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Received: 1 April 2023 | Revised: 24 September 2023 | Accepted: 29 September 2023

DOI: 10.1002/ep.14316

ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

ORIGINAL RESEARCH

Sustainability

Decarbonizing university campuses: A business model for food waste management at Istanbul Technical University (İTÜ) Ayazağa Campus, Turkey

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Funding information
Research Fund of the Istanbul Technical University, Grant/Award Number: 42255

Abstract

Food waste is a significant environmental issue today, as it contributes to depleting natural resources and greenhouse gas emissions from improper management. To address this, alternative food waste management and recovery strategies must be developed to promote nutrient recirculation and move towards decarbonization. University campuses could play a crucial role in pioneering such strategies, through pilot studies and implementation of effective waste management. The aim of this study is to devise a food waste management strategy that provides a more circular and decarbonized economy. A case example was developed based on ITU Ayazağa Campus, Turkey, with annual separated food waste of 577 tonne per year. A Life Cycle Assessment was conducted using the EASETECH software. Four scenarios were evaluated: anaerobic digestion, composting, incineration, and landfill. Of these, incineration resulted in the highest CO_2-eq savings, but lacked decoupling and circularity of resources. Conversely, anaerobic digestion demonstrated the highest circularity and lowest toxicity. Based on these findings, anaerobic digestion was selected for further investigation. Economic transactions for the anaerobic digestion system's business models were analyzed, including revenues, municipality fees, and operating costs. The new economic model is expected to align with circular economy strategies and promote stakeholder collaboration as a significant social outcome.

KEYWORDS
business model, circular economy, food waste, university campus, zero waste

1 | INTRODUCTION

Globally, 1.32 billion metric tonne of food waste (FW) are sent to landfills at a cost to the global economy of over USD 900 billion in wasted resources[1] while simultaneously creating 3.3 billion tonne of greenhouse gases.[2] FW management is a significant environmental problem today, due to depleting natural resources[3] and the use of land resources.[4] Increased focus on FW minimization, aligned with structured waste management (WM) approaches, is a necessity when seeking to solve global problems; however, when it comes to applying this strategy in actuality, too many stakeholders are involved. Pilot studies are thus needed before expanding new strategies to large regional systems.[1]

University campuses could be pioneer hubs for sustainability projects via the living lab concept.[5] Alternative strategies have been developing at the university campuses to recover FW, in order to close nutrient- and carbon-loops which converts FW into value-added products such as organic fertilizers and energy. These strategies seek

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to replace centralized waste management facilities such as landfills and incineration.[6–8] A sustainable FW management model goes further than emissions by designing circular flows of resources. There will also be adverse effects due to the array of land guidance for biomass production, including further greenhouse gas emissions due to indirect land use restrictions.[9] This could cause a rebound effect as it changes production and consumption demands.[9] Closing material loops is not enough to guarantee environmental improvement. Hence, a chosen WM strategy is expected to be delivered in the context of more circular and decarbonized economies.[8,10]

Moving towards a circular economy (CE) will require a shift throughout the value chain, including new business models and consumer behavior.[8] The purpose of the CE is to rethink our economies and eventually decouple our prosperity from materials consumption, carbon emissions and waste. Since the CE tackles climate change and WM by decoupling economic activity from the consumption of finite resources, the need for sustainability and decoupling is therefore increasing.[4] Life cycle assessment (LCA) is a well-established tool for understanding environmental impacts. However, there have been discussions suggesting that LCAs neglect economic and socio-technical aspects.[11] A sustainable business model (SBM) could close the gap since it pursues a sustainable economy, it, therefore promotes resource protection and societal and environmental benefits instead of fostering economic growth alone.[12] Circular business models (CBMs) are an extension of SBMs and comply with the decoupling of economic growth with the consumption of resources.[13] The most commonly used and accepted business model for WM studies is the "Canvas" business model proposed by Osterwalder and Pigneur.[14] Since, Osterwalder and Pigneur's canvas model is driven by economic value,[15] it neglects environmental and social aspects. The transition to a more circular proposition, therefore, requires the expansion of the traditional Canvas business model. A holistic sustainable business model includes a triple bottom line to reconcile traditional economic objectives with social and environmental concerns.[16] Hence, the Triple Layered Business Model Canvas (TLBMC) was suggested by Joyce and Paquin[15] to explore sustainability-oriented business models by adding two layers to Osterwalder and Pigneur's[14] original Canvas model. The TLBMC has been used in several studies, albeit they focused on the sector[12] or company[15] level. The latter authors contended that some users found the TLBMC a bit daunting, due to the number of inputs required. Another study, conducted by Amoussohoui et al.[17] added two segments to the original Canvas model to evaluate financial viability and sustainability, albeit it prioritized technologies rather than conceptual system design. Finally, the Ecocanvas model, provided by Daou et al.[18] was created for circular business and covers several areas in addition to the economy, such as legal and social.

As part of climate change mitigation, Turkey aims to develop sustainable food system practices and create an "Action Plan for the Circular Economy." The plan also includes the objectives of the LCA[19] namely; understanding of the overall nature of the environmental consequences of human activities and gives policy makers with information that identifies the possible environmental effects of these activities. However, FW management impacts at campus level can inspire and lead to larger projects, in order to help solve global problems by providing preliminary results faster.[1] The campus thus become a testing ground where solutions to improve the sustainability of succession and academic operations are sought and tested.[20] Previous studies at universities in Turkey have focused on different topics, such as reducing FW at source,[21] landfill diversion by composting,[22] the biogas potential of anaerobic degradation,[23,24] biogas for heat production[25] and the co-digestion of FW and cattle manure in anaerobic digester.[26] Furthermore, a number of FW-related LCA studies exist at campus level in Turkey[27,28] that found the anaerobic digestion (AD) is the most environmentally friendly solution for organic waste.[28] That said, to the best of our knowledge, no study has created a business model for FW management by using LCA results in combination with circularity and the cost of existing facilities in and outside the campus in the literature.

The aim of this study is to analyze a FW management model that provides a more circular and decarbonized economy at the ITU Ayazağa Campus, Turkey. The goal is to propose a business model that can easily be used by a wider audience. In this regard, this article addresses the following questions: (i) what is the ranking of decarbonization, toxicity, acidification, and eutrophication scenarios, and how is that ranking going to change in the future? (ii) What scenarios have the highest circularity? (iii) What are the net costs and CO_2 abatement costs of the scenarios? We then propose a business model by using results from the previous three questions.

2 | MATERIALS AND METHODS

2.1 | Modeling assumptions

The modeling approach in this study was based on ISO 14040 and ISO 14044 standards.[29,30] CO_2 emissions coefficients from the Intergovernmental Panel on Climate Change (IPCC) 2021 report,[31] for global warming potential (GWP) 20 and GWP 100 years were used for climate impact calculations, while other impact categories were based upon Hauschild et al.[32] The EASETECH v 3.4.1 model[33] was used for calculations, while the background data were obtained from Ecoinvent 3.7.1.[34] To address multi-functionality, and attributional approach was followed, and system expansion was applied according to ISO 14044[30] (see Supporting information Figure S1). The functional unit (FU) in this study was the annual source-separated and treated FW (577 tonne/year) from the ITU Ayazağa Campus. Since the WM project is applicable in the long term, future conditions in the year 2050 were included in the calculations. The average grid mixes in 2020 and 2050 were calculated, as changes in the electricity mix could affect CO_2 savings due to changes in fossil fuel substitution.

2.2 | System boundaries and scenarios

In this study the circularity of the FW was defined as the distribution of nutrients (N, P) back into the soil during land application. Four scenarios were created (Figure 1) to determine the most circular, environmentally

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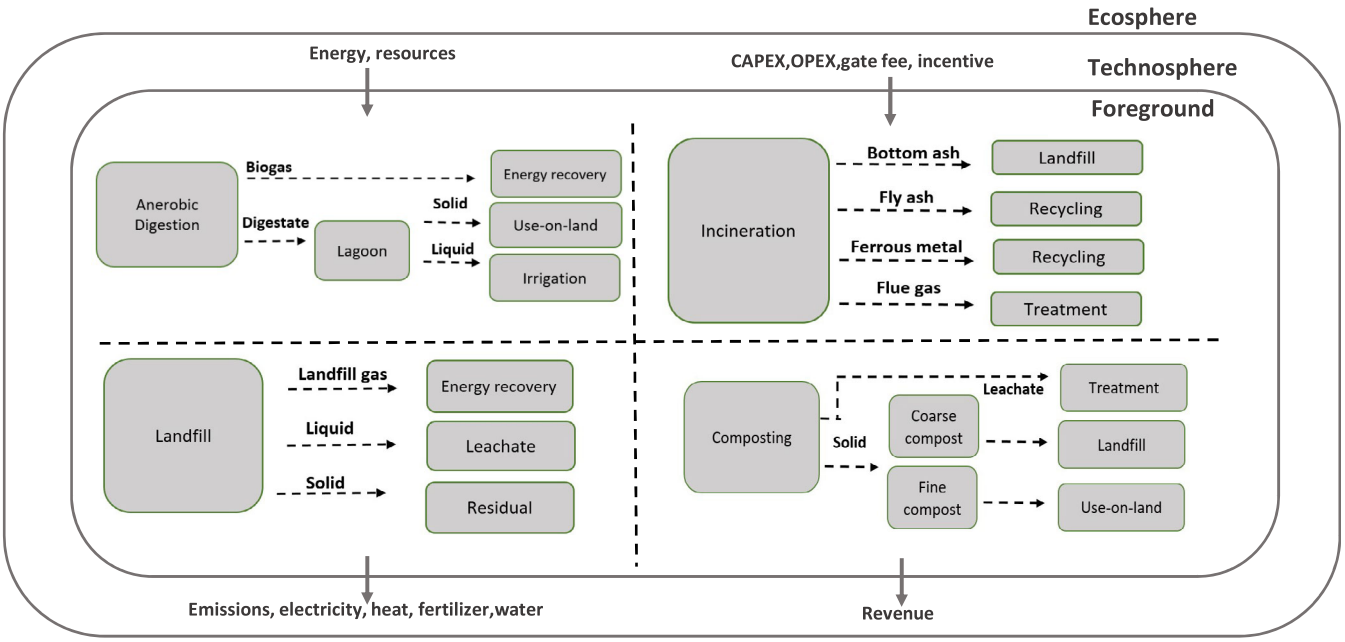


FIGURE 1 System boundaries of the waste management scenarios (photographs of the facilities were shown in Supporting information Figure S3).

and economically feasible FW management method and business model as follows: an AD facility at the campus, composting, incineration and a landfill facility, which are operated by the municipality (outside of the campus). These scenarios also compared centralized and decentralized WM facilities.[35] Composting and incineration facilities are located 26 km away from the campus, while the landfill is 112 km away. Hence, emissions that occur during the transportation of waste were included in the calculations, except for the AD scenario, where it was assumed to be negligible, an assumption discussed further in the results (Tables S1–S3). A zero-burden assumption[36] was made for environmental impacts resulting from FW production and WM facilities. The AD is operated under mesophilic conditions (37°C), and biogas produced in the facility supplies the heat required by the digester, whilst electricity produced from the biogas reduces the use of fossil fuels used in the production of electricity.[37] Methane loss from AD is assumed at 2%.[38] The digestate is treated in an artificial lagoon. After treatment, the solid part is used as fertilizer in the campus park-garden areas, and the liquid part is used for fertigation. Thus, less inorganic fertilizer and water consumption will be required. The total energy consumption in the digester is 49 kWh/tonne of waste. While 18.3 kWh of this amount is used by pumps and technical equipment, 30.6 kWh of energy is needed to heat the reactor. The composting unit is designed as a tunnel system with an 8-week active composting cycle.[39] The average moisture content[37] of input material is 74% while output changes by between 20% and 28%.[40] After composting, the materials are screened with a Ø15 mm trommel screen, and undersized material is used in Istanbul Metropolitan Municipality (IMM) parks, while oversized material is sent to a landfill. Electricity consumption involved in tunnel composting is 53 kWh/tonne.[41] Data on the land application of N and P, in terms of circularity, were based on Gençsoy,[40] Yoshida et al.[42] and Cobo et al.[43] The N and P circularity indicators have been defined as the quantity of nutrients that are recycled, applied to the soil and absorbed by the soil to the amount of nutrient present in the collected FW.[43] The incineration plant's (Figure S2) energy requirements are 25% electricity and 69% heat recovery efficiency according to design (Tables S4 and S5).[44] In the landfill scenario (which is the current FW management policy for the campus), waste is sent to the regional landfill (Seymen). Waste degradation rates at the landfill for each waste category were taken from De la Cruz and Barlaz.[45] Gas collection and gas engines are installed at the landfill (Tables S6–S8), as well as leachate collection and treatment.[45]

2.3 | Data inventory

Waste production data were provided by a field study at the campus. Most of the AD data were primary, except for lagoon data and gas leakage inventory, for which literature data were used as a proxy. Operational data for the other three facilities were provided by the literature, and cost data were provided via personal interviews with the municipality, market price investigations, and the literature. A summary of the environmental and economic inventories is given in Table 1, whilst a detailed inventory is provided in the Supporting Information.

2.4 | Sensitivity scenarios

Sensitivity analyses were conducted for changes such as; various methane loss rate (14.9% loss),[38] biogas upgrading[46] in the AD facility and different energy recovery performances (Tables S14–S16) at the incineration plant.[47]

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TABLE 1 Summary of the environmental and economic inventories.

Anaerobic digestion	Value	Source
Leaking gas (%)	2	Scheutz and Fredenslund[38]
Electricity consumption (kWh/tonne waste)	49	Primary data, 2019[a]; Boldrin et al.[41]
Methane content	65	Primary data, 2019
Wheel loader diesel consumption (L/tonne)	1	Lipasto[48]
Methane potential (L/kgVS)	370	Akça et al.[37]
Composting[b]		
Electricity consumption (kWh/tonne waste)	53	Boldrin et al.[41]
Wheel loader diesel consumption (L/tonne)	1	Lipasto[48]
Leachate		
Leachate treatment (kWh/kg COD)	1.5	Turkish Water Institute[49]
Landfill		
Electricity consumption (kWh/tonne waste)	5	Manfredi et al.[50]
Diesel consumption (L/tonne waste)	1	Manfredi et al.[50]
Energy recovery—CH_4 in landfill gas (%)	55	Keskin[51]
Incineration		
Water consumption (kg/tonne waste)	397	ELPCA[52]
Energy recovery—electricity (%)	25	IMM[44]
Energy recovery—heat (%)	69	IMM[44]
Energy recovery—electricity (%)—sensitivity	26	Bisinella et al.[47]
Energy recovery—heat (%)—sensitivity	62	Bisinella et al.[47]
Cost inventory		
Biomass energy-incentive (€/kWh)	3.2	Official Gazette of the Republic of Turkey[53]
Thermal waste treatment-incentive (€/kWh)	3.1	
Landfill gas-incentive (€/kWh)	1.9	
Minimum wage (€/month)	347	Official Gazette of the Republic of Turkey[54]
Electricity (€/kWh)	0.12	Energy Map[55]
Natural gas (€/kWh)	0.04	IGDAŞ[56]
Waste transportation (€/tonne)	9.6	Primary data, 2020

Abbreviation: IMM, Istanbul Metropolitan Municipality.
[a]Primary data: field study was done on Ayazağa Campus by the authors for the environmental and personal interviews relating to the cost data.
[b]For composting facility inventory data see Supporting information (Tables S9–S13).

2.5 | Economic calculations

Capital costs, operational costs, and revenues were included in the economic calculations. Inventory data were obtained from the municipality via personal interview and technical reports. The currency of Turkish Lira converted to Euro. A real interest rate of 3% was applied and annualized with a WM facility's lifetime of 30 years.[57] Economic calculations in the case study were evaluated according to a widely established investment valuation method, as in Equation (1) (net future value).

$$F = P(1+i)^n, \tag{1}$$

where, P: present value. F: future value of the given amount of money. i: interest rate per period ($i = 3\%$ for this study). n: year ($n = 30$ years for this study).

The net cost of each scenario was calculated by subtracting revenues from the sum of investment and operating costs, while the CO_2 abatement cost was calculated by using Equation (2).[46] Details of the operational cost items are indicated in the Supporting Information.

$$CO_2 \text{ abatement cost} = \frac{\text{Net cost } (€/\text{year})}{\text{Avoided emission } (\text{ton } CO_2 \text{ avoided/year})}. \tag{2}$$

Currently, Turkey has a financial incentive to produce energy from waste, in the form of electricity production from biogas, thermal treatment, and landfill gas. However, this incentive is currently only valid until 2025,[53] and there is a high chance of policy changes due to economic conditions in the country. A change in the electricity mix and incentive policy could thereby affect net costs and CO_2 abatement costs. Hence, future cost calculations were considered with and without incentives. In addition, the EU Emissions Trading System (EU ETS) scenario was calculated for the future.

The EU ETS policy addresses climate change and the reduction of greenhouse gas emissions in a cost-effective manner. The ETS is essentially a market-based mechanism for reducing carbon dioxide.[50] Municipal waste incineration is currently excluded from the EU ETS, but the European Parliament has recently agreed to include municipal incinerators by 2026.[58] The study conducted by CE Delft projects the price of the EU ETS at 90 €/tonne[59]; hence, this value was used during cost calculations. Even though Turkey is not a member of the EU, there is a strong relationship between Turkey and EU countries, so there is a high possibility of applying the ETS in Turkey in the near future.

3 | RESULTS AND DISCUSSION

3.1 | Environmental impacts

3.1.1 | Circularity

Circularity was calculated by considering putting nutrients back into fields (and substituting raw materials by using less chemical fertilizer).

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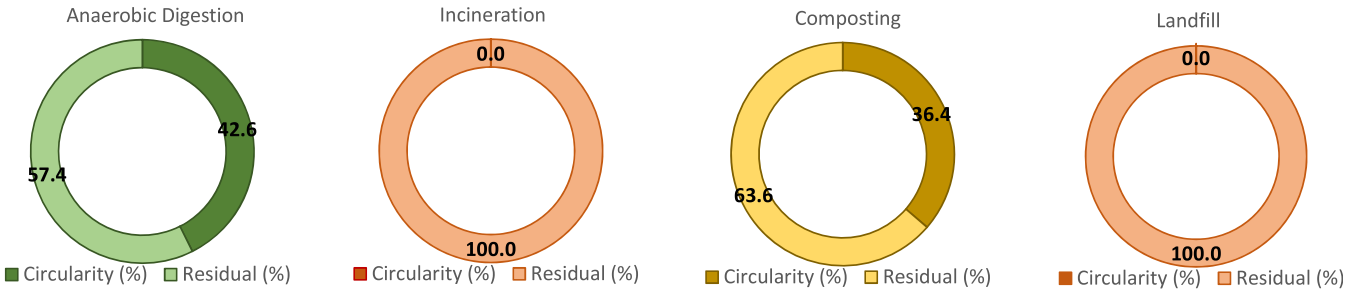


FIGURE 2 Nutrient circularity (%) of the FW management scenarios.

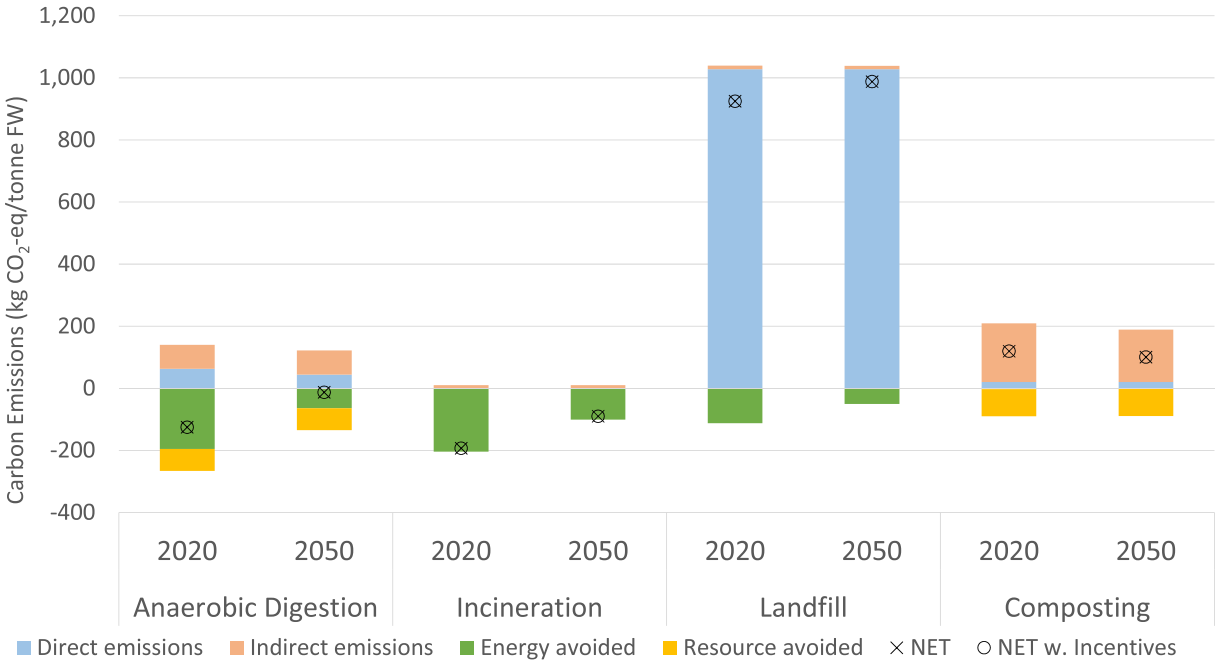


FIGURE 3 Net carbon emissions of different FW management scenarios (kg CO_2-eq/tonne FW) (results for FU were shown in Supporting information Figure S6).

It was found at its highest in the AD scenario at 42.6%, followed by composting at 36.4%, while for landfill and incineration circularity was zero, as illustrated in Figure 2. Details of nutrient (N, P) distribution during land application is shown in the Supporting Information (Tables S17–S19). While incineration has the greatest carbon savings, there is neither decoupling nor circularity for natural resources.

3.1.2 | Carbon emissions

The net impacts are presented in Figure 3. According to the results for 2020, incineration had the most savings (−192 kg CO_2-eq/tonne FW), followed by AD (−126 kg CO_2-eq/tonne FW), composting (119 kg CO_2-eq/tonne FW), and the landfill (924 kg CO_2-eq/tonne FW). Figure 3 shows the contribution analysis of the scenarios per tonne FW (results for FU were shown in Supporting information Figures S4 and S5). Most of the burdens were from electricity consumption and input-specific emissions in the incineration scenario, but chemical usage (e.g., sodium hydroxide, ammonia) also has a significant impact (Figure 3). Most of the savings were from fossil-based electricity substitution followed by heat substitution. Landfill burdens mostly originated from uncollected landfill gas. For composting, net burdens were observed due to energy consumption in the plant and the different efficiencies of use-on-land applications for chemical and compost fertilizer. The AD scenario generated net savings through electricity substitution, but heat substitution was lower, due to the temperature requirements (mesophilic) of the digester itself. Consequently, landfill remained the worst option, followed by composting, which is a similar outcome to that of Slorach et al.[60] and Culaba et al.[61] Net savings were observed for the AD and incineration scenarios; hence, these two options were found preferable for decarbonization of FW management at Ayazağa Campus.

In the original scenario, the use of fossil source (coal and natural gas) is expected to decrease from 57.7% to 23.2% by 2050 (Tables S20 and S21), with a change in electricity coefficient from 0.55 to 0.18 kg CO_2-eq for GWP 100 years. The results (Table S22)

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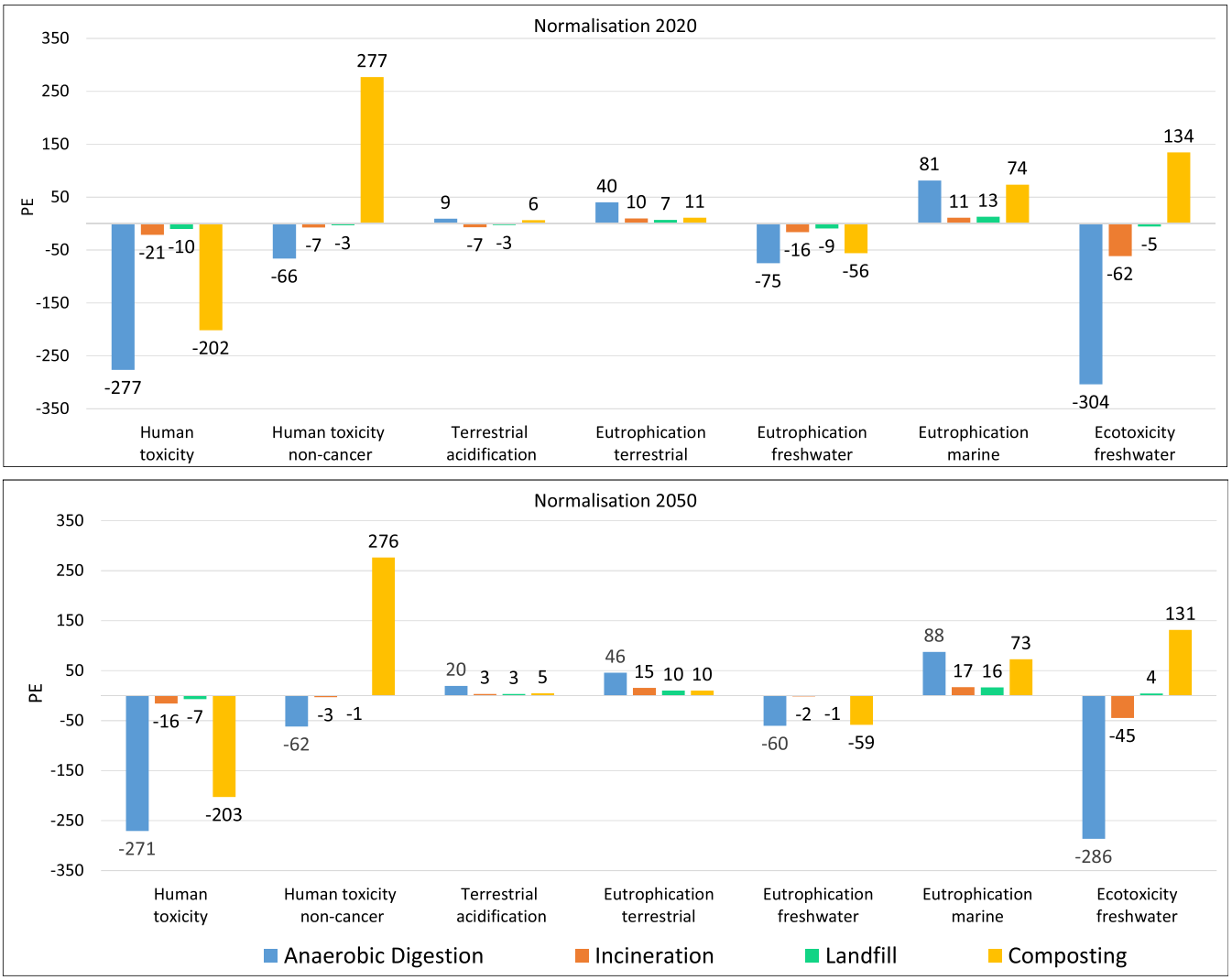


FIGURE 4 Other impact categories net impacts for (FU) (results for FU were shown in Supporting information Figures S25–S27).

indicate that the change in electricity mix has an effect on the overall results, but it does not alter the ranking of scenarios as it illustrated in Figure 3. GWP 20 years coefficient results shows that the impacts of landfill are more dramatic from a shorter time point of view, due to the large releases of methane. Consequently, all decarbonization scenarios (including 20-year and 100-year GWP) were preferable to AD and incineration rather than landfilling.[62]

The findings of the sensitivity analysis scenario for methane loss demonstrated a decrease in net benefits with regards to climate change impacts for AD, however the ranking of FW management scenario selection has not been effected. The Biogas upgrading scenario showed that, additional savings occurred in 2020 and 2050 for biogas upgrading, but they were negligible since biogas upgrading itself also consumes chemicals (especially amine scrubbing—Table S16), water, and electricity.[46] The results did not show major alterations with the implementation of biogas upgrading, rankings. An additional sensitivity analysis was performed on the change in energy recovery from the incineration plant. Although heat and electrical recovery is down compared to the original scenario there were no changes in the preferred technologies' rankings. Detailed sensitivity analysis results are given in Table S21.

3.1.3 | Other environmental impacts

Fertilizer application on soil has significant burdens in eutrophication and acidification-related impact categories. The results indicate that the ranking of the acidification category in FW management scenario are similar to those of the climate change category.[62] AD and composting have high marine eutrophication due to nitrate emissions into ground water, nitrogen oxide release during combustion processes and high nitrate emissions on digestate application. However, AD had net savings in all categories except eutrophication marine owing to energy substitution (Figure 4).

While, the nutrient circularity (especially N) was very high in the AD which leads to high eutrophication marine effects, incineration

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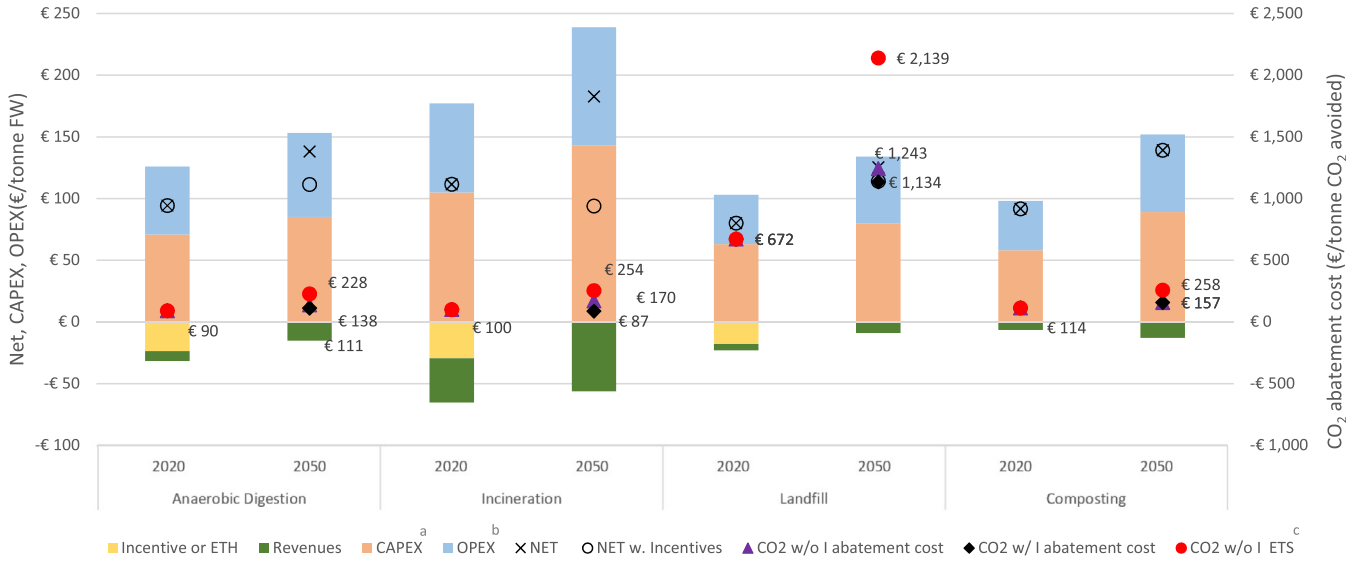


FIGURE 5 Net, capital, and operational costs per tonne food waste management (€/tonne FW) (CAPEX: capital expenses, OPEX: operating expenses, ETS: emissions trading system) (net impact results per FU provided in Supporting Information Table S24).

had the highest freshwater eutrophication because of the phosphates in the fly ash. Meanwhile, credits for mineral fertilizers offset the impact from electricity used for composting, resulting in a net-negative in eutrophication freshwater. AD is the best option, saving, as the credits for electricity and fertilizers are higher than process emissions. The potential of freshwater eutrophication was the lowest in AD. Furthermore, the eco-toxicity of AD in freshwater was an order of magnitude lower than that of incineration. Terrestrial acidification was high for both composting and AD due to ammonia released to the air during compost maturation and digestate application, respectively. AD has negative values for human toxicity, while incineration has poor performances in terms of cancerous human toxicity, due to the emissions of bottom ash transport and landfilling. Finally, all impact categories have slightly higher burdens in 2050 compared to 2020 due to the difference in energy mix (Figure 4).

3.2 | Financial costs

Financial costs in the form of capital, operations, and revenues were calculated and illustrated in Figure 5. Electricity substitution was the main source of revenue. Hence, AD and incineration saw savings from the operation due to high financial incentives provided by government, albeit these will most likely fade away in the future. Therefore, net costs were calculated for 2050, both including and excluding incentives. Net value when considering the incentives is indicated in Figure 5 with a circle. Landfilling and composting has the lowest operation costs (40 €/tonne FW) however landfilling has lower net cost (80 €/tonne FW) compared to composting (92 €/tonne FW) due to additional revenue coming from landfill gas energy recovery in 2020 (Tables S23 and S24). AD had the second highest net cost (94 €/tonne FW) in 2020 however, it has lower net cost than composting (138 €/tonne FW) in 2050 due to high revenue coming from energy recovery. Incineration has a higher net cost in both 2020 (112 €/tonne FW) and 2050 (w/o 183 €/tonne FW).

The landfill had the lowest net costs in 2020. However, costs associated with reducing CO_2 emissions from landfills were the highest. The CO_2 abatement cost was almost 10 times higher than in other scenarios, due to less CO_2 savings in the landfill. Therefore, landfilling was not preferable. AD had the second highest net cost (94€) in 2020, due to high OPEX (operating expenses) compared to landfill and composting. However, the costs involved in reducing CO_2 were the lowest in 2020 (€111) and 2050, with no incentive scenario (€138), due to significant CO_2 savings. Incineration had the highest net costs in all scenarios, due to high OPEX and CAPEX (capital expenses). CO_2 abatement costs of incineration (87€, 170€, 254€) were lower than landfill (1134€, 1243€, 2139€) and composting (157€, 157€, 258€). Composting, with and without incentive scenarios, had the same results (157€), because there is no energy recovery from composting. Nevertheless, composting still had lower CO_2 abatement costs in all scenarios compared to landfilling, due to CO_2 savings made during the process.

The ETS scenario results show that Turkey would promote the recovery and recycling of organic matter if ETS were included in the WM system.[59] This is especially relevant to the landfill scenario, which has the highest CO_2 abatement costs (2139€), while composting (258€) and AD (228€) have the lowest. The ETS scenario only alters the incineration and composting CO_2 abatement cost ranking. Consequently, the AD scenario has the lowest CO_2 abatement costs in all scenarios, except for the incentive scenario.

3.3 | Scenario selection for the business model

When analyzing the carbon emissions, circularity, and cost calculation results, AD offers a promising opportunity to progress in the waste

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hierarchy by decoupling waste treatment. Small-scale AD plants have been gaining attention in terms of a shift towards a more decentralized system.[55] Decentralized systems have advantages over the traditional centralized system due to reduced transportation needs, increased public participation, and the reinforcement of local nutrient and energy loops.[63] Decreasing fossil fuel is one of the advantages of AD.[60] In addition, previous studies have found that AD is the most beneficial solution for managing FW.[64,65] Similarly, Guven et al.[66] established that incineration results in more savings due to high energy efficiency assumptions. This findings could be attributed to using the design values of the plant due to a lack of operational data. Previous studies carried out on university campuses in China[67] and the USA[68] also found AD as an efficient strategy for FW management, which has advantages over incineration and landfilling such as the valorization of FW, stakeholder partnerships, public participation from the beginning and increasing awareness regarding source separation.[69] Stakeholders are defined as groups or individuals who may be affected by activities related to BMs,[70] but in circular BM systems, creating value should be a co-operative effort. However, it is important to know that a much more significant benefit would be obtained through FW production prevention in terms of both economic and environmental aspects, as the largest impacts are from the production of food that is wasted—much more than the management itself.[60] There is no doubt that CE principles and the waste hierarchy give priority to AD and composting over incineration and landfill.[60] Thus, AD was selected for further FW management elaboration with regard to the business plan.

3.4 | Business model

Technology development is often considered sufficient for real-life applications, but social acceptance and feasible business strategies are also needed.[71] In addition, it is not possible to define WM under a single stakeholder, as it requires the cooperation of multiple stakeholders. The feedstock business model in this study do not prioritize economic performance but concentrate rather on the efficient use of resources while maintaining economic viability by reducing energy and material consumption and upgrading generated waste.[69] Local actors can provide important inputs into system design by responding to needs and challenges.[35] Hence, it is important to include all stakeholders in the business model design stage. The business model plan for FW management at Ayazağa Campus using AD is compatible with the Osterwalder and Pigneur[14] and Lagrasta et al.[72] Canvas model, which is illustrated in Table 2.

The proposed BM will align with the CE by slowing down, closing, and narrowing flows while creating value.[73] Ellen Macarthur Foundation (EMF)[74] promotes the cascading back of nutrients in the soil. However, some elements of the BM, such as key activities, key resources, channels, and value proposition, are not clearly defined by the EMF.[75] Biorefineries are widely used for FW management in BMs. The authors of this study decided to use the original Canvas model with the caveat of inserting two additional levels, namely the environmental and social.[72] This model has common SBM and CBM clusters, namely resource efficiency (narrowing loops), resource longevity (slowing, closing loop) and economic growth, but it does not belong to either. Instead, it is a simplified version of CBMs.[73]

In the model created for ITU, stakeholders, and income/expenditure tools are defined with how food waste sent to the AD system will travel within the CE. According to the proposed model, key partners are logistic partners and university administration/residents, in the short term, and municipality and farmers in the medium term. Local willingness to separate waste at source is a significant key resource, which in the case of ITU was found to be receptive to engaging in this scenario. Renewable energy production in the form of biogas, chemical fertilizer substitution from recovered nutrients, and closing the loop for waste are quantitative value propositions in the BM, whereas raised awareness about waste to energy and nutrient circulation concepts are qualitative value propositions. Customers on the small scale are techno-park (university science and business parks within the campus, set up to enhance research and development and collaboration with industries), campus residents (students, academic staff, and administrative staff), and university administration in the initial stage. Potential customers are the district municipality and local farmers in the medium term. Sources of income are fertilizers and electricity. In addition, if a special agreement is made with the district municipality, an additional source of income may be created. Operating costs are the salary of the technician working at the facility, the transportation of waste from the cafeteria to the facility, and other costs. The cooperation of internal and external stakeholders, living lab experience, stakeholder engagement, and increased awareness are important social outcomes. The prevention of FW and the implementation of a practical solution for managing it accordingly represent an important social value of the proposed BM.[12] The suggested BM also engages the community in managing FW, and feedback is provided during deliverance by personal contact.[12]

The public could rely on renewable biological sources while pursuing economic growth through initiatives consistent with CBMs.[76] Nevertheless, each study comes with its own limitations. First, Zaman[16] clarified that the major issues challenging the success of the WM business are finding potential partners and creating public-private partnerships. In addition, a lack of regulatory policies and standards that support new business models and competition with fossil fuels also act as barriers.[69,75] Second, while it may be feasible to expect feedstock without impurities in homogeneous university cafeterias, it is not realistic to expect feedstock without impurities in wider more heterogeneous communities as there is a larger risk of cross contamination.[77] This problem can be overcome by raising public awareness about source separation and increasing recycling rates.[78] In addition, in recent years anaerobic digestion of low-contaminated organic waste has been carried out by separate collection at the source in places that generate high amounts of FW such as bazaars, wholesale markets and dining halls. As an example, a biomethanization facility with a capacity of 150 tons/day has been operated since 2021 in Istanbul that accepts FW collected separately from bazaars, markets, hotels and universities.[79] This example can be applied in other

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TABLE 2 Business model for FW management on Ayazağa Campus, according to the Osterwalder and Pigneur[14] Canvas model and Lagrasta et al.[72]

Key partners • Logistic partners • University administration/ residents (students, staff, etc.) • Municipality • Farmers	*Key activities* • Manage resource flow • Biogas production • Fertilizer production • Education of local partners *Key resources* • Local willingness to separate waste at source • Human resources • Know how • Employees	*Value propositions* • Biogas, renewable energy production (avoiding fossil fuel during energy consumption) • Fertilizer (organic) • Closing loop for waste • Raised awareness on waste to energy concept	*Customer relationships* • Pilot cases • Education about CE • Visiting possible local partners *Channels* • Infrastructure for electricity • Local sales	*Customer segments* *Small scale* • Technopark • Campus residents • University administration Medium-scale • Municipality • Farmers (both scales) or gardening
Cost structure • O&M technical • Salary • Logistics • Capital costs for infrastructure		*Revenue streams* • Fertilizer sale • Electricity sale • Agreement with district municipality		
Social and environmental requirements • Experiment (living lab) • Stakeholder engagement • Monitoring system • Increased awareness		*Social and environmental benefit* • Being a pioneer for the CE in the region • Nutrient recovery • Avoiding landfill and methane release into the atmosphere		

Note: The environmental and social levels from this model is shown in purple in this table.

cities. A previous questionnaire study conducted on Ayazağa Campus shows a public willingness to participate in zero waste (to landfill) management and source separation of waste.[80] However, quantitative social aspects specific to FW should be measured in the future. Finally, rebound effect is a significant problem for the long term applications. A properly implemented BM can avoid the rebound effect by aiming to produce the minimum amount of waste and maximum practical benefit from products with biomass cascading, waste hierarchy and efficiency when using biomass or renewable resources.[81] However, due to the unforeseeable nature of highly complex systems, such as a CE market system, it is likely impossible to find meaningful conditions that are both necessary and appropriate.[82] While we acknowledge the limitations of the study, this does not negate the value of these results, highlighting the important relationships between decarbonization and circularity in multiple FW management scenarios.[10]

The decarbonizing ranking results revealed that three scenarios other than the landfill scenario achieve the zero-waste-to-landfill target, albeit the results are very different in terms of circularity, carbon emissions, and costs. This indicates that a variety of aspects should be considered before selecting technologies for goal-originated WM systems and BM planning. This study compared a decentralized pilot-scale AD facility with full-scale centralized incineration, composting, and landfill facilities. The effect of a centralized AD plant is a significant topic for larger-scale studies. Transport-related emissions in AD (decentralized) have been omitted in this study due to lack of knowledge of where AD cites will be placed, there is therefore not enough to information to assess whether omitting this transport has any impact on the conclusion. Previous studies have shown that waste collection fuel consumption may range from 1.4 to 10.1 L of diesel/tonne of waste.[83] A collection of source separated FW (feedstock) and transportation of digestate will lead to additional efforts, which results in increased fuel consumption and emissions.[78] Care should therefore be taken to find an appropriate balance between the scale of the facility and the collection distance while selecting the site for centralized AD facilities.[65] The BM should be verified for larger studies as it was previously the case for similar models such as Ecocanvas[18] and TLBMC.[15] This research is a non-profit academic study: how it will be utilized by businesses and possible partnerships with various stakeholders should be considered in the future.

University campuses represent small-scale cities within the living lab concept to investigate new solutions and tackle potential challenges for a wide range of real-world problems.[5] Circular models not only reduce the environmental impact of the linear model but also foster sustainable living throughout the campus.[84] Various obstacles exist to use circular models in practice at different scales and wider communities[85] namely; lack of awareness of the circularity concept among people, strict governance structures, regulatory barriers, constrained stakeholder collaboration, financial obstacles (unclear market demand, lack of external funding opportunities) technical know-how to engage in new business models.[86,87] These obstacles must be overcome through pilot applications and research before being implemented on a wider audience. Universities can use this research to develop a business case for circularity implementation. The development of further

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studies can also benefit from its use as a baseline for further research is needed to examine barriers and opportunities for BM implementation in other sectors.[87,88]

4 | CONCLUSIONS

The new business model in this study seeks to create a platform for sharing ideas while promoting best practices relating to the environmental and economic aspects of WM. The emission calculations show that incineration offers the greatest carbon savings, followed by AD, but it provides neither decoupling nor circularity for natural resources. Also, it has high toxicity compared to the AD. Additionally, current and future cost calculations show that incineration has the highest uncertainty in terms of net costs, while AD has the highest circularity and lower uncertainty for the future. The business model is designed in tandem with the living lab concept, in which the end-user is actively engaged in the planning and finalization of the system. While, the quantitative outcome is renewable energy production in terms of biogas, chemical fertilizer substitution, and closing of the nutrient loops, a qualitative outcome is seen in raised awareness on waste to energy concepts. On the other hand, rebound effect production trends and consumer demands are significant indicators to be conquered.

AUTHOR CONTRIBUTIONS

Kadriye Elif Maçin: Conceptualization; writing – original draft; methodology; visualization; data curation; formal analysis; investigation; writing – review and editing. **Osman Atilla Arıkan:** Writing – review and editing; supervision; conceptualization. **Mahmut Altınbaş:** Resources; project administration. **Anders Damgaard:** Conceptualization; writing – review and editing; formal analysis; methodology; supervision.

ACKNOWLEDGMENTS

The authors would like to thank İbrahim Demir for his scientific contribution and the Research Fund of the Istanbul Technical University for its financial support of this research as part of Project ID: 42255. The author, K.E. Maçin, was supported by the Scientific and Technological Research Council of Türkiye 2214/A International Doctoral Research Fellowship Program – during the study. The business model approach in this manuscript was originally inspired by Aarhus University's Circular Bioeconomy PhD course.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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How to cite this article: Maçin KE, Arıkan OA, Altınbaş M, Damgaard A. Decarbonizing university campuses: A business model for food waste management at Istanbul Technical University (İTÜ) Ayazağa Campus, Turkey. *Environ Prog Sustainable Energy*. 2024;43(2):e14316. doi:10.1002/ep.14316

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