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Decision Analysis

A comprehensive approach to the feasibility assessment of on-campus food waste composting

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Abstract

Food waste management is increasingly being emphasized globally due to its economic and environmental impacts and strategic transformation towards sustainability. This can be observed from the increasing number of zero food waste (ZFW) initiatives that are being adopted by communities and institutions, including universities. Food waste composting, in particular, is increasingly being used for food waste recovery on university campuses. Campus sustainability managers are often challenged with the interrelated impacts of economic and noneconomic factors when selecting a composting system and the sensitivity and risks involved in such a decision. Reviewed research highlights the need for a comprehensive assessment of economic and operational feasibility in order to adopt an effective on-campus food waste composting system. This paper presents a methodological framework for assessing the feasibility of on-campus food waste composting systems. In addition to the composting project's economic feasibility, the framework utilizes the analytical hierarchy process to integrate non-economic criteria into the assessment of composting alternatives. The framework then analyzes the sensitivity of the present worth of each composting system to projected changes in the economic parameters used. The framework also models the impacts of variability in the operational parameters of the composting system. Assessment values are then integrated into a normalized ranking of the alternative composting systems. The framework is illustrated through the assessment of three alternatives for installing on-campus food composters in a major university. The results provide insight and guidelines for adopting economically effective food waste recovery systems and ZFW initiatives for green and sustainable university campuses. *Integr Environ Assess Manag* 2022;18:964–977. © 2021 SETAC

KEYWORDS: Analytical hierarchy process, Campus sustainability, Economic feasibility, Food waste composting, Sensitivity analysis

INTRODUCTION

Societies, corporations, and academic institutions around the world are witnessing increasing amounts of food waste. This is mainly the result of the growing demand on ready-to-eat meals and fast food, excessive food purchases, and ineffective food processing and consumption practices (FAO, 2020). As explained by Pichtel (2005), this has significantly increased the cost of solid waste collection and disposal and, consequently, contributed to pollution (i.e., greenhouse gas emissions) and the scarcity of natural resources (i.e., water, soil, energy). This phenomenon has developed into a global challenge, as observed from data reported on the economic and environmental impacts of disposing of food waste in landfills (EPA, 2018; FAO, 2020; World Bank Group, 2019).

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Food waste management is increasingly emphasized by various sectors of the economy as an effective approach to food waste recovery and recycling. Such an approach has demonstrated economic savings and payback through reduced waste, generated energy, and reduced environmental burden (Ng et al., 2020). This is evident from the various zero food waste (ZFW) initiatives that are increasingly being adopted by municipalities, communities, and academic institutions (Gustavsson et al., 2011). The overall objective of such initiatives is to support the effort of adopting green solutions and attaining sustainability in line with the global trend of circular economy (Slorach et al., 2020b).

University campuses, in particular, consume a large amount of food and generate a substantial amount of food waste (Alias et al., 2017). Wulansari et al. (2019) emphasized food waste as a primary component of solid waste on university campuses. Several other studies attempted to assess the amount and impacts of on-campus food waste. For example, Vázquez et al. (2020) estimated that the amount of biowaste generated by university canteens in the University

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of A Coruña (UDC), Spain, varies between 6 and 100 kg/day. Abdelaal et al. (2019) also analyzed quantitatively and qualitatively the food waste generated at various food outlets on a university campus in Qatar. They emphasized that most of the waste was avoidable. In an earlier study, Danielle et al. (2010) found that more than 70% of on-campus solid waste could have been diverted through waste reduction, recycling, and composting activities.

Several universities have established offices for campus sustainability and initiated projects for food waste recycling and recovery (i.e., closed-loop food processing; Waliczek et al., 2016) to replace traditional food waste treatment (e.g., landfill and incineration). As discussed in Kwon (2009), sustainability offices in universities have emphasized the need for alternative treatment of food waste and for converting food waste into value-added products, such as fertilizers, sources of energy, compost, and soil enhancers. A common example of these systems is food waste composting (Awasthi et al., 2020). Vázquez et al. (2020) estimated that compostable biowaste can vary widely from 17% to 60% of total campus solid waste. Several other studies addressed the environmental and economic feasibility of these systems including household food waste treatment (Slorach et al., 2020a), on-site food composting (Guo et al., 2020), and centralized or decentralized community-based and residential waste management (Pai et al., 2019).

However, the economic feasibility of ZFW initiatives continues to be a common concern to universities. Reviewed literature revealed few studies that characterized on-campus food waste (Vázquez et al., 2020). As detailed in the Review of Related Literature section, these studies recommended composting for food waste recovery and recycling but did not propose a comprehensive approach to assessing the economic feasibility of on-campus food composting. Cost–benefit analysis (CBA; e.g., Mu et al., 2017) and life cycle assessment (LCA; e.g., Ascher et al., 2020) are the approaches commonly used to assess the economic feasibility of food recovery systems. In addition to CBA and LCA, another group of studies utilized multi-criteria decision analysis (MCDA), based on the analytical hierarchy process (AHP; e.g., Brenes-Peralta et al., 2020) and mathematical programming (e.g., Lin & Huang, 2019).

Reviewed studies focused mainly on the financial feasibility of composting solutions, with less attention paid to noneconomic criteria and the sensitivity and risks involved in the decision. As discussed in Saer et al. (2013), the comprehensive evaluation of ZFW initiatives should consider both economic and noneconomic factors (e.g., composter specifications, performance, and supplier procurement and support). These criteria affect the economic feasibility of the composting system, directly and indirectly. Over the project life cycle, the economic feasibility of a selected composting system is also sensitive to changes in the economic parameters and the risks caused by variability in its operating conditions. Armington et al. (2020) highlighted the need to address these challenges and analyzed the impacts of variability in commercial and institutional food waste generation on sustainable management systems. Teague (2011) has also emphasized the impacts of variability and risks on the economic feasibility of implementing a food-waste-to-compost program at the University of Arkansas. These assessment aspects were further investigated in the relevant literature in the Review of Related Literature section.

The present paper presents a methodological framework for a comprehensive assessment of the economic feasibility of on-campus food waste composting systems. The framework consists of three phases: literature search and data collection, setup of assessment modules, and selection of the food waste composting system. It integrates financial analysis with AHP to account for economic and noneconomic criteria of the decision. It then analyzes the sensitivity of the food waste composting project to the changes in key economic parameters and estimates the risk caused by the operational variability in the composting system. The framework functionality is illustrated through an assessment of the economic feasibility of installing a composting system on the campus of a major local university in the United Arab Emirates (UAE).

REVIEW OF RELATED LITERATURE

As the economy accelerates and populations grow, food waste also grows in households, communities, and large institutions (Gustavsson et al., 2011). Canteens and cafeterias on university campuses are a common source of food waste that eventually ends up as municipal solid waste. Following the trend of circular economy (Slorach et al., 2020a), this waste should be avoided, reduced, and treated to recover value-added products and resources.

A review of the literature reveals an increasing number of methodological and empirical studies of food waste reduction and recovery. Ng et al. (2020) discussed the recent advances in the sustainable approaches to the conversion and reutilization of food waste to valuable bioproducts. Shangzhen et al. (2018) also presented an overview of the latest research on anaerobic digestion, composting, and other developments in food waste management along with the different technologies used in this industry. This section presents a review of the limited literature on food waste composting in universities and explores the approaches used for its economic assessment. It also positions the research within current literature and highlights its contributions.

On-campus food waste composting

Composting is considered by many researchers as an effective strategy to treat an excessive amount of household and community-based food waste. It is a process that transforms food waste into compost that can be used to generate energy or as fertilizer and soil enrichment. Composters are pieces of equipment used to generate compost from food waste. Further details of composting and composter technologies can be found in Haug (1993).

Awasthi et al. (2020) discussed the changes and global trends in food waste composting. They confirmed that composting can be an economically feasible and reliable technology for food waste recycling. Cerda et al. (2018) also discussed the status and challenges of composting food waste and highlighted the long-term economic benefits of food composting. Several other studies have related food composting to closed-loop food processing and the growing trend of circular economy (Bekchanov & Mirzabaev, 2018).

On university campuses, food composting is increasingly being used as universities start to adopt on-site and community-based initiatives for food waste treatment. The websites of main universities around the globe highlight multiple on-campus green and sustainability projects including food waste composting. However, the peer-reviewed literature includes only a limited number of studies that analyze on-campus food composting. Danielle et al. (2010) studied waste characterization at the Prince George campus of the University of Northern British Columbia (UNBC) to determine the amount and composition of waste generated in key campus operational areas, and provide recommendations on strategies for waste minimization. They highlighted the role of food composting in waste reduction and recycling. Alias et al. (2017) presented a case study of food waste generation and management on a university campus in Malaysia. They identified the type and quantity of waste generated in each cafeteria on the campus and evaluated several methods of food waste management. They recommended composting for food waste management, because a large quantity of waste was produced. Similarly, using focus groups and a national survey, Kwon (2009) studied food waste management in college and university food service operations. Composting was selected as most likely to reduce food waste among food disposal methods in university food service operations. Vázquez et al. (2020) assessed the amount of biowaste generated by university canteens at the University of A Coruña, Spain. They recommended decentralized composting to produce high-quality organic fertilizers for university urban gardens while reducing the environmental burdens of both waste management and agricultural practice. Finally, Dahlawi and El Sharkawy (2021) assessed the solid waste management practices followed at the main campus of a university in Saudi Arabia. Data on the composition of on-campus solid waste samples revealed that 19% of the waste is compostable materials. As the campus has large areas of green landscapes and several gardens, the study strongly recommended establishing an on-campus compost system to reduce the cost of green and food waste disposal and produce large amounts of high-quality compost. Table 1 presents a summary of the on-campus food composting studies reviewed.

Approaches to composting feasibility assessment

Several approaches were used in the literature to assess the economic feasibility of food waste recovery and recycling systems. Cost–benefit analysis and LCA are the approaches commonly used (De Menna et al., 2018). In addition to the costs of environmental impact, CBA and LCA often include costs of capital, maintenance, and production of recycled products. Benefits typically include revenue generated from using and selling food compost, reduced solid waste, and saved energy and water, in addition to improved image and culture. For example, Mu et al. (2017) examined the environmental and economic impacts of the composting system at Kean University in New Jersey, USA. Using CBA, they demonstrated that the composting system could generate a profit by selling vegetables grown with compost to the student cafeteria and to local communities. When educational and environmental benefits were included in the analysis, the generated revenue had increased. They recommended in-vessel composting to be utilized by universities or food markets that generate significant food waste across the United States. Similarly, Edwards et al. (2018) used LCA to compare the environmental impact of seven

TABLE 1 Summary of on-campus food waste composting studies

Article	Campus	Study focus	Recommendation
Danielle et al. (2010)	University of Northern British Columbia (UNBC)	Amount and composition of waste	Food composting for waste reduction and recycling
Alias et al. (2017)	Universiti Tun Hussein Onn Malaysia	Type and quantity of waste	Food composting for large-quantity waste
Kwon (2009)	National Association of College and University Food Services	Food waste management	Food composting to reduce food waste
Vázquez et al. (2020)	University of A Coruña (UDC), Spain	Biowaste assessment	Decentralized food composting to produce high-quality organic fertilizers
Dahlawi and El Sharkawy (2021)	Main university campus, Saudi Arabia	Solid waste management (SWM) practices	On-campus compost system to reduce food waste disposal and produce high-quality compost
Mu et al. (2017)	Kean University, New Jersey	Environmental and economic impacts	In-vessel composting for food markets that generate significant food waste

TABLE 2 Summary of assessment approaches to food waste composting

Used assessment approach	Article	Considered assessment aspects			
		Feasibility	Noneconomic	Sensitivity	Risk
Cost–benefit analysis (CBA)	Mu et al. (2017)	Yes	No	No	No
Life cycle assessment (LCA)	Edwards et al. (2018); Ascher et al. (2020); Cakar et al. (2020); Slorach et al. (2020a); Saer et al. (2013); Cristóbal et al. (2018)	Yes	No	No	No
Analytical hierarchy process (AHP)	Babalola (2015); Brenes-Peralta et al. (2020)	Yes	Yes	No	No

contemporary food waste management systems. Ascher et al. (2020) utilized net present worth analysis to evaluate the economic feasibility of a community-based food waste treatment scheme for Glasgow, UK. They used LCA to evaluate the environmental impacts of the scheme. Cakar et al. (2020) also presented an LCA of the environmental impacts of food waste in Turkey. They calculated embedded carbon, water, and energy footprints throughout the food supply chain. Slorach et al. (2020a) considered the life cycle environmental and economic implications of recovering energy and material resources from food waste. Finally, Cristóbal et al. (2018) presented a study of prioritizing and optimizing sustainable measures for food waste prevention and management according to environmental and economic criteria. They used LCA and mathematical programing to estimate economic measures and used different weighting sets to prioritize food waste prevention plans.

Multi-criteria decision analysis was also used as a common umbrella for selecting and prioritizing food composting systems and ZFW initiatives. In particular, AHP (Saaty, 2008) was adopted as a common MCDA method to account for both economic and noneconomic criteria of the decision. With AHP, decision alternatives and criteria are arranged in a hierarchical structure and pairwise comparisons are established using a numerical scale to assess their relative importance. The AHP then follows a systematic set of steps to assess the relative importance weights of decision criteria and alternatives and synthesize them into a final ranking or prioritization of decision alternatives.

For example, Babalola (2015) used AHP to evaluate different waste management options and their applicability in Japan, including compost. Brenes-Peralta et al. (2020) proposed a decision-making framework to evaluate four food waste-to-energy scenarios based on anaerobic digestion and composting. The framework combines linear programming for route optimization, LCA for cost and environmental impacts, and AHP for prioritizing the alternatives. The evaluation was built on a case study of five universities in Costa Rica. Results favored composting from an ease-of-use perspective. Table 2 presents a summary of approaches used for assessing food waste composting systems in the reviewed articles and identifies the key aspects considered in the assessment.

Some recent studies utilized special approaches beyond CBA, LCA, and MCDA for assessing initiatives for food waste management. For example, Ghinoi et al. (2020) presented a network approach to developing a food waste management system. They analyzed the structure of multiplex relations among stakeholders involved in the network of food waste management systems. Goodman-Smith et al. (2020) presented a mixed-methods study of retail food waste in New Zealand. Lin and Huang (2019) presented a mathematical programming model to trade-off and optimize costs and environmental impacts of food waste recycling. Finally, Judd and Elser (2019) used exploratory research to study personal waste management in higher education. They illustrated how a quadruple bottom line framework (the traditional triple bottom line framework plus educational value) may affect decisions to adopt a sustainability practice in higher education.

Study contributions

This paper contributes to the limited literature on the economic assessment and feasibility of ZFW initiatives, with a focus on food waste composting on university campuses. Reviewed literature includes two groups of studies (summarized in Tables 1 and 2) that discussed the current practice and recent advances in reutilization of food waste on university campuses. As shown in Table 1, reviewed studies have assessed campus food wastes for amount and composition without specifying methods for assessing the economic feasibility of the food composting projects. They collectively recommended composting for on-campus food waste management and emphasized the need to adopt a comprehensive approach to assess its economic feasibility. The same was emphasized by Lim et al. (2019), including the need to consider the sensitivity and risk involved in selecting the composting system. Several studies (e.g., Alias et al., 2017) have also emphasized the economic assessment of food composting systems over their service life while integrating noneconomic factors into the assessment and considering the sensitivity and risks involved in their financial measures.

Table 2 shows that none of the reviewed approaches has addressed all of these assessment aspects. Most approaches assessed the financial feasibility of food composting using CBA and LCA with no consideration of the noneconomic factors and the prospected changes in the key economic factors of the decision. This paper contributes mainly to this research gap. It utilizes AHP to integrate economic and noneconomic selection criteria of the composting system and applies sensitivity analyses to assess the impact of prospected changes in the key economic parameters of the project's worth. Furthermore, the Monte Carlo simulation (MCS) is used to model and assess the risk of operational variability over the service life of the composting system. Finally, the proposed approach integrates these tools into an overall assessment score to prioritize the alternatives to on-campus food waste composting systems.

PROPOSED FRAMEWORK

Figure 1 presents the proposed methodological framework for the economic assessment of food waste composting as a ZFW initiative.

The framework consists of three complementary phases. The first phase includes a literature review of on-campus food composting systems and their economic assessment methods in addition to the collection of data relevant to the food composting project. The collected data includes different types of costs that are essential to initiate and operate the food composting system. This includes capital costs, operating and maintenance costs, and compost production costs (food waste collection, labor, energy, water, and overhead), in addition to the costs of taxes, inflation, and depreciation. Data on expected revenues, savings, and benefits obtained from food waste composting should be

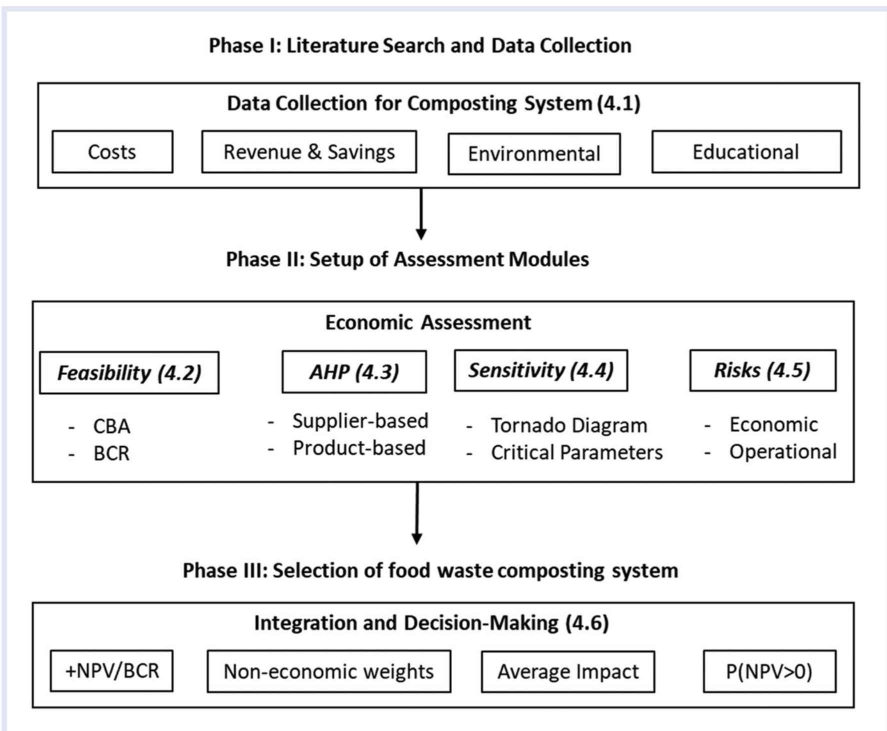

FIGURE 1 Framework for the economic assessment of on-campus food waste composting. AHP, analytical hierarchy process; BCR, benefit-to-cost ratio; CBA, cost–benefit analysis; NPV, net present value

also collected. This includes revenues from selling and using compost, value of energy produced, savings from solid waste reduction, and environmental impacts (reduced emissions and saved water and energy), in addition to intangible educational value (improved green image and university ranking). The economic value of these benefits needs to be estimated on a case-by-case basis for all available food composting options or systems. This necessarily requires the collection of further noneconomic data on the specifications and performance of each composter as well as supplier capacity and after-sales support.

The second phase of the proposed framework focuses on the setup of four assessment modules. First, the CBA is used to assess the economic feasibility based on a cash flow of costs and benefits over the expected service life of each composter. The cash flow is used to determine the present value (PV) of costs, PV of benefits, and the net present value (NPV) of each proposed composting system. A benefit-to-cost ratio (BCR) is also determined for each composting alternative by comparing the PV of the ZFW project benefits with its costs. An AHP module is then utilized to integrate the noneconomic factors into the assessment of the food composting systems. Two AHP submodules are used to assess both the product-based and the supplier-based criteria weights. Product-based criteria include the composter's key specification and performance measures, whereas supplier-based criteria include supplier capacity, experience, and after-sale support. These noneconomic factors affect, directly and indirectly, the economic performance of the food waste composting system.

The third assessment module in the second phase utilizes sensitivity analysis to assess the impacts of changes in the critical economic or financial parameters of the project's present worth (PW). This includes sensitivity to financial parameters such as minimum acceptable rate of return (MARR), inflation rate, depreciation rate, and so forth. These parameters are subject to increase and decrease over the composter life cycle, which reflects positively or negatively on the project cash flow. A tornado diagram is used to display the results of sensitivity analysis. In the fourth module, MCS is used to estimate the risk in the project's NPV caused by variability in the operational parameters of the composter (e.g., compost productivity, operating hours, reduced impacts, etc.).

The last phase of the proposed framework focuses on integrating the outcomes obtained from the four modules of the third phase into an overall ranking of composting alternatives. The ranking is based on a weighted average of the selected outcome values from the four assessment modules (i.e., BCR, weights of AHP criteria, average impact on PW, and probability of project economic success or P(NPV > 0). To this end, an assessment value (AV) is derived from each assessment module and is defined as:

- AV_1: The assessment value for the feasibility module is estimated based on the BCR of each alternative, where:

$$\text{BCR} = \text{PV(project benefits)}/\text{PV(project costs)}. \tag{1}$$

- AV_2: The assessment value for AHP_s module is estimated based on the AHP results for supplier-based assessment.
- AV_{3A}: The assessment value for AHP_p module is estimated based on the AHP results for product-based assessment.
- AV_{3B}: The assessment value for the Sensitivity (S) module is estimated based on the average impact of changes expected in the economic factors on the project's PW, where:

$$\text{Average impact} = \sum(\text{changes in PW})/\text{number of factors}. \tag{2}$$

- AV_4: The assessment value for the Risk (R) module is estimated based on the probability of project economic success, where:

$$\text{Probability of project success} = P(\text{NPV}) > 0. \tag{3}$$

Because assessment values are of different scales, a normalized weight of each AV in the four modules (feasibility, AHP, Sensitivity, Risk) is determined as follows (AHP has two submodules):

$$N(AV_i) = AV_i/\sum(AV_i),\ \text{where } i = 1, 2, 3, 4, 5. \tag{4}$$

Finally, a set of relative importance weights are assigned to these five outcomes based on the managerial priorities for selecting the composting system. If the set of relative importance weights for the five assessment values is $W = (W_1, W_2, W_3, W_4, W_5)$, then the final weight of each composting alternative (A) is determined as follows:

$$W_A = W_1 \times N(\text{BCR}) + W_2 \times N(\text{AHP}_s) + W_3 \times N(\text{AHP}_p) + W_4 \times N(S) + W_5 \times N(R). \tag{5}$$

Such comprehensive weighting establishes an overall ranking of each proposed food composter, which facilitates the selection of an effective and economically viable food waste composting system.

ILLUSTRATION OF FRAMEWORK APPLICATION

The proposed framework in Figure 1 was applied to assess the economic feasibility of a ZFW initiative that includes the selection and installation of a food waste composting system within the campus of a major university in the United Arab Emirates (UAE). Currently, there is no food waste treatment system on campus and, according to the university sustainability office, all of the 750 kg of daily food waste is collected by a local municipality and sent to a landfill. The ZFW project was initiated by the campus sustainability office as an alternative to generating solid waste. This waste has resulted in increasing the costs of waste collection, transportation, and treatment by the local municipality in addition to its negative environmental impacts through pollution (i.e., greenhouse gases). The initiative is also expected to improve on-campus life (i.e., a green campus) and to improve the overall university ranking.

To proceed with the initiative, the office of campus sustainability solicited proposals from several composter suppliers. Two proposals were received from one composter manufacturer and a third from a supplier (reseller) of composting systems. The proposal includes installing one large composter for the food waste at the student center and 18 small kitchen-sized composting units in the kitchens of academic buildings around campus. The major challenge for the sustainability office is determining how to comprehensively verify the economic feasibility of the ZFW initiative and to select the most effective and economically viable food waste composting system.

Data collection

Relevant data to implement the framework were collected from multiple sources. The primary data were collected from the office of campus sustainability and the suppliers of food composters. The secondary data were collected from reviewed literature and relevant websites. Table S1 summarizes the data collected and used in the study. The details of information and specifications collected for the three composting alternatives (A1, A2, and A3) are summarized in Table S2.

As seen in Table S1, the focus was on collecting data on parameters that are critical to the economic feasibility of the ZFW initiative. In addition to the cost of the composter and the savings from food waste recovery or recycling, the economic feasibility is affected by interest rates, inflation rates, taxes, as well as environmental costs. Table S1 also quantifies the economic value that can be obtained from the improved university ranking and presents the economic parameters that were used in the financial analysis. These parameters were also used for AHP pairwise comparison and sensitivity analysis.

Initial feasibility assessment

The following three alternatives were short-listed by the university sustainability office for the on-campus composting system:

1. Alternative (A1): This alternative includes a food composting solution with free upgrade to newer models of composters when available.
2. Alternative (A2): This alternative is proposed by the same manufacturer of A1 and includes a free upgrade from "composting" to "energy production" in two years.
3. Alternative (A3): This alternative is a composting solution from a different supplier but without any upgrade potential.

Using the collected specifications and cost data presented in Table S2, a cash flow was established for each alternative over a 10-year service life, outlining project costs and benefits. These costs and benefits were used to estimate its NPV and BCR. Table 3 summarizes the economic evaluation of the three composting alternatives.

TABLE 3 The economic evaluation of the three food composting alternatives

Economic evaluation (CBA)	A1	A2	A3
Project cost (AED)	1 094 653	1 090 470	1 067 177
Project benefit	851 175	1 423 806	774 233
BCR	0.78	1.31	0.73
NPV	AED 243 478	AED 333 335	AED 2 929 000

As shown in Table 3, alternatives A1 and A3 are not financially feasible because they both have a negative NPV and less than 1.0 BCR. Alternative A2 was found to be financially feasible with a positive NPV and a BCR > 1. Therefore, A2 can be selected based on the initial financial feasibility. Relying only on such financial analyses when assessing composting systems leads to multiple issues that can limit the actual returns of the project and increase its operational costs. As discussed earlier, most of these issues are related to the impacts of noneconomic factors on the composting system and prospected changes in its economic parameters and operational conditions. The next assessment modules will complement the financial analyses by considering noneconomic factors as well as the sensitivity and risks involved in the decisions of selecting A2 for on-campus composting.

Analytical hierarchy process results

For a more comprehensive evaluation, AHP is used to integrate relevant noneconomic factors into the decision of selecting the food composter. Based on the nature and the requirements of the food waste composting system, two sets of noneconomic criteria were identified by the office of campus sustainability: supplier-based and product-based. For supplier-based, six main criteria were used to evaluate the three alternatives in AHP analyses. These criteria include the supplier's customer list, number of employees, customer feedback, maintenance responsiveness, availability of spare parts, and staff training. For product-based, five main criteria were used in the evaluation including process limitation, composting odor, feed continuity, batch processing time, and country of manufacture. The campus sustainability office identified these criteria based on their discussion with composting experts and other users of composting systems. The criteria represent the key factors that affect the relationship with the supplier (e.g., procurement and support) and the key functionalities of the composters.

The 1–9 Saaty scale (Saaty, 2008) was used to develop the AHP pairwise comparison matrix. Team-based qualitative assessments, developed by the specialists and manager of the campus sustainability office, were used to estimate the

TABLE 4 AHP pairwise comparison and weighting of supplier-based criteria

Supplier evaluation criteria	Customer list	Number of employees	Customer feedback	Maintenance responsiveness	Spare parts availability	Worker training
Customer list	1.000	4.000	0.333	0.250	0.250	1.000
Number of employees	0.250	1.000	0.167	0.143	0.111	0.200
Customer feedback	3.000	6.000	1.000	0.500	0.500	3.000
Maintenance responsiveness	4.000	7.000	2.000	1.000	0.500	4.000
Spare parts availability	4.000	9.000	2.000	2.000	1.000	5.000
Training	1.000	5.000	0.333	0.250	0.200	1.000
Importance weights	***0.081***	***0.028***	***0.185***	***0.264***	***0.359***	***0.083***
Consistency ratio (CR)	***0.032***					

AHP, analytical hierarchy process.

numerical scales. Table 4 presents the developed AHP matrix and the resulting weights for the supplier-based criteria.

As shown in Table 4, the availability of spare parts and the supplier's maintenance responsiveness had the greatest weights of relative importance. They both counted for approximately 60% of the weight. Evidently, the operational efficiency of the composter depends greatly on those two noneconomic factors. The number of supplier employees was found to be of least importance. The resulting consistency ratio (CR) was found to be acceptable (i.e., <10%). The two suppliers were then compared using the six selection criteria, and the results obtained were integrated accordingly. The overall ratings for the two suppliers were found to be 0.698 for the first supplier (manufacturer of A1 & A2) and 0.302 for the second supplier (supplier of A3). This further supports the results of the financial feasibility of the A2 food waste composting alternative.

Similarly, AHP was applied to the product-based criteria. As shown in Table 5, five composters' criteria were used to evaluate the three alternatives. The 1–9 Saaty scale was used to develop the AHP pairwise comparison matrix using team-based qualitative assessments of the numerical scales. Table 5 presents the developed AHP matrix and the resulting weights for the product-based criteria.

As shown in Table 5, the odor of the composting process had the greatest weight of relative importance followed by the process limitation. These two factors account for 75% of the weight. For the sustainability office, these two factors greatly affect the sustainability of the composting system. The other product criteria were found to be of marginal importance. The resulting CR was also found to be acceptable (i.e., <10%). The three products (composting alternatives) were then assessed using the five criteria, and the results were accumulated accordingly. The overall ratings for the three composters were found to be 0.335, 0.325, and 0.340 for A1, A2, and A3, respectively. Although the results are close, alternative A3 received the highest weight. A2, which is most financially feasible, received the least weight of relative importance based on the product-based criteria.

TABLE 5 AHP pairwise comparison and weighting of product-based criteria

Product evaluation criteria	Limitation on through-feed composition	Odor of composting process	Continuous through-feed	Average batch time	Country of manufacturer
Limitation on through-feed composition	1.000	0.500	2.000	5.000	8.000
Odor	2.000	1.000	5.000	7.000	9.000
Continuous through-feed	0.500	0.200	1.000	2.000	5.000
Average batch time	0.200	0.1428	0.500	1.000	3.000
Country of manufacturer	0.125	0.111	0.200	0.333	1.000
Importance weights	***0.276***	***0.482***	***0.134***	***0.073***	***0.035***
Consistency ratio (CR)	***0.027***				

AHP, analytical hierarchy process.

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Because both A1 and A2 are from same manufacturer, the sustainability office is expected to work with the manufacturer to improve these product-based aspects.

Sensitivity analyses of economic parameters

Sensitivity analysis was performed to assess the impacts of potential changes on key economic parameters over the project's economic life cycle. The sensitivity analyses also identified the decision's critical economic factors. The analyses covered 14 economic parameters, including MARR, electricity and water tariff, service life, capital cost, etc. Present worth impacts were estimated at each change (marginal increase or decrease) in these economic parameters. Sensitivity analyses were focused on the second food composting alternative (A2) because it has the best BCR and highest NPV.

A tornado diagram was used to visually capture the impact of these changes on the PW of the A2 project. As shown in Figure 2, the tornado diagram of A2's sensitivity analyses provides a ranking of the 14 economic parameters. The diagram shows that A2's PW is only sensitive to half of these parameters. It is most sensitive to the benefits (value) expected to the overall university ranking and the university green ranking when adopting this green and sustainable food waste composting solution. As shown in Figure 2, the project's PW ranges from losses of 200k to a profit of 1M (in AED currency; at the time of writing, 1 US dollar equals approximately AED 3.7). Such a great impact reflects the expected increase in the project's economic value to the university in increased enrollment and attracted funding. Second, the project's PW is sensitive to four parameters (expected changes to the amount of food waste, number of workers, labor salary, and energy generated from compost). Other factors starting from service life to salvage value have less impact on the project's PW.

Results of sensitivity analyses provide the decision-maker with a clear picture of the changes expected in the project value under different scenarios. The least sensitive composting alternative would be preferred (i.e., more robust to unwanted changes in the economic factors and conditions). The average impact of changes in these economic factors on the project's PW was relatively less for A2 than for A1 and A3. This makes A2 the preferred option. The sustainability office will definitely try to control the changes in these critical economic factors (i.e., top seven in the tornado diagram). Special attention needs to be paid to the top two factors because they create a significant impact on the project's PW. This is expected to be the case in a university context due to the economic implications of the academic status.

Risk analysis of operational parameters

After developing a control plan and scenario analyses to deal with the sensitivity of composting alternatives to the economic factors (cost–benefit factors), the comprehensive assessment required consideration of the impacts of operational variability on the benefits obtained from the composting project. Certain parameters are sought to contribute to the gains obtained from the composting process, including composter productivity, amount of saved food, and reduced environmental impacts (i.e., energy,

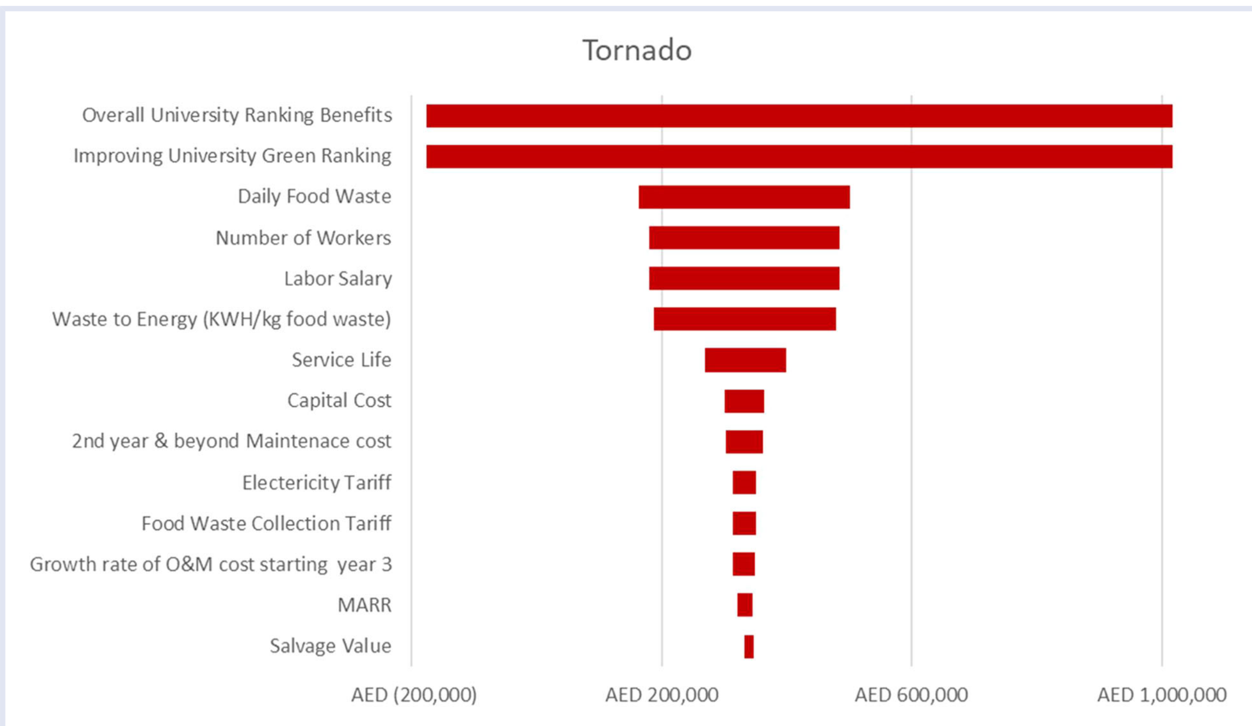

FIGURE 2 Tornado diagram of A2 sensitivity analyses

water, and emissions). The variability and uncertainty in these parameters will eventually shape the overall economic benefits of the project.

Typically, these parameters change probabilistically or stochastically. Historical data, if available, can be used to estimate the probability distribution that represents the uncertainty in each parameter. Data fitting, which is a typical practice in simulation studies for modeling the variability impacts, can be used to identify the distributions and estimate their parameters. If data are not available, benchmark data or expert opinion can be used. An MCS method using the @Risk software package was used in this study to model operational variability and conduct risk analyses. Monte Carlo is a group of computational methods that use a large number of random samplings to estimate certain numerical results. In this study, MCS assesses risk involved in the composter selection by sampling from a set of probability distributions that represent the operational variability of the composting system. It runs thousands of replications and produces many possible outcomes (a distribution of project value). Results can then be analyzed to estimate the probability of a certain outcome occurrence (i.e., probability of a loss). Further details of MCS can be found in Rubinstein and Kroese (2017).

In MCS, model inputs represent the critical operational variables that, directly or indirectly, affect the economic viability of the composting system. The data collected on these inputs were fit to standard probability distributions. Model output was set at the project economic value in NPV. The MCS model was then set to run many iterations and estimate a distribution for model output. This distribution is a more realistic assessment than the deterministic values of NPV. It also provides decision-makers with mean and standard deviation of NPV, estimates the project's worst-case and best-case scenarios, and allows for estimating the project's success probability (e.g., $P(NPV > 0)$). In this study, the risk analysis with MCS involves the following steps:

1. Set variables to the operational parameters that behave probabilistically during the project's service life.
2. Collect data (historical or benchmarked) on these variables.
3. Fit data to standard distributions.
4. Simulate many replications (e.g., 1000 replications).
5. Estimate variability in project gains (mean and standard deviation of NPV) and the probability of project success, $P(NPV > 0)$.

To illustrate this procedure, five operational parameters of food composting were modeled. As shown in Table S3, these parameters include operational hours, compost productivity, and environmental gains (produced energy, reduced water, and CO_2 emissions). Distributions on these parameters were obtained from the campus sustainability office. The office used the performance data provided by the suppliers of the composting systems to set each distribution type and parameters. Table S3 summarizes the distributions and parameters used to model the variability in these operational parameters.

The project NPV is set as a model output in the simulation. One thousand iterations were used in the simulation to model variability and generate an NPV distribution. Figure 3 shows the results of the simulation for the NPV of the A2 project. Results reveal that project NPV is greatly affected by variability in the modeled operational parameters. It ranges from approximately 213.2 to 451.4 k, with a mean of approximately 333 k and a standard deviation of approximately 37.5 k. Figure 3 also shows that A2 still reports a positive NPV under variability in the five operating parameters with no losses expected.

Risk analysis was then similarly expanded to assess the impacts of variability in the critical economic parameters (identified by the tornado diagram in Figure 2) on the NPV distribution. This combined the impacts of economic and operational variability as an extreme scenario. The simulated NPV distribution was used to determine the probability of the project's success, $P(NPV > 0)$, for the three proposed alternatives of the composting systems. Details of their distributions are not shown for the sake of brevity. Table 6 summarizes the results of risk analyses for the three composting alternatives (A1, A2, and A3).

As shown in Table 6, NPV was found to be greatly affected by the variability in economic parameters compared with operational parameters. This resulted in the high level of variability and low success probabilities for A1 and A3. Overall, negative means of NPV were obtained for the three alternatives (this is expected under a worst-case scenario of high variability in the critical economic factors). Results for A2 were relatively better than for A1 and A3. A2 has the highest mean NPV and best chance of success (i.e., $P(NPV > 0) = 27.9\%$). A2 also encompasses the greatest variability estimates (i.e., highest standard deviation). This implies that the sustainability office should be prepared for all scenarios and take proactive measures to control the impacts of variability in economic parameters and, consequently, reduce the risk of the composting system being less economically viable.

Results integration and analyses

This section integrates and analyzes the results obtained from implementing the four assessment modules of the proposed framework (i.e., CBA, AHP, Sensitivity, and Risk). The objective is to establish a comprehensive economic assessment of the three alternatives. This was achieved through financial, sensitivity, and risk analyses. However, a final ranking of these alternatives is sought to be of value-added for managers to facilitate implementation. As explained in the Proposed Framework section, the final ranking of composting alternatives is determined using a weighted sum of the assessment normalized values (estimated using Formulas 1–4) and the priority weights (set by the sustainability manager and office experts). This weighted sum is determined using Formula 5. The set

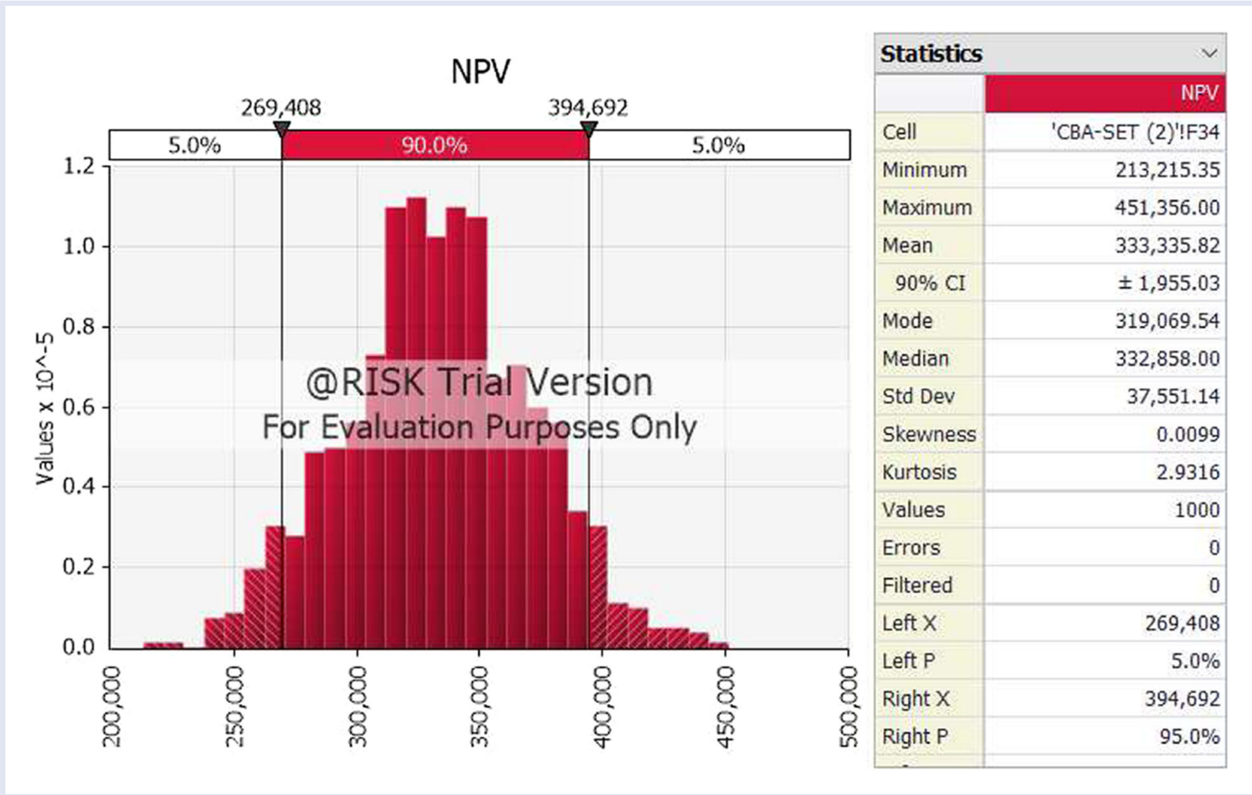

FIGURE 3 Simulation results for net present value (NPV) of project A2

priority weights reflect the value of the results obtained from the four evaluation tools (BCR, AHP, Sensitivity, and Risk) to management decision. Table S4 presents a summary of the overall weighting (ranking) of the three food waste composting alternatives.

As shown in Table S4, management has assigned 50% of the weight to the financial feasibility of the composter in terms of BCR. Noneconomic factors are given 20% of the weight, and both sensitivity and risk are assigned 15% each. A2 has achieved the highest overall weighting and thus will be given priority for implementation. It has the best BCR, highest AHP supplier weight, lowest AHP product weight, least sensitivity in terms of impact on project PW, and lowest risk (highest probability of project success). Technically, A2 is also more promising for generating energy from compost, in addition to the other typical benefits of food composting.

Such assessment is comprehensive because it integrates the economic assessment (i.e., BCR) with a noneconomic assessment (i.e., AHP supplier and product). It also considers the sensitivity of each alternative to the economic factors and the risk to its financial feasibility caused by variability in operational and economic parameters. For its effective implementation, the composting system needs to be controlled over its service life through its critical operational and economic factors. The university also needs to capitalize on intangible benefits of the ZFW initiative.

TABLE 6 Risk analysis for the three composting systems

	Alternative food waste composting systems		
	A1	A2	A3
Parameter			
Mean NPV (AED)	465 387	247 945	468 965
Probability of success	5.82%	27.90%	3.60%
Risk measures			
Probability of loss	94.18%	72.10%	96.40%
Standard deviation	279 467	360 556	258 699

NPV, net present value.

CONCLUSION

This paper presents a comprehensive framework for the economic assessment of on-campus food waste composting in the context of a ZFW initiative. The framework integrates four assessment modules: CBA for financial feasibility, AHP for noneconomic factors, sensitivity analysis for changes in key economic parameters, and risk analysis for variability in operating conditions. As outlined in the literature research, the integration of these assessment modules facilities a comprehensive economic assessment of on-campus composting systems and contributes to closing the gaps highlighted in existing studies. This also supports the global trend towards sustainability and green economy in which universities play a key role in terms of research and education.

The framework application was illustrated through a case study of selecting a food waste composting system for a university campus. The NPV of the cash flow developed for each composting alternative was used to determine the initial financial feasibility followed by the application of AHP, sensitivity, and risk modules. Results revealed that integrating the noneconomic factors of the decision using AHP helped to prioritize composting alternatives based on a set of critical aspects of the assessment (i.e., supplier selection, after-sale support, and composter performance). Sensitivity analysis identified the critical economic factors that can affect the long-term financial health of the adopted composting system. Risk analysis with MCS assessed the impact of operational variability on the economic viability of the composting project and estimated its probability of success. Finally, the framework integrated these assessment modules into an overall ranking (i.e., a weighted average of their normalized values) to provide decision-makers with a comprehensive measure for selecting and adopting an effective composting system. The campus sustainability office is expected to adopt the composting system with the highest ranking and set measures to reduce its operational variability and control changes in the economic factors. The proposed framework can also be automated and turned into a decision support system.

Managerial implications

Interest in ZFW initiatives, and food waste composting in particular, has been growing among sustainability managers, who have always been challenged by the funding and economic feasibility of such initiatives. Using the proposed framework, managers can first confirm the financial feasibility of the composting system. They can then utilize AHP results to allocate resources and set internal action plans that capitalize on the noneconomic factors of the composters (e.g., managing system maintenance and performance) and to procure their service parts and market their compost products (e.g., to farms). They can also monitor the critical economic factors (based on the priority derived from sensitivity analysis) and control the operating conditions of the composting system (based on results of risk analysis).

Universities and academic institutions can also benefit from the proposed framework. For example, they can capitalize on the economic and academic gains of the food waste composting project in improved campus environment, green ranking, and the university's overall image. However, successful and, it is to be hoped, profitable university food waste composting projects can be only maintained through the collective effort and collaboration of various campus entities. Different campus stakeholders need to support the composting project, especially canteens, faculties, and student bodies. Finally, as recommended in Ebrahimi and North (2017), adoption of the developed framework should be combined with a holistic evaluation of policy factors influencing effective zero-waste management at institutions of higher education.

Limitations and directions for future research

This work has multiple limitations that can affect the applicability and generality of the results obtained. The CBA analysis based on PW and NPV is greatly affected by the accuracy of the economic assumptions and parameters employed. Food waste composting is particularly impacted by the estimations of the tangible gains obtained from the project, such as the value of food compost, fertilizer, and energy generated. It is also affected by the estimations of the intangible gains of the project, such as university ranking and green image. The reliability of AHP results are also sensitive to the credibility of the pairwise comparisons set by management for both the supplier criteria and product criteria. The resulting CR value at each matrix can be used to check the consistency of these managerial judgments. More quantitative data should always be collected to support the objectivity and consistency of these judgments.

The sensitivity analysis of the project's PW depends on the validity of the changes imposed on the key economic parameters. More economic insight will be helpful in setting the allowances for these changes. Similarly, the credibility of MCS results used for risk analysis depends on the validity of the probability distributions used, the limitations of the random number generator (RNG) used, and the setup of simulation run controls (e.g., number of iterations). Further statistical analysis will be helpful in this regard. Finally, the ranking of composting alternatives based on a weighted sum of the normalized values obtained from the four assessment modules is affected by the differences in the normalization scale and the selected weights of relative importance. To provide realistic estimates for these weights, management may need further insight into the impacts of changes in the critical economic factors over the project life cycle and on the expected variability in the economic and operating conditions of the food composting system.

Future work can, therefore, include a study to identify specific economic and noneconomic factors that affect the economic feasibility of ZFW initiatives in general and on-campus food composting in particular. Data analytics algorithms applied to large-scale empirical data collected from multiple campuses will greatly improve data credibility and coverage. A full-blown simulation of the composting process to estimate its operational and financial performance over the service life will also improve the applicability of the proposed framework. Finally, and to attain sustainability in terms of the triple bottom line, further studies can be directed at integrating more environmental and social impacts into the economic evaluation of on-campus food composting. Within a university context, these studies can incorporate the educational aspects of the composting system as well as the impact of ZFW initiatives on the student experience and campus environment.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data, associated metadata, and calculation tools are available from corresponding author Raid Al-Aomar (raid.alaomar@gju.edu.jo)

SUPPORTING INFORMATION

The supporting information contains data collected for the study (Tables S1 and S2), details of the used probability distributions (Table S3), and weights for overall ranking of composting options (Table S4).

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