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Research Article

Designing A Sustainable Waste Chain Network for Banana Farm Under Uncertainty: A Case Study

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Abstract

In recent years, due to the significant increase in global food demand, waste management in the agri-food industry has emerged as a major and complex challenge. The literature review indicates a significant gap in research, as no prior studies have investigated the waste chain configuration problem for banana farms specifically. Consequently, this study aims to address this gap by focusing on designing an efficient waste chain system for banana farms, incorporating all three pillars of sustainability—financial, social, and environmental. Waste produced in banana farms after harvesting can be repurposed in various industries, including energy production, compost manufacturing, and animal feed. Therefore, this research proposes a multi-objective mathematical model to optimize sustainability goals. Additionally, to address uncertainties in the model, the Robust Fuzzy Optimization (RFO) method is applied. Next, the study introduces a novel solution approach named stochastic Chebyshev Multi-Choice Goal Programming with Utility Function (CMCGP-UF) and tests it using a real-world case study. The results demonstrate both the effectiveness and efficiency of the developed method. Moreover, the results of the sensitivity analysis show that the total profit has decreased by increasing the capacity of facilities while the environmental impacts have decreased. Moreover, the achieved results indicate that increasing the rate of recyclable waste has a positive impact on the total profits and social impacts while has a negative impact on Z2.

Keywords: Waste Chain Configuration; Agri-food Waste Management; Sustainability; Banana Farm; Goal Programming

1. Introduction

The agri-food industry is vital to today's world as it serves as the backbone of global food security, economic stability, and sustainable development. It encompasses the entire food production process, from farming and processing to distribution and consumption (Rațu et al., 2023). This sector not only provides essential nourishment to billions of people but also generates significant employment opportunities and drives economic growth in many regions (Nath et al., 2024). In this context, waste management in the agri-food industry is vital for promoting environmental sustainability, enhancing economic efficiency, and ensuring food security. By effectively managing waste, businesses can reduce pollution, conserve natural resources, and minimize costs associated with disposal and treatment. This not only helps in complying with environmental regulations but also fosters innovation through the recovery of valuable by-products, such as compost or bioenergy. By effectively managing the waste, businesses can reduce their ecological footprint, promote circular economy practices, and improve their overall operational efficiency (Mehmood et al., 2021).

Bananas are one of the most widely consumed fruits globally, playing a crucial role in the agri-food industry due to their nutritional value, economic significance, and versatility. Rich in essential vitamins and minerals, bananas contribute to food security and provide a vital source of income for millions of smallholder farmers, particularly in tropical regions. The banana industry supports extensive supply chains, from cultivation to distribution, and is a key export product for many countries, driving economic growth and employment. Waste management is critical in the banana supply chain, especially during the harvest process. In this regard, after harvesting the fruit bunch, huge plant bio-waste is generated, out of which pseudo-stem (30-34%), flower and bracts (5%) and rhizome (12-14%) together contribute 50 percent of the banana plant (Alzate Acevedo et al., 2021). This waste can be utilized in different fields such as manufacturing compost, animal feed and generating energy.

In recent years, the importance of the sustainability concept has been dramatically increased (Adisa et al., 2024). Overall, sustainability refers to the practice of meeting present needs without compromising the ability of future generations to meet their own needs. It encompasses a balanced approach to economic growth, environmental protection, and social equity, aiming to create systems that are resilient and regenerative (Nayeri et al., 2020; Sazvar et al., 2022). The importance of sustainability lies in its potential to address pressing global challenges such as climate change, resource depletion, and social inequality. By promoting sustainable

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*Corresponding author Email address: f.rezaei.zeynali@gmail.com practices, we can ensure the responsible use of natural resources, protect ecosystems, and foster communities that thrive economically and socially (Abulibdeh et al., 2024).

In the field of agri-food waste chain configuration, especially by considering the sustainability dimensions, in the literature, several works have been published, some of the most related of them are reviewed in the following. For example, (Chauhan et al., 2018) focused on the agri-food waste management problem by considering the sustainability dimensions. For this purpose, the authors employed the interpretive structural modelling approach for determining the drivers for sustainable agri-food waste management. According to the achieved results, training and awareness programs and information dissemination were the vital drivers. (Cicculo et al., 2021) investigated the agri-food waste management problem by considering the circular economy aspect. In this way, they examined the role of technologies for the food waste prevention. (Gholian-Jouybari et al., 2023) studied the reverse logistics for the agri-food supply chain based on the circular economy metrics for soy products. The authors suggested a mixed-integer model that optimized the sustainability dimensions. Moreover, the authors solved the proposed model using metaheuristic algorithms. (Perdana et al., 2023) addressed the role of circular economy in the waste management problem for the agri-food industry. In this regard, the authors attempted to examine how governance supports can help to maximize agricultural waste and minimize food loss. (Kumar et al., 2024) investigated the approaches for decreasing agricultural waste based on the sustainable development pillars. The authors suggest approaches like crop rotation, integrated pest management, and organic farming techniques to minimize chemical inputs and optimize resource usage. (Hernandez et al., 2024) focused on the sustainable agriculture waste management using the artificial intelligence tools. To this end, the authors analyzed data from various case studies and conducted a comprehensive literature review. Their results demonstrated that using artificial intelligence could significantly improve resource optimization, cost reduction, and operational efficiency. (Tran et al., 2024) studied agricultural waste collection and transport network design problem. For this purpose, the authors proposed a mathematical programming model that minimized collection cost, establishment cost, and transportation cost, and tried to stop burning waste and use the waste to produce bio-organic fertilizer.

Despite the efforts of researchers for publishing the papers in the field of agri-food logistics configuration problem, there is no academic work that focused on the banana waste chain network configuration, especially with the sustainability pillars. In this regard, the current work proposes a multi-objective mathematical programming model to design a waste chain network for the banana. Also, to deal with uncertainty, this research uses the RFO method. Finally, the proposed model is solved by developing a novel solution approach named stochastic CMCGP-UF. All in all, this study contributes to the literature by focusing on the waste chain configuration problem for banana based on the sustainability pillars under uncertainty for the first time. The main novelties of this research are as follows: (i) designing a waste chain for the banana farms based on the sustainable development pillars, and (ii) developing a new and efficient solution procedure to solve the research problem.

In this work, the problem definition and mathematical model are presented in Section 2. Uncertainty modeling is provided in Section 3. Solution approach is presented in Section 4. Numerical results are presented in Section 5. Eventually, conclusions are provided in Section 6.

2. Problem Definition and Mathematical Model

As aforementioned, this research focuses on configuring a waste chain network for the banana by considering the sustainability dimensions. The considered waste chain consists of six echelons including Banana farms as waste generation points, collection centers (CCs), recycling centers (RCs), animal husbandry (AH), demand points for energy (DE), and demand points for compost (DC) (see Figure 1). In this regard, after collecting the generated waste in farms by CCs, they inspected in this center. The percentage of the collected waste that can be recycled are shipped to the recycling centers and the others are sent to animal husbandry. In the recycling centers, the percentage of waste that has been converted to compost are sent to DCs and the percentage of waste that has been converted to energy are sent to DEs. In this work, the sustainability concept has been considered based on the following points: (i) the financial aspect is considered by minimizing the total cost as a objective function, (ii) the environmental impacts are considered by minimizing the total GHG emitted by the recycling and transportation activities, and (iii) the social impacts are incorporated by maximizing the number of created job opportunities.

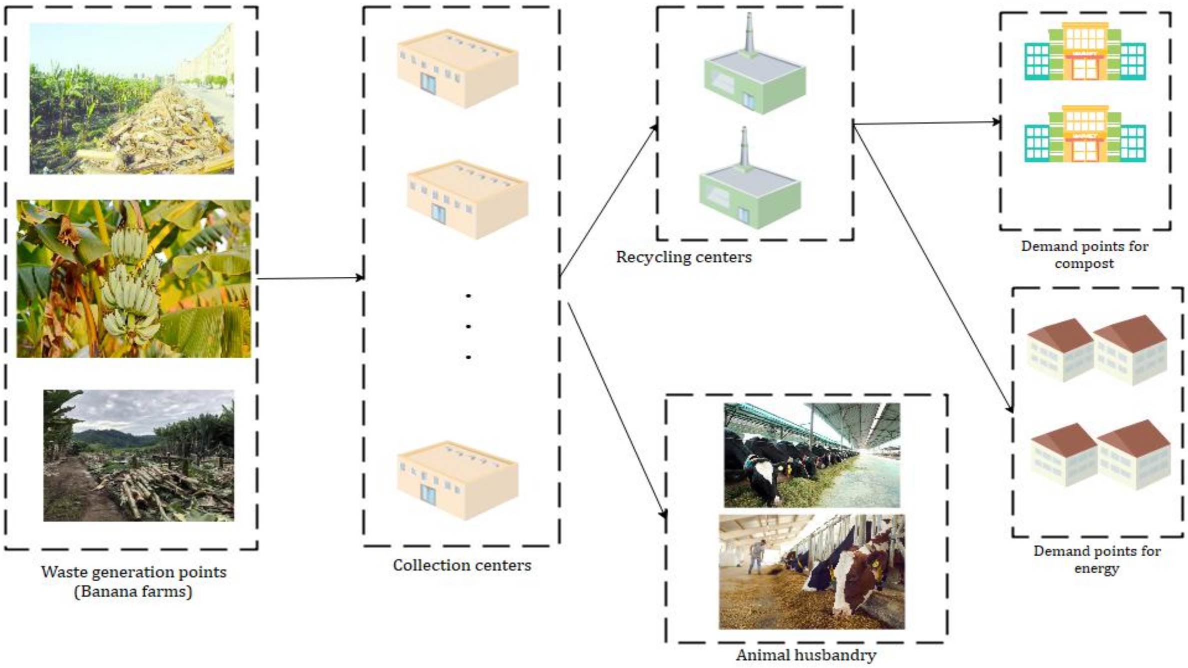

Fig. 1. The configured waste chain

In the following, the required notations for the mathematical model are presented.

Indices

f	Index of banana farms
i	index of CCs
r	index of RCs
j	Index of DCs
k	Index of DEs
q	Index of AHs
t	Index of periods

Parameters

$\widetilde{BWQ}_{ft}$	The quantity of generated waste in farm f in period t
$\widetilde{BC}_{ft}$	The waste collection cost from farm f in period t
$\widetilde{CF}_{i}$	The cost of opening collection center i
$\widetilde{RF}_{r}$	The cost of opening recycling center r
$\widetilde{RO}_{rt}$	The operational cost in RC r in period t
$\widetilde{CSH}_{jt}$	The cost of shortage of compost in DC j in period t
$\widetilde{ESH}_{kt}$	The cost of shortage of compost in DE k in period t
$\widetilde{ASH}_{qt}$	The cost of shortage of compost in AH q in period t
$\widetilde{TC}_{t}$	The unit of transportation cost in period t
$\widetilde{PC}_{jt}$	The selling price of compost in DC j
$\widetilde{PE}_{kt}$	The selling price of energy in DE k
$\widetilde{PA}_{qt}$	The selling price of collected waste in AH q
$CapR_{r}$	The capacity of RC r
$CapC_{i}$	The capacity of CC c
$\widetilde{EED}_{kt}$	The demand for energy in DE k
$\widetilde{CED}_{jt}$	The demand for compost in DC j
$\widetilde{AED}_{qt}$	The demand for fodder in AH q
$Dis_{ff'}$	Distance between nodes f and f',(f and $f' \in \{f,i,j,r,k\}$)
μ_{t}	The percentage of recyclable collected waste in period t
ρ_{t}	The rate of converting the collected waste to compost in period t

β_t	The rate of converting the collected waste to energy in period t
$\widetilde{EIT}_t$	GHG emitted by the transportation activities in period t
$\widetilde{ERC}_t$	GHG emitted by the recycling activities in period t
$\widetilde{CPJ}_i$	The job opportunities created when CC i is opened
$\widetilde{RPJ}_r$	The job opportunities created when RC r is opened
Decision variables	
RR_r	1 if RC r is opened; 0 otherwise
CC_i	1 if CC i is opened; 0 otherwise
WFC_{fit}	The amount of the collected waste shipped between nodes f and i in period t
WCR_{irt}	The amount of the collected waste shipped between nodes i and r in period t
WRC_{rjt}	The amount of compost shipped between nodes r and j in period t
WRE_{rkt}	The amount of energy shipped between nodes r and k in period t
QCA_{iqt}	The amount of the collected waste shipped between nodes i and q in period t
BA_{qt}	The quantity shortage in demand point q in period t
BE_{kt}	The quantity shortage in demand point e in period t
BC_{jt}	The quantity shortage in demand point d in period t

Based on the above-mentioned descriptions, the mathematical model for the research problem can be formulated as follows.

$$
\begin{aligned}
Max\ Z1 = {} & \left(\sum_r\sum_j\sum_t \widetilde{PC}_{jt}.WRC_{rjt} + \sum_r\sum_k\sum_t \widetilde{PE}_{kt}.WRE_{rkt} + \sum_i\sum_q\sum_t \widetilde{PA}_{qt}.QCA_{iqt}\right) \\
& -\Bigg(\sum_r \widetilde{RF}_r.RR_r + \sum_i \widetilde{CF}_i.CC_i + \sum_i\sum_f\sum_t \widetilde{BC}_{ft}.WFC_{fit} \\
& + \sum_i\sum_f\sum_t \widetilde{CO}_{it}.WFC_{fit} + \sum_i\sum_r\sum_t\sum_k \widetilde{RO}_{rt}.(WCR_{irt} + WRE_{rkt}) \\
& + \sum_q\sum_t \widetilde{ASH}_{qt}.BA_{qt} + \sum_k\sum_t \widetilde{ESH}_{kt}.BE_{kt} + \sum_j\sum_t \widetilde{CSH}_{jt}.BC_{jt} \\
& + \sum_t TC_t.\Bigg(\sum_f\sum_i Dis_{fi}.WFC_{fit} + \sum_r\sum_k Dis_{rk}.WRE_{rkt} \\
& + \sum_i\sum_q Dis_{iq}.QCA_{iqt} + \sum_i\sum_r Dis_{ir}.WCR_{irt} + \sum_j\sum_r Dis_{rj}.WRC_{rjt}\Bigg)\Bigg)
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
Min\ Z2 = {} & \sum_i\sum_r\sum_t\sum_k \widetilde{ERC}_t.(WCR_{irt} + WRE_{rkt}) \\
& + \sum_t \widetilde{EIT}_t.\Bigg(\sum_f\sum_i Dis_{fi}.WFC_{fit} + \sum_r\sum_k Dis_{rk}.WRE_{rkt} \\
& + \sum_i\sum_q Dis_{iq}.QCA_{iqt} + \sum_i\sum_r Dis_{ir}.WCR_{irt} + \sum_j\sum_r Dis_{rj}.WRC_{rjt}\Bigg)
\end{aligned} \tag{2}
$$

$$
Max\ Z3 = \sum_r \widetilde{RPJ}_r.RR_r + \sum_i \widetilde{CPJ}_i.CC_i \tag{3}
$$

$$\sum_{i} WFC_{fit} = \widetilde{BWQ}_{ft} \qquad \forall f,t \qquad (4)$$

$$\sum_{r} WCR_{irt} = \sum_{f} \mu_t . WFC_{fit} \qquad \forall i,t \qquad (5)$$

$$\sum_{q} QCA_{iqt} = \sum_{f} (1-\mu_t) . WFC_{fit} \qquad \forall i,t \qquad (6)$$

$$\sum_{i} QCA_{iqt} + BA_{qt} \geq \widetilde{AED}_{qt} \qquad \forall q,t \qquad (7)$$

$$\sum_{j} WRC_{rjt} = \sum_{i} \rho_t . WCR_{irt} \qquad \forall r,t \qquad (8)$$

$$\sum_{r} WRC_{rjt} + BC_{jt} \geq \widetilde{CED}_{jt} \qquad \forall j,t \qquad (9)$$

$$\sum_{k} WRE_{rkt} = \sum_{i} \beta_t . WCR_{irt} \qquad \forall r,t \qquad (10)$$

$$\sum_{r} WRE_{rkt} + BE_{kt} \geq \widetilde{EED}_{kt} \qquad \forall j,t \qquad (11)$$

$$\sum_{r} \sum_{q} \left(WCR_{irt} + QCA_{iqt} \right) \leq CapC_i . CC_i \qquad \forall i,t \qquad (12)$$

$$\sum_{j} \sum_{k} \left(WRC_{rjt} + WRE_{rkt} \right) \leq CapR_r . RR_r \qquad \forall r,t \qquad (13)$$

$$\begin{array}{l} RR_r, CC_i \in \{0,1\}; \\ WFC_{fit}, WCR_{irt}, WRC_{rjt}, WRE_{rkt}, QCA_{iqt}, BA_{qt}, BE_{kt}, BC_{jt} \geq 0 \end{array} \qquad (14)$$

Equation (1) maximized the total profits of the waste chain. Relation (2) minimizes the total environmental impacts and also equation (3) maximizes the social impacts. Constraint (4) shows the amount of waste sent from the farm to the collection center. Constraint (5) calculates the quantity of waste shipped from CCs to RCs. Constraints (6) and (7) compute the quantity of waste shipped from CCs to AHs and the related shortage. Equations (8) and (9) calculate the amount of compost shipped from RC to DC and the related shortage. Relations (10) and (11) compute the amount of energy shipped from RC to DE and the related shortage. Equations (12) and (13) respectively show the capacity constraints for CCs and RCs. Finally, constraint (14) demonstrates the range of decision variables.

3. Uncertainty Modeling

Uncertainty, which is defined as the difference between required data and the amount of available data for doing a task, is one of the critical challenges for logistics managers (Mamashli et al., 2021). In this study, for dealing with uncertainty, we use one of the RFO approach. The main reasons for using this method are that it has been widely used in the literature and showed good performance (see (Foroozesh et al., 2023; Mirzagoltabar et al., 2023; Mondal et al., 2024; Nayeri et al., 2022) and it can efficiently handle the uncertainty using optimality robustness and feasibility robustness concepts. This method is formulated based on the Necessity (Nec), Possibility (Pos) and fuzzy number expected value (Nayeri et al., 2020; Talaei et al., 2016). In the following, we have defined this method briefly. Let $\tilde{\alpha} = \alpha_{(1)}, \alpha_{(2)}, \alpha_{(3)}, \alpha_{(4)}$ is a trapezoidal fuzzy number (TFN). Then, consider the following compact model where $\tilde{c}$ shows the fuzzy coefficient of the objective function, f is the deterministic coefficient of objective function, $\tilde{d}$, $\tilde{L}$, and $\tilde{N}$ are the fuzzy coefficient of constraints, A, B, and S are the deterministic coefficient of constraints, and y and x are the decision variables.

$$\begin{aligned} & Max\ Z = f.y + \tilde{c}.x \\ & A.x \geq \tilde{d} \\ & B.x = \tilde{L} \\ & S.x \leq \tilde{N}.y \end{aligned} \tag{15}$$

Based on the literature, the fuzzy version of Model (15) can be written as Model (16) (Mamashli & Javadian, 2020; Sazvar et al., 2021). In this model, σ_j as the satisfaction level of j-th uncertain constraint.

$$\begin{aligned} & Max\ Z = f.y + \frac{c_1 + c_2 + c_3 + c_4}{4}.x \\ & A.x \geq \left(1 - \sigma_j\right).d_2 + \sigma_j.d_1 \\ & B.x \geq \left(1 - \frac{\sigma_j}{2}\right).\left(\frac{L_1 + L_2}{2}\right) + \left(\frac{\sigma_j}{2}\right).(\frac{L_3 + L_4}{2}) \\ & B.x \leq \left(1 - \frac{\sigma_j}{2}\right).\left(\frac{L_3 + L_4}{2}\right) + \left(\frac{\sigma_j}{2}\right).(\frac{L_1 + L_2}{2}) \\ & S.x \leq \left(\left(1 - \sigma_j\right).N_2 + \sigma_j.N_1\right).y \end{aligned} \tag{16}$$

In the next step, based on the literature, the robust counterpart for the above model can be formulated as Model (17). In this model, π_i shows the penalty cost for the feasibility robustness, η denotes the penalty cost for the optimality robustness, and where $E[Z]$ is the objective function of Model (16). Moreover, $Zmax$ is the worst value of the objective function shown ($Zmax = f.y + c_4.x$).

$$\begin{aligned} Min\ Z = {} & E[Z] + \eta.(Zmax - E[Z]) + \pi_1.\left(d_4 - \left(1 - \alpha_j\right).d_3 + \alpha_j.d_4\right) \\ & + \pi_2.\left(L_4 - \left(1 - \frac{\alpha_j}{2}\right).\left(\frac{L_1 + L_2}{2}\right) + \left(\frac{\alpha_j}{2}\right).(\frac{L_3 + L_4}{2})\right) \\ & + \pi_3.\left(\left(1 - \frac{\alpha_j}{2}\right).\left(\frac{L_3 + L_4}{2}\right) + \left(\frac{\alpha_j}{2}\right).\left(\frac{L_1 + L_2}{2}\right) - L_1\right) \\ & + \pi_4.\left(\left(1 - \alpha_j\right).N_2 + \alpha_j.N_1 - N_1\right) \\ & A.x \geq \left(1 - \alpha_j\right).d_3 + \alpha_j.d_4 \\ & B.x \geq \left(1 - \frac{\alpha_j}{2}\right).\left(\frac{L_1 + L_2}{2}\right) + \left(\frac{\alpha_j}{2}\right).(\frac{L_3 + L_4}{2}) \\ & B.x \leq \left(1 - \frac{\alpha_j}{2}\right).\left(\frac{L_3 + L_4}{2}\right) + \left(\frac{\alpha_j}{2}\right).(\frac{L_1 + L_2}{2}) \\ & S.x \leq \left(\left(1 - \alpha_j\right).N_2 + \alpha_j.N_1\right).y \end{aligned} \tag{17}$$

4. Solution Approach

As aforementioned, this article develops a novel method called stochastic CMCGP-UF to solve the proposed multi-objective model. This approach is the extended version of the recently introduced method (i.e., CMCGP-UF) in which different scenarios are considered for the weights and deviations. In this section, at the outset, we present the CMCGP-UF and then develop the new approach. CMCGP-UF is a recently developed method suggested by (Nayeri, Khoei, et al., 2023). The main advantages of this approach are as follows: (i) incorporating decision makers' preference, (ii) considering multiple aspiration levels, (ii) incorporating both equity (achieving the most balanced solution) and efficiency (maximizing the aggregate achievement) dimensions, and (iv) applying a linear utility function. Model (18) demonstrates the formulation of the mentioned method. In this model, the mathematical formulation of k-th objective function is shown by $f_k(X)$, a continuous decision variable is denoted by y_k, the negative deviation of y_k from $f_k(X)$ is demonstrated by d_k^-, the negative deviation of y_k from $f_k(X)$ is represented by d_k^+, the lower and upper bound of aspiration level are respectively denoted by $U_{k,min}$ and $U_{k,max}$, the normalized deviation of y_k from $U_{k,min}$ is demonstrated by ξ_k^-, the weight of ξ_k^- is represented by w_k^{ξ}, D is the maximum value for deviations, the weight of deviations is shown by w_k^d, and the utility value is demonstrated by λ_k.

$$
\begin{array}{ll}
\text{minimize } \left[\eta D + (1-\eta)\left(\sum_{k}\left[w_k^d(d_k^+ + d_k^-) + w_k^{\xi}.\xi_k^-\right]\right)\right] & \\
\text{Subject to} & \\
f_k(X) + d_k^- - d_k^+ = y_k & \forall\, k \\
w_k^d(d_k^+ + d_k^-) + w_k^{\xi}\xi_k^- \leq D & \forall\, k \\
\lambda_k \leq \dfrac{U_{k,max} - y_k}{U_{k,max} - U_{k,min}} & \forall\, k \\
U_{k,min} \leq y_k \leq U_{k,max} & \forall\, k \\
\lambda_k + \xi_k^- = 1 & \forall\, k \\
d_k^+ , d_k^- , y_k , \eta_k , \xi_k^- \geq 0 & \forall\, k
\end{array}
\qquad (18)
$$

Besides all merits of this method, this is a deterministic approach and its drawback leads to reducing the flexibility of the method (Nayeri, Sazvar, et al., 2023). In this regard, to enhance the performance of CMCGP-UF, the current study aims at developing its stochastic version. For this purpose, let S shows the set of scenarios indexed by s and P_s is the probability of each scenario. In this regard, y_k, $U_{k,max}$, $U_{k,min}$, d_k^+, d_k^-, ξ_k^-, and λ_k, are converted to the scenario-based parameters and variables. Therefore, the formulation of the stochastic CMCGP-UF are as follows (Model (19)).

$$
\begin{array}{ll}
\text{minimize } \left[\eta D + (1-\eta)\left(\sum_{k}\sum_{s} P_s.\left[w_k^d(d_{ks}^+ + d_{ks}^-) + w_k^{\xi}.\xi_{ks}^-\right]\right)\right] & \\
\text{Subject to} & \\
f_k(X) + d_{ks}^- - d_{ks}^+ = y_{ks} & \forall\, k,s \\
w_k^d(d_k^+ + d_k^-) + w_k^{\xi}\xi_{ks}^- \leq D & \forall\, k,s \\
\lambda_{ks} \leq \dfrac{U_{ks,max} - y_{ks}}{U_{ks,max} - U_{ks,min}} & \forall\, k,s \\
U_{ks,min} \leq y_{ks} \leq U_{ks,max} & \forall\, k,s \\
\lambda_{ks} + \xi_{ks}^- = 1 & \forall\, k,s \\
d_{ks}^+ , d_{ks}^- , y_{ks} , \xi_{ks}^-, D \geq 0 & \forall\, k,s
\end{array}
\qquad (19)
$$

It should be noted that this method can be normalized (if required) using relation (20) and (21) where f_k^{max} is the maximum value of the k-th objective function and f_k^{min} shows the minimum value of the k-th objective function.

$$
\sum_{k}\left[w_k^d\left(\frac{d_{ks}^+ + d_{ks}^-}{f_k^{max} - f_k^{min}}\right) + w_k^{\xi}.\xi_{ks}^-\right] \qquad (20)
$$

$$
w_k^d\left(\frac{d_{ks}^+ + d_{ks}^-}{f_k^{max} - f_k^{min}}\right) + w_k^{\xi}\xi_{ks}^- \leq D \qquad (21)
$$

5. Numerical results

5.1. Case study and input data

This study focuses on the agriculture waste management problem. in this regard, The main motivations to study agricultural waste management stem from the pressing need to protect the environment and promote sustainability in farming practices. Agricultural waste, if not managed properly, can lead to significant environmental degradation, including soil contamination, water pollution, and greenhouse gas emissions. By understanding and addressing these issues, researchers and practitioners can develop strategies that minimize the negative impacts of agricultural waste on ecosystems. This is crucial for maintaining biodiversity, preserving natural resources, and ensuring that agricultural practices do not compromise the health of the environment for future generations. Additionally, effective agricultural waste management presents economic opportunities and enhances food security. By repurposing waste materials into valuable resources such as compost, bioenergy, or animal feed, farmers can reduce disposal costs while creating new revenue streams. This not only improves the profitability of agricultural operations but also contributes to a circular economy where resources are reused rather than discarded. Furthermore, reducing waste enhances overall agricultural productivity, which is vital for meeting the growing global demand for food. In this context, studying agricultural waste management is essential for fostering sustainable practices that benefit both the economy and society as a whole. As aforementioned, this study considers a case study in Iran. In this regard, Chabahar is one of the most spectacular cities in Iran. Due to its ideal climate, this city has the best banana farms in Iran. In recent years, about 8,000 hectares of Sistan and Balochistan farms have been devoted to the cultivation of tropical fruits, including bananas. According to the statistics of the Ministry of Agriculture of Iran, the first rank of banana production in Iran is given to Sistan and Baluchistan province. Due to the benefit of this province from the humidity of the sea and also being close to the equator, Sistan and Baluchistan has a good potential in producing tropical products. In this research, we consider eight farms (waste generation points), five potential locations for establishing the collection centers, three potential points for opening the recycling centers, five animal husbandries, three demand points for energy (DE), five demand points for compost (DC), and nine period. Moreover, the values of the fuzzy parameters are presented in Table 1. Also, Table 2 shows the percentage of recyclable collected waste, rate of converting the collected waste to compost, and the rate of converting the collected waste to energy.

Table 1
The values of the fuzzy parameters

Parameter	$Value$			
	α_1	α_2	α_3	α_4
$\widetilde{CF}_i$ (Million Toman)	$U[100\ 150]$	$U[150\ 200]$	$U[200\ 250]$	$U[250\ 300]$
$\widetilde{RF}_r$ (Million Toman)	$U[350\ 400]$	$U[400\ 450]$	$U[450\ 500]$	$U[500\ 550]$
$\widetilde{BC}_{ft}$ (Toman)	$U[50\ 100]$	$U[150\ 200]$	$U[250\ 300]$	$U[300\ 350]$
$\widetilde{BWQ}_{ft}$(Ton)	$U[60\ 80]$	$U[80\ 100]$	$U[100\ 120]$	$U[120\ 140]$
$\widetilde{TC}_t$ ((Toman/Ton − Km))	$U[0.115\ 0.120]$	$U[0.020\ 0.125]$	$U[0.125\ 0.130]$	$U[0.130\ 0.135]$
$\widetilde{EIT}_t$	$U[0.035\ 0.040]$	$U[0.040\ 0.050]$	$U[0.050\ 0.060]$	$U[0.060\ 0.070]$
$\widetilde{CPJ}_i$	$DU[20\ 25]$	$DU[25\ 30]$	$DU[30\ 35]$	$DU[35\ 40]$
$\widetilde{RPJ}_r$	$DU[30\ 35]$	$DU[35\ 40]$	$DU[45\ 50]$	$DU[50\ 55]$

Table 2
The values of other parameters

Parameter	$Value$
μ_t	$U[0.6\ 0.8]$
ρ_t	$U[0.4\ 0.6]$
β_t	$U[0.4\ 0.6]$

5.2. Computational results

In this section, the results of solving the suggested multi-objective model using the developed solution method are presented. In this regard, we consider three scenarios named the pessimistic ($P_1 = 0.25$), most likely ($P_2 = 0.50$) and optimistic ($P_3 = 0.25$) for the developed solution method. In this regard, the values of $U_{ks,min}$ and $U_{ks,max}$ for each objective function in each scenario have been presented in Table 3. Eventually, the final results are shown in Table 4. According to this figure, the value of the first objective function is equal to 9251136.3, the value of the second objective function is equal to 275.7, and the value of the third objective function is equal to 175. Moreover, the obtained outputs demonstrate that recycling centers #1 and #3 have been opened. Also, based in the results, collection centers #2, #4, and #5 have been established.

Table 3
The values of $U_{ks,min}$ and $U_{ks,max}$

Objective function	**Aspiration level**	**Scenario**		
		$S1$	$S2$	$S3$
$Z1$	$U_{ks,min}$	9926380.89	9350650.80	8864258.13
	$U_{ks,max}$	31764418.85	31792212.71	31911329.29
$Z2$	$U_{ks,min}$	305.5	275.3	261.6
	$U_{ks,max}$	733.2	798.4	654.0
$Z3$	$U_{ks,min}$	0	0	0
	$U_{ks,max}$	149	170	184

Table 4
The results of solving the proposed model

Variable	Value
$Z1$	9251136.3
$Z2$	275.7
$Z3$	175
RR_1	1
RR_3	1
CC_2	1
CC_4	1
CC_5	1

5.3. Sensitivity analysis

5.3.1. Capacity

Since capacity is one of the key parameters of the proposed model, in this section, we conduct a sensitivity analysis to observe its impact on the outputs. For this purpose, the suggested model is solved by considering various values for the capacity. In this way, Figure 2 depicts the outputs of the sensitivity analysis for the first objective function. As shown in this figure, increasing the capacity has a significant positive impact on the first objective function. Additionally, Figure 3 shows the changes in the second objective function according to changes in the capacity parameter. This figure indicates that by increasing the capacity parameter, Z2 has decreased. Eventually, Figure 4 illustrates the behavior of the third objective function due to changing the capacity parameter. Based on the results, by increasing the capacity parameter, Z3 has decreased.

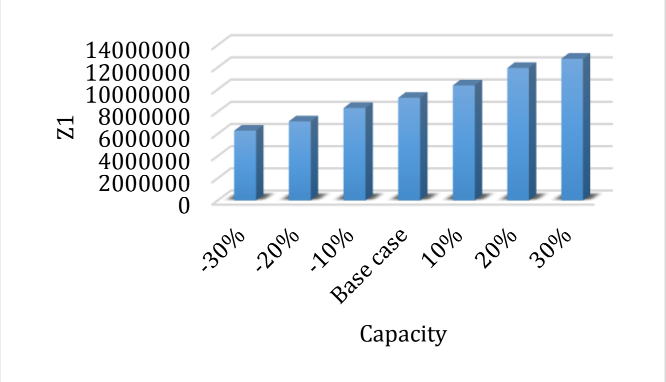

Fig. 2. Changes in Z1 due to changing the capacity parameter

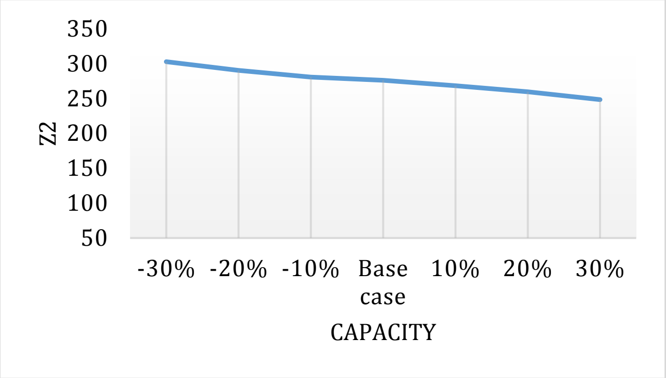

Fig. 3. Changes in Z2 due to changing the capacity parameter

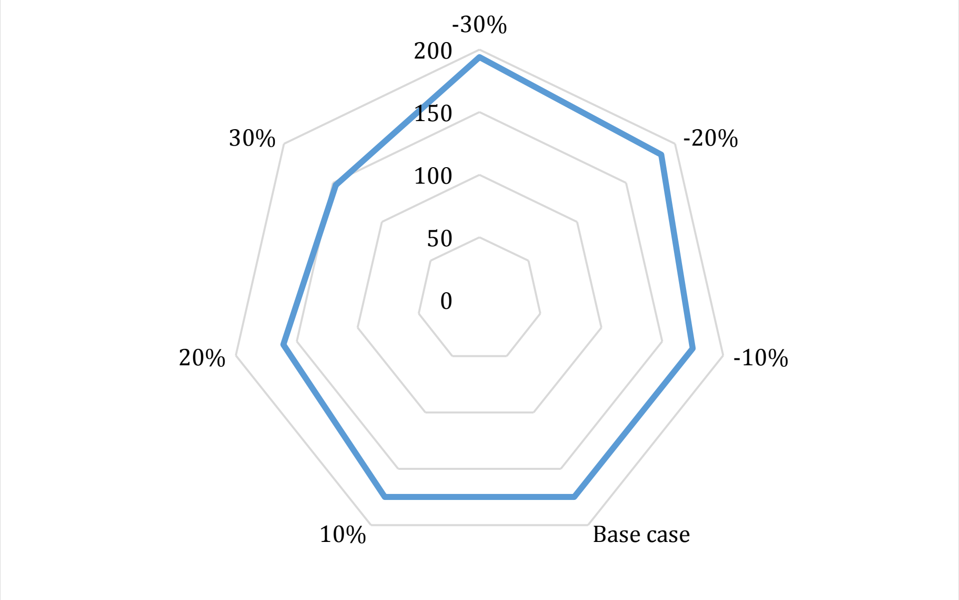

Fig. 4. Changes in Z3 due to changing the capacity parameter

5.3.2. Rate of recyclable waste

To observe the role of μ_t in the research problem, a sensitivity analysis has been conducted in this section. In this regard, by considering different values for μ_t, the suggested model is solved and the achieved results have been shown in Figure 5. As can be seen in Figure 5, when μ_t has increased, all objective functions have increased, too. Indeed, increasing μ_t has a positive impact on Z1 and Z3 while has a negative impact on Z2. S

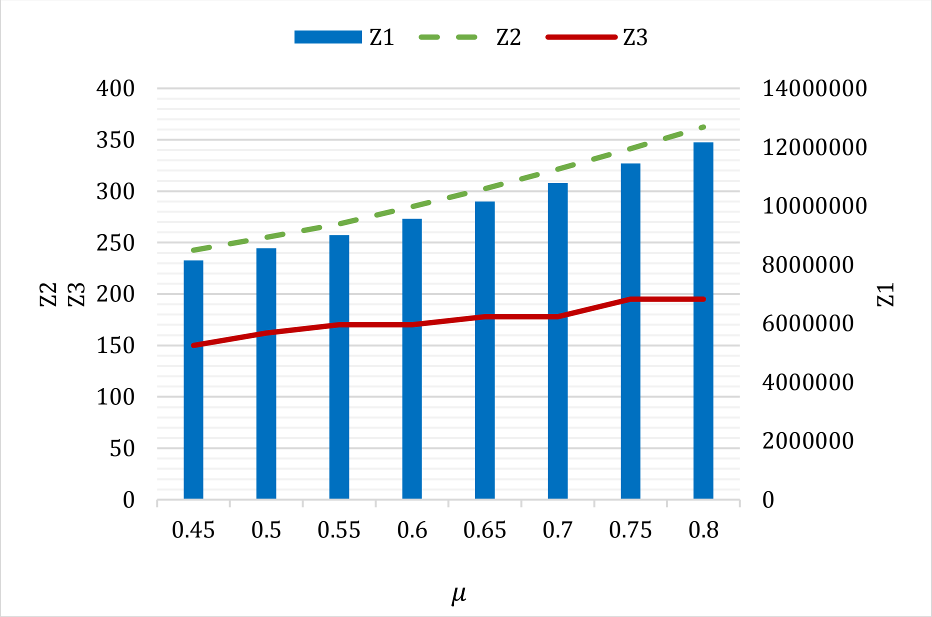

Fig. 5. The behavior of the research problem due to changing μ_t

5.3.3. Robustness analysis

In this section, a sensitivity analysis has been conducted on the robust penalty cost. In this regard, by considering different values for the π_i parameter, the value of the total cost and the related penalty cost are analyzed. The achieved outputs are depicted in Figure 6. According to the outcomes, when the π has increased, the total cost has risen too. However, by increasing π, the total penalty cost has reduced. Actually, the results indicate that increasing the π parameter leads to ding the feasible solution space but increasing the total costs. Indeed, the expected total penalty cost (model robustness) has reduced by raising π while the expected total cost (the solution robustness) has increased.

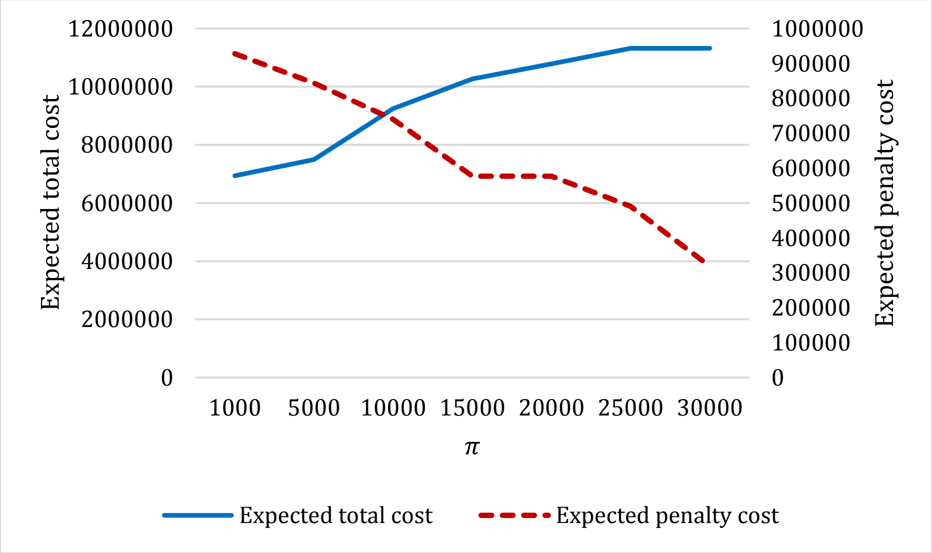

Fig. 6. The results of sensitivity analysis on π

5.4. Performance of the Developed Stochastic CMCGP-UF

In this section, the effectiveness of the developed solution approach is examined. In this way, we generate several test problems and solve them using the CMCGP-UF and the developed stochastic CMCGP-UF (SCMCGP-UF), and compare their results. In this regard, Table 5 presents the values of the objective functions of two methods. As shown in this figure, the developed method outperforms the traditional method because its objective function (total deviations) is less than the CMCGP-UF method in all instances

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Table 5
Comparing the results of the CMCGP-UF and the developed SCMCGP-UF

Test problem	CMCGP-UF	SCMCGP-UF
1	0.284	0.267
2	0.392	0.385
3	0.573	0.528
4	0.748	0.716
5	0.943	0.925
6	1.18	1.09
Average	0.6866	0.6518

5.5. Managerial Insights

Sustainable waste management in the agri-food industry is essential for minimizing environmental impact while maximizing resource efficiency. The sector generates significant amounts of organic waste, including crop residues, food processing by-products, and unsold produce. To address these challenges, managers must adopt a holistic approach that integrates waste reduction strategies across the supply chain. This includes implementing practices such as precision agriculture to optimize input use, enhancing storage and transportation methods to reduce spoilage, and fostering partnerships with local organizations for food recovery initiatives. Another critical aspect of sustainable waste management involves the adoption of circular economy principles. This means transforming waste into valuable resources rather than viewing it as a burden. For instance, agri-food businesses can explore opportunities for composting organic waste or converting it into bioenergy through anaerobic digestion. By investing in technologies that facilitate these processes, managers can create new revenue streams while contributing to soil health and energy sustainability. Furthermore, promoting a culture of innovation within the organization can encourage employees to identify and implement creative solutions for waste repurposing. This research can provide a good perspective to agri-food industry managers to configure efficient waste chain networks for reducing the environmental impacts and also earning revenue from the collected waste.

5.6. Theoretical implications

In addition to the managerial insights, the theoretical implications of each academic article are critically important. In this regard, the main theoretical implication of this study is related to investigating the circular economy-based waste management problem for the Banana farms for the first time. In this regard, investigating circular economy-based waste management in banana farms has significant theoretical implications that extend our understanding of sustainability in agricultural practices. First, it challenges the traditional linear model of waste management, which typically emphasizes disposal and waste reduction. By adopting a circular economy framework, researchers can explore how agricultural waste can be transformed into valuable resources, thus promoting a more holistic view of resource utilization. This shift in perspective encourages the development of innovative practices that not only minimize waste but also enhance the overall efficiency of agricultural systems. The theoretical exploration of these practices can lead to new models that integrate waste management with production processes, fostering a more sustainable approach to agriculture. Second, this investigation contributes to the body of knowledge surrounding ecosystem services and their role in agricultural productivity. By examining how banana farm waste can be repurposed, such as through composting or biogas production, researchers can better understand the ecological benefits derived from waste management practices. This includes improved soil health, increased biodiversity, and reduced greenhouse gas emissions. The theoretical implications here extend to the broader discourse on agroecology and sustainable farming, as they highlight the interconnectedness of agricultural practices and environmental health. Such insights can inform policy decisions and guide future research on sustainable agricultural systems.

6. Conclusions and Future Directions

Sustainable agri-food waste management is important in today’s world because it minimizes environmental impact, conserves resources, reduces greenhouse gas emissions, enhances soil health, and promotes circular economy practices. Therefore, the current study addressed the waste chain configuration problem for banana farms with sustainable development pillars under uncertainty. To this end, this work suggested a multi-objective mathematical model that optimized the sustainability dimensions. Then, to tackle the uncertainty, this study used an efficient approach called RFO. Also, to solve the suggested multi-objective model, this article developed a new solution method named stochastic CMCGP-UF. It should be noted that this study focused in a real-world case study in Iran. The obtained results showed that increasing the capacity parameter has a significant positive impact on the total profits and GHG emissions objective functions. Also, based on the achieved results, by increasing the rate of recyclable waste, the total profit has increased. Moreover, the outcomes demonstrated the efficiency and effectiveness of the developed solution method. Future studies can add other crucial dimensions like resilience and digitalization to the current work. Also, developing data-driven approaches by combining data mining and optimization methods to deal with uncertainty is another direction for future papers. Additionally, future researchers can develop metaheuristic algorithms to solve the proposed model on large-scale instances in a reasonable time.

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