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Triple Bottom-Line Evaluation of the Production of Animal Feed from Food Waste: A Life Cycle Assessment

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Abstract
This study applies a triple bottom line (TBL) framework that incorporates the environmental, economic, and social impacts of producing animal feed from food waste (FW) collected at the post-consumption stage of the food supply chain. The environmental bottom line (BL) is conducted using life cycle assessment (LCA), the economic BL is calculated using the net present value (NPV), while the social BL is assessed using the strengths, weaknesses, opportunities, and threats (SWOT) analysis. The results within the environmental BL indicate that at a 13.8% recovery rate, animal feed produced from a ton of FW saves 0.33 m² equivalent of crop land but requires 3.5 tons of water compared to 0.9 tons and 0.78 tons for landfilling and incineration for FW treatment respectively. In addition, the production of animal feed from one ton of FW emits 1064.6 kg CO₂-eq, compared to 823.6 kg CO₂-eq using landfilling and 781.9 kg CO₂-eq when incinerated. The economic BL indicates a profit of $3.65/ton from incinerating FW, compared to cost of $93.8 and $137.6 per ton for animal feed production and landfilling of FW respectively. The analytic hierarchy process (AHP) is applied to integrate the TBL scores and rank the scenarios accordingly. AHP recommends animal feed and incineration over landfilling by a fourfold higher score. A simulation using an augmented simplex lattice mixture (ASLM) design recommends incineration with energy recovery over animal feed production from FW collected at the consumer stage. Sensitivity analysis indicates that the production of animal feed from FW is environmentally feasible if the safe recovery rate exceeds 48%, which is possible for FW collected at early stages of the food supply chain.

References

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Graphical Abstract

Environmental BL

- Life Cycle Assessment (LCA)
  - ISO-14040/4
    - (SimaPro 8.0 Software)
  - LCI processes
    - (Eco Invent 3.0)
  - Impact categories
    - (ReCipe V1.10)

Economic BL

- Net Present Value (NPV)
  - Cost Analysis
    - (Recurring and Nonrecurring)
  - Pretreatment, treatment, and disposal
  - Annual equivalence (AE)

Social BL

- SWOT Analysis
  - Key indicators:
    - Employment
    - Quality of life
    - Health & safety
    - Land usage
    - Byproducts
    - Legislation

Multicriteria Decision-Making:

Analytic Hierarchy Process (AHP)

Augmented simplex lattice mixture (ASLM) optimization

Keywords
- Food waste
- Animal feed
- Life cycle assessment (LCA)
- Economic evaluation
- Social evaluation
- Multicriteria analysis
- Sensitivity analysis
- Optimization
- Kuwait

Abbreviations

- A Annual series
- AE Annual equivalence
- AHP Analytical hierarchy process
- AL0 Agricultural land occupation
- ASLM Augmented simplex lattice mixture design
- BL Bottom line
- c_{ax} Disamenity and disposal costs for scenario x
- CBA Cost–benefit analysis
- CC Climate change human health
- CE Circular economy
- c_{tx} Cost of initial investment for scenario x
- c_{mx} Cost of maintenance and operation for scenario x
- CR_y Criteria y based on national strategy
- c_{tx} Cost of transportation for scenario x
- EPA Environmental Protection Agency
- EU European Union
- FAO Food and Agriculture Organization
- FD Fossil depletion
- FU Functional unit
- FW Food waste
- g Arithmetic gradient
- GCC Gulf Corporate Council
- GDP Gross domestic product
- GHG Greenhouse gasses
- HH Human health
- HT Human toxicity
- i Annual market interest rate
- ISO International Standardization Organization
- LFG Landfill gas
- LCA Life cycle assessment
- LCI Life cycle inventory
- LCIA Life cycle impact assessment
- MCDM Multicriteria decision-making
- ME Marine ecotoxicity
- MENA Middle East and North African
Mo  Maintenance and operation
MSW  Municipal solid waste
NPV  Net present value
OD  Ozone depletion
P  Present value
p  Product recovery prices
PAAF  Public Authority for Agriculture and Fish
PAHW  Public Authority for Housing and Welfare
PT  Points according to Recipe normalization scale
POF  Photo chemical oxidant formation
R_{bx}  Revenues from environmental externalities savings for scenario x
R_{ex}  Revenues from energy savings for scenario x
R_{px}  Revenues from byproduct material recovery savings for scenario x
SDG  Sustainable Development Goals
SR  Scenario
SWOT  Strength weakness opportunity threat assessment
T  Transportation
TBL  Triple bottom line
TC  Total cost

The Statement of Novelty

The present study is the first of its endeavor to identify the threshold upon which animal feed production is considered feasible when recovered from municipal solid waste. The present study is also the first to establish this assessment using a triple bottom line (TBL) framework that is based on life cycle assessment, net present value (NPV) calculations and key social dimensions, which uses simulation based optimization and AHP to compare food waste (FW) treatment scenarios. The results are particularly helpful for researchers and policy makers planning to improve organic and FW management through applying principles of circular economy. The study has wider repercussions for food and water security, in addition to contributing to climate change abatement strategies.

Introduction

If food loss and waste were a country, they would be the third largest source of greenhouse gas emissions [139]. The Food and Agriculture Organization (FAO) defines FW as wholesome edible material intended for human consumption, arising at any point in the food supply chain that is instead discarded, lost, degraded or consumed by pests. It is estimated that approximately 1.3 billion tons of edible food is wasted throughout global food supply chains every year [65]. This corresponds to approximately one-third of all food produced for human consumption [65]. A total cost amounting to approximately $1 trillion ($700 billion in environmental costs and $900 billion in social costs) is reported per year due to FW [64].

Food losses and waste cut across food chains, vary by food group and are specific to the region or country [67]. The UNEP Food Waste Index [139] looks mainly at the consumer stage of FW and analyzes losses and waste per sector: retail, food service and household. The FW index report [139] indicates that approximately 931 million tons of FW was generated in 2019, 61% of which came from households, 26% from food services and 13% from retail (see Fig. 1a).

Analysis by FAO [63] indicates that most of the FW occurs
preconsumption in production and retail (see Fig. 1b). However, a closer look at FW per supply chain stage per commodity per region conducted by FAO [66] indicates that the amount of FW per food supply chain depends on the city and region.

FW is an intersecional problem that has social, environmental, economic and moral dimensions, as it puts disadvantaged and marginalized communities at its forefront [23, 37, 149]. The 2030 agenda for Sustainable Development Goals (SDG) and the 26th UN Climate Change Conference [37] in Glasgow have emphasized the importance of FW reduction and urge governments, nongovernmental organizations and businesses to collaborate and take action toward improving the FW problem. Target 12.3 of the SDG calls for decreasing the per capita global FW rate at retail and consumer levels by nearly half by 2030, in addition to reducing food losses along the production and supply chains [66]. Unfortunately, the latest estimates suggest that the global amount of food losses and waste is higher than previously calculated statistics [33].

FW exerts substantial stress on water consumption and loss levels, especially in water-scarce areas such as the Middle East and North African region (MENA) [1, 4, 12, 74, 145]. As Aleisa and Al-Zubari [5] indicate, 70% of water is consumed in the agricultural sector, of which one-third is wasted. The Gulf Corporation Council states (GCC) of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates consume more water through FW than other countries in MENA due to their higher gross domestic product (GDP) and prosperity, which is directly related to increasing food consumption and FW levels [100].

FW is challenging due to its high moisture and degradation level, protein-rich organic composition, and odor and rotting properties [20, 27, 31, 147, 149]. Due to these characteristics, FW is described as a ‘wicked problem’ [110]. The food recovery hierarchy triangle places FW waste prevention at the top, followed by the options of reuse, recycling, recovery, and finally disposal [58, 141, 144]. Managing FW systems through the process of producing animal feed from waste ranks third in the hierarchy triangle. This tier is intended to encourage resource efficiency of waste, material recycling, and nutrient recovery [102, 136]. The valorization of FW to produce feed considers waste to be a valuable secondary resource and aligns with the circular economy (CE) framework [56, 94, 127]. The implementation of a CE framework for FW management systems is not yet systematic due to the lack of supporting legislation, infrastructure, and health and safety challenges [40, 47]. In addition, COVID-19 has added an extra layer of complexity to the possibility of spread of the disease through redistributed excess FW [41, 129, 149].

A FW management system’s efficiency is assessed according to how much material is lost, the quality of the product, the material or substance created, and the energy and water requirements [56]. The selection of a FW management system is dependent on the FW sources and characterization, in addition to the treatment center’s infrastructure capacity [93, 149]. When selecting among alternatives, measuring the recovered products and resources stemming from these disposal systems is extremely vital [55].

FW impacts climate change [110], which is the result of the increased absorption of infrared radiation by the atmosphere due to the emission of greenhouse gases (GHG) from waste sources [86]. With regard to GHG emissions, FW that decomposes anaerobically generates methane gas (CH₄), which, when released in the environment, has 25–37 times the warming effects of carbon dioxide (CO₂) [72, 86, 103]. GHG emissions attributed to FW and loss account for 8 to 10% of anthropogenic emissions worldwide [47]. From a life cycle perspective, FW accumulation throughout food supply chains increases the demand for commercial food production and places additional strains on the agricultural ecosystem [99] and the consumption of fertilizers and depletion of scarce essential nutrients [6, 47, 96, 120, 135].

This study presents a multicriteria decision-making analysis (MCDM) to evaluate the impact of utilizing FW collected from households, farms and local businesses as animal feed as opposed to using sanitary landfills (baseline) and incineration with energy recovery across a TBL framework. The scope of the present study is the consumer echelon of the food supply chain, for FW received from retail, food service and household [139]. The environmental bottom line (BL) is conducted using life cycle assessment (LCA) through a consequential open-loop modeling system with avoided saved animal feed production and shipping. A sensitivity analysis is conducted to investigate several recovery rates of animal feed from FW to identify a break-even point beyond which the production of animal feed from FW is considered environmentally feasible. The economic (BL) is calculated using NPV that incorporates initial investment, operation and maintenance, transportation, and inflation costs, and revenues realized from anticipated energy recovery, materials savings and other externalities. The social BL is measured using strengths, weaknesses, opportunities, and threats analysis (SWOT) for each scenario across social indicators that include impacts on quality of life, health and safety, legislation, etc. The scenarios are cross-evaluated using the analytical hierarchy process (AHP) with respect to seven criteria that define national priorities and strategies. The country context is a rentier state of high consumption and an arid environment: Kuwait. The augmented simplex lattice mixture (ASLM) is applied to test the sensitivity of the results across the multiple criteria while accommodating the inherited correlation of weight assignments across the exclusive alternatives. A simulation of multiple weight
assignment is conducted using ASLM and compared to AHP results.

**Literature Review FW LCA**

LCA has been frequently applied to assess FW treatment options such as landfilling, composting, incineration with or without energy recovery, recycling, and a combination of various scenarios [2, 3, 18, 27, 31, 43, 55, 92, 98]. FW has been used as feedstock to produce different biomaterials, bioenergy, and other high-value products [39, 104, 133, 136]. LCA to evaluate system expansion is usually applied to assess savings in energy, fertilizers, and soil improvement materials compared to traditional landfills in FW management applications [31, 55, 140]. Within waste management systems, LCA has also been applied to assess the impacts of byproducts, such as slurries for biogas production, feed products, leachate landfill gas (LFG), and biofertilizers produced from composting processes [31, 95]. The work on Loctier [97] examined how stakeholders can transform FW into other commodities. Kim and Kim [92] discussed avoided products, such as bread production, saved as a result of using FW for the production of feed. The work of Mosna, et al. [108], Brancoli et al. [27], and Brancoli et al. [26] focused on the production of animal feed from waste bakery products. Lee et al. [95] assessed the impacts of utilizing FW to make feed and its effect on reducing the need for commercial feed purchasing or production, processes that require both land and water. In their study, Mosna et al. [107] assessed the impact of valorizing meat from packaged FW using LCA, which reduced the global warming potential, water consumption and land use by 56.4%, 22.6% and 87.5%, respectively. Bernstad Saraiva Schott and Andersson [20] studied the generation of electricity and heat via the incineration of FW, and Guven, Wang, and Eriksson [75] further studied making use of the steam generated from these incineration plants to generate electricity. Pourreza Movahed et al. [116] calculated the amounts of FW sent to management systems while considering the weight of the selected FW management systems (e.g., landfilling, incineration, and composting) as a decision variable to minimize both energy consumption and emissions [90]. Life cycle costing (LCC) of FW has been addressed by Lundie and Peters [98] and Nicole and Francesco [111] using the return on investment (ROI) as an indicator to compare the systems.

In general, the data for social assessments are collected through observations, interviews with experts and stakeholders, government reports, and public questionnaires to assist policy makers and improve municipality strategic plans for waste management [46, 130, 150]. Shahba et al. [126] have assessed the impact of waste on-site segregation from a social perspective, and Allesch and Brunner [13] applied SWOT to analyze food streams. Technical, social, legal, and spatial factors have been integrated and evaluated repeatedly using AHP within the LCA framework [69, 91]. The AHP approach includes a broad analysis of both objective and subjective aspects and criteria related to the presented problem [94, 137].

**Methodology**

The methodology (see Fig. 2) depicts the MCDM for evaluating the impact of utilizing FW as animal feed as opposed to using sanitary landfills and incineration with energy recovery across a TBL framework. The waste assessed is the total FW collected at post consumption received from retail, food service and household.

**FW Scenarios**

Let $SR_x$ denote scenario $x$, where $x = 1$ for the animal feed production SR, $x = 2$ for the sanitary landfiling SR, and $x = 3$ for the incineration SR. For each $SR_x$, the general reference flows include the process inputs: energy materials, chemicals, outputs: process emissions, leachates, waste, etc., and credited/saved products or materials. These are described next.

**Animal feed production from FW ($SR_1$)**

For $SR_1$, animal feed production (see Fig. 3a), FW is fed into the hopper for initial sorting. All nonorganic matter is removed either via machinery racks or manually. The collected FW is shredded, and waste particles are reduced to a diameter of $<3.0$ mm. Consecutive thermal processes of drying and dehydration remove approximately 50–70% of the moisture content (Henry H. [80]. The water content is further reduced by adding drying ingredients or agents such as wheat bran, saw dust, and beet pulp. These processes are followed by secondary sorting and a deodorizing process. The mixture is then fermented by premixed bacteria containing various yeast and lactic acid species at a temperature of 80 °C for 4–10 h on the basis of $10^6$–$10^8$ viable bacteria per kilogram of mixed FW [125]. The mixture undergoes hydrolysis, which entails an additional fermentation process for 1–2 days in a sealed silo at 120–180 °C. Finally, the paste produced is extruded into feed pellets. During the process, wastewater is generated, treated and released into the environment. Any residues stemming from the processes are sent to a sanitary landfill, where LFGs are treated before being released. Using this process, 1 ton of FW produces 135 kg of animal feed [125].
Sanitary Landfilling of FW (SR₂)

For SR₂, sanitary landfilling (see Fig. 3b), FW is compressed through drainage pipelines and then layered with soil. The leachate is treated via nitrification, chemical coagulation, and anaerobic digestion at a 90% efficiency [95]. The leachate amount accounts for 0.31 m³/ton of the total FW amount treated. Half of the LFG consists of 50% methane [59], which is used to generate electricity to offset the use of fossil fuels [18, 19, 92, 93, 137, 147]. The remaining LFG is flared.

Incineration with Energy Recovery (SR₃)

Guven et al. [75] consider incineration as an inefficient option to treat FW due to its high moisture content. However, because of its relative to its robustness, it is still applied in many countries [32]. Kuwait is also planning to embark on a large-scale MSW incinerator. A waste-to-energy facility will accommodate half of Kuwait’s MSW, including FW. For this reason, incineration with energy recovery is considered. In SR₃, FW is fed by a crane and a refuse hopper to the main grate incinerator and into a combustion chamber (furnace) (see Fig. 3c). FW then passes through an electric precipitator, where ash and residue, including bottom ash, are generated. The ash discharger is a pusher type with a water bath in which the 500–600 °C hot slag is cooled to 40–70 °C [94]. The generated FW then undergoes gas scrubbing. The energy recovered from the scrubbed gas is converted into power in the form of heat, due to the high moisture content of FW [89]. Bottom ash is sent to landfills, and the LFG and leachate are treated.

Environmental BL

The LCA conducted to evaluate the environmental BL followed the requirements outlined by ISO 14040/4 [87]. The goal of the LCA is to assess the realized benefits and burdens associated with the application of FW as animal feed as opposed to landfilling and incineration at the consumer stage. The functional unit (FU) considered is 1 ton of FW received from retail, food service and household [139]. The system boundary is gate-to-grave. It incorporates the assessment of FW from the resource extraction phase (or collection) to the use phase (production of animal feed, waste processing through landfilling, or generation of electricity and power via incineration) and finally the disposal phase of residues and resources [27, 147]. The consequential open-loop modeling system is based on ISO 14044 [88] and ILCD [85].

Post consumption FW is transported to treatment facilities. It is the same across all three scenarios and thus discounted. Additional details are provided in the discussion section. The majority of animal feed in Kuwait is imported from Australia and shipped by sea [11]. Transoceanic freight of avoided animal feed shipped internationally is considered [18, 19, 55, 83, 92, 98]. For the European Union (EU), most animal feed is imported from China [29, 54, 71]. For EU studies, export and import shipping distances need to be adjusted accordingly. In addition, within facilities’ treatment, material handling and transportation is included using local

![Fig. 2 MCDM framework to evaluate the FW management scenarios](image-url)
Fig. 3  a SR1: production of animal feed from FW, b SR2: sanitary landfill of FW and c SR3: incineration of FW with energy recovery
prices for diesel with an annual inflation rate of 0.73% for diesel prices. Treatment facility infrastructures such as the construction demolition of plants, buildings, roads, etc., for the selected processes are included within the scope using the inventory processes.

The landfill facility, obtained from Ecoinvent as process-specific burdens, has a municipal waste landfill capacity of 1.8 million m³ with a construction phase of five years. It is equipped with a leachate and landfill gas collection system with no energy recovery. The incinerator has an operational lifetime of 30 years. The incinerator is a modern grate incinerator. It includes a waste bunker, steam boiler, electrostatic precipitator, and wet scrubber. It landfills the bottom and boiler ash. Additionally, obtained from Ecoinvent as process-specific burdens, municipal waste incineration has an operation capacity of 100,000 tons/year. The incinerator has an operational lifetime of 40 years. The animal feed production facility was customized, however, with regard to the processes in its system, rather than the available facilities in the database.

Model foreground data are collected from Kuwait Municipality reports and interviews with employees and field experts. Some model background data are obtained from average data and interpolation from the literature, as opposed to obtaining the data from single sources (see Appendices). Inventories are built using the Ecoinvent database V1.10. The life cycle impact assessment (LCIA) categories are calculated on characterized and normalized midpoint levels. A sensitivity analysis is conducted to determine the impact of varying the current animal feed extraction rate from the FW treatment to 13.5%.

With regard to animal feed production (SR1), the amount of feedstock produced depends on FW type and stage in the supply chain. In our case, the recovery rates range between 13.5% and 90%. This yield ranges widely and is dependent primarily on the type of FW collected at the source [124], which is further explored in the sensitivity analysis of this study. For this study, an extraction rate of 135 kg/ton of FW is assumed based on post consumption FW estimates (see Appendix 1—Table 4). The electricity requirements range between 19.4 and 25 kWh/ton FW, and the liquified nitrogen gas levels required for the processes are between 30 and 40 m³. In addition, the amount of wastewater generated is between 370 and 640 kg, and approximately 179 to 360 kg of the FW collected is lost during drying processes. As a result of the treatment, an additional 59 to 120 kg of residues and screenings are produced, and they need to be further landfilled and treated [92, 95, 98, 125].

The literature indicates that landfilling (SR2) inventories energy consumption ranges between 25 and 35 kWh/ton of FW. Water usage is approximately 0.11 m³ for treatment [83, 138]. In addition, treating 1 ton of FW recovers a minimum of 55 kWh and a maximum of 85 kWh with the baseline drawn at 35 kWh for this study (see Appendix 1—Table 4). The LFG produced and collected ranges between 147 and 250 m³, and the generation efficiencies range between 29.4 and 68% [95, 101, 128, 129].

The primary energy required for FW treatment via incineration (SR3) ranges from 75 to 95 kWh [128]. Energy recovered from the processes can be obtained at an efficiency rate of 11% to 22% [101]. The amount of energy acquired reaches a maximum of 338 kWh/ton FW, and it generally ranges between 120 and 310 kWh [92, 101, 128, 129]. The natural gas required for incinerating FW ranges from a minimum of 10 MJ to a maximum of 17 MJ. In addition, the diesel required for emission control is estimated at 0.6 kg/ton FW. As a result of the incineration processes, ash is generated at rates between 150 and 250 kg/ton of FW and requires further landfiling (see Appendix 1—Table 4).

The life cycle impact assessment (LCIA) categories considered were selected based on relevance [88], existing literature [78] and geographic region [3]. These include: Climate change human health (CC), ozone depletion (OD), human toxicity (HT), photochemical oxidant formation (POF), agricultural land occupation (ALO), natural land transformation (ME), and fossil depletion (FD). These are assessed on characterized and normalized levels at the midpoint using the Recipe V1.10 midpoint (H) method [84]. The carbon footprint and cumulative energy demand analysis are also assessed using the IPCC 2013 method [132] and by the Frischknecht et al. [68] method respectively. The water footprint has also been assessed for each scenario using the Boulay et al. [25] water scarcity impact method. A sensitivity analysis is conducted to determine the impact of varying the current animal feed extraction rate of 13.5% from the FW treatment.

**Economic BL**

Let NPV_x denote the NPV for each scenario SR_x (see Eq. (1)), where x ∈ {1, 2, 3}. AE_x indicates the annual equivalent for SR_x, which is calculated using Eq. (2) based on a uniform series (A) and present (P) of worth factor (PA), and capital recovery factor (A/P) over a lifetime (n). C_i, denotes the cost of the initial investment (I) for SR_x, which comprises the summation of all prefinancing costs, construction work expenses, and equipment installation costs. C_max represent the cost of maintenance and operation (mo) for each SR_x acquired during the preinstallation, main treatment, and posttreatment phases. The inflation in costs of mo, transportation (t), and product recovery prices (p) are incorporated in the cash flows as the arithmetic gradient (g), where je(m, t, p). An annual 3% accounts for the increase in wages, maintenance, and operation rates [41, 150]. C_t is the cost for transportation (t) for each SR_x and is subject to an annual gradient of 0.73% accounting for diesel inflation.
rates evaluated for facility transportation [131].  
\( C_{\text{as}} \) denotes the additional expenditures \((a)\) that account for environmental, disamenity and disposal costs under the given \( SR_x \). Let  
\( R_{ex}, R_{px}, R_{bx} \) denote the realized revenues from energy savings \((e)\), byproduct material recovery \((p)\), and saved environmental externalities \((b)\). The discount rate \((i)\) is 6.67% compounded annually, and the economic conversion factors are allocated accordingly for each calculated value.

\[
NPV_x = C_{I_s} + C_{\text{max}}(P/A, g_{\text{as}}, i, n) + C_{I_s}(P/A, g_s, i, n) + C_{\text{ext}}(P/A, i, n) + R_{ex}(P/A, i, n) + R_{px}(P/A, g_p, i, n) + R_{bx}(P/A, i, n) 
\]

(1)

\[
AE_x = NPV_x(A/P, i, n) 
\]

(2)

**Social BL**

The social indicators for SWOT analysis are selected based on the work of Aleisa and Al-Jarallah [2] and include (1) the quality of life effect on civilians and employees, (2) health and safety regulations, (3) land usage by the systems, (4) byproducts stemming from waste management systems, and (5) legislation and political influences. SWOT analysis is followed by a qualitative and quantitative analysis of the internal and external factors associated with each SR [15, 122]. The organizations selected for the SWOT analysis provided representation and feedback for the indicators needed. The conducted SWOT analysis is the result of interviews with experts in the fields of urban planning and waste management at the Public Authority for Housing and Welfare (PAHW), electrical and civil engineers from the Ministry of Electricity and Water, agricultural and environmental engineers from the Public Authority for Agriculture Affairs and Fish Resources (PAAF), researchers and environmentalists from the Kuwait Institute for Science and Research and specialized professors from Kuwait University. The experts selected represented all of the backgrounds needed to collect data for the selected indicators.

**Multicriteria Decision-Making Evaluation**

The MCDM evaluation is conducted through AHP [121] and later through ASLM optimization. The initial phase of the AHP method involves the construction of the hierarchy decision tree (see Fig. 4). Level I of the AHP decision tree reflects the overall goal of the study, Level II explains the criteria affecting the decision, and Level III presents the different SRs to be assessed. Seven evaluation criteria \((CR_y, y = 1, 2, \ldots, 7)\) are considered:

- **Emissions into the environment \((CR_1)\):** Based on the work of Angelo et al. [14] and Contreras et al. [36], the alternatives are scored in regard to the LCA-characterized CC midpoint impact category.
Hygiene conditions impacting human health (CR2): These criteria are based on the work of Fantke, Ernstoff, Huang, Csiszar, and Jolliet [62]. The alternatives are scored based on the LCA-characterized human HH, OD, HT and PM impact category results.

Annual operation costs (CR3): Based on the work of Genrowicz et al. [69], Khalili and Duecker [91], Laso et al. [94], Pourreza Movahed et al. [116], the alternatives are scored in regard to the annual operation costs calculated in NPV.

Missed opportunities (CR4): This indicator is measured by the employability of each SR and the recovery of raw materials to provide resource opportunities [8, 21, 81, 134, 141]. Under SR1, the process produces 135 kg of animal feed/ton FW [125], SR2 produces 147 m³ LFG/ton FW, and SR3 results in the production of 310 kWh of energy/ton FW [83]. After reviewing all the findings, the SRs are scored based on a series of meetings with experts in waste management at the PAHW and the rankings of Coban et al. [35] and Hidalgo et al. [82].

Achieving national targets (CR5): This criterion measures the alignment of an SR to meet the National Development Plan of 2035. The goals of the national plan include (1) global positioning and enhancing the presence of Kuwait, (2) human capital and promotion of youth involvement and productivity, (3) living environment enhancement aimed at damage control, (4) infrastructure development, modernization, and quality of life improvement, and finally (5) development of economic prosperity and diversification and reduction in the dependency of Kuwait on oil as a single income source.

Social acceptance (CR6): This criterion is measured based on (1) technological uncertainty and other compliance issues with regulatory standards, (2) controversies around SRs, if any, (3) impact on land use, and (4) public resistance toward a given SR. The meetings were conducted with experts in waste management from PAHW [114], in addition, the rankings of Hidalgo et al. [82] and Su et al. [134] are considered.

Ability to meet technical requirements (CR7): The evaluation of this criterion is based on (1) the time required to implement a given SR, (2) the ability to meet the technology-related maintenance requirements, (3) the availability of space for the expansion plans associated with the SR, (4) the infrastructure requirements of the SR, and (5) the amount and availability of qualified personnel and staff requirements of the various SRs. The rankings and scores of Coban et al. [35] and Vučijak et al. [141] are applied.

Data Collection and Inventories

The feedstock characteristics are provided in Table 1. The FW feedstock composition and moisture content vary according to the region studied, and these aspects influence the treatment required [20, 27, 31, 95, 147]. The LCA inventories (Environmental BL) for including chemical additives, energy, recovered energy and saved (credited) material are provided in Appendix 1. The economic data collection (Economic BL) required for NPV is provided in Appendix 2, and the data for the social BL are provided in Appendix 3 for each of the SRs.

Life Cycle Impact Assessment (LCIA)

A comparison of the characterized LCIA values is depicted in Fig. 5a. The results indicate that the relative environmental impact is the worst for producing animal feed (SR1) (for post consumption FW) across the impact categories considered except for ALO and HT. Using the IPCC 2013 method [132], SR1 had the highest CO2 equivalent emissions (see Appendix 1—Table 5). For one ton of FW treated, animal feed, SR1 emits 1064.6 kg CO2-eq, compared to landfilling at 823.6 kg CO2-eq and incineration at 781.9 kg CO2-eq. The results are consistent with cumulative energy demand analysis [68]. The highest contributor to the overall negative impacts of animal feed production (SR1) was the energy use in the FW thermal treatment and shredding. Animal feed extracted from consumer-stage FW has a relatively high water footprint. Treating animal feed with one ton of FW requires 3.5 tons of water compared to 0.9 and 0.78 tons of water for landfilling and incineration, respectively, using the Boulay et al. [25] water scarcity impact method.

The normalized results rescale the characterized results with reference to the average emissions of a global citizen using factors established by the Recipe V1.10 midpoint (H) method [84]. Normalization, although optional according

| Parameter                     | Unit    | Value |
|-------------------------------|---------|-------|
| pH                            | –       | 6.1   |
| Electrical conductivity       | μS/cm   | 9458  |
| Water content                 | %       | 59    |
| Organic matter                | %       | 57    |
| Ammonia                       | mg/kg   | 317   |
| Total nitrogen                | g/100 g dry matter | 1.34 |
| Dissolved organic carbon      | g/kg    | 101   |
| Carbon nitrogen ratio (C/N)   | –       | 23    |
to ISO 14044 [88], is mandatory for product environmental footprint analysis of the EU [123]. The normalized results are shown in Fig. 5b, using the points (pt) indicates that the realized benefit in ALO exceeds the disadvantages that result in other impact categories. The potential savings realized from producing animal feed from FW is 118% compared to landfilling and incineration. For every 1 ton of FW treated, 0.33 m² per year of crop land area is saved. The advantage of landfilling and incineration over animal feed production from FW is due to energy recovery from methane gas and flue gas that is used in energy production.

As indicated earlier, the percent recovery is highly dependent on the properties of the feedstock. FW and losses collected from farms and earlier echelons of the food supply chain would yield higher recovery rates. In this study, the assumption of a 13.5% recovery rate was based on the IPCC 2013 method [132], d the cumulative energy demand by the Frischknecht et al. [68], and e the water footprint using the Boulay et al. [25] water scarcity impact method.
consumer stage using characteristics presented in Table 1 [138]. The feed recovery rate can achieve 90%, but this is feasible if the FW originating from yard or farm waste requires only minimal treatment before being provided to animals. A sensitivity analysis is conducted to investigate several recovery rates of 13.5%, 20%, 40%, 50%, 70%, 80% and 100%, which could predict the impact when FW is collected at the beginning of the food supply chain. Separate LCA models are compiled using calculated credits for each case. A plot of the normalized LCIA results is generated and shown in Fig. 6. From an environmental perspective, the production of animal feed from FW could outperform landfilling and incineration at a 48% recovery rate or higher, and at this break-even point, the LCIA endpoint categories under the animal feed scenario (SR1) are improved up to 17.21% for less damage to human health (HH), 11.98% for less damage to the ecosystem (ES), and 52.38% for less damage to resource availability (R).

**Economic Assessment**

The cost breakdown and NPV assessment are calculated using Eqs. (1) and (2) on two levels with and without the cost of purchasing animal feed to account for the missed opportunity cost when FW is wasted while being a potential source for animal feed [8, 16, 112]. The results are provided in Appendix 2. For FW collected at the consumption stage, incineration (SR3) is the most financially viable due to the recovered energy. The realized profit from incineration per ton of FW feedstock is 1.1 KD (~$3.65). However, the net incurred cost is 28.3 KD (~$93.8) for animal feed production (SR1) and 41.51 KD (~$137.6) for landfilling (SR2) for each ton of FW treated. While applying the missed opportunity assumption [8], the cost of treating 1 ton of FW is 38 KD (~$126.54), KD 52.5 (~$174.83) and 9.9 KD (~$33) for the animal feed scenario, landfilling and incineration, respectively. Animal feed cost is high due to thermal and shredding processes and low recovery rates (13.5%) at the consumer stage. For landfills, the largest cost contributor is the disamenity costs.

**Social Assessment**

Waste treatment facilities can be categorized as semi-obnoxious due to their impact on the quality of life of surrounding areas. The SWOT analysis investigated the social impacts for each SR with respect to the impact on the quality of life, health and safety regulations involved in the systems, and land usage by the systems and byproducts produced, in addition to any associated external legislation and political influences. The results are provided in Appendix 3. The main social threat of animal feed production (SR1) concerns health and safety issues, especially after the cattle mouth and foot disease outbreak that took place in the UK in 2001. The main weakness is the low proportion of recovered feed and high variability of caloric/nutrient values with respect to FW collected at the consumer stage. Landfills (SR2) and incinerators (SR3), on the other hand, have the advantage of being mature technology and robust to feedstock properties. Their weakness is realized in being low in accordance with the waste hierarchy according to CE. In addition to their threats to surrounding land price degradation, the field experts interviewed have suggested recommendations regarding the following: establishing a national system that incorporates different stakeholders, decentralizing current FW waste management systems, handling the different stages at the supply chain in a timely manner, revising the regulations regarding FW management systems along the food supply chain, establishing a data monitoring center to establish informed decisions that are tailored to specific food types, launching community-based pilot projects, encouraging private-government partnerships, and increasing public awareness and training.
Multicriteria Evaluation

The Saatay [121] method starts by weighing the criteria with respect to each other and then ranks alternatives according to these criteria through pairwise comparison. Then, the overall score is finally derived through cross multiplication [2]. The ranking of criteria by weights according to the pairwise comparisons is provided in Table 2. The results rank CR3: annual operation costs (44.7%), as most important, followed by CR4: missed opportunities (26.4%), then criteria CR5: reaching national targets (7.2%), CR6: social acceptance (7.2%), and finally CR1: emissions into the environment (7.15%).

The score of each SR across the AHP criteria is provided in Table 3. The scores are rescaled to 0–10 [141, 143]. The final step involves the cross-multiplication of the relative criteria weights in Table 2 with indicator scores in Table 3 to obtain the overall score depicted in Fig. 7. As shown in Fig. 7, SR1: animal feed scenario (45.0%) and SR1: incineration (43.2%) rank higher than SR2: landfilling (11.8%) and the consumer stage FW.

Sensitivity Analysis

In this section, a sensitivity analysis is applied to systematically investigate the impact of the weights of each CRy on the overall global score. Since in AHP, the summation of weights assigned to the criteria must equal one, an increase in the score for any SR will cause a decrease in the scores of the other SRs. The methodology for sensitivity should accommodate the inherited collinearity from correlated scores [7]. Developed by Scheffé (1958–1965), the ASLM design has the advantage of accommodating this correlation for the summation of scores equal to a constant, one [38]. Here, the weights of each CRy represent the vertices of the ASLM. Thus, the design consists of the seven simplex-lattice design components that consist of points defined by equally spaced 0–1 coordinate settings [105]. The design is augmented from the standard simplex lattice to investigate the response to interior points, as opposed to the standard simplex or centroid simplex mixture designs [7]. The Cox response trace plots depict the sensitivity of each SR to a systematic variation in CRy values. The results are obtained using Minitab 16 statistical software. The Cox response trace plots for SR1 (Appendix 4) indicate that if all CRy weights are set equal at 1/7, the resultant score of SR1 would be approximately 0.5. In addition, SR1 is most likely to score highest when weights for CR4, CR5 and CR6 have been assigned to higher weights as opposed to CR1, CR2 and CR3. SR2 is most sensitive to the weights of CR2, CR5 and CR7. SR3 is most sensitive to weights assigned for CR3 through CR6.

The optimization plot (see Fig. 8) shows the sensitivity of each CR (columns) to the global scores on SRs (rows). Simulating the ASLM model across the design space indicates that, overall, CR2 and CR6 are the most influential factors. The optimizer converges to CR2 = 0.65 and CR6 = 0.34. Accordingly, the final scenario scores yield SR1 = 0.27, SR2 = 0.34 and SR3 = 0.38. Hence, incineration is favored given the recovery rate of 13.5% of the post-consumption stage. This result is different from the AHP panel weighing system, which favored animal feed (SR1).

Discussion

Food Waste at the Post Consumption Stage

This research conducts a TBL analysis on animal feed production from FW at the post-consumption stage, based on [139]. This stage was chosen based on local current conditions. However, in general, food supply chains are complex
and often multinational and range vastly in scale from specialty crops to large-scale commodity grains. This makes traceability of composition, state, losses and waste quantity a challenging task [47, 66, 149]. Within food supply chains, one-third to half of all agricultural produce is wasted before reaching the consumer [30, 47, 79]. The collection point from which FW is collected within the food supply chain, including farms, markets, wholesale, retail and homes as well as socioeconomic factors, significantly influences treatment options [73]. The work of Xue et al. [146] indicates

![Table 3: Summarized valuation of all criteria of the different scenarios](image)

1Salemdeeb et al. [125], 2Hong et al. [83], 3Lee et al. [95]
that the food loss proportions in production, post-harvest and consumption are 24%, 24% and 35%, respectively. The consideration of side flows, which are food losses during the primary production of food able to be consumed by humans, could be avoided with minimum or no additional processing [77]. The length, location and type of operation of the food supply chain echelons and waste also have a considerable impact on FW reduction and handling [22, 34, 115]. The work of Bottani et al. [24] indicates that regardless of the scenarios considered, the total cost of the reverse logistics system is primarily determined by the cost of transport activities required to collect packaged FW from the retail store and ship it to the distribution centers. The high collection cost will render some considered scenarios infeasible for some nations. For Kuwait, considering the supply chain in FW treatment could change the contractual amount of waste collection, as distances, amounts and procedures will differ. In 2017, MSW collection alone cost the government over $372 million over a 5-year period [10]. In 2019, the MSW collection contractual amount over the following five-year period increased to $855 million [9]. With approximately 7000 tons/day of MSW, the cost per ton of MSW transport is $66.93 per ton. Since organic and FW comprise 45% of the MSW treated, the FW collection cost is $30.1 per ton for collection excluding only landfilling cost. Considering the supply chain echelon from which FW is collected requires considering the transportation cost of each alternative to better realize feasibility tradeoffs. This research analyzed the

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**Fig. 7** Global scores of the SRs with criteria priority rank in parentheses

**Fig. 8** Optimized global scores using ASLM mixture optimization (Minitab 16)
feasibility of extracting animal feed from FW at the consumption stage using the costs above. Proposing strategies that involve earlier supply chain echelons would improve nutrient recovery and reduce the environmental footprint, however, they might increase costs.

**Safety Comes First**

Adequate treatment of FW and sufficient quality control, regulation and management are of utmost importance [48]. The cattle mouth and foot disease outbreak that took place in the UK in 2001 and resulted in losses of up to 8 billion pounds [106, 117] is a salient case. An investigation indicated that the origin of this outbreak was in a pig abattoir in Essex in February of the same year,1 which was licensed to feed processed FW under the Animal Byproducts legislation of 1999 [42]. As a result, the UK immediately banned the production of animal feed from FW. In addition, in 2002, the European Commission (EC) issued directive 1774/2002 banning the catering of waste produced within the EU community that contains animal by-products from being fed to farmed animals other than fur animals [50]. The EC 1774/2002 directive was further amended by EC 1069/2009 [51] and EC 142/2011 [52] in regard to exemptions from veterinary checks of former directives. The regulations were further revised to address fish and meat surplus and catering residues in EC 68/2013 and EC 2017/1017, among others [53]. In the US, FW-containing animal products have been treated with high temperatures (100 °C) for at least half an hour to be suitable as swine feed [142]. The US congress has also passed laws, under the Swine Health Protection Act, that specify the required temperatures for processing FW to animal feed [125]. Facilities that use FW to produce animal feed must ensure that the waste is not subjected to oxygen during the stages of processing and must comply with the regulatory requirements for safe storage times and temperatures [76]. In New Zealand, the same requirements are mandated but for a duration of 6 min. In other Asian countries, such as South Korea, the landfilling of FW is banned. Approximately 45% of the FW is utilized as animal feed and a similar amount as compost [47, 92]. In Japan, more than half of FW is used as animal feed, accumulating to 1.19 M total digestible nutrient tons [109]. Research indicates that adequate treatment and heating of treated feeds has minimal public health risks [127]. Studies show that the meat composition of FW constitutes approximately 3.5% of FW Mosna et al. [107]. Fruits and vegetables present the highest amount of FW generated at both the primary production and consumption stages [30]. Adequate thermal processing conditions of FW that ensure compliance of the highest biosafety standards yield highly nutritional feed for monogastric animals. The plant-based discard in the waste provides high dietary fiber content, and in combination with other postconsumer FW such as meats, baked goods and diaries, and other additives, a balanced dietary feed is feasible to produce [17].

The EU has supported and funded research and projects, such as NOSHAN and REFRESH, that promote the use of FW to produce feed within regulatory guidelines, in addition to designing processes that convert FW into animal feed for non-fur animals and fish [60, 102]. The feed material and processes are governed by legislation to ensure that safety is guaranteed through intensive monitoring processes [97], with the exception of the reuse of meat waste within the feed production processes [128, 129]. Removing animal proteins that are not part of ruminants’ natural diet [49] must comply with the regulatory requirements for safe storage times and temperatures [76].

For the case of Kuwait, waste from abattoirs and poultry production is now sent to a crematorium to minimize health risk at landfills. This practice is expected to minimize animal product content in FW obtained from typical MSW. In all cases, and as indicated by the sensitivity analysis, not achieving the 48% breakeven recovery renders the animal feed production from FW infeasible. This is a long leap from the tested 13.5% threshold and therefore requires segregation early in the food supply chain [60, 148] to outweigh the cost of contamination in animal feed processed from FW. Accompanied by FW reduction, this allows for better alignment to CE framework objectives [113, 136]. Hence, circularity concepts and improved methods of feed production from FW are encouraged in recent research studies without compromising health and safety [117].

**Conclusions**

This study conducted a multicriteria evaluation for utilizing FW from MSW as animal feed at the post-consumption stage from using a TBL framework. Because the FW was recovered from the post-consumption phase, a relatively low recovery of 13.5% animal feed was realized. Sorting and consecutive thermal treatment could reduce the feedstock volume by 50–70%. The environmental BL was assessed using LCA in accordance with ISO 14040/4 [88] using a gate-to-grave consequential open-loop model with avoided saved animal feed production and shipping from conventional sources. Compared to landfilling and incineration with energy recovery, animal feed production from post-consumer MSW had the highest environmental burden, despite the inclusion of saved conventional feed production, except

1 Alternative theories also exist.
for agricultural land occupation and human toxicity. For one ton of FW treated, animal feed emitted 1064.6 kg CO₂-eq compared to landfilling at 823.6 kg CO₂-eq and incineration at 781.9 kg CO₂-eq; the results are consistent with cumulative energy demand analysis. The highest contributor to the overall negative impacts of animal feed production was the energy use in the FW thermal and crushing processes. In addition, the treatment of one ton of FW to animal feed required 3.5 tons of water compared to 0.9 tons and 0.78 tons of water for landfilling and incineration, respectively. Despite these disadvantages, the agricultural land occupation benefit of animal feed production is significant. For every 1 ton of FW treated, 0.33 m² per year of crop land area is saved. However, if FW is collected from the pre-consumption phase, a higher recovery rate and less processing is needed. The break-even analysis indicated that not until the recovery rate of animal feed exceeds 48% will animal feed from FW have overall environmental benefits that outweigh processing. The economic BL applied NPV for the animal feed scenario while incorporating initial investment, operation and maintenance, transportation, and inflation costs, and revenues realized from anticipated energy recovery, materials savings and other externalities. The economic analysis was conducted on two levels and with/without incorporating the cost of missed opportunity. The cost of animal feed was $93.8 per ton of FW feed based on unsubsidized energy prices. The cost of landfilling per ton was $137.6, while incineration generated a net profit of $3.65 per ton of feed. The social BL was assessed using SWOT analysis of interview results with experts and officials working in areas related to the social sub-criteria. Health and safety were the main weaknesses that experts identified as animal feed production from MSW FW, as was the perception of low and unstable caloric/nutrient value. Landfills and incinerators were perceived as mature and robust FW treatment technologies by the interviewees. Landfilling scored worst in degrading the land price of the surrounding land. The overall comparison using AHP resulted in almost a tie between the animal feed (45.0%) and incineration (43.2%) scenarios, which both outperformed landfilling (11.8%) by almost a fourfold score. Sensitivity analysis was conducted using the Cox response trace plot of an ASLM design to accommodate inherited collinearly of mutually exclusive alternatives. Using ASLM-based simulation, the global scenario scores were SR₁ = 0.27, SR₂ = 0.34 and SR₃ = 0.38. Hence, incineration was favored with energy recovery for FW at postconsumer with a feed recovery of 13.5%. This result was different from the AHP panel weighing system, which favored animal feed.

Food supply chains are complex and vary vastly across regions in scale and composition. For the consumer stage, the feed recovery was relatively low. Collecting FW throughout the supply chain requires region-specific data and legislation reform. It also requires systematic testing and awareness to improve the public acceptance and avoid political gridlocks associated with mitigating FW losses.

Appendix 1: Additional data Environmental BL

See Tables 4 and 5.
### Table 4  LCA inventories

| Parameters | Unit | Value | Source |
|------------|------|-------|--------|
| **Animal Feed Scenario (SR)_{1}** | | | |
| **Input** | | | |
| FW | Ton | 1 | Estimated and averaged from Kim and Kim [92], Lee et al. [95], and Salemdeeb et al. [125] |
| Electricity for FW treatment | kWh | 22.87 | |
| LNG for FW treatment | m³ | 33.3 | |
| Diesel for FW treatment | liter | 0.1 | |
| Water for FW treatment | kg | 2.515 | |
| Electricity for wastewater treatment | kWh | 1.5 | |
| Diesel for landfill screening treatment | liter | 0.04 | |
| Electricity for LFG flaring treatment | kWh | 0.1 | |
| Electricity for leachate treatment | kWh | 0.2 | |
| Leachate treatment efficiency | % | 90 | |
| **Output** | | | |
| Animal feed produced | Kg | 135 | |
| Wastewater generated and treated | Kg | 549.3 | |
| Screenings and residue | Kg | 79.3 | |
| Balance FW (lost in drying) | Kg | 269.5 | |
| LFG generated and treated | m³ | 12 | |
| Leachate generated and treated | m³ | 0.04 | |
| **Credited** | | | |
| Wheat and barley commercial feed | kg | 135 | [124] |
| **Landfilling Scenario (SR)_{2}** | | | |
| **Input** | | | |
| FW | ton | 1 | Estimated and averaged from [83] (Peter C. [128, 129] [95, 101] |
| Water for FW treatment | m³ | 0.11 | |
| Low-density polyethylene treatment | m³ | 7.54–05 | |
| Pesticides for FW treatment | kg | 3.77E-02 | |
| Energy Required | kWh | 30 | |
| Electricity for LFG flaring treatment | kWh | 1.6 | |
| Electricity for leachate treatment | kWh | 1.3 | |
| Leachate treatment efficiency | % | 90 | |
| Diesel for FW treatment | Liter | 0.35 | |
| **Output** | | | |
| Leachate generated and treated | kg | 549.3 | |
| LFG generated and treated | m³ | 147 | |
| LFG power generation | m³ | 18 | |
| **Credited** | | | |
| LFG generation efficiency | % | 29.4 | |
| Electricity recovered | kWh | 35 | |
| **Incineration Scenario (SR)_{3}** | | | |
| **Input** | | | |
| FW | Ton | 1 | |
| Diesel for FW treatment | Liter | 0.85 | Quiroga et al. [118] |
| Natural gas for FW treatment | MJ | 14 | Di Maria and Micale [45] |
| Electricity for FG treatment | kWh | 75 | Gentil et al. [70] |
| Electricity for air emissions control | kWh | 13 | Evangelisti et al. [61] |
| Diesel for emission control into air | Kg | 0.6 | |
| **Output** | | | |
| Ash generated and landfilled | Kg | 250 | Brunner and Rechberger [28] |
Appendix 2: Data for Economic BL

See Table 6.

Table 4 (continued)

| Parameters                | Unit  | Value | Source                        |
|---------------------------|-------|-------|-------------------------------|
| Credited                  |       |       |                               |
| Net electricity recovery  | kWh   | 310   | Di Maria and Micale [45]      |
| Electric conversion efficiency | %  | 22    |                               |

Table 5  LCIA results

| Method                  | Impact category | Unit   | Animal feed (SR₁) | Landfilling (SR₂) | Incineration (SR₃) |
|-------------------------|-----------------|--------|-------------------|-------------------|--------------------|
| ReCiPe midpoint (H)     | CC              | DALY   | 0.001495          | 0.001188          | 0.00113            |
|                         | OD              | DALY   | 1.1E−07           | 1.1E−07           | 1.06E−07           |
|                         | HT              | DALY   | 0.000309          | 0.00033           | 0.000215           |
|                         | POF             | DALY   | 2.69E−07          | 1.77E−07          | 1.93E−07           |
|                         | ME              | species.yr | 1.9E−09        | 1.62E−09          | 9.47E−10           |
|                         | ALO             | species.yr | − 5.1E−05      | 9.58E−06          | 9.6E−06            |
|                         | FD              | $      | 41.25853          | 31.2647           | 29.3534            |
| IPCC [132]              | IPCC GWP 100a   | kg CO₂ eq | 1064.599        | 823.5906          | 781.9288           |
| Cumulative energy demand| Non-renewable, fossil | MJ  | 1064.599        | 823.5906          | 781.9288           |
| Boulay et al. [25] (Water scarcity) | Water Scarcity Index | m³  | 3157.479        | 939.3437          | 784.7435           |

Table 6  Cost breakdown per ton under each FW SR

| Cost                          | Activity                        | Cost (KD/ton of FW treated) SR₁ | SR₂ | SR₃ |
|-------------------------------|---------------------------------|---------------------------------|-----|-----|
| Initial¹,²,⁴,⁶               |                                 | (60.303)                        | (13.306) | (40.250) |
| Land¹                        |                                 | (4.697)                         | (11.611) | 1.161 |
| Operational and maintenance¹,²,⁴,⁶ | FW treatment                    | (43.848)                        | (10.014) | 17.667 |
|                              | Wastewater treatment            | (0.638)                         | −     | −    |
|                              | Odor treatment                  | (0.427)                         | −     | −    |
| Transportation¹,²             | Out of facility                 | (1.572)                         | (1.908) | (0.686) |
| Externalities¹,³,⁴,⁶          | Environmental costs             | (4.629)                         | (16.401) | (17.711) |
|                              | Disamenity costs                | (22.105)                        | (9.937) | (1.889) |
|                              | Disposal costs                  | 0                               | (15.600) | (3.397) |
| Recovered³,⁴,⁵,⁶             | Energy conservation             | 23.861                          | 7.633  | 27.215 |
|                              | Product (LFG, electricity, and animal feed) | – | 2.966 | 5.857 |
|                              | Environmental benefits          | 18.367                          | 5.141  | 16.104 |
|                              | Lifespan of the facility (years)⁷ | 20                             | 10     | 25    |

¹Kuwait Ministry of Electricity and Water, ²Rafiee et al. [119], ³Lam et al. [93], ⁴Slorach et al. [128, 129], ⁵Korean Ministry of Environment, ⁶Salemddeeb et al. [125], ⁷Simapro 8.0 and costs were averaged accordingly
Appendix 3: Data for Social BL

See Tables 7, 8 and 9

Table 7 SWOT analysis results for SR1—production of animal feed from FW

| Internal conditions                          | External conditions                                                                 |
|---------------------------------------------|----------------------------------------------------------------------------------|
| Animal Feed Scenario (SR1)                  |                                                                                  |
| **Strengths**                               |                                                                                  |
| S1: availability of land for system application |                                                                                  |
| S2: promotes reduction in GHG emissions and better environmental options |                                                                                  |
| S3: savings in production of commercial feed and expenses |                                                                                  |
| S4: new technology to promote the development of CE and rural economy |                                                                                  |
| S5: clearly indicated procedures and standardized applications available |                                                                                  |
| **Weaknesses**                              |                                                                                  |
| W1: might not receive social acceptance     |                                                                                  |
| W2: low price of the recycled waste         |                                                                                  |
| W3: may be unprofitable without government funding or feed-in tariffs |                                                                                  |
| W4: High calorie variability                |                                                                                  |
| W5: only applicable for sorted FW           |                                                                                  |
| **Opportunities**                           |                                                                                  |
| O1: chance to spread awareness of FW in Kuwait and increase environmental awareness |                                                                                  |
| O2: gain extensive support from the government and private sectors |                                                                                  |
| O3: Kuwait becomes a pioneer in FW management efforts in the region |                                                                                  |
| O4: reduction in the use of unsanitary landfills |                                                                                  |
| O5: creation of economic incentives for the private sector and establishment of new government collaborations between the Ministry of Municipality and PAAF |                                                                                  |
| O6: use of existing infrastructures to create production lines |                                                                                  |
| O7: possible acquisitions of ideas and emerging markets abroad |                                                                                  |
| **Threats**                                 |                                                                                  |
| T1: insufficient funds for stakeholders and farmers supporting FW management |                                                                                  |
| T2: food safety hygiene and sanitary control issues |                                                                                  |

1 Bernstad and la Cour Jansen [18, 19], Bernstad Saraiva Schott and Andersson [20], Brancoli et al. [27], Ekvall et al. [57], Hong et al. [83], Kim and Kim [92], Yeo et al. [147]

Table 8 SWOT analysis results for SR2—sanitary landfill scenario of FW

| Internal conditions                          | External conditions                                                                 |
|---------------------------------------------|----------------------------------------------------------------------------------|
| Sanitary Landfilling Scenario (SR2)         |                                                                                  |
| **Strengths**                               |                                                                                  |
| S1: availability of land for system application |                                                                                  |
| S2: mature technology                       |                                                                                  |
| S3: no need for additional legislation      |                                                                                  |
| S4: robust to all types of MSW and FW       |                                                                                  |
| S5: low labor skill and cost                |                                                                                  |
| S6: generates electricity for facilities    |                                                                                  |
| **Weaknesses**                              |                                                                                  |
| W1: very high environmental impact          |                                                                                  |
| W2: no engineering of landfills to prevent leakage and to properly generate LFG and electricity |                                                                                  |
| W3: no monitoring of land pollution occurrence |                                                                                  |
| W4: no segregation at the source of FW from MSW and no recycling practiced |                                                                                  |
| **Opportunities**                           |                                                                                  |
| O1: reduction in the use of unsanitary landfills |                                                                                  |
| O2: funding is available and sufficient, provided by the government as a local service markets abroad |                                                                                  |
| **Threats**                                 |                                                                                  |
| T1: surrounding land price degradation      |                                                                                  |
| T2: massive GHG emissions and environmental impacts |                                                                                  |
| T3: risk of safety in the case of fire outbreaks |                                                                                  |
| T4: health hazards to urban communities near the facilities |                                                                                  |
| T5: low motivation among the population to support this waste program |                                                                                  |

1 Bernstad and la Cour Jansen [18, 19], Bernstad Saraiva Schott and Andersson [20], Brancoli et al. [27], Ekvall et al. [57], Hong et al. [83], Kim and Kim [92], Lam et al. [93], Thyberg and Tonjes [137], Yeo et al. [147]
Table 9  SWOT analysis results for SR, incineration of FW with energy recovery

| Internal conditions | External conditions |
|---------------------|---------------------|
|                     |                     |
| **Incineration Scenario (SR,)** | **Opportunities** |
| **Strengths**        | **O1**: reduction in the use of unsanitary landfills |
| S1: availability of land for system application | **O2**: funding is available and sufficient, provided by the government as a local service markets abroad |
| S2: no need for additional legislation | **Weaknesses** |
| S3: robust to all types of MSW and FW | **W1**: very high environmental impact |
| S4: low labor skill and cost | **W2**: applicable to dried FW only |
| S5: generates electricity for facilities | **W3**: public disapproval, especially to locate facilities near residential areas |
| **Weaknesses**        | **W4**: high oil and coal costs |
| W1: very high environmental impact | **W5**: no monitoring of air pollution created |
| W2: applicable to dried FW only | **W6**: no presorting of FW from MSW |
| W3: public disapproval, especially to locate facilities near residential areas | **W7**: lack of skilled workforce specialized in improving the current system |
| W4: high oil and coal costs | **Threats** |
| W5: no monitoring of air pollution created | **T1**: risk of safety in the case of fire outbreaks |
| W6: no presorting of FW from MSW | **T2**: health hazards to urban communities near the facilities |
| W7: lack of skilled workforce specialized in improving the current system | **T3**: low motivation among the population to support this waste program |

1Bernstad and la Cour Jansen [18, 19], Bernstad Saraiva Schott and Andersson [20], Denafas et al. [44], Guven et al. [75]

Appendix 4: Global Sensitivity Analysis

See Figs. 9, 10 and 11.

Fig. 9  Cox response trace plot for SR,
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All data generated or analyzed during this study are included in this published article.

The authors declare no conflict of interest.

1. Al-Shayji, K., Aleisa, E.: Characterizing the fossil fuel impacts in water desalination plants in Kuwait: a Life Cycle Assessment approach. Energy 158, 681–692 (2018). https://doi.org/10.1016/j.energy.2018.06.077

2. Aleisa, E., Al-Jarallah, R.: A triple bottom line evaluation of solid waste management strategies: a case study for an arid Gulf State, Kuwait. The International Journal of Life Cycle Assessment 23(7), 1460–1475 (2018). https://doi.org/10.1007/s11367-017-1410-z

3. Aleisa, E., Al-Jarallah, R., Shehada, D.: The effect of geological and meteorological conditions on municipal waste management
4. Aleisa, E., Al-Mutairi, A., Hamoda, M.: Reconciling water circularity through reverse osmosis for wastewater treatment for a hyper-arid climate: a life cycle assessment. Sustain. Water Resour. Manag. 8, 83–99 (2022). https://doi.org/10.1007/s40899-022-00671-8

5. Aleisa, E., Al-Zubari, W.: Wastewater reuse in the countries of the Gulf Cooperation Council (GCC): the lost opportunity. Environ. Monit. Assess. 189(11), 553–568 (2017). https://doi.org/10.1007/s10661-017-6269-8

6. Aleisa, E., Alsulaili, A., Almuzaini, Y.: Recirculating treated sewage sludge for agricultural use: Life cycle assessment for a circular economy. Waste Manage. 135, 79–89 (2021). https://doi.org/10.1016/j.wasman.2021.08.035

7. Aleisa, E., Heijungs, R.: Leveraging life cycle assessment and simplex lattice design in optimizing fossil fuel blends for sustainable desalination. Int. J. Cycle Assess. 25(4), 744–759 (2020). https://doi.org/10.1007/s11668-020-01738-4

8. Aleisa, E., Heijungs, R.: Leveraging life cycle assessment to better promote the circular economy: a first step using the concept of opportunity cost. Sustainability (2022). https://doi.org/10.3390/su14063451

9. Alenizi, B.: More than 285 million worth of cleaning contracts for 5 years. Local. Anbaa (2019). https://www.alanba.com.kw/

10. Alenizi, B.: More than 124 million worth of cleaning contracts for 5 years. Local. Anbaa (2020). https://www.alanba.com.kw/

11. AlJaber, S.: Kuwait Flour Mills & Bakeries Company. Kuwait (2020)

12. Aljuwaisseri, A., Aleisa, E., Alshayji, K.: Environmental and ecological evaluation: an example using the Analytical Hierarchy Process. Biol. Conserv. 3(1), 215–229 (1989). https://doi.org/10.1016/0026-4448(89)90037-2

13. Allesch, A., Brunner, P.H.: Assessment methods for solid waste management: A literature review. Waste Manage. Res. 32(6), 461–473 (2014). https://doi.org/10.1177/0734242X14535653

14. Angelo, A.C.M., Saraiva, A.B., Climaco, J.C.N., Infante, C.E., Valle, R.: Life cycle assessment and multi-criteria decision analysis: selection of a strategy for domestic food waste management in Rio de Janeiro. J. Clean. Prod. 143, 744–756 (2017). https://doi.org/10.1016/j.jclepro.2016.12.049

15. Anselin, A., Meire, P.M., Anselin, L.: Multicriteria techniques in ecological evaluation: an example using the Analytical Hierarchy Process. Biol. Conserv. 49(3), 215–229 (1989). https://doi.org/10.1016/0006-3207(89)90037-2

16. Averkamp, H. (2020). Lost opportunity definition. Accounting Coach, LLC. https://www.accountingcoach.com/terms/L/lost-opportunity

17. Baltensperger, D., Basu, M., Dhou, Z.: The role of agricultural science and technology in Climate 21 Project implementation. CAST Commentary QTA2021–1 June 2021

18. Bernstad, A., la Cour Jansen, J.: A life cycle approach to the management of household food waste – A Swedish full-scale case study. Waste Manage. 31(8), 1879–1896 (2011). https://doi.org/10.1016/j.wasman.2011.02.026

19. Bernstad, A., la Cour Jansen, J.: Review of comparative LCAs of food waste management systems – Current status and potential improvements. Waste Manage. 32(12), 2439–2455 (2012). https://doi.org/10.1016/j.wasman.2012.07.023

20. Bernstad Saraiva Schott, A., Andersson, T.: Food waste minimization from a life-cycle perspective. J Environ Manage 147, 219–226 (2015). https://doi.org/10.1016/j.jenvman.2014.07.048

21. Borrello, M., Caracciolo, F., Lombardi, A., Pascucci, S., Cembali, L.: Consumers’ perspective on circular economy strategy for reducing food waste. Sustainability (2017). https://doi.org/10.3390/su9010141

22. Bottani, E., Casella, G., Nobili, M., Tebaldi, L.: An analytic model for estimating the economic and environmental impact of food cold supply chain. Sustainability 14(8), 4771 (2022)

23. Bottani, E., Casella, G., Tebaldi, L., Montanari, R., Fava, B., Vignali, G., Volpi, A.: Economic evaluation of scenarios of food waste recovery in reverse logistics. In: Economic Evaluation of Scenarios of Food Waste Recovery in Reverse Logistics. Francesco Turco, XXIV (2018)

24. Bottani, E., Vignali, G., Mosna, D., Montanari, R.: Economic and environmental assessment of different reverse logistics scenarios for food waste recovery. Sustain. Prod. Consum. 20, 289–303 (2019). https://doi.org/10.1016/j.jclepro.2019.07.007

25. Boulay, A.-M., Bulle, C., Bayart, J.-B., Deschênes, L., Margini, M.: Regional characterization of freshwater use in LCA: modeling direct impacts on human health. Environ. Sci. Technol. 45(20), 8948–8957 (2011)

26. Brancoli, P., Bolton, K., Eriksson, M.: Environmental impacts of waste management and valorisation pathways for surplus bread in Sweden. Waste Manag. 117, 136–145 (2020). https://doi.org/10.1016/j.wasman.2020.07.043

27. Brancoli, P., Rousta, K., Bolton, K.: Life cycle assessment of supermarket food waste. Resour. Conserv. Recycl. 118, 39–46 (2017). https://doi.org/10.1016/j.resconrec.2016.11.024

28. Brunner, P.H., Recherberger, H.: Waste to energy—key element for sustainable waste management. Waste Manag. 37, 3–12 (2015). https://doi.org/10.1016/j.wasman.2014.02.003

29. Cadillo-Benalcazar, J.J., Renner, A., Giampietro, M.: A multi-scale integrated analysis of the factors characterizing the sustainability of food systems in Europe. J. Environ. Manage. 271, 110944 (2020). https://doi.org/10.1016/j.jenvman.2020.110944

30. Caldeira, C., De Laurentis, V., Corrado, S., van Holstefijn, F., Sala, S.: Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. 149, 479–488 (2019). https://doi.org/10.1016/j.resconech.2019.06.011

31. Carlsson, M., Naroznova, I., Moller, J., Scheutz, C., Lagerkvist, A.: Importance of food waste pre-treatment efficiency for global warming potential in life cycle assessment of anaerobic digestion systems. Resour. Conserv. Recycl. 102, 58–66 (2015). https://doi.org/10.1016/j.resconrec.2015.06.012

32. CEWEP: Landfill taxes and bans overview (2020). https://www.cewep.eu/wp-content/uploads/2017/12/Landfill-taxes-and-bans-overview.pdf

33. Champions 12.3: SDG TARGET 12.3 ON FOOD LOSS AND WASTE: 2021 PROGRESS REPORT (2021). https://champions123.org/sites/default/files/2021-09/21_WP_Champions_Progress%20Report_v5.pdf

34. Chauhan, C., Dhir, A., Akram, M.U., Salo, J.: Food loss and waste in food supply chains. A systematic literature review and framework development approach. J. Clean. Prod. 295, 126438 (2021). https://doi.org/10.1016/j.jclepro.2021.126438

35. Coban, A., Erits, I.F., Cavdaroglu, N.A.: Municipal solid waste management via multi-criteria decision making methods: A case study in Istanbul, Turkey. J. Clean. Prod. 180, 159–167 (2018). https://doi.org/10.1016/j.jclepro.2018.01.130

36. Contreras, F., Hanaki, K., Aramaki, T., Connors, S.: Application of analytical hierarchy process to analyze stakeholders preferences for municipal solid waste management plans. Boston, USA. Resour. Conserv. Recycl. 52(7), 979–991 (2008). https://doi.org/10.1016/j.resconec.2008.03.003

37. COP26: UNITING THE WORLD TO TACKLE CLIMATE CHANGE. Paper presented at the 26th UN Climate Change Conference (COP26), Glasgow, UK (2021)
38. Cornell, J.A.: Experiments with Mixtures: Designs, Models, and the Analysis of Mixture Data. Wiley, New York (2002)
39. Daihya, S., Amrani, N., Sravan, J.S., Chatterjee, S., Sarkar, O., Venkata Mohan, S.: Food waste biorefinery: Sustainable strategy for circular bioeconomy. Biores. Technol. (2017). https://doi.org/10.1016/j.biortech.2017.07.176
40. Dame-Korevaar, A., Boumans, I.J.M.M., Antonis, A.F.G., van Klink, E., de Olde, E.M.: Microbial health hazards of recycling food waste as animal feed. Future Foods 4, 100062 (2021). https://doi.org/10.1016/j.fufo.2021.100062
41. De Menna, F., Dietershagen, J., Loubierre, M., Vittuari, M.: Life cycle costing of food waste: a review of methodological approaches. Waste Manag. 73, 1–13 (2018). https://doi.org/10.1016/j.wasman.2017.12.032
42. Defra: Origin of the UK Foot and Mouth Disease epidemic in 2001 (2002). http://adlib.everysite.co.uk/resources/000/095/936/fmdorigins1.pdf
43. den Boer, J., den Boer, E., Jager, J.: LCA-1WM: A decision support tool for sustainability assessment of waste management systems. Waste Manag. 27(8), 1032–1045 (2007). https://doi.org/10.1016/j.wasman.2007.02.022
44. Denafas, G., Ruzgas, T., Martuzevičius, D., Shmarin, S., Höffmann, M., Mykhaylenko, V., et al.: Seasonal variation of municipal solid waste generation and composition in four East European cities. Resour. Conserv. Recycl. 89, 22–30 (2014). https://doi.org/10.1016/j.resconrec.2014.06.001
45. Di Maria, F., Micale, C.: Life cycle analysis of management options for organic waste collected in an urban area. Environ. Sci. Pollut. Res. Int. (2014). https://doi.org/10.1007/s11356-014-3330-9
46. Disna, E.: SWOT analysis of urban waste management: a case study of Balangoda suburb. J. Glob. Ecol. Environ. 5, 73–82 (2016)
47. Dou, Z., Gallagan, D., Shurson, G., Thomson, A.: Food supply chain and waste in climate mitigation. Paper Presented at the The Role of Agricultural Science and Technology in Climate 21 Project Implementation Introduction (2021).
48. Dou, Z., Toth, J.D., Westendorf, M.L.: Food waste for livestock feeding: Feasibility, safety, and sustainability implications. Glob. Food Sec. 17, 154–161 (2018). https://doi.org/10.1016/j.gfs.2017.12.003
49. EC: No 999/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. EC, Ispra (2001). https://eur-lex.europa.eu/legal-content/en/TXT/PDF/?uri=CELEX:32001R0999-20130701&from=en
50. EC: Regulation (EC) No 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption (2002). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32002R1774
51. EC: Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation) (2009). https://eur-lex.europa.eu/eli/reg/2009/1069/oj/eng
52. EC: COMMISSION REGULATION (EU) No 142/2011. EC, Brussels (2011). Retrieved from https://eur-lex.europa.eu/eli/reg/2011/142/oj
53. EC: Commission Regulation (EU) 2017/1017. EC, Brussels (2017). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R1017
54. EC: AGRI-FOOD TRADE STATISTICAL FACTSHEET: European Union—China. EC, Brussels (2022). https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/document/agrifood-china_en.pdf
55. Edwards, J., Burn, S., Crossin, E., Othman, M.: Life cycle costing of municipal food waste management systems: the effect of environmental externalities and transfer costs using local government case studies. Resour. Conserv. Recycl. 138, 118–129 (2018). https://doi.org/10.1016/j.resconrec.2018.06.018
56. Edwards, J., Othman, M., Crossin, E., Burn, S.: Life cycle inventory and mass-balance of municipal food waste management systems: decision support methods beyond the waste hierarchy. Waste Manag 69, 577–591 (2017). https://doi.org/10.1016/j.wasman.2017.08.011
57. Ekvall, T., Assefa, B., Björklund, A., Eriksson, O., Finnveden, G.: What life-cycle assessment does and does not do in assessments of waste management. Waste Manag. 27(8), 989–996 (2007). https://doi.org/10.1016/j.wasman.2007.02.015
58. EPA: Sustainable Management of Food. Food Recovery Hierarchy. EPA, Washington, DC. https://www.epa.gov/sustainable-management-food/food-recovery-hierarchy
59. EPA: Basic Information about Landfill Gas. Landfill Methane Outreach Program (LMOP). EPA, Washington, DC (2022). https://www.epa.gov/lmop/basic-information-about-landfill-gas
60. EU: EU Research Turning Food Waste into Feed. EC, Maastricht (2016). https://ec.europa.eu/programmes/horizon2020/en/node/1228
61. Evangelisti, S., Tagliaferri, C., Clift, R., Lettieri, P., Taylor, R., Chapman, C.: Life cycle assessment of conventional and two-stage advanced energy-from-waste technologies for municipal solid waste treatment. J. Clean. Prod. 100, 212–223 (2015). https://doi.org/10.1016/j.jclepro.2014.03.062
62. Fantke, P., Ernstoff, A.S., Huang, L., Csiszár, S.A., Jolliet, O.: Coupled near-field and far-field exposure assessment framework for chemicals in consumer products. Environ. Int. 94, 508–518 (2016). https://doi.org/10.1016/j.envint.2016.06.010
63. FAO: Global Food Loss and Food Waste. United Nations (2011). https://www.fao.org/fileadmin/user_upload/sustainablility/pdf/Global_Food_Losses_and_Food_Waste.pdf
64. FAO: The State of Food and Agriculture. Innovation in Family Farming. FAO, Rome (2014)
65. FAO: The State of Food Security and Nutrition in the World. Building Climate Resilience for Food Security and Nutrition. FAO, Rome (2018)
66. FAO: Food Loss and Food Waste. FAO, Rome (2021). https://www.fao.org/food-loss-and-food-waste/flw-data). from United Nations https://www.fao.org/food-loss-and-food-waste/flw-data
67. FAO, IFAD, UNICEF, WFP, & WHO: The State of Food Security and Nutrition in the World: Food & Agriculture Organization. FAO, IFAD, UNICEF, WFP, & WHO, Rome (2020)
68. Frischknecht, R., Jungbluth, N., Althaus, H.-J., Hischier, R., Doka, G., Bauer, C., et al.: Implementation of life cycle impact assessment methods. Data v2. 0 (2017). Ecovent report No. 3 (2007)
69. Generowicz, A., Kulczycka, J., Kowalski, Z., Banach, M.: Assessment of waste management technology using BATNEEC options, technology quality method and multi-criteria analysis. J. Environ. Manag. 92(4), 1314–1320 (2011). https://doi.org/10.1016/j.jenvman.2010.12.016
70. Gentil, E.C., Damgaard, A., Hauschild, M., Finnveden, G., Eriksson, O., Thorneloe, S., et al.: Models for waste life cycle assessment: Review of technical assumptions. Waste Manag. 30(12), 2636–2648 (2010). https://doi.org/10.1016/j.wasman.2010.06.004
71. Giampietro, M., Cadillo Benalcazar, J., Deli, L.J., Manfroni, M., Pérez Sánchez, L., Renner, A., et al.: Report on the Experience of Applications of the Nexus Structuring Space in Quantitative Storytelling. MAGIC (H2020–GA 689669) Project Deliver 4, 30 (2020)
72. Giwa, A.S., Xu, H., Chang, F., Zhang, X., Ali, N., Yuan, J., Wang, K.: Pyrolysis coupled anaerobic digestion process for food waste and recalcitrant residues: fundamentals, challenges, and considerations. Energy Sci. Eng. 7(6), 2250–2264 (2019). https://doi.org/10.1002/ese3.503
73. Gokarn, S., Kuthambalayan, T.S.: Analysis of challenges inhibiting the reduction of waste in food supply chain. J. Clean. Prod. 168, 595–604 (2017). https://doi.org/10.1016/j.jclepro.2017.09.028
74. Gustafsson, J., Cederberg, C., Sonesson, U., Emanuelsson, A.: The Methodology of the FAO Study: “Global Food Losses and Food Waste—Extent, Causes and Prevention.” Food and Agriculture Organization of the United Nations, Düsseldorf (2013)
75. Guven, H., Wang, Z., Eriksson, O.: Evaluation of future food waste management alternatives in Istanbul from the life cycle assessment perspective. J. Clean. Prod. 239, 117999 (2019). https://doi.org/10.1016/j.jclepro.2019.117999
76. Hall, M.: Techno-environmental analysis of generating animal feed from wasted food products. Thesis, Rochester Institute of Technology (2016)
77. Hartikainen, H., Mogensen, L., Svanes, E., Franke, U.: Food waste quantification in primary production—the Nordic countries as a case study. Waste Manag. 71, 502–511 (2018). https://doi.org/10.1016/j.wasman.2017.10.026
78. Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I.: Life Cycle Assessment: Theory and Practice. Springer, Cham (2017)
79. Henningsson, S., Hyde, K., Smith, A., Campbell, M.: The value of resource efficiency in the food industry: a waste minimisation project in East Anglia, UK. J. Clean. Prod. 12(5), 505–512 (2004). https://doi.org/10.1016/j.s0959-6526(03)00104-5
80. Kartchner, H.H.: USA Patent No. F. D. Corporation, Houstan (2008)
81. Herva, M., Roca, E.: Ranking municipal solid waste treatment alternatives based on ecological footprint and multi-criteria analysis. Ecol. Indic. 25, 77–84 (2013). https://doi.org/10.1016/j.ecolind.2012.09.005
82. Hidalgo, D., Martin-Marroquin, J.M., Corona, F.: A multi-waste management concept as a basis towards a circular economy model. Renew. Sustain. Energy Rev. 111, 481–489 (2019). https://doi.org/10.1016/j.rser.2019.05.048
83. Hong, J., Li, X., Zhaojie, C.: Life cycle assessment of four municipal solid waste management scenarios in China. Waste Manag. 30(11), 2362–2369 (2010). https://doi.org/10.1016/j.wasman.2010.03.038
84. Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., van der Zwaan, M., van der Voet, E., van der Meer, F., Wester, R.: The Methodology of the FAO Study: “Global Food Losses and Food Waste—Extent, Causes and Prevention.” Food and Agriculture Organization of the United Nations, Düsseldorf (2013)
85. Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., et al.: ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization (RIVM Report 2016-0104). RIVM De zorg voor morgen begint vandaag, Bilthoven (2016). https://www.rivm.nl/bibliothek/rapporten/2016/0104.pdf
86. IPCC: Climate Change 2021 The Physical Science Basis. IPCC, Geneva (2021). https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WG1_Full_Report.pdf
87. ISO 14040: Environmental Management. Life Cycle Assessment. Requirements and Guidelines. Amendment 2: The International Organization for Standardization (ISO), Geneva (2020)
88. ISO 14044: Environmental Management—Life Cycle Assessment—Requirements and Guidelines. The International Organization for Standardization (ISO), Geneva (2006)
89. Jin, C., Sun, S., Yang, D., Sheng, W., Ma, Y., He, W., Li, G.: Anaerobic digestion: An alternative resource treatment option for food waste in China. Sci. Tot. Environ. 779, 146397 (2021). https://doi.org/10.1016/j.scitotenv.2021.146397
90. Keng, Z.X., Chong, S., Ng, C.G., Ridzuan, N.I., Hanson, S., Pan, G.-T., et al.: Community-scale composting for food waste: a life-cycle assessment-supported case study. J. Clean. Prod. 261, 121220 (2020). https://doi.org/10.1016/j.jclepro.2020.121220
91. Khalili, N.R., Duecker, S.: Application of multi-criteria decision analysis in design of sustainable environmental management system framework. J. Clean. Prod. 47, 188–198 (2013). https://doi.org/10.1016/j.jclepro.2012.10.044
92. Kim, M.-H., Kim, J.-W.: Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Sci. Tot. Environ. 408(19), 3995–4006 (2010). https://doi.org/10.1016/j.scitotenv.2010.04.049
93. Lam, C.-M., Yu, I.K.M., Medel, F., Tsang, D.C.W., Hsu, S.-C., Poon, C.S.: Life-cycle cost-benefit analysis on sustainable food waste management: the case of Hong Kong International Airport. J. Clean. Prod. 187, 751–762 (2018). https://doi.org/10.1016/j.jclepro.2018.03.160
94. Lasso, J., Margallo, M., Garcia-Herrero, I., Fullana, P., Bala, A., Gazulla, C., et al.: Combined application of Life Cycle Assessment and linear programming to evaluate food waste-to-food strategies: seeking for answers in the nexus approach. Waste Manag. 80, 186–197 (2018). https://doi.org/10.1016/j.wasman.2018.09.009
95. Lee, S.-H., Choi, K.-I., Osako, M., Dong, J.-I.: Evaluation of environmental burdens caused by changes of food waste management systems in Seoul, Korea. Sci. Tot. Environ. 387(1), 42–53 (2007). https://doi.org/10.1016/j.scitotenv.2007.06.037
96. Leinweber, P., Bathmann, U., Buczko, U., Douhaire, C., Eichler-Löbermann, B., Frossard, E., et al.: Handling the phosphorus paradox in agriculture and natural ecosystems: scarcity, necessity, and burden of P. Ambio 47(1), 3–19 (2018). https://doi.org/10.1007/s13280-017-0968-9
97. Loctier, D.: REFRESH—the EU project aimed at drastically reducing food waste (2020). https://www.euronews.com/next/2020/10/12/refresh-the-eu-project-aimed-at-dramatically-reducing-food-waste
98. Lundie, S., Peters, G.M.: Life cycle assessment of food waste management options. J. Clean. Prod. 13(3), 275–286 (2005). https://doi.org/10.1016/j.jclepro.2004.02.020
99. Luo, Z., Hu, S., Chen, D., Zhu, B.: From production to consumption: a coupled human-environmental nitrogen flow analysis in China. Environ. Sci. Technol. 52, 2025–2035 (2018). https://doi.org/10.1021/acs.est.7b03471
100. Macarther, E.: Towards the Circular Economy, Economic and Business Rationale for an Accelerated Transition. Ellen MacArthur Foundation, Cowes (2013)
101. Majumder, R., Livesley, S.J., Gregory, D., Arndt, S.K.: Biosolid stockpiles are a significant point source for greenhouse gas emissions. J. Environ. Manag. 146, 3998–4084 (2015). https://doi.org/10.1016/j.jenvman.2014.04.016
102. Metcalfe, P., Moates, G., Waldron, K.: Detailed hierarchy of approaches categorised within waste pyramid (2017). https://eu-refresh.org/sites/default/files/D6_3_Valorisation_hierarchy_Final_0.pdf
103. Miller, S.: 6 Reasons why your city needs a foodwaste solution (2020). https://www.foodcycler.com/post/6-reasons-why-your-city-needs-a-food-waste-solution
104. Mirabella, N., Castellani, V., Sala, S.: Current options for the valorization of food manufacturing waste: a review. J. Clean. Prod. 65, 28–41 (2014). https://doi.org/10.1016/j.jclepro.2013.10.051
105. Montgomery, D.C.: Design and Analysis of Experiments. Wiley, Hoboken (2013)
106. Mort, M., Convery, I., Bailey, C., Baxter, J.: The health and social consequences of the 2001 foot and mouth disease epidemic in
North Cumbria. Lancaster University, UK (2004). http://www.lancs.ac.uk/shm/dhir/research/healthandplace/finalreport.pdf. Accessed 4 Jan 2010

107. Mosna, D., Vignali, G., Bottani, E., Montanari, R.: Environmental benefits of pet food obtained as a result of the valorisation of meat fraction derived from packaged food waste. Waste Manage. 125, 132–144 (2021). https://doi.org/10.1016/j.wasman.2021.02.035

108. Mosna, D., Vignali, G., Bottani, E., Montanari, R.: Life cycle assessment of a new feed production obtained by wasted flour food collected from the distribution and retail phases. Int. J. Food Eng. 12(9), 807–825 (2016). https://doi.org/10.1515/ijfe-2016-0046

109. Nakashi, T., Takayabu, H.: Production efficiency of animal feed obtained from food waste in Japan. Environ. Sci. Pollut. Res. (2022). https://doi.org/10.1007/s11356-022-20221-1

110. Näränen, E., Mesiranta, N., Mattila, M., Heikkinen, A.: Food Waste Management: Solving the Wicked Problem. Springer, Cham (2019)

111. Nicole, U., Francesco, R.: Food Waste Management (Sector) in a Circular Economy (I. o. W. Management Ed.). Vienna, Austria (2018)

112. OECD: OECD Glossary of Industrial Organisation Economics and Competition Law. Directorate for Financial, Fiscal and Enterprise Affairs, OECD, Paris (1993). https://www.oecd.org/regreform/sectors/2376087.pdf

113. Oliveira, M.M., Lago, A., Dal’ Magro, G.P.: Food loss and waste in the context of the circular economy: a systematic review. J. Clean. Prod. 294, 126284 (2021). https://doi.org/10.1016/j.jclepro.2021.126284

114. PAHW: PAHW new residential areas [Press release] (2020)

115. Porter, S.D., Reay, D.S., Higgins, P., Bomberg, E.: A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. Sci. Tot. Environ. 571, 721–729 (2016). https://doi.org/10.1016/j.scitotenv.2016.07.041

116. Pourreza Movahed, Z., Kabiri, M., Ranjbar, S., Joda, F.: Multi-attribute decision-making methods in SWOT analysis of mine waste management (case study: Sirjan’s Golgohar iron mine, Iran). Resour. Policy 51, 67–76 (2017). https://doi.org/10.1016/j.resourpol.2016.11.002

117. Shurson, G.C.: “What a waste”—can we improve sustainability of food animal production systems by recycling food waste streams into animal feed in an era of health, climate, and economic crises? Sustainability 12(17), 7071 (2020)

118. Srivastava, P.K., Kulshreshtha, K., Mohanty, C.S., Pushpangadan, P., Singh, A.: Stakeholder-based SWOT analysis for successful municipal solid waste management in Lucknow, India. Waste Manag. 25(5), 531–537 (2005). https://doi.org/10.1016/j.wasman.2004.08.010

119. Statista: Average annual OPEC crude oil price from 1960 to 2021. N. Sönnichsen (2020). https://www.statista.com/statistics/262858/change-in-opec-crude-oil-prices-since-1960/ Accessed 10 Feb 2020

120. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M., Allen, S.K., Boschung, J., et al.: Climate Change 2013: the physical science basis. In: Contribution of Working Group I to the Fifth Assessment Report of IPCC the Intergovernmental Panel on Climate Change (2014)

121. Strati, I., Oropoulov, V.: Recovery of carotenoids from tomato processing by-products—a review. Food Res. Int. 65, 311–321 (2014). https://doi.org/10.1016/j.foodres.2014.09.032

122. Su, J.-P., Chieu, P.-T., Hung, M.-L., Ma, H.-W.: Analyzing policy impact potential for municipal solid waste management decision-making: a case study of Taiwan. Resour. Conserv. Recycl. 51(2), 418–434 (2007). https://doi.org/10.1016/j.resconrec.2006.10.007

123. Sutton, M.A., Howard, C.M., Kanter, D.R., Lassaletta, L., Möring, A., Raghuram, N., Read, N.: The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond. One Earth 1(1), 10–14 (2021). https://doi.org/10.1016/j.oneear.2020.12.016

124. Teigiserova, D.A., Hamelin, L., Thomesen, M.: Towards transparent valorization of food surplus, waste and loss: clarifying definitions, food waste hierarchy, and role in the circular economy. Sci. Tot. Environ. 706, 136033 (2020). https://doi.org/10.1016/j.scitotenv.2019.136033

125. Thygberg, K.L., Tonjes, D.J.: The environmental impacts of alternative food waste treatment technologies in the U.S. J. Clean. Prod. 158, 101–108 (2017). https://doi.org/10.1016/j.jclepro.2017.04.169
138. Tong, H., Shen, Y., Zhang, J., Wang, C.-H., Ge, S., Tong, Y.: A comparative life cycle assessment on four waste-to-energy scenarios for food waste generated in eateries. Appl. Energy (2018). https://doi.org/10.1016/j.apenergy.2018.05.062

139. UNEP: Food Waste Index Report. UNEP, Nairobi (2021). https://www.unep.org/resources/report/unept-food-waste-index-report-2021

140. Vandermeersch, T., Alvarenga, R.A.F., Ragaert, P., Dewulf, J.: Environmental sustainability assessment of food waste valorization options. Resour. Conserv. Recycl. 87, 57–64 (2014). https://doi.org/10.1016/j.resconrec.2014.03.008

141. Vučijak, B., Kurtagić, S.M., Silajdžić, I.: Multicriteria decision making in selecting best solid waste management scenario: a municipal case study from Bosnia and Herzegovina. J. Clean. Prod. 130, 166–174 (2016). https://doi.org/10.1016/j.jclepro.2015.11.030

142. Westendorf, M.L.: Food waste as animal feed: an introduction. In: Food Waste to Animal Feed, pp. 3–16. Iowa State University Press, Ames (2000)

143. Woon, K.S., Lo, I.M.C., Chiu, S.L.H., Yan, D.Y.S.: Environmental assessment of food waste valorization in producing biogas for various types of energy use based on LCA approach. Waste Manage. 50, 290–299 (2016). https://doi.org/10.1016/j.wasman.2016.02.022

144. WRAP: Household Food and Drink Waste in the United Kingdom 2012. WRAP, Banbury (2013)

145. WRI & UNEP: Reducing Food Loss and Waste. WRI & UNEP, Washington, DC (2013). http://pdf.wri.org/reducing_food_loss_and_waste.pdf

146. Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, Å., et al.: Missing food, missing data? A critical review of global food losses and food waste data. Environ. Sci. Technol. 51(12), 6618–6633 (2017). https://doi.org/10.1021/acs.est.7b00401

147. Yeo, J., Chopra, S.S., Zhang, L., An, A.K.: Life cycle assessment (LCA) of food waste treatment in Hong Kong: on-site fermentation methodology. J. Environ. Manag. 240, 343–351 (2019). https://doi.org/10.1016/j.jenvman.2019.03.119

148. Yetkin Özbük, R.M., Coşkun, A.: Factors affecting food waste at the downstream entities of the supply chain: a critical review. J. Clean. Prod. 244, 118628 (2020). https://doi.org/10.1016/j.jclepro.2019.118628

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