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A circular food supply chain network model to reduce food waste

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Abstract

Food loss and waste (FLW) is a growing global problem throughout the world. The rapid increase in food waste and deficiencies in treatment processes have led to greater harm to the environment. A circular food supply chain (FSC) is now an essential means of encouraging circular economy. Proper food waste treatment and recycling operations can not only benefit the environment, but these wastes can also be used as raw material for production in a circular economy. In this study, a circular food supply chain network model is designed to reduce the food waste generated in the circular food supply chain systems of municipalities. Then, a mixed-integer linear programming model is generated to model the proposed circular food supply chain network model. The MILP model is a network model aimed at reducing the food waste generated. To do so, two objectives are considered: the overall cost of the network is minimized and the amount of distributed food waste from the generation nodes to the end nodes is maximized. Due to the bi-objective nature of the proposed mathematical model, the Improved Augmented Epsilon Constraint method (AUGMECON2) is implemented to solve the problem optimally. To illustrate the applicability and effectiveness of the proposed mathematical model, two real-life case studies were carried out in Izmir, the third largest city in Turkey. The computational results demonstrate that the proposed model is beneficial for both small and large municipalities since it provides the Pareto-optimal set where the total amount of distributed food waste is maximized and the total cost is minimized.

Keywords Food supply chain · Food waste · Circular economy · Network model · Mixed-integer linear programming · Bi-objective optimization

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1 Introduction

The rapid increase in population and demand for food increases food production as well as food loss and waste in the world. According to the report FAO (2011), approximately 1.3 billion tons of food is wasted every year. This represents one-third of the food produced; food waste has now become a problem throughout the world (FAO, 2011). Moreover, the food waste generated by the increase of people's demands and the uncontrolled use of resources worldwide causes damage to the environment (Ju et al., 2017; Thyberg & Tonjes, 2016). Food waste is categorized as either avoidable (e.g., slices of bread or meat) or unavoidable (Hansen, 2019; Shaw et al., 2018). While unavoidable food waste is disposed of at landfill sites, it can enter the circular economy through animal feed and composting. (Derqui et al., 2020; Mogale, Cheikhrouhou, et al., 2020). For this reason, considering food waste in line with circular economy principles is an extremely important issue to cope with the challenges of food waste management (Gao et al., 2017). Food waste management is extremely important in terms of the timely distribution of food waste (Jouzdani & Govindan, 2021). When problems such as distribution and collection in food waste management are overcome, an increase in edible foods is the inevitable result; this contributes to a more circular economy (Mogale, Cheikhrouhou, et al., 2020).

Circular economy is a new production model based on sustainability and innovation that ensures recycling of produced waste, minimizing raw material costs while maximizing both resource efficiency and environmental benefits (Fragoso & Figueira, 2021; Jurgilevich et al., 2016). A circular economy provides solutions to move to a sustainable food system and aims to evaluate wasted food and its many products such as plastics, bottles, napkins and oil by reusing, recycling, or transforming into energy such as biodiesel (Martin-Rios et al., 2018).

From the point of view of the municipalities, food waste circulation requires the collection, operation and distribution of food and food-related waste (Sulis et al., 2021). The work involves sending non-edible preparation food wastes, non-edible serving wastes and oil wastes to food treatment and recycling facilities (Unuofin et al., 2021); sending edible serving wastes to food banks (Mandal et al., 2021), sending food wastes left on plates to animal shelters and sending other wastes such as bottles, napkins or paper to third-party recycling centers. This requires a well-organized network model (Nicastro & Carillo, 2021). Therefore, an effective network model is needed to operate a circular food supply chain in a circular economy with the help of computational logistics models.

Computational logistics models, such as mixed-integer linear programming (MILP), are used to solve large-scale problems that may arise; they can achieve high efficiency, improved transportation efficiency and high resource utilization (Koh et al., 2013; Sahebjamnia et al., 2020). Moreover, proper application of computational logistics such as MILP in waste management can facilitate the reduction of waste in the food and beverage industry, the maximization of resource efficiency and produce sustainable results within the framework of the circular economy (Bieber et al., 2018). The MILP model is an appropriate model to minimize cost in network models (Entrup et al., 2007). Therefore, our aim is to create a supply chain network model for food waste using a MILP model; this can reduce the waste of food, oil, plastic and paper in the food industry and contribute them to the circular economy.

As a result, the research questions of the study can be summarized as;

- **RQ1:** What kind of network should be proposed based on circular economy to recycle/reuse the food waste of non-profit organizations and local governments?
- **RQ2:** How can we optimize two objectives with limited resources with the proposed network model in the circular food supply chain?

With regard to the problems in circular food supply chains, to propose a network model based on circular economy to recycle/reuse the food waste for non-profit organizations and local governments and to optimize two objectives with limited resources with the proposed network model in the circular food supply chain, four research objectives are listed below;

- To design a food supply chain network covering all stakeholders in line with the system approach
- To integrate circular economy principles with the proposed network model to reduce/recycle the food waste
- To generate a mathematical model for the proposed food supply chain network model
- To implement the generated mathematical model in real-life examples

A detailed literature review regarding circular food supply chain networks and food waste management was conducted to arrive at possible answers to these research questions. Based on the information obtained from the literature review, a circular food supply chain network model was designed aimed at reducing the food waste generated in the circular food supply chain systems of municipalities. Then, a MILP formulation was generated based on the operations research perspective to mathematically model the proposed circular food supply chain network model. To show the effectiveness and advantages of the proposed network model and mathematical model, and to implement them in real life, two case studies were conducted. The Improved Augmented ε-Constraint (AUGMECON2) method of Mavrotas and Florios (2013) was implemented to optimize two objective functions: (i) maximization of the distributed food waste and (ii) minimization of the total cost of the network. This study is unique in two aspects: (1) this is the first study where a circular food supply chain network model has been suggested for the treatment of food waste to the best of our knowledge and (2) the proposed model is a bi-objective model aimed at maximizing the distributed food waste within the supply chain while minimizing the total cost of the network simultaneously. The theoretical contributions of the study are then put into practice in two real-life cases.

The remainder of the paper is structured as follows. Section 2 presents the literature review regarding the circular food supply chain network model. Section 3 gives the problem definition, including a detailed explanation of the proposed circular food supply chain network model and the generated MILP model. The solution methodology is explained in Sect. 4. Section 5 covers two real-life case studies in Bornova and Izmir, Turkey, as an implementation of the study. Section 6 discusses the theoretical and practical implications for managers and policymakers. The conclusion and suggestions for future work are presented in Sect. 7.

2 Literature review

The literature review consists of an examination of circular food supply chains, mathematical models to reduce food waste in food supply chains and discussions about these studies. First of all, the circular food supply chain is explained in detail.

2.1 Circular food supply chain

Food waste is a growing and worrying problem; the increase in food waste causes both economic losses and global warming all over the world (Melikoglu et al., 2013; Validi et al., 2014). There is real concern over the pollution caused by food wastes and the reduction of natural resources (Dora et al., 2020). Because of economic and social damage, effective management of food waste is one of the issues that is gaining importance all over the world for the continuation of sustainable development (Storup et al., 2016; Vizzoto et al., 2020).

To prevent natural resources from becoming exhausted, the most basic rule in nature, the substance flow cycle, must be operated in a balanced manner by circular economy principles (FAO, 2013; Mogale, Krishna Kumar, et al., 2020). It is extremely important to reuse, recycle and obtain raw materials from wastes in a circular economy approach (Bottani et al., 2019; Fancello et al., 2017). The circular economy is a model in which wastes are recycled in a holistic process, enabling reuse of waste and raw materials, plus efficient use of energy and all resources with a zero-waste approach (Rizos et al., 2017). With the circular economy approach, everything that was previously considered as waste becomes a resource. Therefore, it is beneficial to adopt circular economy principles, especially for the treatment of food waste. A circular economy provides recycling of food wastes as raw materials; biodiesel can also be produced with recycling; such a system generates a closed-loop following circular economy principles (Ribul et al., 2021). However, in addition to the inclusion of waste in the circular economy, it is extremely important to ensure circularity in the entire food supply chain process (Lavelli, 2021). In other words, the classification of food and food-related wastes as well as sending them to the appropriate facilities are vital; these are important steps in food supply chain networks from the perspective of the circular economy.

After considering the relevant literature, one of the most crucial things observed for the reduction of food waste is to have a circular food supply chain network model (Farooque et al., 2019; Van Engeland et al., 2020). Circular food supply chain network models enable waste to be evaluated and the amount of waste generated to be reduced (Jouzdani & Govindan, 2021). Circular food supply chain network models contribute to a zero-waste approach (Baratsas et al., 2021); this is in stark contrast to waste being sent to landfills, as seen in linear food supply chain network models (Despoudi et al., 2021).

In circular food supply chains, it is necessary to ensure circularity at every stage of the supply chain (Kazancoglu et al., 2021). In this way, the generation of food waste is minimized (Batista et al., 2021), with a minimum amount of waste left over at the end of the supply chain (Farooque et al., 2019). A well-planned circular food supply chain network model provides operational excellence in the process and contributes to the zero waste approach (Fakhrzad & Goodarzian, 2021; Nasir et al., 2017), the main principle of the circular economy. In addition, the network model in the circular food supply chain also provides environmental sustainability by transforming the waste generated into raw materials (Jouzdani & Govindan, 2021).

To sum up, the generation of food waste is increasing rapidly worldwide (Fakhrzad & Goodarzian, 2021). As an example, in Europe, annually, approximately 88 million tonnes of food is wasted (Scalvedi & Rossi, 2021) and in the USA, 30% of all produced food is wasted (Pitchford, 2021). It is extremely important to manage these wastes in the framework of a circular economy. The review of the current literature highlights some interesting studies on reverse logistics in the circular food supply chain. The reverse flow of food requires more complicated analysis compared to forward flow as stated in the study of Kim et al. (2014). Bottani et al. (2018) provided a routing and location model to discover various ways to recover packaged food waste, generated at the retail stage of a food supply chain, instead of disposing of the waste in landfill sites. This research has also been applied in a case study in the Emilia-Romagna region of Italy. Wen et al. (2018) proposed an IoT-based food network for restaurant food waste. Their work covers the design, implementation and evaluation of IoT-based networks for a case study in Suzhou, China, where it considers generation, collection, transportation and final disposal of restaurant food waste.

In the following section, studies on mathematical models to reduce food waste in food supply chains are discussed.

2.2 Studies on mathematical models to reduce food waste in food supply chains

In a comprehensive analysis of FLW in food supply chains, Luo et al. (2021) proposed a conceptual framework from an operational management perspective. Luo et al. (2021) have made various contributions in this field. Firstly, they explained the impacts of food loss and waste regarding social, economic and environmental aspects; they provided a research potential to reduce these impacts. Next, they categorized the stages of the food supply chain in which food loss and waste can be encountered. According to their categorization, food loss and waste can be seen in *(i) production, (ii) post-harvest handling and storage, (iii) processing, (iv) distribution and market and (v) consumption* stages of the food supply chain. Then, they also categorized solution methodologies to analyze food loss and waste. Qualitative research, empirical analysis, life cycle assessment, deterministic optimization, stochastic programming, robust optimization as well as simulation were all employed for their analysis. Based on their examination of the solution methodologies, food loss and waste management from the operational management perspective are seen as a research gap to be studied in greater depth to model real-life food waste problems.

Recently, several studies showed that the food waste that occurred in FSC can be better treated with circular economy approaches in various industries. For example, Principato et al. (2019) performed a study on food waste treatment in pasta production based on a circular economy. The study describes the life cycle of pasta production providing options for the food generated at each phase of production from the circular economy perspective. For example, they illustrated that the food waste that occurred in the production phase of the pasta can often be reused—giving them to food banks, using them as animal feeds, or composting them. They also indicated the need for further research in the field of treatment of food waste generated at the consumption level of the pasta supply chain. As another example, Secondi et al. (2019) aimed to minimize the tomato sauce food waste that is generated from cultivation to retail by quantification of FLW in FSC. Karwowska et al. (2021) demonstrated that the consumption stage generates the most waste among all stages of FSC in the meat sector. These are examples of efforts to reduce food waste during the stages of FSC in different industries.

There are many studies that focus on minimizing FLW at various stages of FSC by using mathematical modeling methodologies. Firstly, Widodo et al. (2006) provided a deterministic periodical harvesting and delivery scheduling model maximizing the satisfied demand level that yields minimization of the loss function. The loss function consists of two losses, that is, the loss occurred in the distribution stage and the loss occurred by premature harvesting in the production stage of agricultural fresh products. Entrup et al. (2007) included shelf life consideration to reduce wastage in their deterministic production scheduling model in yogurt production. Ahumada and Villalobos (2009) proposed a deterministic tactical planning and distribution model maximizing the producer's total profit minus the loss function for product deterioration. The loss function considers the loss that occurred in the distribution stage and during the storage of fresh produce. Later, Orgut et al. (2015) constructed a deterministic capacitated network flow model to distribute donated food that is kept at a food bank. The network flow model aims to maximize the distributed amount of donated food over the distribution network. In terms of robust optimization applications, An and Ouyang

(2016) presented a bi-level supply chain network model to maximize total profit and minimize the post-harvest loss, considering the yield factor is uncertain. Next, Banasik et al. (2017) maximized the producer's total profit and minimized the total production, holding and waste exergy losses in their deterministic production planning model. The waste exergy losses are computed by the multiplication of the total waste amount with the exergetic value of products. Another food waste reduction study was performed as a microeconomy-based theoretical model by Katare et al. (2017) for consumption level food waste. They maximized the consumer's utility, subject to a budget constraint for waste taxes, namely, social-optimal government incentive and disposal tax. Lee et al. (2017) studied a stochastic programming model on scheduling gleaning operations at a food bank, given the uncertainty of the arrival times of donations and attendance of gleaners. The objective of the model is to maximize the total volume gleaned, leading to minimizing the food waste that occurred due to excess crops. Li et al. (2017) carried out an optimal packaging and inventory control policy to minimize cost while aiming to reduce waste. From the supply chain network model design perspective, Zhang and Jiang (2017) generated a robust optimization model with three objectives: maximizing the profit of the network, minimizing the emissions and minimizing the uncollected kitchen waste to reduce the cooking oil waste. Another deterministic strategic and tactical vegetable production system was introduced by Brulard et al. (2018) to maximize the economic revenue of a farm in a vegetable farming operation. The loss function of this study consists of transportation and storage losses.

Recently, several studies have aimed to construct a simulation model to monitor food loss and waste and to establish the main root causes of this waste. For example, Fikar (2018) presented an inventory and routing optimization model in a decision support system that integrates with agent-based simulation. Janssen et al. (2018) illustrated the amount of food waste reduction achieved with the application of their inventory model by a simulation model. Lastly, Teller et al. (2018) analyzed the root causes of the food waste that occurred in retail stores, mainly at the distribution and market stage, by a process simulation model.

Studies regarding food loss and waste reduction generated at different stages of the food supply chain are summed up in Table 1. The columns of Table 1 are modeling approach, model type, objective type, objective functions, food waste type and the FSC stage where FLW is generated. The second column of Table 1 is inspired by the classification presented in the study of Luo et al. (2021).

Table 1 summarizes the articles which aim to reduce different food waste types produced at various stages of FSC with a mathematical approach. Although there are several studies about food waste reduction, to the best of our knowledge, there is no study proposing a network model to reduce the food waste generated at the consumption stage of the food supply chain within the circular approach. Hence, the contribution of this study is ensured in the last entry of Table 1. The study of Luo et al. (2021) motivated us to process our research as follows. Our study aims to reduce the food waste generated at the consumption stage of the food supply chain and reuse/recycle this waste in a circular food supply chain network. As a result, the main objective is the reduction of economic and environmental impacts of food waste in the circular food supply chain. Among all methodologies, deterministic optimization is chosen as the solution methodology since the gap is explicitly depicted by the study of Luo et al. (2021). Hence, this is the first study proposing a circular food supply chain network model to reduce food waste in a bi-objective framework. The introduced model minimizes the total cost of the network and maximizes the distributed food waste within the network. To deterministically optimize the introduced supply chain network model, a MILP has been generated. Therefore, in the following section, the proposed model, covering all stakeholders in line with the system approach and circular economy principles, is provided.

Table 1 Literature review for mathematical models which consider FLW reduction at different stages of FSC

Author(s)	Modeling Approach	Model Type	Objective Type	Objective Function(s)	Food Waste Type	The FSC stage that the FLW is generated
Widodo et al. (2006)	Deterministic optimization	Periodical harvesting and delivery scheduling model	S	Maximizing the satisfied demand level	Agricultural fresh products	Production, distribution and market
Entrup et al. (2007)	Deterministic optimization	Production planning and scheduling model	S	Maximizing the contribution margins of products with shelf-life consideration	Yogurt	Production, distribution and market
Ahumada and Villalobos (2009)	Deterministic optimization	Tactical planning and distribution model	S	Maximizing producer's total profit minus the loss function for product deterioration	Crops	Distribution and market
Orgut et al. (2015)	Deterministic optimization	Capacitated network flow model	S	Maximizing the distributed amount of donated food	Donated food	Distribution and market
An and Ouyang (2016)	Robust optimization/Stochastic Programming	Supply chain network model	B	Maximizing total profit and minimizing the post-harvest loss	Grain	Post-harvest
Banasik et al. (2017)	Deterministic optimization	Production planning model	B	Maximizing the producer's total profit and minimizing the total production, holding and waste exergy losses	Food	Production

Table 1 (continued)

Author(s)	Modeling Approach	Model Type	Objective Type	Objective Function(s)	Food Waste Type	The FSC stage that the FLW is generated
Katare et al. (2017)	Deterministic optimization	Microeconomy based theoretical model	S	Maximizing consumer's utility, subject to a budget constraint for waste taxes	Food	Consumption (Household level)
Lee et al. (2017)	Stochastic Programming	Scheduling model for gleaning operation at a food bank	S	Maximizing total volume gleaned (minimizing the food waste that occurred due to excess crops)	Food waste	Processing
Li et al. (2017)	Deterministic optimization	Optimal packaging and inventory control policy	S	Minimizing cost while aiming to reduce waste	Food	Production,
Distribution and market						
Zhang and Jiang (2017)	Robust optimization	Supply chain network model	M	Maximizing the profit of the network, minimizing the emission and minimizing the uncollected kitchen waste	Waste cooking oil	Consumption
Brulard et al. (2018)	Deterministic optimization	Strategic and tactical vegetable production system	S	Maximizing economic revenue of the farm	Vegetable	Production

Table 1 (continued)

Author(s)	Modeling Approach	Model Type	Objective Type	Objective Function(s)	Food Waste Type	The FSC stage that the FLW is generated
Fikar (2018)	Simulation	Inventory and routing optimization model	S B	Minimizing distance and maximizing quality	E-grocery	Distribution and market
Janssen et al. (2018)	Simulation	Inventory optimization model and simulation	S	Minimizing the overall cost of inventory	E-grocery	Distribution and market
Teller et al. (2018)	Simulation	Process simulation model	S	Finding the root causes of the food waste	Food waste occurred at retail stores	Distribution and market
This study	Deterministic optimization	Supply chain network model	B	Maximizing the total food waste distributed and minimizing the total cost of the FSC	Six different food wastes	Consumption

3 The proposed circular food supply chain network model to reduce food waste

In the proposed network model, a circular food supply chain is constructed and analyzed from the point of view of the municipalities. Hence, the missions and responsibilities of municipalities are considered before designing the network. The components of the network model for the circular food supply chain can be categorized into nine classes: *(i) generation nodes, (ii) collection and classification centers, (iii) reuse points, (iv) third-party recycling centers, (v) treatment and recycling centers, (vi) fertilizer companies, (vii) biodiesel producers, (viii), landfill sites, and (ix) incineration facilities*. The roles and capabilities of these components for the circular food supply chain process are provided below:

(i) *Generation nodes* produce six different types of food waste: preparation waste (not edible) (w_1), serving waste (not edible) (w_2), edible serving waste (w_3), plate waste (edible for animals) (w_4), bottle, plastic/metal products, napkins/paper (w_5), and oil (w_6).

(ii) *Collection and classification centers* gather all the waste from the generation nodes and classify them according to their category, hence preparing them for transfer to the related downstream nodes.

(iii) *Reuse points* accept the edible foods (w_3 and w_4); food banks use the edible serving waste (w_3) and animal shelters use the plate waste (w_4).

(iv) *Third-party recycling centers* collect bottles, plastic/metal products, napkins/paper (w_5) from the collection and classification points.

(v) *Treatment and recycling centers* can have two treatment technologies: (1) composting and (2) biofuel technologies. The waste types w_1,w_2 and w_6 are transferred from the collection and classification centers to the treatment and recycling centers to be processed. The fertilizer and biodiesel products are obtained as outputs of the processes in these centers. The waste types w_1 and w_2 are processed using composting technology and then transferred to fertilizer companies. Similarly, w_6 is processed using biofuel technology and transported to biodiesel producers. Any leftover materials from the treatment and recycling operations in these centers are transferred either to landfill sites or incineration facilities.

(vi) *Fertilizer companies* collect the composts from the treatment and recycling centers.

(vii) *Biodiesel producers* collect the biofuel products from the treatment and recycling centers.

(viii) *Landfill sites* handle the leftovers of w_1 and w_2 that require to be landfilled.

(ix) *Incineration facilities* handle the leftovers of w_1 and w_2 that require to be incinerated.

These waste types and their roles in the network model are summarized in Table 2.

Assumptions and limitations of the proposed network model are listed below:

- The generation nodes produce the food and food-related waste deterministically on a daily basis. The amounts of daily generation waste type are known in advance.
- Collection and classification centers are the cross-dock facilities where the collected food and food-related waste are sorted and distributed to the related nodes for future operations.
- Treatment centers perform composting and biodiesel production technologies. However, composting technology can only be carried out for w_1 and w_2 and the biodiesel production technology can only be implemented for w_6.
- The fixed costs of facilities are discounted to daily costs, including construction, operation and any other outlay.

Table 2 Summary of the waste types and their destination nodes in the network

Waste type	Definition	Food Banks	Animal Shelters	Third-Party Logistics Centers	Fertilizer Companies	Biodiesel Producers	Landfill sites	Incineration Facilities
w_1	Preparation waste (not edible)				X		X	X
w_2	Serving waste (not edible)				X		X	X
w_3	Serving waste (ready to eat)	X						
w_4	Plate waste (edible for animals)		X					
w_5	Bottle, plastic/metal products, napkins/paper			X				
w_6	Oil					X		

The proposed network model for the circular food supply chain process is summarized in Fig. 1. The flow of this network is forward, meaning that the food waste is generated from the generation nodes and transferred to the related downstream nodes either to be used in another way or to be treated/recycled by appropriate technologies. Any backward flow is not considered in this network since the generated food waste does not need to be returned to the generation nodes. In generation nodes, six different types of food waste can be generated. Then, the generated wastes are collected in collection and classification centers. The food waste types w_3 and w_4 are transferred to the reuse points, whereas the entire amount of w_5 is transferred to third-party recycling centers. The remaining waste types, w_1, w_2 and w_6 are transported to the treatment and recycling centers to be treated with two technologies, composting and biofuel production. After this stage, these wastes can be transferred according to the needs of the fertilizer companies, biodiesel producers, landfill sites and incineration sites. Note that the third-party recycling centers, fertilizer companies and biodiesel producers are assumed to be out of the scope of municipal government. Therefore, the fixed and operational costs of these sites as well as transportation costs to these nodes are not considered in this network model. Hence, these nodes are presented in green color in the model.

The proposed network model is a deterministic optimization model that decides how to handle the generated food waste. The aim is to realize the maximum amount of food waste to be distributed to the end nodes at a minimum cost. In the following section, the proposed MILP model for the circular food supply chain process is presented.

3.1 Mathematical model of the proposed circular food supply chain network model

A MILP model was generated to mathematically model the proposed circular food supply chain network model. The sets, parameters and decision variables for the proposed mathematical model are provided in Tables 3, 4 and 5, respectively.

Table 3 Sets of the mathematical model

Sets	Definition
G	Waste generation nodes
C	Collection and classification centers
R	Reuse points (food banks and shelters)
T	Treatment and recycling centers
P	Third-party recycling centers
B	Biodiesel companies
L	Landfill sites
I	Incineration facilities
N	Set of all nodes ($N = G \cup C \cup R \cup T \cup P \cup F \cup B \cup L \cup I$)
E	Set of edges
Q	Treatment technologies (q = 1 for composting and q = 2 for biodiesel)
W	Food waste types (w = 1 for preparation waste (not edible), w = 2 for serving waste (not edible), w = 3 for serving waste (ready to eat), w = 4 for plate waste (edible for animals), w = 5 for bottle, plastic, metal or paper products, and w = 6 for oil)

Table 4 Parameters of the mathematical model

Parameters	Definition
ac_{ij}	The transportation cost (\$ per kg per km) on edge $(i, j) \in E$
fc_j	The fixed cost (\$ per day) of building and operating the facility $j \in N \backslash (G \cup T)$
fc_{qj}	The fixed cost (\$ per day) of building and operating the treatment facility $j \in T$ with treatment technology $q \in Q$
g_{wi}	Amount of waste $w \in W$ generated at node $i \in G$
α	The percentage of waste types 1 and 2 composted at treatment centers
β_w	The percentage of loss during the treatment process for each waste type $w \in W$
δ_{jw}	The waste handling capacity of facility $j \in N \backslash (G \cup T)$
δ_{qjw}	The waste handling capacity of treatment facility $j \in T$ for food waste type $w \in W$ with treatment technology $q \in Q$

Table 5 Decision variables of the mathematical model

Decision Variables	Definition
x_{ijw}	The amount of food waste type $w \in W$ transported through the edge (i, j)
τ_{jw}	The amount of food waste type $w \in W$ transferred to node $j \in N \backslash (G \cup T)$
τ_{qjw}	The amount of food waste type $w \in W$ treated at treatment node $j \in T$ with treatment technology $q \in Q$
y_j	1, if a collection, reuse, landfill, incineration facility is established at node $j \in C \cup R \cup L \cup I$; 0, otherwise
y_{qj}	1, if a treatment center is established at node $j \in T$ with treatment technology $q \in Q$; 0, otherwise

Using the notations, parameters and decision variables given above, the following bi-objective MILP model is developed within the framework of the network model given in Fig. 1.

3.1.1 Objective functions

$$min \sum_{(i,j)\in E} \sum_{w\in W} ac_{ij} * x_{ijw} + \sum_{j\in N\backslash(G\cup T)} fc_j * y_j + \sum_{q\in Q} \sum_{j\in T} fc_{qj} * y_{qj} \tag{1}$$

$$max \sum_{j\in N\backslash(G\cup C\cup T)} \sum_{w\in W} \tau_{jw} \tag{2}$$

The first objective function in Expression (1) minimizes the total cost, i.e., the sum of transportation costs to transport multiple waste types among facilities and the fixed costs to open and operate the facilities. The second objective function in Expression (2) aims to maximize the total delivered food wastes to reuse points, third-party recycling centers, fertilizer companies, biodiesel producers, landfill sites and incineration facilities.

$$\sum_{i\in C} x_{ijw} \leq g_{wi} \forall i \in G, w \in W \tag{3}$$

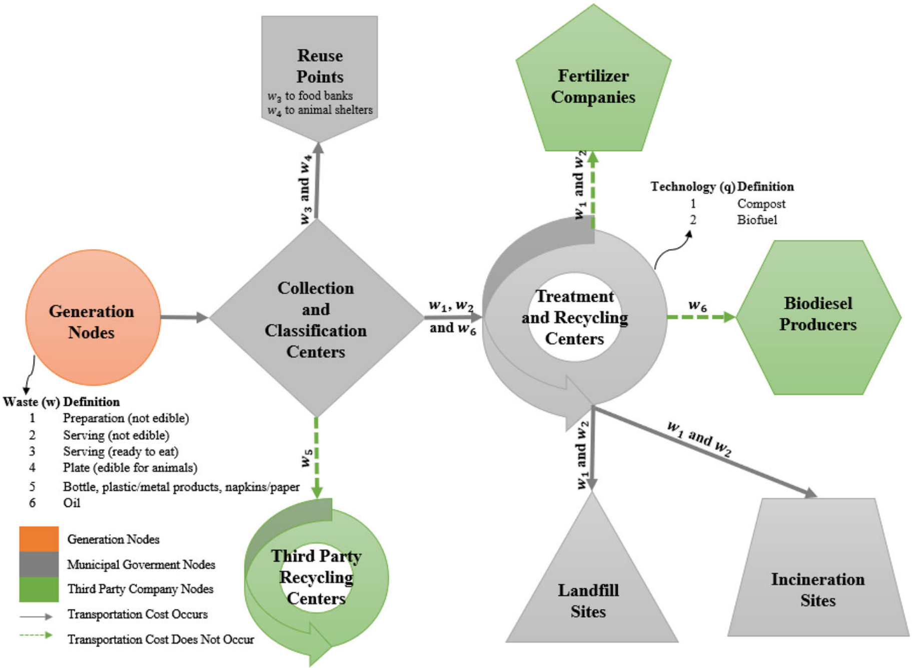


Fig. 1 The framework of circular food supply chain network model to reduce food waste

Constraint (3) ensures that the total amount of food waste transported to collection centers does not exceed the total waste generated at generation nodes.

$$\sum\nolimits_{i\in G} x_{ijw} = \sum\nolimits_{i\in R\cup P\cup T} x_{jiw} \forall j \in C, w \in W \tag{4}$$

Constraint (4) defines the flow balance from collection and classification centers to reuse points, third-party recycling centers and treatment and recycling centers.

$$\sum\nolimits_{i\in C} x_{ijw} = \sum\nolimits_{i\in L\cup I} x_{jiw} + \sum\nolimits_{i\in F\cup B} x_{jiw}/(1-\beta_w) \forall j \in T, w \in W \tag{5}$$

$$(1-\beta_w)(\alpha)\sum\nolimits_{i\in C} x_{ijw} = \sum\nolimits_{i\in F} x_{jiw} \forall j \in T, w \in \{w_1, w_2\} \tag{6}$$

Similarly, node flow balance constraints from treatment and recycling centers to fertilizer companies, biodiesel producers, landfill sites and incineration facilities are shown in constraints (5) and (6). Note that only a fraction of each waste type w_1 and w_2 is treated with compost technology at treatment centers. Also, a treatment loss occurs in composting and biodiesel processes at treatment centers.

$$\sum\nolimits_{i\in N:(i,j)\in E} x_{ijw} = \tau_{jw} \forall j \in N\backslash(G\cup T), w \in W \tag{7}$$

$$\sum\nolimits_{i\in N:(i,j)\in E} x_{ijw} = \sum\nolimits_{q\in Q} \tau_{qjw} \forall j \in T, w \in W \tag{8}$$

Constraint (7) defines the total flow of all waste types that are processed at all facilities except treatment centers. Constraint (8) calculates the total flow of all waste types that are processed at treatment centers with treatment technology q.

$$\tau_{jw} \leq \delta_{jw} * y_j \forall j \in C \cup R \cup L \cup I, w \in W \tag{9}$$

$$\tau_{jw} \leq \delta_{jw} \forall j \in P \cup F \cup B, w \in W \tag{10}$$

$$\tau_{qjw} \leq \delta_{qjw} * y_{qjw} \forall j \in T, w \in W, q \in Q \tag{11}$$

Capacity limitations of the facilities are enforced by constraints (9), (10) and (11).

$$x_{jiw}, \tau_{jw}, \tau_{qjw} \geq 0; y_j, y_{qj} \in \{0, 1\} \tag{12}$$

Boundary constraints on the decision variables are defined in constraint (12).

4 Solution approach

This study proposes a framework for a circular food supply chain network model to reduce food waste. As another contribution, we have developed a MILP model to mathematically model the proposed circular food supply chain network. The MILP model considers two objective functions: (1) the minimization of the total cost of the network model and (2) the maximization of the total food delivered while accounting for food-related wastes. Since these objective functions are conflicting and the model has a bi-objective nature, a non-dominated solution set (i.e., a Pareto-optimal set) is enumerated for the problem. To construct the Pareto-optimal set, the dominance relationship definition of Deb (2001) is used. A solution s_1 dominates another feasible solution s_2 (denoted as $s_1 \succ s_2$) if the following two conditions are satisfied: $\forall h \in 1, \ldots, H;\ f_h(s_1) \leq f_h(s_2)$ and $\exists h \in 1, \ldots, H;\ f_h(s_1) < f_h(s_2)$, where h is the index of a minimization type objective. Solution s_1 is indifferent to another solution s_2 (denoted as $s_1 \sim s_2$) if the following condition is satisfied: $\forall h \in 1, \ldots, H;\ f_h(s_1) \nleqq f_h(s_2)$. Amongst a set of solutions S, the non-dominated set of solutions includes the elements of the set S^* that is not dominated by any element of S. The non-dominated set of the entire feasible search space is called the Pareto-optimal set of solutions.

There are various solution approaches for bi-objective optimization problems, such as the weighting sum method, weighted Tchebycheff method, goal programming method, augmented weighted Tchebycheff method and ε-constraint method. In this study, the Improved Augmented ε-Constraint method of Mavrotas and Florios (2013), an advanced version of the Augmented ε-Constraint method of Mavrotas (2009), has been employed to find the Pareto-optimal solutions of the bi-objective circular food supply chain network model problem for waste management. Similar to the classical ε-constraint method, the augmented ε-constraint method optimizes one of the objective functions, while the remaining objective functions are defined as constraints. Unlike the classical ε-constraint method, the objective function constraints are specified as equalities with the inclusion of required slack/surplus variables in the augmented ε-constraint method. Therefore, the objective function includes these slack or surplus variables as a secondary part of the formulation to ensure the Pareto optimality. Hence, weak Pareto-optimal solutions are avoided by this method. Iteratively, a range of single-objective models is solved optimally by updating the right-hand sides of these constraints. The improved augmented ε-constraint method eliminates redundant iterations by using a bypass coefficient without violating the accuracy of the Pareto-optimal set. By doing so, a significant number of redundant grid points are not searched and the Pareto-optimal set can be found faster and more effectively. An extensive explanation of the improved augmented ε-constraint method can be found in Mavrotas and Florios (2013). There is also another variant of the epsilon constraint method that is introduced to the multi-objective optimization literature, named as the simple augment ε-constraint method (Zhang & Reimann, 2014).

In this study, the Improved Augmented ε-Constraint method (AUGMECON2) of Mavrotas and Florios (2013) is implemented to solve the MILP model as presented in Sect. 3.1. The total distributed food and food-related wastes (Expression (2)) is considered as the objective function while the total cost of the network model (Expression (1)) is considered as a constraint.

5 Case studies and computational results

The proposed network model has been implemented in two case studies where realistic and comprehensive networks are generated considering the details of the proposed model. To demonstrate the applicability and effectiveness of the proposed model, two case studies are conducted since this study is considered from a municipal government perspective. The first case study represents a small municipality and the second one represents a large municipality.

5.1 Case study 1: Bornova District, Izmir, Turkey

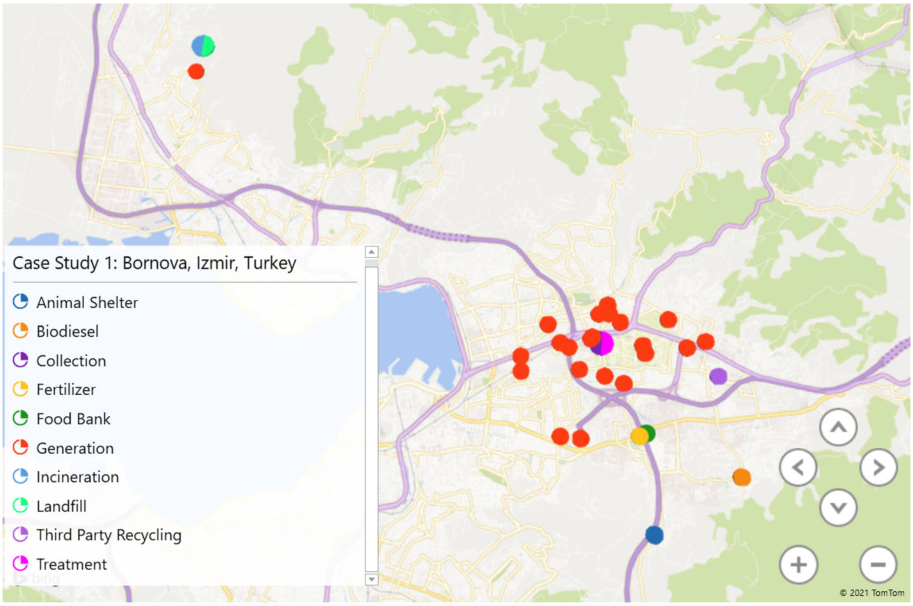
Firstly, a case study is conducted in Bornova, Izmir, Turkey. This case study consists of twenty-two food waste generation nodes, two reuse points, one collection and classification center, one treatment and recycling center, one fertilizer company, one biodiesel producer, one landfill site and one incineration site. The locations of the collection and classification centers, together with the treatment and recycling centers, are the same in this case study. The geographical map of all facilities in Case Study 1 is depicted in Fig. 2.

The capital and operating costs of the third-party recycling centers, the fertilizer companies and the biodiesel producers are not included in the model. However, they are a part of the proposed network model even though they are not part of the municipal government.

As the generation nodes, the district of Bornova within the city of Izmir includes various hospitals, universities, shopping malls, high schools, hotels as well as the 57th military brigade, the Municipality of Bornova, the Distinct Governorship of Bornova and Işıkkent Organized Industrial Zone. As reuse points, a food bank and Izmir Metropolitan Municipality dog care center are included in the case study.

In a recent report (COMCEC, 2017), an estimation of the food waste generated by a Turkish household per year is provided. Using these yearly averages, we obtained the daily generated food waste per Turkish household by dividing these values by 360 days as in Table 6. Furthermore, the waste generated by serving food is not considered separately as being edible or not edible in COMCEC (2017). Therefore, it is assumed that two-thirds of the waste obtained from serving food is not edible (w_2) and one-third of the waste obtained from serving of food is edible (w_3). Hence, the not edible serving waste (w_2) and edible serving waste (w_3) values are obtained as recorded in Table 6. After calculating the average food waste per day per person in kg for w_1, w_2, w_3 and w_4 types of waste, the average food waste per meal per person for each waste type is obtained for use in the food waste generation amount of generation nodes.

According to WWF (2018), the total bottle, plastic/metal products, napkins/paper waste (w_5) generated in Turkey is 144 tons per day. For oil waste (w_6), the total waste generated per year in Turkey is shown as 350,000 tons as recorded by Kılıç and Kılıç (2017). Using



*This figure is created by the 3D Maps tool of Microsoft Office Excel

Fig. 2 The geographical map of all facilities in case study 1

Table 6 The estimation of generated food waste (w_1, w_2, w_3, w_4) by a Turkish Household

Food waste	w_1	w_2+w_3	w_4	w_4	w_4
Average food waste per year (kg)	784	754	15	502.67	251.33
Average food waste per day (kg)	2.18	2.09	0.04	1.40	0.70
Average food waste per day per person (kg)	0.544	0.524	0.010	0.349	0.175
Average food waste per meal per person (kg)	0.181	0.177	0.003	0.116	0.058

this information, the total generated w_5 and w_6 wastes per day per person are obtained as shown in Table 7.

After obtaining the daily generated waste amount of each waste type, we calculated the total waste generations at each generation node by multiplying these values by the number of people at each generation node. The distances among all nodes are obtained using Google

Table 7 The amounts of daily generated food wastes w_5 and w_6 in Turkey

	w_5	w_6
Total waste generated per day (ton)	144	972.22
Total waste generated per day per person (kg)	0.0018	0.012
Total waste generated per meal per person (kg)	0.0006	0.004

Table 8 Cost analysis of technologies

	Capital cost (USD/t)	Operating cost (USD/t)	Variable cost (USD/t)	Total unit cost (USD/t)
Landfill	500	0.4	1.3	501.7
Incineration	800	0.6	2.0	802.6
Composting	250	0.2	0.5	250.7

Maps. Upon calculating the distances, the transportation costs among nodes are calculated according to Liotta et al. (2015), which reports the unit transportation cost as 0.1526 USD per ton per km.

The capacity of the food bank is 1500 daily meals and the daily food consumption of a person is taken as 0.5 kg. Hence, the capacity of a food bank is assumed to be 250 kg per day (1500*0.5*(1/3)). Only w_3 type can be transferred to food banks. The daily food consumption of a dog is taken on average as 0.3 kg. With the animal shelter housing 500 dogs, their capacity is calculated to be 150 kg per day. Only w_4 type can be transferred to animal shelters.

The collection and classification centers are assumed to be operating as a cross-docking facility with a capacity of 75 tons per day. This capacity value is scaled by the weights of each food waste type and the resulting capacity for each type is obtained. The location of the collection and classification center is calculated by using the center of gravity method considering the locations of all generation nodes. The location of the treatment and recycling center is assumed to be the same as the collection and classification center. The capacity of a treatment and recycling center is adapted from Levis et al., 2010 who give capacity as 55,000 tons per year (153,000 kg per day). Since this value is significantly larger than the available generated food waste amount, the capacity of the treatment and collection center is taken as 50,000 kg per day in this case. Then, this capacity is distributed to w_1 and w_2 according to their weights for the composting technology. Since biodiesel production technology processes only w_6 type, the capacity of w_6 is taken as 50,000 kg per day for the technology in the treatment and recycling center. The capacities of the third-party recycling center, fertilizer producers and biodiesel producers are taken as infinity. Finally, the capacity of landfill and incineration sites can be a maximum of 20,000 tons per year (Official Gazette of Turkey, 2010). Hence, the daily capacity of each is considered as 55,555 kg with waste types w_1 and w_2 having equal shares.

Tan et al. (2014) presented an optimal process network for municipal solid waste management in Iskandar, Malaysia. We have adapted the capital, operating and variable costs of the landfill, incineration and composting technologies from this study as reported in Table 8.

According to World Bank, 2020, the cost of opening and operating a collection and classification center in Turkey is \$325,119 per ten years (equivalent to \$32,511.9 per year or \$90.31 per day). The annual cost of biodiesel production cost is taken as \$18,238.11 as stated in Duarte et al. (2012). The daily equivalent of this value is \$50.66 per day.

5.2 Case study 2: Izmir, Turkey

The Izmir case study, a larger area, consists of 125 food waste generation nodes, 66 reuse points, 3 collection and classification centers, 3 treatment and recycling centers, 1 fertilizer

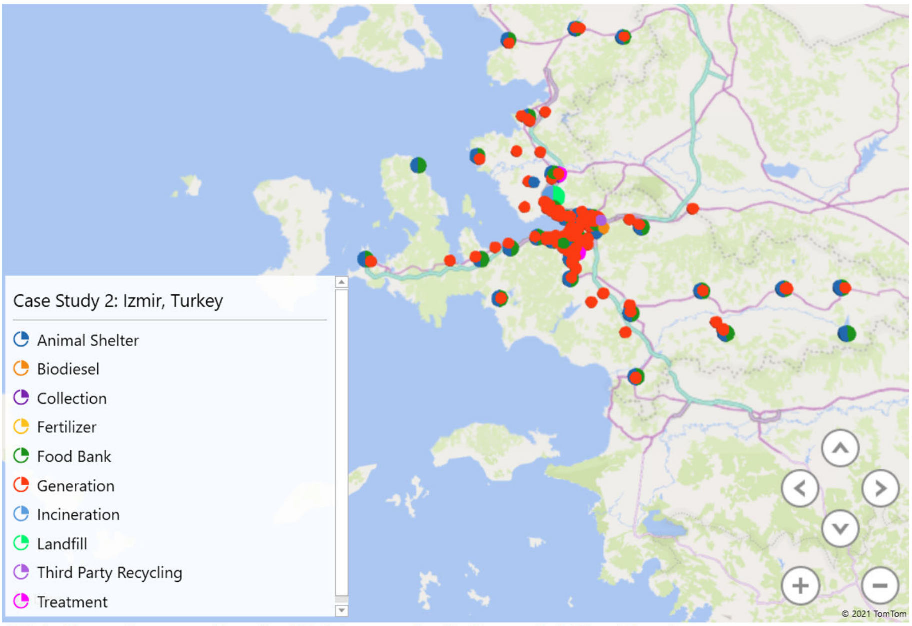


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Fig. 3 The geographical map of all facilities in case study 2

company, 1 biodiesel producer, 2 landfill sites and 2 incineration facilities. Similar to the Bornova case, the locations of the collection and classification centers plus the treatment and recycling centers are assumed to be the same in this study. The geographical map of all facilities in Case Study 2 is depicted in Fig. 3.

Also, the capital, operating and variable costs of the third-party recycling centers, the fertilizer companies and the biodiesel producers, as well as the distribution costs to these nodes, are not included in the model since they are not part of the municipal government. However, they are included in the proposed network model.

The Izmir case study covers 30 districts of the city of Izmir. Its generation nodes include various shopping malls, hospitals, universities, high schools, army districts, hotels, industrial districts, bus terminals and an international airport. As reuse points, three food banks and three animal shelters in Izmir are considered. To meet the capacity in the model, 60 additional reuse points are designated. The same calculation steps of the Bornova case study are followed to generate case data for Izmir. The comparison of cases regarding their size is listed in Table 9.

There are some other differences to be mentioned. The capacity of a collection and classification center is increased to 150,000 kg per day and the capacity of a treatment and recycling center is increased to 120,000 kg per day to meet the increased requirements of generation nodes. The capacities of new candidate food banks and animal shelters remain the same. However, the opening and operating costs of candidate food banks and animal shelters are considered as $2,936.85 per month (equivalent to $97.89 per day). All information for the case studies and their computational results can be found in the supplementary materials.[1]

[1] All test problem data and their solutions are provided as an online supplement at https://okabadurmus.yasar.edu.tr/research/circularfoodwaste/.

Table 9 Comparison of case studies

Number of	Bornova District, Izmir, Turkey	Izmir, Turkey
Food waste generation nodes	22	125
Reuse points	2	66
Collection and classification centers	1	3
Treatment and recycling centers	1	3
Fertilizer companies	1	1
Biodiesel producers	1	1
Landfill sites	1	2
Incineration facilities	1	2

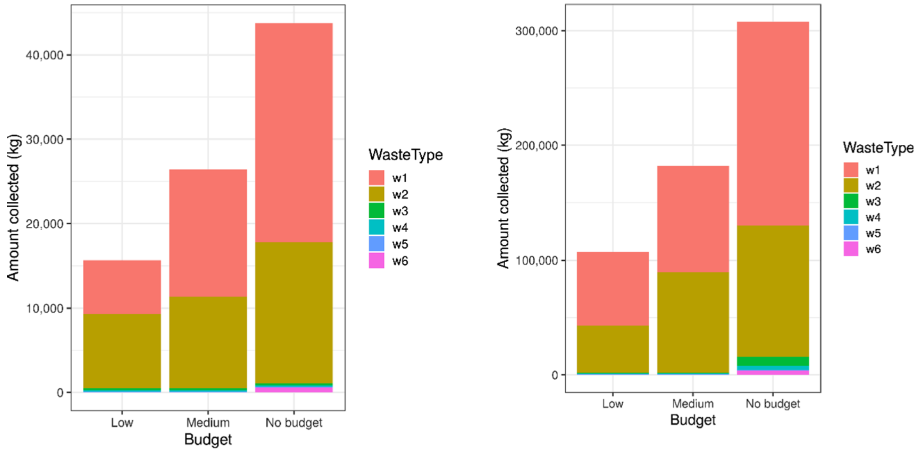
5.3 Computational results

Our Bornova and Izmir case studies address a real problem in practical terms for small and large municipal governments. Bornova, with a population of 451,000, is one of the most densely populated districts of Izmir while Izmir is the third largest city in Turkey with a population of 4.3 million people. The total daily amount of food waste generated in Bornova and Izmir is 52,243 kg and 356,578 kg, respectively.

The MILP models of the two case studies are solved with the AUGMENCON2 method using the IBM ILOG CPLEX Solver on Clemson University Palmetto Cluster server computers (Intel Xeon E5-2665 8-core processor with 64 GB RAM). The Pareto-optimal solution sets of Bornova and Izmir cases are found in 6.51 and 2,078.32 min, respectively. Note that all instances are solved optimally.

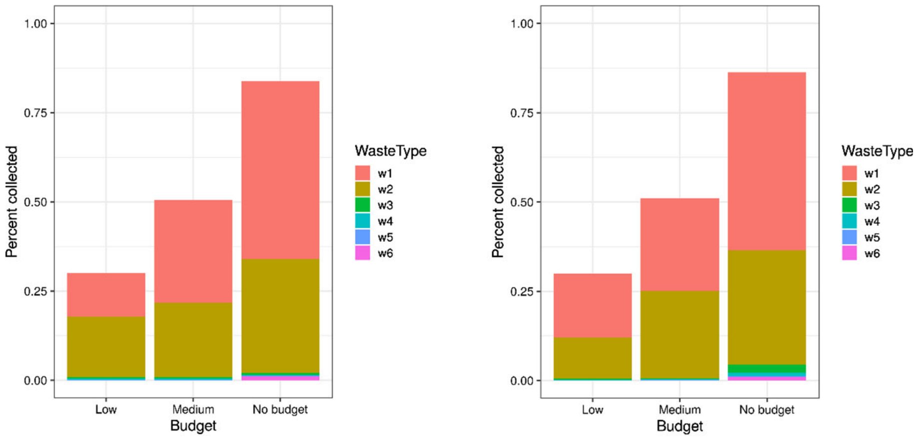
Although the Pareto-optimal solution set is found with all cost levels, three budget levels (i.e., low, medium and no budget) are considered in our computation to better demonstrate the effect of a budget restriction. The total amount of the collected food waste of Bornova and Izmir cases under these three budget scenarios is shown in Fig. 4; there is a similar trend for both cases. According to Fig. 4a, 16,079 kg, 26,300 kg and 43,790 kg of daily food and food-related waste are collected in the Bornova study under low, medium and no budget scenarios, respectively. Similarly, according to Fig. 4b, 107,009 kg, 182,022 kg, and 307,756 kg is collected in the Izmir study under low, medium and no budget scenarios, respectively. A no-budget scenario facilitates the maximum amount of collected waste for both scenarios.

The total percentage of all collected food types for the Bornova and Izmir studies under three budget scenarios is presented in Fig. 5. One important inference from this is that the entire amount of generated food waste could not be collected in both cases due to limited processing capacity. According to Fig. 5a, 30.8%, 50.3% and 83.8% of 52,243 kg of generated food waste is collected from all generation nodes under low, medium and no budget scenarios in Bornova. Similarly, Fig. 5b shows that 30.0%, 51.0% and 86.3% of 356,578 kg generated food waste is collected from all generation nodes under the same budget scenario in Izmir. Although the collected food waste percentages follow a similar trend in both Bornova and Izmir, there are small differences between the cases. For example, there is a slight increase in the percentage of w_3 in the no-budget scenario in Izmir. Also, the percentage of w_1 in



(a) Bornova **(b)** Izmir

Fig. 4 Collected food waste amounts of all food waste types for low, medium and no-budget scenarios



(a) Bornova **(b)** Izmir

Fig. 5 Collected food waste percentages of all food waste types for low, medium and no-budget scenarios

Izmir case is higher than in Bornova, whereas the percentage of w_2 in Izmir is lower than in Bornova.

The collection percentages of different waste types within the total collected waste percentage of the Bornova and Izmir studies are presented in Fig. 6. In the no-budget scenario of both studies, the entire amount of w_1, w_2, w_5, and w_6 is collected. However, the entire amount of w_4 is only collected in the Izmir case. As the percentage of total collected waste increases, the percentages of collected w_1, w_2 and w_5 types of food waste increase more significantly than the others. Among these, the most dramatic increase is seen in waste type w_5 since it is transported from collection and classification centers to third-party recycling

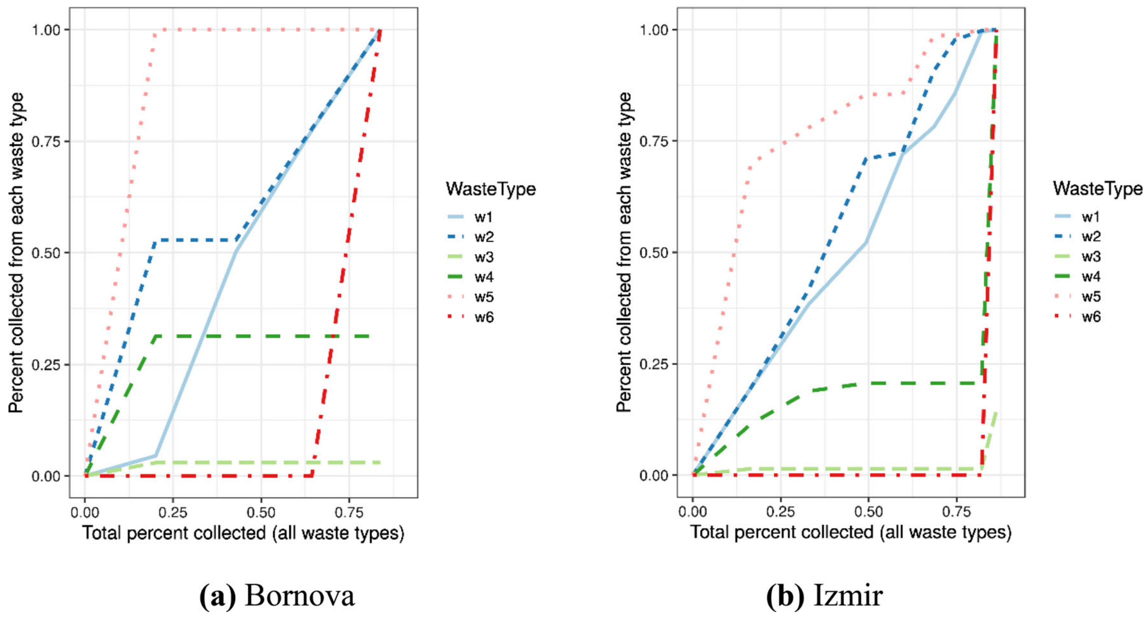
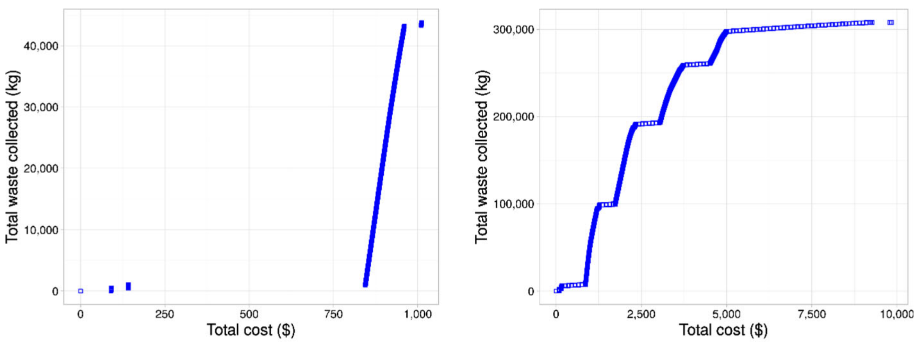


Fig. 6 The comparison of the percentages of all collected food waste types and the percentage of the total collected waste

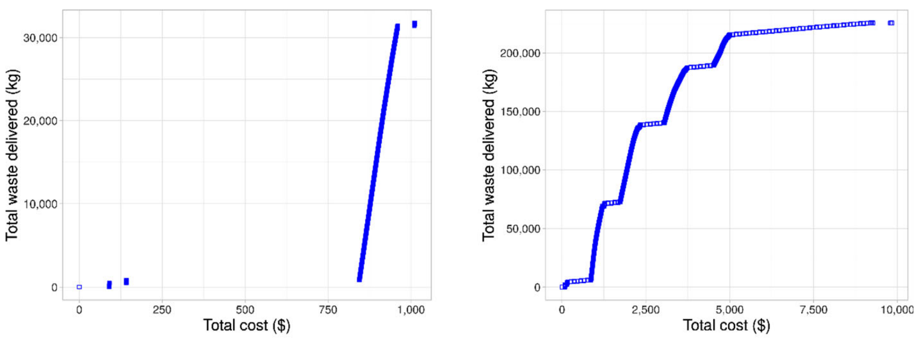
centers without incurring any cost to the municipal government. On the other hand, the collected percentages for w_3, w_4 and w_6 types do not increase as quickly as for waste types w_1, w_2 and w_5. The limited capacities of processing waste types w_3 and w_4 limit their increase after their processing capacity is reached. Hence, the model collects the amount of these waste types up to the demand of the reuse points. Also, waste type w_6 is not collected until other waste types are collected due to the high fixed cost of the biodiesel facility. Because the capacity of reuse points is larger in the Izmir case, w_3 and w_4 are also collected similarly to w_6. Hence, the order of collection of waste types based on their collection preference is w_5,w_2, w_1, w_3, w_4 and w_6.

The Pareto-optimal solutions that maximize the total collected waste amount and minimize the total cost are given in Fig. 7 for both Bornova and Izmir studies. In Fig. 7a, due to the small size of the Bornova case and limited options to open facilities, there are jumps for the total collected food waste. On the other hand, Fig. 7b has a more uniformly distributed Pareto-optimal set, but the effect of opening facilities is visible through the horizontal lines. Similar to Figs. 7, 8 shows the Pareto-optimal solutions that maximize the total delivered waste amount and minimize the total costs for Bornova and Izmir. As expected, Fig. 8 follows



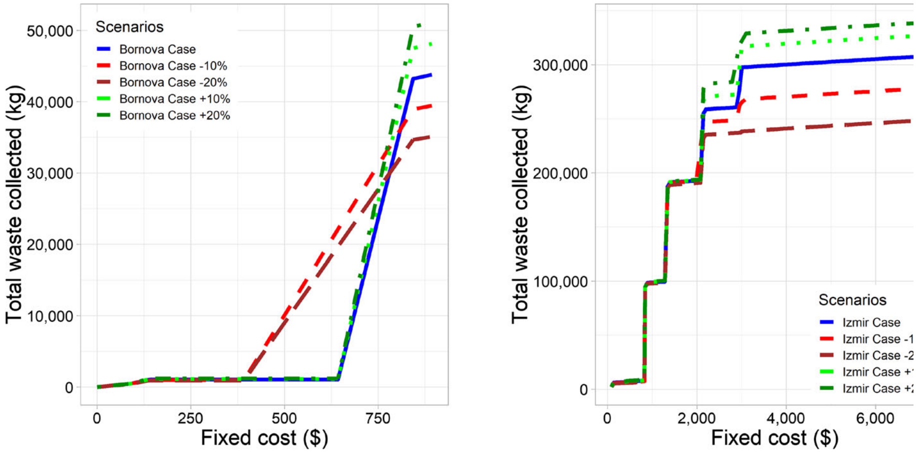
(a) Bornova **(b)** Izmir

Fig. 7 Pareto-optimal solutions for total cost and the amount of collected waste



(a) Bornova **(b)** Izmir

Fig. 8 Pareto-optimal solutions for total cost and the amount of delivered waste



(a) Bornova **(b)** Izmir

Fig. 9 Sensitivity analysis of the collected food waste

the same trend as Fig. 7 for both Bornova and Izmir. However, the amount of collected waste is significantly higher than the amount of distributed waste since there are losses in treatment and recycling centers for w_1, w_2 and w_6. Both figures show that as the total cost of the designed network increases, both collected and delivered waste amounts increase.

According to the implementation, results show that only 83.8% and 86.8% of the circular food is collected from the generation nodes in Bornova and Izmir, respectively. The amounts collected for w_3 and w_4 waste types are significantly less than the available daily generated amounts.

Since the total waste generated can significantly fluctuate within a year due to various reasons (such as holidays, school schedule, and tourist season) and the local governments should justify their investments, a sensitivity analysis is also conducted to determine the effect of changing amounts of the generated food waste. To this end, the generated food and food-related waste for both Bornova and Izmir cases is considered to be increased and decreased by 10 and 20 percent. As presented in Fig. 9, an increase in fixed cost, which includes capital investments by the municipalities, can significantly increase the collected amount of food waste. However, the marginal increase in the collected food waste significantly decreases as the fixed cost gets closer to the maximum for all cases. For example, the average increase in collected food waste of all Bornova scenarios when the fixed cost is increased from 842.71 to 893.37 (the maximum fixed cost, which is a 6.01% increase) corresponds to a 1.10% increase in the average collected food waste. Increasing the fixed cost to the maximum (1.41% increase) can increase only 0.05% of the collected food waste for all Izmir scenarios. Also, the decrease in the generated food waste directly translates into the reduction of the collected food waste in all scenarios. For example, a 10% reduction in Bornova and Izmir cases reduces the total collected food waste by 9.87% and 9.63%, respectively. Similarly, a 20% decrease in the generated amount creates a 19.75% and 19.26% reduction in the collected amount for Bornova and Izmir cases, respectively. However, an increase in generated amount does not always increase the collected amount proportionally as in the reduction scenarios, even with the maximum fixed cost. For example, although a 10% increase in the Bornova case corresponds to a 9.87% increase in the collected amount, it only increases 6.34% in the

Izmir case. Similarly, a 20% increase in the generated amount helps increase collected food waste by only 16.84% in the Bornova case and 10.27% in the Izmir case. This result suggests that the capacity is limited due to certain food waste types (especially w_3 and w_4).

6 Discussion and implications

Food waste has dramatically increased in recent years, and as a result, the collection and treatment of waste foods have become significant issues (Girotto et al., 2015; Pradenas et al., 2020). Effective management of food and food-related waste not only reduces the amount of waste but also contributes to the circular economy (Unger et al., 2018). Depending on the types of food and food-related waste generated—edible or non-edible food, oil, bottles, etc.—the management of each waste may differ (Martin-Rios et al., 2018). Therefore, an appropriate network model is needed to collect and evaluate food waste from the moment it occurs (Ribeiro et al., 2019; Unger & Razza, 2018). An effective network model for waste management provides benefits for both the circular economy and sustainability (Storup et al., 2016; Validi et al., 2020).

The main contributions of this study can be summarized as suggesting a circular food supply chain network model and proposing a bi-objective model; this model maximizes reuse of the distributed food waste within the supply chain and minimizes the total cost of the network simultaneously.

The implications of the study can be separated into theoretical and managerial implications. Since generated food and food-related wastes are increasing year on year, efficient management of these wastes has now become a crucial issue for the circular economy (Validi et al., 2020). As the main theoretical contribution, this study is the first to propose a network model for food and food-related waste treatment based on circular economy principles by using a bi-objective model. An additional contribution of this study is to develop a MILP model to mathematically model the proposed circular food supply chain network model focusing on the consumption stage.

From the managerial perspective, these wastes are not only an environmental issue; the fact that there are few community organizations to support both people and animals poses a major social problem (Sridhar et al., 2021). Therefore, the numbers and capacities of food banks and animal shelters should be increased. This study highlights another practical implication; instead of equal prioritization of the waste types, a network should be designed according to the weighted prioritization of food and food-related waste by implementing the proposed model.

For the food waste treatment process, it is not only very important to establish a facility, but also to make an effective network model (Annosi et al., 2021). The selection of locations for facilities to process, distribute and use food and food-related waste efficiently is a critical issue in terms of logistics (Jouzdani & Govindan, 2021). The questions of where, how many and how to set up the collection or treatment facilities of food and food-related wastes can be addressed through good planning and an effective network model for the environment, the economy and society in general, in line with circular economy principles. Policymakers in municipalities and local governments must plan carefully. If proposals are made to build a new facility or an existing facility is to be enlarged, the installed capacity of the existing facility can be increased by modeling it as new facilities in the additional capacity model.

Due to the rapid increase in food waste, countries have been making new regulations to improve food waste treatment. Along with these regulations, work is progressing to meet more demanding collection and recycling targets. This proposed model ensures that the targets of municipalities are aligned with the goals of the entire country.

The proposed network model serves as a systematic guide on the subject, as it is determined as a useful model for reducing losses in circular food supply chains and contributing to the circular economy of the resulting wastes. This means that another important issue is the practical usability of the proposed model. It enables the decision process and investment decisions to be made with a more logical and holistic perspective, especially for managers. This point of view enables managers to make accurate decision analyses on the subject.

Another implication of the proposed network model is that it enables cost–benefit analysis in the feasibility studies. Therefore, the proposed model can be used not only by local governments but also by private companies to provide a cost–benefit analysis for investment in a circular food supply chain.

One of the important practical implications is that the proposed model can be implemented in not only food and food-related wastes but also for other types of waste such as solid waste or e-waste by municipalities. Thus, municipalities can design circular cities that can reduce waste, keep goods and components in use and reproduce natural systems (Beullens & Ghiami, 2021; Wenzel, 2019).

7 Conclusion

In conclusion, in this study, a circular food supply chain network model is designed to reduce the food waste generated in the circular food supply chain systems of municipalities. Then, a MILP model was generated to model the proposed circular food supply chain network model. Moreover, the Improved Augmented ε-Constraint (AUGMECON2) method of Mavrotas and Florios (2013) was implemented to optimize two objective functions: *(i)* maximization of the reuse of distributed food waste and *(ii)* minimization of the total cost of the network. This study is unique in two aspects: (1) this is the first study where a circular food supply chain network model has been suggested for the treatment of food waste to the best of our knowledge, and (2) the proposed model is a bi-objective model aiming to maximize the reuse of the distributed food waste within the supply chain and to minimize the total cost of the network simultaneously. These contributions of the study are applied in two real-life cases to confirm their practical value.

As mentioned before, one-third of the food produced worldwide is wasted every year. Food waste and food-related waste are the most beneficial type of wastes in terms of circular economy principles. However, the alarming increase in food waste threatens not only the environment and the economy but wider aspects of society. Moreover, since food waste treatment is a vital issue for the circular economy, it is crucial to design a network for food and food-related waste treatment. An effective circular food supply chain system can only be provided by a well-designed network. Therefore, computational logistics can be employed to design a network for an efficient circular food supply chain.

In this study, a circular network model for the circular food supply chain process is proposed. This model includes generation nodes, collection and classification centers, reuse points, third-party recycling centers, treatment and recycling centers, fertilizer companies, biodiesel producers, landfill sites and incineration facilities for the circular food supply chain systems of municipalities. Six different types of food and food-related wastes are identified in the network model of the circular food supply chain process: preparation waste (not edible) (w_1), serving waste (not edible) (w_2), edible serving waste (w_3), plate waste (edible for animals) (w_4), bottle, plastic/metal products, napkins/paper (w_5) and oil (w_6). Then, a MILP model is implemented in two real-life case studies to demonstrate the use of the model in small and large circumstances. In both instances, the model aims to collect and distribute the maximum amount of food waste and minimize the total cost using the AUGMECON2 method. The Pareto-optimal sets for both cases show that the municipalities can manage their circular food supply chain processes under different budget scenarios.

As a result of the study, it is determined that w_5 type of waste is the first to be collected among all waste types; it is directly transferred to third-party recycling centers from the collection nodes; it does not incur any cost. On the other hand, w_6 is the last waste type to be collected due to the high fixed cost to process w_6 and its production losses. The preferred collection order of waste types is identified asw_5,w_2,w_1,w_4, w_3 and w_6. However, the entire amount of generated wastes cannot be collected due to capacity limitations at the downstream nodes. In the no-budget scenario, the entire amount of onlyw_1,w_2,w_5, and w_6 are collected. The entire amount of w_4 types were only collected in the large case study. It is noted that the Pareto-optimal set of the Bornova study is less uniformly distributed than the Izmir study due to the limited number of available facilities.

This study provides valuable information for policymakers, managers and stakeholders. Implementation of the model proposed in the study will ensure an effective circular food supply chain management, i.e., food logistics. The results obtained in this study facilitate new arrangements regarding collection and distribution and making decisions about which waste type should be increased. In other words, it is expected that the adaptation of the lessons learned from these case studies to the problems faced by policymakers, managers and stakeholders will contribute to a better evaluation of food and food-related waste within the framework of the circular economy.

As a limitation of the study, the generation nodes produce the food and food-related waste deterministically on a daily basis. For future studies;

- Stochastic waste generation processes can be considered. As another limitation, the prioritization of food and food-related waste is considered equal in this study.
- Based on the theoretical contribution proposed in the study, studies on the network model can be made in more depth.
- As another future research direction, the priorities of food and food-related waste can be differentiated; more realistic results can be obtained for municipalities.
- Finally, the proposed model from this study can be used for not only food and food-related wastes but also other types of waste.

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