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Application of recirculation prehydrolysis technology in food waste pretreatment and its environmental impact analysis: a case study in Shanghai

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Food waste is characterized by a high generation rate, high moisture content, and rapid biodegradability, making it a biomass waste with significant resource potential. This study applies life cycle assessment (LCA) using the SimaPro 12.0 software and the ReCiPe 2016 Midpoint method to evaluate the environmental performance of three food waste treatment scenarios in Shanghai (phase I, phase I with 30% recirculation prehydrolysis, and new phase II). The results show the following: (1) the overall system achieved a negative carbon footprint, mainly from the carbon sink effects of biogas power generation, solid waste incineration, and grease recovery; (2) the deodorization unit had the highest carbon emissions, followed by pretreatment and slurry treatment units; (3) standardized results indicated slurry treatment and deodorization, and pretreatment had the greatest environmental impacts; (4) among the scenarios, phase II performed the best in reducing greenhouse gases, controlling ecotoxicity, and improving resource efficiency; and (5) sensitivity analysis identified electricity as the most critical factor, followed by chemicals, while water had a minor influence. This study provides insights into optimizing food waste treatment, enhancing resource recovery, and supporting sustainable waste management.

Environmental significance

Anaerobic digestion is the mainstream technology for food waste treatment, and the recirculation prehydrolysis technology can improve its resource conversion efficiency. This study evaluates the environmental performance of a food waste treatment plant in Shanghai as a case study using LCA, offering insights for optimizing waste treatment, enhancing resource recovery, and supporting sustainable waste management.

1 Introduction

With the implementation of municipal solid waste classification policies, food waste, as the major organic fraction of household waste, presents challenges due to its high moisture content and rapid biodegradability.[1–3] Traditional disposal methods, such as landfilling[4] and incineration,[5,6] are under increasing environmental and resource pressures. Landfilling not only occupies large areas of land but also generates leachate and releases high concentrations of methane, posing significant environmental risks.[7,8] Incineration consumes considerable amounts of energy because of the high water content of food waste and can easily lead to pollutant formation. Under the goals of resource recovery, reduction, and harmless treatment, the development of efficient and environmentally friendly technologies for food waste management has become urgent.[9]

Anaerobic digestion[10] has gradually become the mainstream process for food waste treatment because it enables both the stabilization of organic waste and the recovery of biogas as an energy source.[11] Previous studies have shown that fresh food waste can produce cumulative biogas yields of more than 600 mL per g VS, indicating its high potential for energy recovery through anaerobic digestion.[12] However, in practice, anaerobic systems are often limited by poor substrate degradability and low pretreatment efficiency, resulting in insufficient resource conversion and relatively high environmental burdens.[13]

To overcome these technical barriers and improve the overall efficiency of anaerobic digestion, recirculating prehydrolysis has been proposed as an enhanced pretreatment strategy. The core of this technology lies in coupling solid residue recirculation with bioleaching, thereby improving organic matter degradation and fermentation efficiency while offering good engineering adaptability and potential for large-scale applications. Nevertheless, systematic evaluation and quantitative validation of its environmental performance remain limited, particularly with respect to multidimensional life cycle impact analysis.

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Based on these factors, the present study evaluates the environmental performance of recirculating prehydrolysis in food waste treatment. A case study was conducted on a food waste treatment plant in Shanghai, including the phase I project, phase I with 30% recirculation, and the phase II project. Using life cycle assessment (LCA), the SimaPro 12.0 software, and the ReCiPe 2016 Midpoint method, the study quantified the carbon footprint and multiple environmental impact categories across different technological pathways.[14–16] Sensitivity analysis[17] was also carried out to identify the key emission sources and influencing factors. The aim is to reveal the emission reduction potential and resource recovery value of recirculating prehydrolysis in food waste treatment systems and to provide data support and pathway recommendations for engineering applications.

2 Research methods

2.1 Engineering background

The phase I project of a food waste treatment plant in Shanghai involved a capacity of 530 tons per day and adopted a process of pretreatment, anaerobic digestion, biogas purification, and wastewater and odor treatment (Fig. 1). The pretreatment stage consisted of reception, crushing and screening, bioleaching with screw press dewatering, sand and impurity removal, thermal cooking, and three-phase oil separation. The resulting organic-rich slurry was fed into the anaerobic system. Owing to the high organic solid content of the food waste, phase I applied bioleaching with recirculated prehydrolysis, in which digestate reflux promoted further hydrolysis of partially degraded organic residues, converting particulate organics into soluble substrates that increased COD availability for anaerobic microorganisms and consequently enhanced methane production. Up to 30% of the residues were recirculated to enhance methane production.

The phase II project, completed in 2024, implemented advanced hydraulic disintegration and separation techniques, directly subjecting unscreened food waste to intensive hydro-mechanical treatment. This approach enabled a more efficient transfer of degradable components into the anaerobic system, resulting in increased biogas output and more thorough organic removal. Although the two phases followed distinct technical routes, both shared the common objective of improving organic degradation and methane production. The comparison of the three scenarios is shown in Table 1.

In the recirculating prehydrolysis process applied in this study, a portion of the organic solid residues from the three-phase separation unit was recirculated to the bioleaching

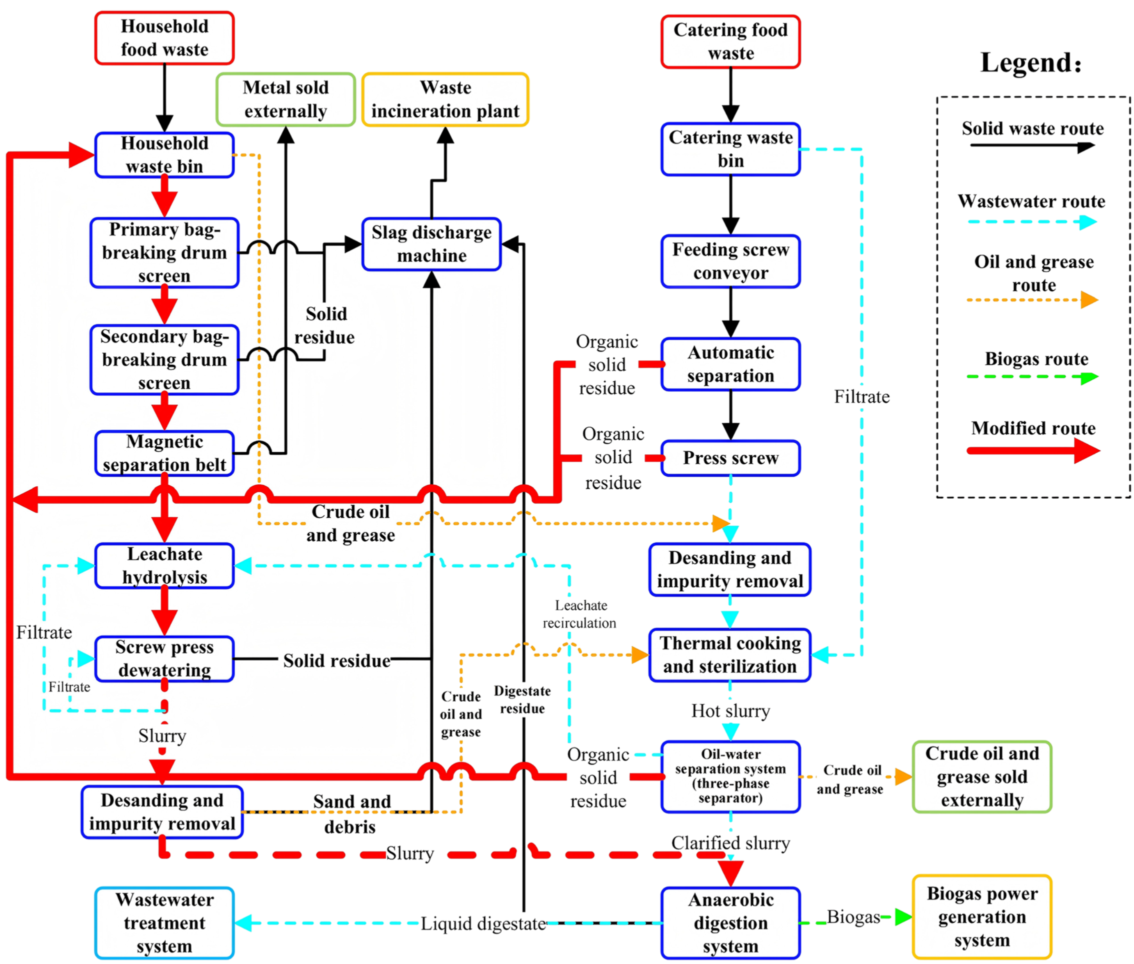

Fig. 1 Process flow diagram of a food waste treatment plant in Shanghai.

Table 1 Comparison of the three food waste treatment scenarios

Item	Phase I	Phase I (30% recirculation)	Phase II
Design capacity	500 t per d food waste and 30 t per d waste oil	500 t per d food waste and 30 t per d waste oil	500 t per d food waste
Pretreatment	Bioleaching, solid–liquid separation, and three-phase oil extraction	Bioleaching, solid–liquid separation, three-phase oil extraction, and recirculating bioleaching hydrolysis	Disintegration and separation, solid–liquid separation, and three-phase separation
Anaerobic digestion	Homogenization, anaerobic digestion, and centrifugal dewatering	Homogenization, anaerobic digestion, and centrifugal dewatering	Homogenization, anaerobic digestion, and centrifugal dewatering
Biogas purification	Filtration and pressurization, wet desulfurization, and dry desulfurization	Filtration and pressurization, wet desulfurization, and dry desulfurization	Filtration and pressurization, wet desulfurization, and dry desulfurization
Wastewater treatment	MBR, nanofiltration, and reverse osmosis	MBR, nanofiltration, and reverse osmosis	MBR, nanofiltration, and reverse osmosis (capacity expansion of phase I)
Odor treatment	Chemical scrubbing, plant-liquid spraying, and biological deodorization	Chemical scrubbing, plant-liquid spraying, and biological deodorization	Chemical scrubbing, plant-liquid spraying, and biological deodorization (capacity expansion of phase I)

reactor, where it underwent hydrolysis and acidification, together with the newly introduced food waste. This process converted particulate organic matter into soluble organics that are more readily utilized during anaerobic digestion, thereby prolonging the hydrolysis stage and improving substrate availability for the digestion system.

To evaluate the effectiveness of the recirculating prehydrolysis process, on-site experiments were conducted at two recirculation ratios (20% and 30%), and the results were compared with the non-recirculation condition. With increasing recirculation ratio, the specific biogas yield per unit COD increased from 0.59 Nm^3 per kg COD to 0.78 Nm^3 per kg COD (Table S1). Due to limitations in the temporary process pipeline, the maximum recirculation ratio applied in the recirculating prehydrolysis experiment was 30%. In this study, LCA was conducted for three scenarios: the phase I project, phase I with 30% recirculation, and the phase II project.

2.2 Life cycle assessment methodology

This study employed the SimaPro 12.0 software for life cycle modeling and analysis, with the ReCiPe 2016 Midpoint method selected for impact assessment.[18,19] The LCA procedure included four stages: goal and scope definition, life cycle inventory (LCI) compilation, life cycle impact assessment (LCIA), and interpretation of results.[20,21]

2.3 Goal and scope

This study used one ton of food waste treatment as the functional unit, with the system boundary encompassing the entire chain of environmental footprints from initial collection and transportation to final disposal. The boundary was clearly divided into eight core stages, including collection and transportation, pretreatment, anaerobic digestion, digestate

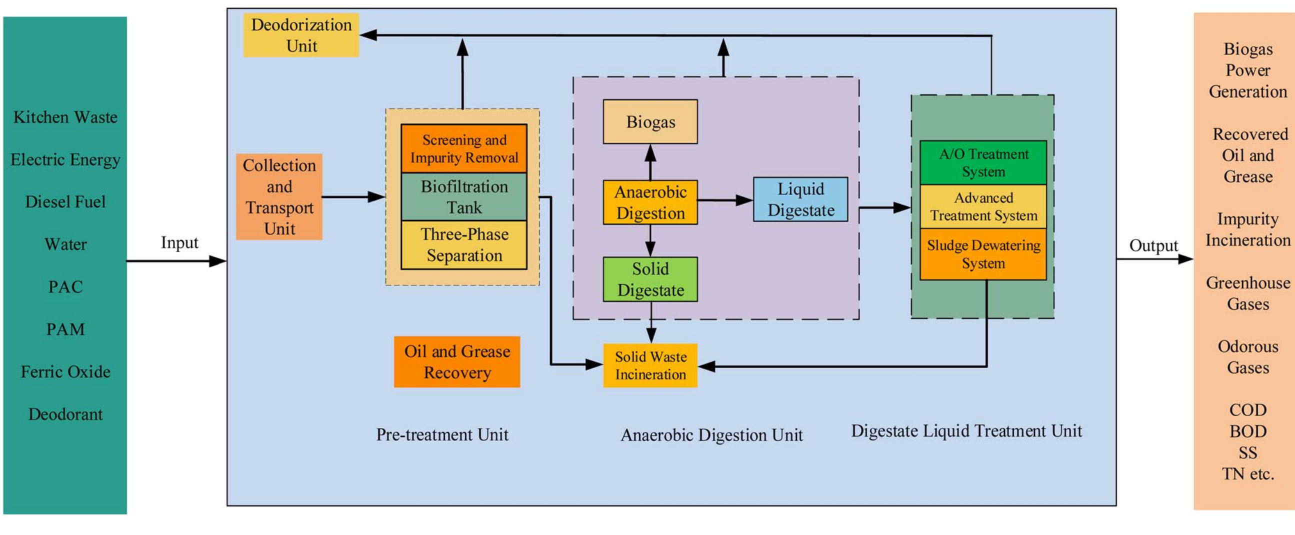

Fig. 2 System boundary of an anaerobic digestion treatment model for the phase I kitchen waste project in Shanghai.

treatment, biogas purification and utilization, deodorization, oil recovery, and incineration of impurities. Fig. 2 illustrates the system boundary, along with the material and energy flows among these units.

2.4 Life cycle inventory development

The input and output inventories for food waste treatment are presented in Table 2. Key material inputs included chemicals and tap water, while primary energy inputs included electricity and diesel, with their consumption obtained from project records. Background data were sourced from the Ecoinvent 3.9.1 database. Pollutant emissions were divided into atmospheric and water categories. Emissions of CO and NO_X from transportation vehicles were estimated in accordance with GB 18352.6-2016 (China VI standard). Odorous gas emissions, including NH_3 and H_2S, from the pretreatment stage were regulated under the class II limits of GB 14554-93. Emission factors of SO_2 and NO_X from biogas combustion were based on data for gas-fired boilers in the Manual of Pollutant Discharge Coefficients of Industrial Pollution Sources, while dust emissions were calibrated with fluidized bed incineration parameters reported in the Practical Handbook of Environmental Protection Data. Effluent from digestate treatment was required to meet the class III standard of GB 8978-1996, with actual discharge volumes determined from monitoring data before off-site release. In terms of resource recovery, separated impurities and digestate were incinerated for power generation, while waste oil was used for biodiesel production. Off-site treatment processes were beyond the system boundary, and their environmental benefits were evaluated using literature data. Specifically, the life cycle inventory of biodiesel production from waste cooking oil reported by Zhao *et al.*[22] was adopted, and the incineration stage was modeled with reference to the life cycle system of sludge incineration.[23]

Table 2 Life cycle inventory of kitchen waste

Category	Parameter	Unit	Phase I project
Input	Kitchen waste	t	530
	Diesel	kg t^{-1}	4.64
	Electricity	kwh t^{-1}	88.09
	Water	kg t^{-1}	10.84
	PAC	kg t^{-1}	0.13
	PAM	kg t^{-1}	0.06
	Na_2CO_3	kg t^{-1}	0.30
	Urea	kg t^{-1}	2.03
	Deodorant	kg t^{-1}	0.37
	Methanol	kg t^{-1}	7.50
	NaOH	kg t^{-1}	0.06
	H_2SO_4	kg t^{-1}	0.75
	Calcium hydroxide	kg t^{-1}	4.51
	Activated carbon	kg t^{-1}	0.20
Output	Biogas power generation	kwh t^{-1}	122.86
	Biodiesel	kg t^{-1}	40.00
	Electricity from impurity incineration	kwh t^{-1}	161.99
	CH_4	kg t^{-1}	0.0040
	N_2O	kg t^{-1}	0.06
	NO_X	kg t^{-1}	0.41
	SO_2	kg t^{-1}	0.53
	CO	kg t^{-1}	0.18
	NH_3	kg t^{-1}	0.56
	H_2S	kg t^{-1}	0.04
	Flue dust	kg t^{-1}	21.40
	COD	kg t^{-1}	0.40
	BOD_5	kg t^{-1}	0.20
	TN	kg t^{-1}	0.40
	NH_3–N	kg t^{-1}	0.25
	SS	kg t^{-1}	0.01

To comprehensively assess the system carbon footprint, a material and energy flow analysis of the food waste treatment process was conducted to quantify energy inputs and outputs, as well as resource use and pollutant emissions in each treatment unit. This analysis clarified the distribution of materials and energy consumption across the system and provided data support for the environmental impact assessment. The material and energy consumption, along with resource recovery and pollutant emissions in each unit of the food waste treatment system, are analyzed as follows.

In the collection and transportation unit, vehicles consumed a total of 1047 L of fuel per day. In the pretreatment unit, 536 t of food waste were processed daily, of which 201.64 t of large impurities were separated and transported for incineration. At the same time, 9.88 t of crude oil was recovered and sold as feedstock for biodiesel production. Water consumption in the pulping section was 0.45 t d^{-1}, and electricity use reached 8795.76 kWh d^{-1}. In the anaerobic digestion unit, the liquid fraction entered the system, producing 15.2 t of digestate per day, which was dewatered and transported for disposal. This stage also generated 34 384.4 m^3 of biogas and 452.65 t of digestate liquor, while consuming 2336.96 kWh d^{-1} of electricity. During biogas purification, Na_2CO_3 and urea were applied for H_2S removal, with daily consumption of 160.8 kg and 101.84 kg, respectively. Power generation from biogas resulted in NO_X, SO_2, and dust emissions, and electricity consumption at this stage was 653.92 kWh d^{-1}. The digestate treatment unit required 0.07 t of PAC and 0.03 t of PAM per day, generating direct emissions of CH_4 and N_2O, and consumed 7713.04 kWh d^{-1} of electricity. The deodorization unit removed odorous gases such as NH_3 and H_2S released from pretreatment, with electricity consumption of 10 301.92 kWh d^{-1}. Crude oil separated during pretreatment was sold for biodiesel production, and since actual data were unavailable, the life cycle inventory of biodiesel production from waste oil reported by Zhao *et al.*[22] was adopted, with detailed inputs and outputs per functional unit listed in Table S2. Finally, impurities were incinerated at high temperatures for power generation through thermal energy conversion.

3 Results and discussion

3.1 Carbon footprint contribution analysis

Based on the material and energy flow analysis, the generation and treatment of food waste are closely related to greenhouse gas emissions.[24] Contribution analysis showed that direct

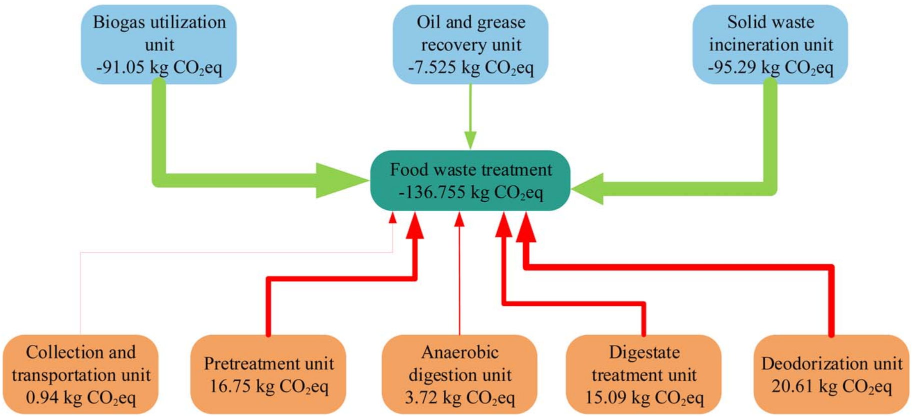

Fig. 3 Carbon footprint contribution of each unit in the system.

emissions accounted for about 15.5%, primarily originating from collection and transport vehicle exhaust, process emissions during treatment, and biochemical units. Indirect emissions accounted for about 18.9% and were mainly associated with energy and material consumption. Resource and energy recovery contributed for 65.6% of the carbon footprint, with biogas power generation, solid waste incineration, and oil recovery creating carbon sinks considered as negative emissions. Thus, although the phase I project consumed substantial energy and generated greenhouse gases, overall negative carbon emissions were achieved through these recovery pathways.

According to the ReCiPe2016 Midpoint method, the carbon footprint per ton of food waste treated was −136.755 kg CO_2eq, indicating a positive environmental effect of this treatment mode. This net negative carbon footprint aligns with findings from Wang *et al.*,[25] who reported that electro-anaerobic digestion of organic solid waste achieved a 18.0–42.6% lower carbon footprint compared to conventional anaerobic digestion, primarily due to enhanced energy conversion efficiency. The contributions of different units are shown in Fig. 3. Without considering resource and energy recovery, the footprint was 57.11 kg CO_2eq, of which the deodorization unit contributed 20.61 kg CO_2eq, accounting for 36.09%, the highest share. This was mainly due to continuous ventilation and electricity required to operate equipment, as well as the use of energy-intensive chemicals, which increased greenhouse gas emissions. The pretreatment and digestate treatment units contributed 16.75 kg CO_2eq and 15.09 kg CO_2eq, corresponding to 29.33% and 26.42%, respectively. Anaerobic digestion and collection contributed 3.72 kg CO_2eq (6.51%) and 0.94 kg CO_2eq (1.65%). The pretreatment unit consumed 32% of the total electricity due to processes such as automatic sorting and bioleaching, consistent with the findings of Jin *et al.*[26] Digestate treatment consumed 26% of the total electricity, and Huang *et al.*[27] also reported that wastewater treatment systems in food waste anaerobic plants accounted for about 42% of the total electricity demand.

Environmental benefits mainly arose from the biogas utilization, oil recovery, and impurity incineration units, which achieved −91.05 kg CO_2eq, −7.525 kg CO_2eq, and −95.29 kg CO_2eq, respectively. Biogas and solid waste incineration offset part of the electricity purchased. Zhou *et al.*[28] reported that biogas utilization in anaerobic digestion yielded 93.55 kg CO_2eq of negative emissions from electricity recovery, which is comparable to the results of this study.

The carbon footprint of the treatment system was influenced by multiple factors. As shown in Fig. S1, direct pollutant emissions contributed the most at 67.4 kg CO_2eq (44.98%), consistent with the findings of Ascher *et al.*,[29] stating that avoided emissions represent the largest negative contribution and that enhancing resource recovery efficiency can further reduce impacts. Electricity consumption followed with 64.3 kg CO_2eq (42.91%). In contrast, contributions from chemicals, diesel, and water were relatively small, at 17.2 kg CO_2eq, 0.94 kg CO_2eq, and 0.009 kg CO_2eq, respectively. Negative emissions were mainly achieved through energy and material recovery, particularly electricity recovery from biogas and incineration, which offset 60.79% of emissions, while oil recovery offset 4.85%. These results demonstrate that biogas utilization, solid waste incineration, and oil recovery are the key pathways for realizing environmental benefits in food waste treatment.

3.2 Characterization and normalization analysis

The characterization results of 18 environmental impact indicators for each treatment unit over the life cycle are presented in Table S3. Six key environmental indicators were selected for analysis: including Global Warming Potential (GWP), Photochemical Ozone Formation–Human Health (OFH), Terrestrial Ecotoxicity Potential (TETP), Marine Ecotoxicity Potential (METP), Human Toxicity Potential (HTP), and Fossil Fuel Consumption (FFC). The cumulative contribution of the food waste treatment system to these six indicators is approximately 50%. In the results, positive values indicate negative environmental impacts arising from material and energy consumption and pollutant emissions, whereas negative values indicate environmental benefits derived from the substitution of conventional resources and energy. The contributions of each treatment unit and factor to OFH, TETP, METP, HTP, and FFC are analyzed in Fig. 4.

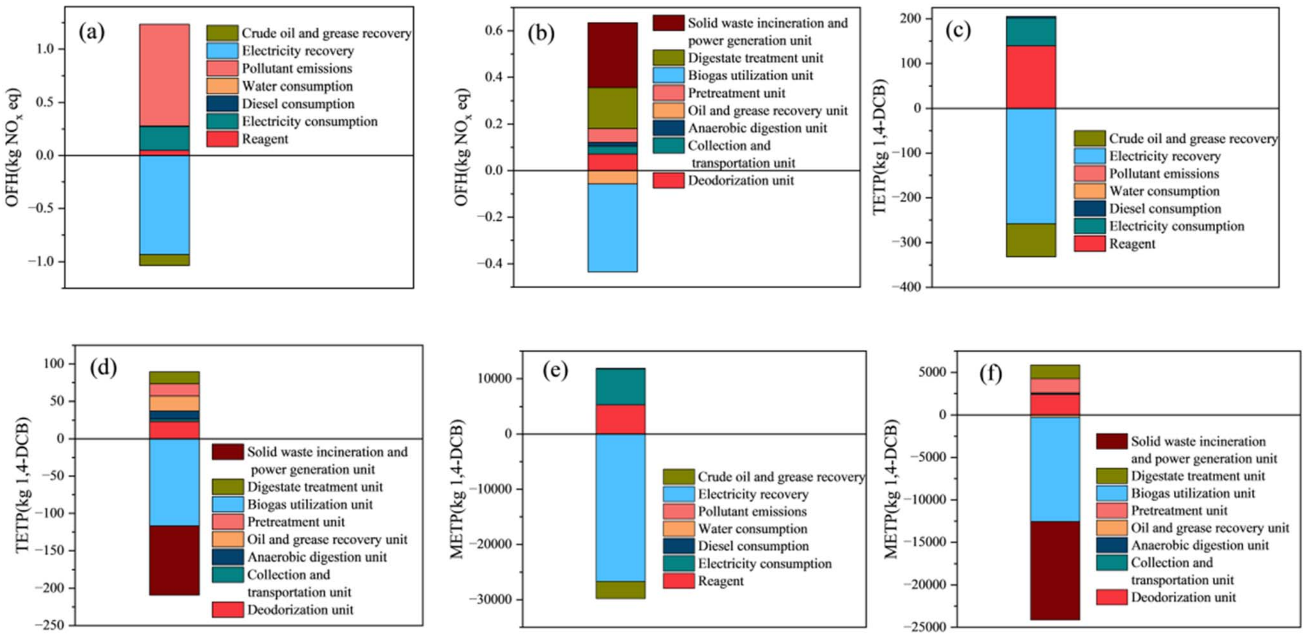

Fig. 4 Impact of the food waste treatment on (a) and (b) OFH, (c) and (d) TETP, and (e) and (f) METP.

As shown in Fig. 4a, pollutant emissions, electricity, and chemical consumption are the primary contributors to OFH, followed by diesel and water, while the recovered crude oil and electricity provide some mitigation. Fig. 4b shows that the waste residue incineration unit contributes the most due to VOC and NO_X emissions, while the leachate treatment unit also contributes significantly due to methane emissions (Zhou *et al.*[28]). The deodorization and pretreatment units exhibit high burdens due to electricity consumption, and CO and NO_X emissions from fossil fuel combustion in the collection and transportation unit also contribute to photochemical pollution.[30]

Fig. 4(c and d) indicate that the deodorization and oil recovery units contribute the most to TETP, mainly due to chemical consumption, with 139.46 kg 1,4-dichlorobenzene (1,4-DCB) generated per ton of food waste; thus, chemical use is the main source of terrestrial ecotoxicity. Fig. 4(e and f) show that the deodorization and pretreatment units contribute the most to METP, primarily driven by electricity and chemical use. The deodorization unit, relying on fossil fuel-based electricity and extensive chemical use, is the major contributor to marine ecotoxicity.

Fig. 5(a and b) indicate that in HTP, digestate treatment, deodorization, and pretreatment units contributed the most, with chemical and electricity consumption as the main sources. This finding suggests that human carcinogenic toxicity potential mainly resulted from the intensive use of chemicals and pollutant emissions related to fossil fuel-based power generation.[31] Fig. 5(c and d) show that in FFC, the largest contributors were digestate treatment, deodorization, pretreatment, collection and transportation, anaerobic digestion, oil recovery, solid waste incineration, and biogas utilization in descending order. The primary influencing factor was electricity consumption, followed by chemical use, pollutant emissions, diesel and water consumption, as well as crude oil and electricity recovery.

By multiplying the characterization results of each unit by the normalization factors, dimensionless values were obtained, enabling cross-comparison among different environmental categories. The normalization results are presented in Table S4. Fig. 5e shows that the overall environmental impacts of the treatment units followed the order: digestate treatment (0.105), deodorization (0.102), pretreatment (0.075), collection and transportation (0.017), anaerobic digestion (0.013), oil recovery (−0.211), incineration for power generation (−0.434), and biogas utilization (−0.537). Digestate treatment had the greatest negative impact, while biogas utilization, incineration, and oil recovery provided significant environmental benefits through energy recovery and waste reduction. Fig. 5f shows that the total impact of different environmental categories followed the order: OFH (0.0097), TETP (−0.0073), METP (−0.0074), GWP (−0.0235), FFC (−0.0722), and HTP (−0.7705). Overall, the system demonstrated favorable environmental performance and strong sustainability. However, limitations remained in controlling ozone formation, and further improvements should focus on optimizing processes and controlling emissions of ozone precursors, such as VOC_S and NO_X, to enhance environmental compatibility.

In summary, the pretreatment unit contributes substantially to both the carbon footprint and multiple environmental impacts, second only to leachate treatment and deodorization units. Optimizing the pretreatment process, improving energy efficiency, and reducing chemical consumption are key mitigation strategies, while biogas utilization, incineration, and oil recovery provide significant benefits. Further increasing biogas yield, reducing digestate, enhancing oil recovery, and developing biodiesel production will further improve the resource recovery and environmental sustainability of the system.

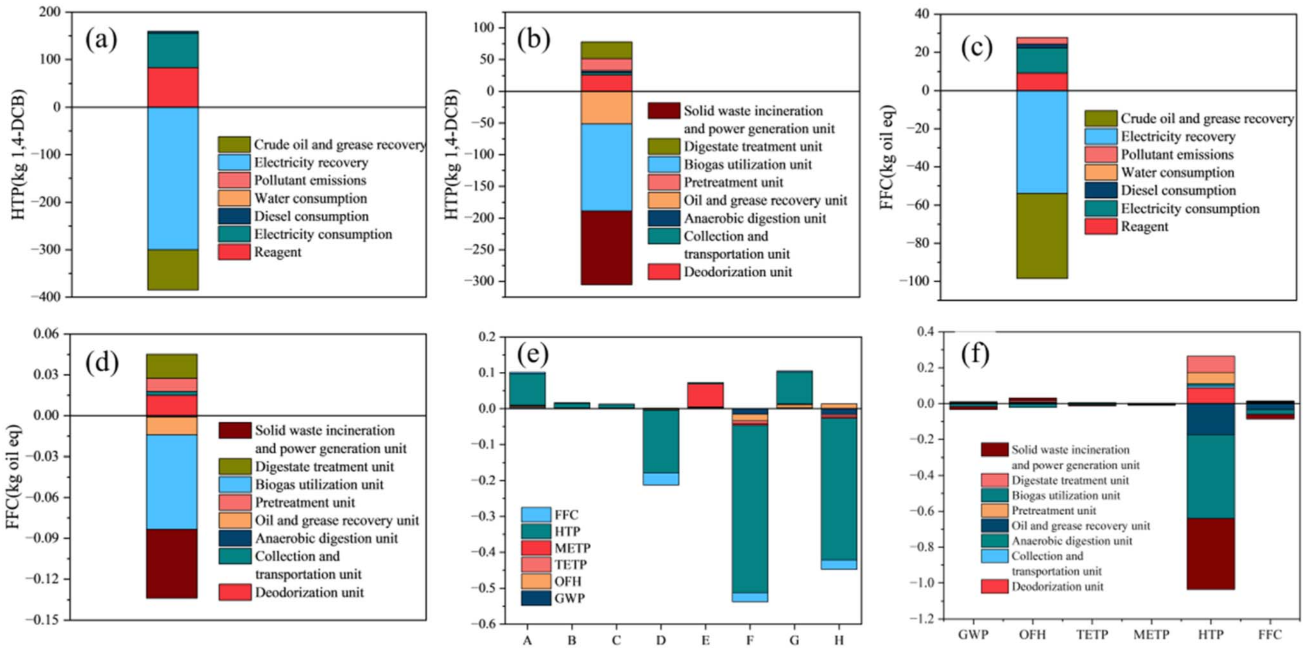

Fig. 5 Impact of the food waste treatment on (a) and (b) HTP and (c) and (d) FFC. (e) Normalized impacts of different units (A–H represent deodorization unit, collection and transportation unit, anaerobic digestion unit, oil and grease recovery unit, pretreatment unit, biogas utilization unit, digestate treatment unit, and solid waste incineration and power generation unit, respectively) and (f) normalized impacts of different indicators.

3.3 Comparative LCA of different scenarios

This study applied the life cycle assessment (LCA) method to systematically compare the environmental impacts of three food waste treatment scenarios: phase I, phase I with 30% recirculation, and phase II in Shanghai. The functional unit was defined as the treatment of one ton of food waste to ensure comparability. The system boundary covered the entire process, including collection and transportation, pretreatment, anaerobic digestion, biogas power generation, oil recovery, incineration of impurities, and leachate discharge, thereby ensuring a comprehensive evaluation. By quantitatively analyzing different environmental impact categories such as global warming potential, human toxicity, and resource consumption, the advantages and disadvantages of each scenario were identified to provide scientific evidence and decision support for optimizing food waste treatment systems.

The input and output inventories of the three scenarios are presented in Table S5, with calculation methods and references provided in Section 2.4. Characterization results quantified and compared the life cycle environmental effects of the three scenarios. Six environmental impact indicators, namely, GWP, OFH, TETP, METP, HTP, and FFC, were selected for analysis, and the results are shown in Table S6. The characterization comparison of the three scenarios is illustrated in Fig. 6a. phase II outperformed phase I in overall environmental impacts, with improvements observed in all categories. OFH improved most significantly, while HTP and FFC also showed considerable improvements, mainly due to more efficient pretreatment, which enhanced electricity recovery and reduced pollutant emissions from solid waste incineration. This advantage aligns with the findings of Nyitrai *et al.*,[32] who demonstrated that a novel two-phase anaerobic dynamic membrane bioreactor system achieved 25% higher methane yield and greater reduction of solids compared to conventional anaerobic digestion, leading to improved environmental performance across multiple impact categories. In contrast, phase I with 30% recirculation achieved limited improvement, with only a slight reduction in ozone formation. Other categories showed little difference, indicating that the recirculation ratio requires further optimization.

A normalized evaluation was performed to unify different impact categories and present standardized values of life cycle environmental impacts. The normalization results are shown in Table S6. Fig. 6b compares the normalized results of GWP, OFH, TETP, METP, HTP, and FFC across the three scenarios. Overall differences were small. Phase II performed the best in HTP, while phase I, with 30% recirculation, also showed some advantage, though the difference was minor, suggesting that further adjustment of the recirculation ratio may be necessary. HTP was associated with electricity and diesel consumption from fossil fuels, whose combustion releases particulates, SO_2, CO, and CO_2. These emissions not only increase environmental pressure but also pose risks to human health. Phase II reduced organic residues through more efficient pretreatment, thereby lowering transportation and incineration requirements and improving HTP performance.

By comparison, phase I and phase I with 30% recirculation showed similar results in most indicators. Phase II reduced the OFH from positive emissions to 1.87×10^{-3}, primarily due to lower diesel consumption. However, compared with the German and Danish systems reported by Jensen *et al.*[33] at −1.7

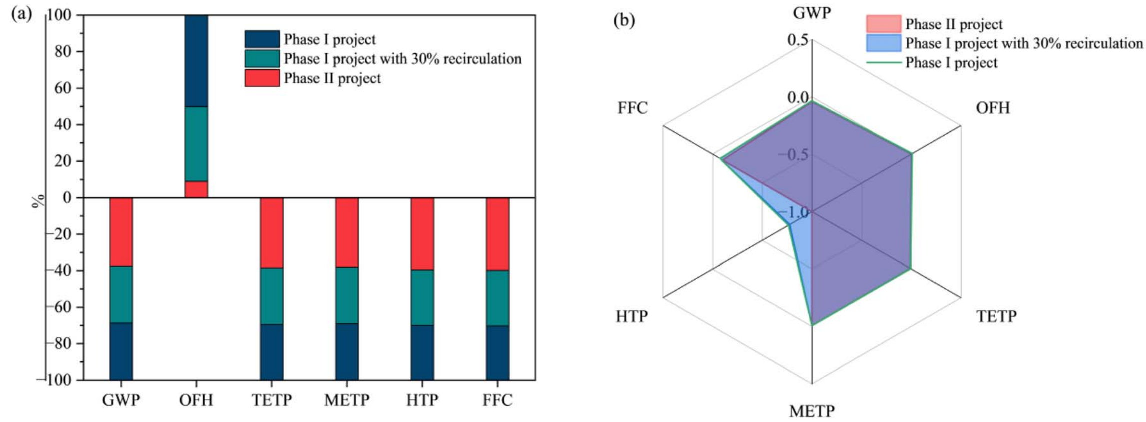

Fig. 6 Comparison of the environmental impacts for the three food waste treatment scenarios: (a) comparison of the characterization results and (b) comparison of the standardization results.

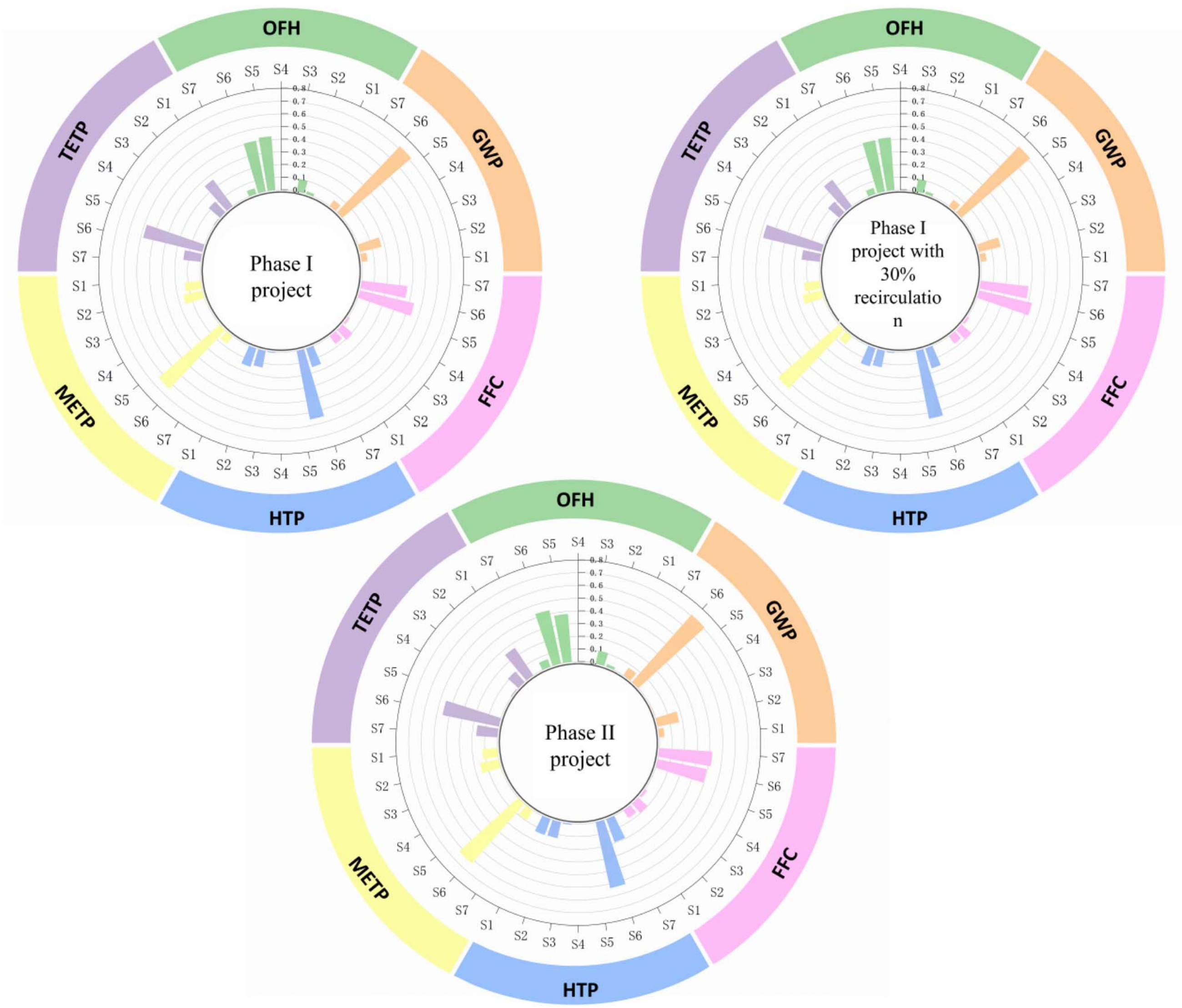

Fig. 7 Contribution of the six environmental impact indicators in the three food waste treatment scenarios.

and −0.2 kg NO_X-eq, respectively, the OFH impact in this study remained higher. This was attributed to low biogas efficiency and insufficient energy recovery, which led to higher NO_X and VOC_S emissions.

Fig. 7 illustrates the contributions of factors including diesel, electricity, natural gas, water, chemicals, electricity recovery, and oil recovery (S1–S7) to the six environmental impact categories of GWP, OFH, TETP, METP, HTP, and FFC across the three scenarios. The results show that phase II performed better in GWP and other indicators due to significant contributions from electricity and oil recovery. Emission reduction was achieved in multiple stages, reflecting environmental benefits and the potential for resource reuse for efficient pretreatment. This indicated stronger system sustainability. Phase I with 30% recirculation showed some environmental advantages compared with phase I, but the effect was limited, and the recirculation ratio still needs to be optimized to reduce emissions.

Overall, the second-phase project demonstrated considerable potential for environmental benefits due to its strong mitigation capacity. Compared with the other two scenarios, this advantage was primarily attributed to the high efficiency of pretreatment, which reduced the generation of solid residues and increased biogas production, thereby enhancing the overall reduction effect. Mechanistically, the recirculation of solid residues enhances the further hydrolysis of particulate organic matter in the bioleaching reactor, converting it into soluble substrates and increasing the COD available to anaerobic microorganisms. This process thereby boosts methane production. Field experiments (Table S1) showed that under a 30% recirculation ratio, the specific biogas yield per unit COD increased to 0.78 $Nm^3\ kg^{-1}$. The first-phase project with 30% recirculation was relatively close to the first-phase project in several aspects, but it still showed some mitigation effect. This finding further verified the potential environmental benefits of applying recirculation prehydrolysis technology, with the bioleaching reactor as the core pretreatment process, in food waste treatment projects.

3.4 Sensitivity analysis

To identify the key factors influencing the LCA results, this study, based on previous research,[34–36] selected electricity,

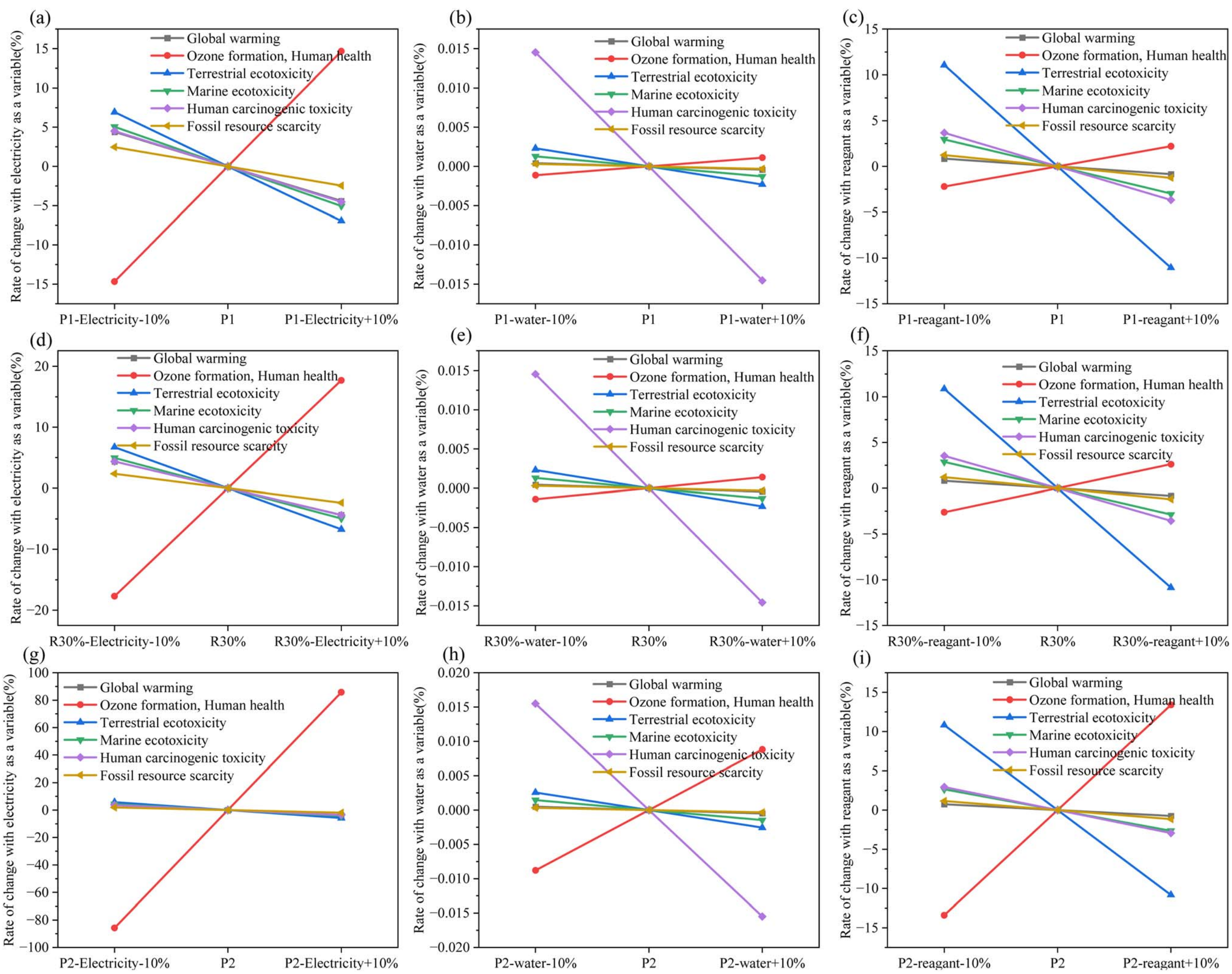

Fig. 8 Sensitivity analysis of the three food waste systems: (a)–(c) P1, (d)–(f) R30%, (g)–(i) P2 (P1 = the Phase I project, R30% = the Phase I project with 30% recirculation, P2 = the Phase II project; −10%/+10% indicate ±10% changes in water, electricity, or chemical consumption).

water, and chemical consumption as the variables affecting environmental impact potentials. A ±10% variation was applied to each variable, and a sensitivity analysis was conducted to evaluate the extent to which these changes influenced the LCA outcomes. The procedure involved adjusting each variable by ±10% while keeping all other parameters constant, and then comparing the resulting variations across different environmental impact categories to assess their sensitivity.

Electricity, water, and chemical consumption were individually varied by ±10%, and new life-cycle models were constructed accordingly. The adjusted data were then applied to calculate the normalized values for these models. The sensitivity analysis results for the three food waste treatment scenarios are presented in Fig. 8.

As shown in Fig. 8, the trends were generally consistent across the three scenarios. Electricity consumption exhibited extremely high sensitivity for indicators such as photochemical ozone formation, terrestrial ecotoxicity, and human toxicity. In particular, the second-phase project showed a variation of ±85.78% in photochemical ozone formation, substantially higher than that in the first-phase (±14.67%) and 30% recirculation scenarios (±17.7%), indicating that this scenario is especially sensitive to electricity fluctuations. This is because the second-phase project adopts a more complex pretreatment and resource recovery configuration than the first-phase project and the 30% recirculation prehydrolysis scenario, introducing additional electricity-driven units (*e.g.*, pumping, mixing, and solid–liquid separation), which increases the contribution of electricity consumption to overall environmental impacts. As photochemical ozone formation is strongly related to NO_X and VOC_S emissions from electricity generation, variations in electricity consumption can amplify the influence of upstream power generation emissions on OFH results. Chemical consumption primarily affected terrestrial ecotoxicity and human toxicity across all scenarios, with variation in impacts ranging between ±10.82% and ±11.06%, indicating that while chemical use is not the most sensitive factor, it still carries environmental significance. The sensitivity of the second-phase project to electricity was much higher than that of the other scenarios, demonstrating that scenario structure and process pathways have a marked influence on sensitivity analysis results. As scenario complexity and treatment intensity increase, the effect of individual variables, such as electricity, on overall environmental performance is further amplified.

The analysis indicates that electricity variation exerts the most significant influence on the anaerobic treatment of food waste, particularly on photochemical ozone formation, terrestrial ecotoxicity, and human toxicity, showing considerable fluctuations. As reported by Slorach *et al.*[37] and Mario Grosso *et al.*,[38] the electricity source significantly affects environmental impacts, and substituting electricity used in anaerobic digestion and incineration with renewable energy can substantially enhance environmental benefits. Chemical consumption is the next most influential factor, mainly affecting terrestrial ecotoxicity and human toxicity. In contrast, water consumption has minimal impact on the system, especially for indicators such as global warming potential and photochemical ozone formation, where its variation is negligible.

4 Conclusion

This study conducted a life cycle assessment (LCA) of three food waste treatment scenarios in Shanghai: the phase I project, the phase I project with 30% recirculation prehydrolysis modification, and the phase II project. The system achieved a net negative carbon footprint, mainly due to biogas power generation, solid waste incineration, and fat recovery, with phase II showing the lowest carbon footprint and highest resource recovery efficiency. Odor control units were the primary emission source, followed by pretreatment and digestate treatment. Phase II outperformed the other scenarios in global warming potential, human toxicity, and fossil fuel consumption due to efficient pretreatment and enhanced energy recovery. Sensitivity analysis identified electricity use as the dominant factor, followed by chemical consumption, while water use had minimal impact.

For practical applications, optimizing high-energy-consuming units (odor control and pretreatment) and integrating renewable energy are recommended to reduce environmental burdens. The advantages of phase II support the scaling of high-efficiency pretreatment in large urban food waste plants. Future research should focus on optimizing prehydrolysis recirculation ratios to balance biogas yield and additional energy use, and expanding the system boundary to include downstream biodiesel production and digestate valorization for a more comprehensive assessment of circular economy benefits.

Author contributions

D. C. (Prof.) contributed to the conceptualization of the work and gave the ideas and goals. D. W. (ME student) summarized the articles and wrote the manuscript. L. W. (MS student), Y. L. (ME student) and H. Y. (MS student) helped to summarize the published articles. F. L. (ME student) and J. P. (ME student) helped to collect and analyze the previously published research articles.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

LCA	Life cycle assessment
MBR	Membrane bioreactor
VS	Volatile solids
LCIA	Life cycle impact assessment
PAC	Poly aluminium chloride
PAM	Polyacrylamide
COD	Chemical oxygen demand
BOD_5	Biochemical oxygen demand (5 day)
TN	Total nitrogen
NH_3–N	Ammonia nitrogen
SS	Suspended solids
VOCs	Volatile organic compounds

NO_X	Nitrogen oxides
1,4-DCB	1,4-dichlorobenzene
GWP	Global warming potential
OFH	Ozone formation–human health
TETP	Terrestrial ecotoxicity potential
METP	Marine ecotoxicity potential
HTP	Human toxicity potential
FFC	Fossil fuel consumption

Data availability

All data supporting this study are included in the article and its supplementary information (SI). Supporting information: detailed supplementary data and figures of this study, including Table S1 (resource recovery data analysis of recirculation experiments), Table S2 (input–output inventory of the pretreatment unit), Fig. S1 (carbon footprint contribution of each system unit), Tables S3 and S4 (characterization and normalization results of 18 life cycle impact indicators for each treatment unit), as well as Tables S5 and S6 (input–output inventory, characterization and normalization results of the three scenarios). Supplementary information is available. See DOI: https://doi.org/10.1039/d5va00468c.

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