measures (y-axis) for different optimization objectives (x-axis: minimizing net cost, total emissions, energy use, standard deviation (stdev) of per capita emissions or stdev of per capita cost). The results show the tradeoffs among measures. Cost-efficient measures may result in the highest emissions and have the lowest energy saving potential. Alternatives that promote emissions and energy use reduction may not have equitable outcomes.

wasted food volumes. In contrast, the equitable distribution of costs favors a relatively balanced allocation to compost and anaerobic digestion facilities. However, it is worth noting that in all scenarios, only a small percentage of wasted food (less than 10%) is prevented through educational initiatives. This limitation is due to the model constraining the amount of wasted food managed through education-based interventions.

3.2. Variations in economic, sustainability, and equity measures

The second set of results compares how each metric varies under different sets of optimization objectives (figure 4). The cost-effective alternative (net cost of $1.3 million) is determined when minimizing net cost. When optimizing sustainability, the net cost increases by about 37%. The equity metrics aiming at minimizing the variation of per-capita cost impact results in a cost estimate similar to the cost-optimal case, while the objective targeting equitable emissions reductions would increase the net cost by 21%.

Optimizing for sustainability results in lower emissions, 120 Mt CO_2eq (minimize emissions) and 240 Mt CO_2eq (minimize energy use), while the other objectives yield much higher emissions ranging from 2700 Mt CO_2eq to 3800 Mt CO_2eq. The goals aimed at cost minimization and equitable emissions impact distribution show the least potential for energy saving. Energy savings could increase by up to 1500% when optimizing energy-saving objectives. Additionally, our analysis reveals that sustainability targets, while effective in emissions reduction, may not necessarily align with objectives of equitable per capita emissions impact distribution. This suggests the need for nuanced approaches to examine and address both environmental and social considerations. Moreover, as sustainability targets allocate a relatively higher portion allocation to education when compared with other measures, they exhibit higher emissions reduction and energy savings potential.

3.3. Changes in cost, sustainability, and equity measures for a resilience scenario

The resilience metrics represent variations in economic, sustainability, and equity indicators in response to a disturbance scenario. This scenario assumes that treatment facilities in one county stop functioning, leading to the transportation of wasted food from that county to others for processing. These metrics assess the effectiveness of this distribution strategy in achieving various objectives.

Resilience of the wasted food management alternative is measured as a change in values of the metrics after a disturbance scenario. The scenario considers an operational disturbance in anaerobic digestion and compost treatment facilities in County B, requiring the transportation of wasted food from this county to Counties A and C. The results of this scenario are shown in figure 5. We observe that net cost increases by 15% to 35% from the baseline case in all optimization alternatives except the minimizing energy use case. The total emissions do not

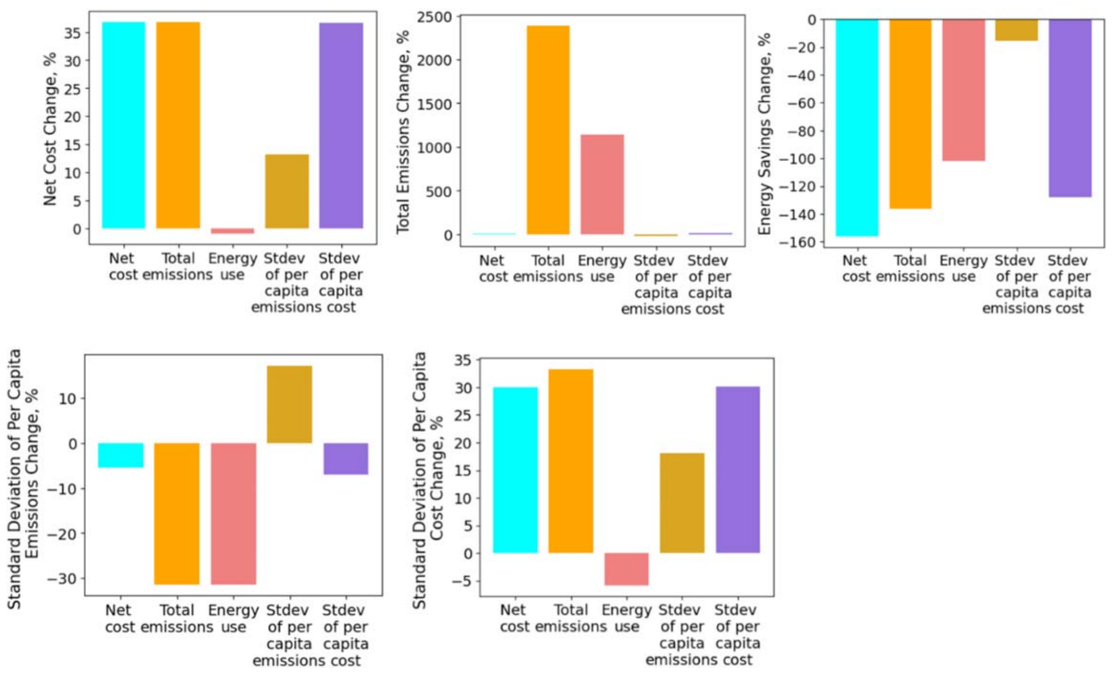

Figure 5. Resilience is measured as a change in economic, sustainability, and equity metrics after a disturbance scenario is introduced in the system. The *x*-axis shows the different objectives, and the *y*-axis shows the change in the respective measures. The response to the disturbance scenario would increase the net cost in almost all optimization cases. Total emissions after disturbance remain relatively the same when optimizing for net cost and equity but increase when targeting sustainability.

change for the resilient system when optimizing for net cost or equity but would increase by more than 1000% when optimizing for sustainability. The results also show that if wasted food is directed from County B to the other counties, energy-saving potential would decline in all cases. The results are not consistently conclusive when optimizing for equity. The findings suggest that equity measures exhibit improvement following the resilience scenario, indicating areas for enhancing the analysis of equity measures and optimizing them.

Overall, the results above show that there are tradeoffs across the different measures. The sustainability approach with minimizing emissions objective results in significant emissions reduction but incurs a higher net cost. Under the sustainability metrics, when opting for minimizing energy use, the choice leads to lower energy consumption, but higher emissions and costs compared to the emissions-minimization strategy. Equity measures strive for a balanced per-capita cost and emissions reductions impact but may not align with sustainability and cost effective goals as they often lead to higher emissions and increased net cost.

4. Discussion

This paper overviews sustainability, equity, and resilience metrics for food waste reduction and develops a prototype model to integrate these metrics into wasted food models. The model simulates the interactions and tradeoffs between the three components within a single framework.

Although the problem formulation in our model considers only three counties, future work could apply the model to study waste management alternatives across diverse regional contexts. This requires using subnational state or county-level data and wasted food estimates in these regions. This work lays the foundation for incorporating sustainability, equity, and resilience measures within the decision-making framework in wasted food research. Building on our approach, future studies could include additional measures for sustainability (*e.g.*, water, cropland, and fertilizer use). The equity measures applied in this study specify a generic income profile. Additional research is needed to include other socio-demographic indicators such as race and education by combining statistical analysis with wasted food generation and disposal behaviors.

The results of our study highlight the importance of designing wasted food management alternatives by considering the tradeoffs across multiple objective dimensions. The conventional cost-effective approach may not imply a sustainable or equitable outcome. This result aligns with existing literature that demonstrates the trade-off between cost-effectiveness and equity in policy design (Goulder and Parry 2008). Sustainability efforts prioritize emissions reductions and energy savings but often come with higher costs. Equity focused strategies aim for fair distribution of costs and emissions reduction impacts but may not be as effective in sustainability outcomes. Resilience scenarios reveal that disruptions can increase costs and affect energy saving potential differently, highlighting the need for balanced approaches that consider operational reliability, cost, emissions, and energy efficiency. This study implies that intervention policies would benefit from examining tradeoffs not only from cost and benefits perspective but also when targeting various sustainability and equity objectives. These outcomes align with findings in other studies that examine the importance of addressing tradeoffs in policy interventions to reduce wasted food and loss (Cattaneo *et al* 2021). Studies have also examined the efficiency of various wasted food management alternatives using life-cycle cost and environmental impacts (Thyberg and Tonjes 2017, Edwards *et al* 2018) and showed to demonstrate the tradeoff between immediate cost savings and long-term environmental performance, highlighting the need for a more holistic approach. The integration of cost, sustainability, environmental, and equity factors suggest the most effective strategies for wasted food management are not only those that focus solely on one dimension but also those that find an equilibrium across all objectives. This shows the need for more multidimensional approach, as indicated in (Parsa *et al* 2024), that considered system thinking approach to wasted food management that incorporates trade-offs between economic, environmental, and social dimensions.

The prototype model considers a single prevention approach, consumer education, and two wasted food diversion technologies, AD and composting. Further research is necessary to examine the impacts of other solutions, such as efficient packaging, improved date labeling, and application to animal feed. Additionally, the model can be modified to include recovery solutions like rescue and donation that have been studied qualitatively (Mariam *et al* 2020). This study could also be integrated into other food system models to develop an improved food system modeling approach toward policy recommendations. The prototype model could be a valuable tool for quantifying and endogenizing sustainability, equity, and resilience metrics in decisions.

While this study lays the groundwork for integrating sustainability, equity, and resilience metrics into wasted food models, it is important to acknowledge its limitations. We have focused on a select few indicators for these metrics, but it is worth noting that sustainability measures could also include impacts on resource utilization such as land, water, and fertilizer. Similarly, equity metrics may extend to encompass various socio-demographic attributes, including racial backgrounds. The cost and revenue analysis do not incorporate government incentives and fees. Furthermore, while our study considers disposal emissions, we recognize the importance of including other emissions components such as those from production, packaging, and distribution. Additionally, the resilience scenario in our study does not account for the time factor and a return to the initial condition.

5. Conclusions

Reducing wasted food is considered a critical strategy to meet food security goals in an equitable, sustainable, and resilient manner. Studies have conceptually analyzed and identified qualitative components of these metrics, but there is a considerable gap in quantitative analysis. This study provides the initial steps to integrate these metrics into wasted food models and systematically analyze impacts from multiple perspectives. Average data are used throughout. The article concludes that optimal wasted food management alternatives may vary when targeting different metrics and that strategies promoting cost-effectiveness may be in tension with sustainability or equity goals and vice versa. By quantifying and highlighting the tradeoffs among sustainability, equity, and resilience metrics within a unified wasted food management framework, this research sheds light on the complex dynamics of wasted food mitigation and various objectives. The optimal choice to build or expand the capacity of treatment facilities and preventive measures for handling wasted food depends on the specific metrics being targeted. With equity metrics, our study illuminates the pivotal role of accounting for equity in the decision-making. This theoretical work provides a foundation for application to case studies that draw on empirical data and highlights the importance of taking a systems approach to meeting sustainability, equity and resilience goals when reducing food waste.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/wastedfoodnsf/RECIPES/blob/main/Modeling_metrics_prototype_model.ipynb.

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