The Life-Cycle Environmental Impact of Recycling of Restaurant Food Waste in Lanzhou, China

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Abstract: The recycling of restaurant food waste can bring environmental benefits and improve food safety for urban residents. We here assessed the entire life cycle of the anaerobic digestion–aerobic composting technique of restaurant food waste recycling using Lanzhou as a case study. We used the CML2001 method provided with the Gabi software and compared the results to those produced using the traditional treatment techniques (landfill and incineration). This work includes a sensitivity analysis of the results. It is here concluded that the anaerobic digestion–aerobic composting technique had the smallest environmental impact of the methods here examined. The life cycle of anaerobic digestion–aerobic composting primarily consumes water, clay, coal, crude oil, and natural gas. The pre-processing phase consumes the most resources, and anaerobic digestion showed the greatest environmental impact. Specific environmental impacts in order from the highest to lowest potential to exacerbate global warming were found to be photochemical ozone production, acidification, eutrophication, marine aquatic ecotoxicity, human toxicity, freshwater aquatic ecotoxicity, and terrestrial ecotoxicity. The main factors associated with different environmental impacts and the environmental impacts themselves were found to differ across different phases. Some environmental impacts were shown to be sensitive to electricity, and the eutrophication potential and photochemical ozone creation potential showed the least sensitivity to all variables. To reduce the environmental impact of the anaerobic digestion–aerobic composting treatment technique, the energy structure and consumption of electricity, water, and diesel need to be optimized.

Keywords: life-cycle assessment; restaurant food waste; anaerobic digestion–aerobic composting; incineration; landfill

1. Introduction

Food waste (FW) creates environmental and food security problems in society due to the impacts associated with both the production and treatment (or reusing) of FW in China. According to the current studies, the amount of FW from the restaurant industry occupied 50% of the total amount of FW [1] and is expected to grow continuously along with an increase in the scale of restaurant industry in the context of persistent urbanization and improvement of the residential living level in China. Restaurant FW has a high water content, high salt content, high organic matter content, and significant temporal and spatial differences in components; it can be harmful but also useful [2]. Traditional treatment techniques, such as landfills and incineration, involve considerable environmental hazards and high costs, and they produce less pronounced economic benefits [3]. Importantly, food waste
is not fully used as a resource. This made the treatment of restaurant food waste a popular topic in the associated research fields. An environmental impact analysis of restaurant food waste treatment, in particular, a life-cycle assessment of the treatment process, would facilitate appropriate selection of treatment techniques and optimization of existing techniques [4,5].

Unlike other municipal solid waste, such as waste paper, waste metal, or construction waste, the recycling of food waste is complex and difficult due to the biological treatment process not only resulting in emissions with negative environmental impacts but also affecting the potential for nutrient and energy recovery through different treatment alternatives [6,7]. Thus, the life-cycle assessment (LCA) of food waste recycling or treatment is full of complexity and uncertainty. The current studies mainly focused on the resource usage, environmental impacts [8–10], and human health impact [11,12] of various recycling or treatment methods, such as feed and fertilizer, composting and landfill disposal [13], incineration, anaerobic digestion, and biodiesel [14]. Anaerobic digestion and incineration are the two most common ways to recycle food waste; however, the former seems to be preferable to incineration for biogenic substrates [15], due to its low cost and convenience [16–19]. Previous studies concentrated on the environmental impact and economic feasibility of the process of obtaining energy (i.e., biogas) from food waste via anaerobic digestion [20–22], and attempted to explore a way to optimize the digestion process [23,24], in an effort to recycle the most food waste while minimizing resource consumption and impact on the environment (e.g., optimization of the pre-treatment stage). LCA is extensively applied in the context of food waste management. However, the LCA of FW is still a complex and emerging field as it includes both technical and biological processes [25]. As Finnveden et al. argued, the system boundaries should be explicitly defined since the biological process of food waste treatment can be highly dependent on factors of the local climate and environment, as well as the LCA of the process, including urban and forest environments, agriculture, landfills, and emissions to the external environmental system [26]. Stichnothe et al. also demonstrated the inconsistency of environmental impact produced by two kinds of boundaries: from waste to products and from waste to product use [27]. Furthermore, the treatment process and parameter selection of LCA could result in profound differences in the results of LCA [6,7]. LCA of FW treatment is regarded as a potential hotspot in the research field of FW management.

The environmental impact of food waste recycling was studied extensively by applying the LCA method, aimed at optimizing the current technology or identifying the best way to recycle food waste [28]. However, Chinese case studies and evaluation of the anaerobic digestion–aerobic composting technique are rare. Restaurant food waste in China differs from that in other countries. It has special characteristics, such as a large production scale, complex composition, and high water, oil, carbon, and nitrogen content [29]. Therefore, it is important to conduct a comprehensive evaluation of the Chinese restaurant food waste treatment process in combination with China’s actual conditions. China produced a total of approximately 91.1 million tons of restaurant food waste in 2015. The average daily production was 250,000 tons. In particular, the restaurant food waste produced in large cities was no less than 60 million tons. However, the capacity to properly treat and dispose of this waste is less than 14,000 tons/day. The daily treatment rate was only 5.25% [30]. Common treatment techniques in China and abroad include incineration, landfill disposal, turning food waste into feedstuff or biogas, composting, and anaerobic digestion [31]. The three food waste treatment techniques in China (turning food waste into feedstuff, turning food waste into fertilizer, and anaerobic digestion) make up 6%, 9%, and 85% of the overall food waste disposal in China, respectively. Anaerobic digestion is the most widely used [32]. The city of Lanzhou was the site of the first experimental project in China addressing food waste. Lanzhou received approval for the resource treatment of restaurant food waste in 2016, and the city gradually built a network of food waste collection points covering the main city area. A total of 16,915 restaurants and 80 restaurant food waste shipping routes were established as of 31 December 2016. A total of 424,108.32 tons of restaurant food waste was disposed of and shipped as of the same date [33]. The reclamation experience of restaurant food waste in Lanzhou is called the “Lanzhou pattern”, which became a national pilot and was promoted throughout the country.
Here, we used the life-cycle theory to assess the environmental impact of the anaerobic digestion–aerobic composting technique. The study also compared the results to those of landfill and incineration techniques, analyzed the energy consumption and environmental impact of the life cycle, explored the principal environmental impacts, and also conducted a sensitivity analysis. As a life-cycle assessment case of restaurant food waste in China, the study is expected to enhance the green and cyclic development of businesses and provide useful suggestions for the reclamation of restaurant food waste in other cities.

2. Materials and Methods

2.1. Life-Cycle Assessment

Life-cycle assessment (LCA) is used to assess the environmental impact of the entire treatment life cycle of a product, process, or activity [34]. It replaces the traditional abstract assessment of a single component with a specific assessment of the whole process. In this way, it can avoid the limitations of traditional assessments of environmental impact, and can quantify environmental impacts effectively [35]. LCA is the most scientific assessment method of environmental impact of products or environmental management [36], and it can comprehensively and thoroughly capture the energy consumption and environmental impact resulting from the entire process of human activity [37]. It is becoming increasingly valued and favored, and it is widely used in the field of environmental engineering. LCA includes four parts: objective and scope, inventory analysis, impact assessment, and explanation of results.

In the study of life-cycle assessment, specific objectives and a scope should be determined based on the research area and potential applications. We attempted to assess the life cycle of restaurant food waste in Lanzhou in terms of the resources consumed and the environmental impact of different phases of the anaerobic digestion–aerobic composting technique, and we compared these results to those produced using traditional treatment techniques, specifically, landfills and incineration. The study is expected to provide data regarding the harmless treatment and reclamation of restaurant food waste, as well as also suggestions for the improvement of treatment techniques. The research scope involves the entire process from the production of restaurant food waste to the final disposal. Specifically, the process has eight phases: collection and transportation, pre-processing, solid composting, anaerobic digestion, biogas power generation and heating, biogas slurry composting, and wastewater treatment. The functional unit is here defined as the treatment of one ton of restaurant food waste. Figure 1 shows the system boundaries of the life cycle of restaurant food waste. After food waste is pre-treated, the liquid phase is subject to anaerobic digestion to generate biogas for power generation and the supply of biogas boilers; the solid phase and biogas residue are subject to aerobic composting to produce organic fertilizer.

Figure 1. System boundaries of life cycle of restaurant food waste.
Figure 2 and Table S1 (Supplementary Materials) list the life-cycle inventory. There are eight phases of input and output, describing the materials, energy, and pollutant emissions. Finally, the paper analyzes and discusses the results of assessment of the life cycle of restaurant food waste and proposes relevant strategies and suggestions.

2.2. Methods and Data Sources

We used the CML2001 method provided by the Gabi software to assess the life cycle of the treatment of restaurant food waste in Lanzhou City. There are eight types of environmental impact, specifically, acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecological toxicity potential (FAETP), global warming potential (GWP100), human toxicity potential (HTP), marine aquatic toxicity potential (MAETP), photochemical ozone creation potential (POCP), and terrestrial ecotoxicity potential (TETP). The paper applied the CML2001 method (CML2001 April 2013, World, year 2000, excluding biogenic carbon (global equivalents)) to conduct standardization of LCA results, thereby allowing a better comparison of environmental impact among various treatment methods of food waste. In addition, to ensure the reliability of the calculation results, we also used the ReCiPe1.08, IMPACT 2002+, and TRACI 2.1 methods. The ReCiPe method is one of the most widely used methods in LCA analysis at present and considers 18 midpoint categories [24]. IMPACT 2002+ is a life-cycle impact assessment methodology developed by the Swiss Federal Institute of Technology. The IMPACT 2002+ life-cycle impact assessment methodology proposes the feasible implementation of a combined midpoint/damage approach, linking all types of life-cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories [38]. TRACI, a stand-alone computer program developed by the United States (US) Environmental Protection Agency, facilitates the characterization of environmental stressors that have potential effects [39].

The data of material and energy inputs and outputs were obtained from ChiNai Bioenergy Limited which is the only company that conducts the centralized recycling and harmless treatment of food waste from restaurants in Lanzhou city, supported by the local government. Some data came from previous works [40–44], and the Gabi software was employed, as it is the most robust LCA method used in the field of sustainable development research (Table 1).
Table 1. Data sources related to the different phases.

| Resources/Substance/Emissions | Phase | Data Source |
|-------------------------------|-------|-------------|
| Diesel, CO₂, CH₄, NOₓ, SO₂, VOC, CO, HC, Pb | Collection and transportation | Chinai Bioenergy; [41–43] |
| Water, electricity, grease, liquid phase, solid phase, H₂S, NH₃, COD, BOD, SS, NH₃-N | Pre-processing | Chinai Bioenergy |
| Electricity, biogas, biogas residue, biogas slurry, wastewater, CO₂, CH₄, COD, BOD, NH₃-N, SS | Anaerobic digestion | Chinai Bioenergy; [8,44] |
| Electricity, CO₂, CO, CH₄, NOₓ, SO₂ | Biogas power generation and heating | Chinai Bioenergy; [9] |
| Water, aerobic composting additive, CO₂, CH₄, SOₓ, VOC, NH₃, PM₁₀, Cd, phosphate, sulfate | Composting | Chinai Bioenergy; [8,44] |
| Wastewater, ferric chloride, electricity, sludge, NH₃, Pb, Cd, Cr, Hg, COD, BOD, NH₃-N, SS, H₂S | Wastewater treatment | Chinai Bioenergy; [24] |

Notes: VOC: Volatile Organic Compounds; COD: Chemical Oxygen Demand; BOD: Biochemical Oxygen Demand; SS: Suspended Solid; PM₁₀: Particulate Matter (PM10).

3. Results and Discussion

3.1. Environmental Impact of Different Methods of Treating Restaurant Food Waste

We assessed the environmental impact of the life cycle of different treatment techniques of restaurant food waste in Lanzhou. Table 2 lists the assessment results. Here, S1 is the anaerobic digestion–aerobic composting technique. This method is currently used in Lanzhou. S2 is the landfill technique, in which restaurant food waste is collected and transported to a trash landfill yard for disposal. S3 is the incineration technique, in which restaurant food waste is transported to an incineration plant for a burning along with municipal solid waste.

Table 2. Environmental impact of different methods of treating restaurant food waste. Equiv—equivalent.

| Category                              | Unit      | S1          | S2          | S3          |
|---------------------------------------|-----------|-------------|-------------|-------------|
| Acidification potential               | kg SO₂-Equiv | 0.2        | 0.34       | 0.5         |
| Eutrophication potential              | kg phosphate-Equiv | 0.11       | 0.3        | 0.1         |
| Freshwater aquatic ecotoxicity potential | kg DCB-Equiv | 0.34       | 0.02       | 0.03        |
| Global warming potential              | kg CO₂-Equiv | 274.57     | 592.65     | 797.8       |
| Human toxicity potential               | kg DCB-Equiv | 0.6        | 0.32       | 1.58        |
| Marine aquatic ecotoxicity potential  | kg DCB-Equiv | 53.05      | 4.92       | 67.26       |
| Photochemical ozone creation potential | kg ethene-Equiv | 0.04       | 0.16       | 0.05        |
| Terrestrial ecotoxicity potential     | kg DCB-Equiv | 0.1        | 0.01       | 0.22        |
| Environmental impact normalized value | -         | 9.84 × 10⁻¹² | 2.19 × 10⁻¹¹ | 2.34 × 10⁻¹¹ |

Notes: DCB: dichlorobenzene.

As shown in Table 2, standardized values of environmental impact of S1, S2, and S3 were 9.84 × 10⁻¹², 2.19 × 10⁻¹¹, and 2.34 × 10⁻¹¹, respectively. The overall environmental impact of S1 was the lowest, that of S2 was medium, and that of S3 was the highest. Anaerobic digestion–aerobic composting technique is an ideal method for food waste disposal. S1 showed greater freshwater aquatic ecotoxicity potential, human toxicity potential, marine aquatic ecotoxicity potential, and underground ecotoxicity than S2 and greater eutrophication potential than S3. The main reason for this is that food waste has the characteristics of high moisture content (e.g., Lanzhou beef noodles), and the anaerobic
digestion–aerobic composting technique requires a certain amount of freshwater for pretreatment, which produces more wastewater. If wastewater produced using this technique can be recycled, then the potential of S1 for all five types of toxicity can be reduced; thus, the overall environmental impact can be reduced. In addition, S1 can turn restaurant food waste into restaurant waste grease, biogas, organic fertilizers, liquid spray fertilizers, microbial agents, and soil conditioners. To an extent, this also solves food safety problems induced by improper food waste reuse, such as feeding pigs with swill and using gutter oil in restaurant food. S1 was found to bring greater economic and ecological benefits than S2 and S3.

3.2. Resource Consumption of Anaerobic Digestion–Aerobic Composting Technique

Table 3 lists the resource consumption across the life cycle of restaurant food waste. There are three types of resources consumed in the treatment of restaurant food waste in Lanzhou. These are, from highest to lowest in terms of consumption, renewable resources, non-renewable fuels, and other non-renewable resources. The renewable resources include water and air. The non-renewable fuels include hard coal, crude oil, lignite, natural gas, peat, and uranium. The non-renewable resources include clay, attapulgite, organic acid, inert rock, limestone, and bentonite. Resource consumption shows heterogeneity across different phases of the treatment life cycle. These phases are, from the highest to lowest consumption, pre-processing, solid composting, wastewater treatment, and collection and transportation. Other phases do not consume any resources or energy. The collection and transportation phase and wastewater treatment primarily consume hard coal, crude oil, and other non-renewable fuels. The solid composting phase primarily consumes clay, attapulgite, organic acid, and other non-renewable resources. In particular, clay and attapulgites can serve as compound fertilizer binders. They have high granulation and particle-forming rates, and they can provide long-term fertilizer maintenance. The phase of pre-processing consumes water resources and electricity.

Table 3. Resource consumption of the life cycle of restaurant food waste (unit: kg).

| Resource Consumption Type                  | Non-Renewable Resources | Renewable Resources | Non-Renewable Energy Resources |
|--------------------------------------------|-------------------------|---------------------|-------------------------------|
| Sum                                        | 33.33                   | 341.98              | 45.61                         |
| Collection and transportation              | 0                       | 0                   | 1.33                          |
| Pre-processing                             | 0                       | 340.32              | 24.25                         |
| Solid composting                           | 33.33                   | 1.67                | 0                             |
| Anaerobic digestion                        | 0                       | 0                   | 0                             |
| Biogas power generation                    | 0                       | 0                   | 0                             |
| Biogas heating                             | 0                       | 0                   | 0                             |
| Biogas slurry composting                   | 0                       | 0                   | 0                             |
| Wastewater treatment                       | 0                       | 0                   | 20.02                         |

Throughout the life cycle, the sources of energy consumed are, in descending order, hard coal, crude oil, natural gas, lignite, peat, and uranium. The non-renewable sources of energy consumed during the pre-processing and wastewater treatment phase are, in descending order, hard coal, crude oil, and natural gas. Collection and transportation consume crude oil, which is primarily used for electricity and diesel. Currently, coal power is the principal source of electricity for Lanzhou. Over the entire life cycle of resource consumption, the principal consumed non-renewable resource is clay, and the major consumed renewable resource is water. Therefore, the reduction of resource consumption in the life cycle of restaurant food waste would involve less consumption of coal, crude oil, clay, and water.
3.3. Assessment of Environmental Impact of Anaerobic Digestion–Aerobic Composting Technique

3.3.1. Environmental Impact of All Phases

As shown in Table 4, after normalizing the assessment of various types of environmental impacts, they were found to be, from greatest to least effect, global warming potential, photochemical ozone creation potential, acidification potential, eutrophication potential, marine aquatic ecotoxicity potential, human toxicity potential, freshwater aquatic ecotoxicity potential, and terrestrial ecotoxicity potential. These results indicate that, in the life cycle of restaurant food waste treatment, the greatest environmental impact comes from the emission of greenhouse gases, and the least pronounced environmental impact is the ecotoxicity potential from toxic and hazardous substances produced from restaurant food waste. The environmental impact of each phase is discussed below.

In the collection and transportation phase, the maximum environmental impact is photochemical ozone creation potential, and the minimum is freshwater aquatic ecotoxicity potential. As shown, carbon monoxide and hydrocarbons emitted by vehicle exhaust emissions in the collection and transportation phase produce photochemical pollution. In the pre-processing phase, environmental impacts from greatest to least were found to be acidification potential, eutrophication potential, and human toxicity potential. The most pronounced environmental impact of the solid composting stage was found to be global warming potential, and the least was found to be terrestrial ecotoxicity potential. The most pronounced environmental impact of the anaerobic digestion phase is global warming potential, and the least is marine aquatic ecotoxicity potential. The most pronounced environmental impact of the biogas power generation and heating phase is global warming potential, and it has no effect on ecotoxicity potential. In the biogas slurry composting phase, environmental impacts from greatest to least are acidification potential, eutrophication potential, and human toxicity potential. The most pronounced environmental impact of the wastewater treatment stage is marine aquatic ecotoxicity potential, which has no effect on global warming potential or photochemical ozone potential. Wastewater treatment releases harmful heavy metals and inorganic substances into freshwater, the atmosphere, and soil, which can directly and indirectly affect the aquatic environment. In addition, the conversion of restaurant food waste into biogas and organic fertilizer can reduce the environmental impact of fertilizer use and coal combustion.

3.3.2. Main Factors Influencing Different Types of Environmental Impacts

Figure 3 shows the main influencing factors of different types of environmental impacts in the life cycle of restaurant food waste across the whole process and different phases. The acidification potential is 0.20 kg SO₂ equivalent (eq), its standardized latent value is $8.36 \times 10^{-13}$, and it mostly originates from solid composting. The main factors influencing acidification potential are, in order, ammonia, nitrogen oxides, sulfur oxides, and hydrogen sulfide. The most influential factor generated during pre-processing, solid composting, and biogas slurry composting is ammonia. The most influential factor produced during collection and transportation and biogas power generation and heating is nitrogen oxides. The most influential factor produced during anaerobic digestion is sulfur oxides, which indicates the acidification is mainly affected by ammonia and nitrogen oxides. The eutrophication potential is 0.11 kg phosphate-eq, its standardized value is $7.16 \times 10^{-13}$, and it is produced mostly during the anaerobic digestion phase. The most influential factors affecting eutrophication potential are chemical oxygen demand, ammonia, phosphate, and nitrogen oxides. In particular, chemical oxygen demand is the main factor influencing anaerobic digestion and wastewater treatment. The main factor influencing pre-processing and biogas slurry composting is ammonia. The main factor influencing solid composting is phosphate. The main factor influencing other phases is nitrogen oxides, which indicated that eutrophication is affected by wastewater emissions more than by any other factor.
Table 4. Normalized value for each environmental impact type.

| Category                     | Acidification Potential | Eutrophication Potential | Freshwater Aquatic Ecotoxicity Potential | Global Warming Potential | Human Toxicity Potential | Marine Aquatic Ecotoxicity Potential | Photochemical Ozone Creation Potential | Terrestrial Ecotoxicity Potential |
|------------------------------|-------------------------|--------------------------|-----------------------------------------|--------------------------|--------------------------|---------------------------------------|--------------------------------------|-----------------------------------|
| Sum                          | 8.36 × 10⁻¹³            | 7.16 × 10⁻¹³             | 1.45 × 10⁻¹³                             | 6.56 × 10⁻¹²             | 2.31 × 10⁻¹³             | 2.73 × 10⁻¹³                          | 9.86 × 10⁻¹³                         | 8.8 × 10⁻¹⁴                       |
| Collection and transportation | 2.11 × 10⁻¹⁴            | 7.28 × 10⁻¹⁵             | 3.71 × 10⁻¹⁵                             | 9.07 × 10⁻¹⁴             | 1.1 × 10⁻¹³              | 2.12 × 10⁻¹⁴                          | 2.11 × 10⁻¹³                         | 9.14 × 10⁻¹⁵                      |
| Pre-processing               | 2.17 × 10⁻¹³            | 6.87 × 10⁻¹⁴             | 0                                        | 0                        | 1.36 × 10⁻¹⁵             | 0                                     | 2.3 × 10⁻¹³                          | 3.61 × 10⁻²¹                      |
| Solid composting             | 2.37 × 10⁻¹³            | 1.46 × 10⁻¹³             | 1.12 × 10⁻¹⁴                             | 1.81 × 10⁻¹²             | 1.91 × 10⁻¹⁴             | 4.12 × 10⁻¹⁴                          | 2.3 × 10⁻¹³                          | 3.61 × 10⁻²¹                      |
| Anaerobic digestion          | 5.02 × 10⁻¹⁴            | 3.47 × 10⁻¹³             | 1.47 × 10⁻¹⁰                             | 2.36 × 10⁻¹²             | 3.72 × 10⁻¹⁶             | 3.54 × 10⁻²³                          | 4.17 × 10⁻¹³                         | 3.61 × 10⁻²¹                      |
| Biogas power generation      | 8.73 × 10⁻¹⁴            | 3.31 × 10⁻¹⁴             | 0                                        | 1 × 10⁻¹²                | 1.88 × 10⁻¹⁴             | 0                                     | 5.22 × 10⁻¹⁴                         | 0                                 |
| Biogas heating               | 1.14 × 10⁻¹³            | 4.33 × 10⁻¹⁴             | 0                                        | 1.3 × 10⁻¹²              | 2.46 × 10⁻¹⁴             | 0                                     | 7.53 × 10⁻¹⁴                         | 0                                 |
| Biogas slurry composting     | 1.08 × 10⁻¹³            | 3.33 × 10⁻¹⁴             | 0                                        | 0                       | 6.79 × 10⁻¹⁶             | 0                                     | 0                                    | 0                                 |
| Wastewater treatment         | 6.09 × 10⁻¹⁶            | 3.73 × 10⁻¹⁴             | 1.3 × 10⁻¹³                             | 0                       | 5.59 × 10⁻¹⁴             | 2.11 × 10⁻¹³                          | 0                                    | 7.89 × 10⁻¹⁴                      |
Figure 3. Main factors influencing different types of environmental impacts.

The global warming potential is 274.57 kg CO$_2$-eq, and its standardized value is $6.56 \times 10^{-12}$. It has the highest overall impact on the environment of any of the environmental impacts studied here; its effects come primarily from the pre-processing, solid composting, biogas heating, and biogas slurry composting phases. The main factors influencing it are carbon dioxide and methane. The main factors influencing each phase remain roughly consistent throughout the process. These results indicate that global warming is more affected by inorganic and organic matter from exhaust gas emissions than by any other factor. In addition, the study did not involve biological carbon, which comes from biomass in wastes. It has high carbon content and porous properties. Biological carbon can increase the water storage capacity of the soil and protect soil microbes. It can absorb a large quantity of carbon during
its growth; thus, it plays an important role in protecting the environment [27]. The photochemical ozone creation potential is 0.04 kg ethene-eq, its standardized value is $9.86 \times 10^{-13}$, and it comes mostly from anaerobic digestion. The most influential factors produced during the photochemical ozone creation potential are methane (some of which is not fully burned), hydrocarbon, nitrogen oxides, carbon monoxide, and VOC (Volatile Organic Compounds). In particular, the most influential factors produced during collection and transportation phase are hydrocarbon and VOC. The most influential factor produced during the anaerobic digestion and solid composting phases is methane. The most influential factor produced during the biogas power generation and heating phase is nitrogen oxides. These results indicate that photochemical ozone creation is mainly affected by organic matter from exhaust gas emissions.

The freshwater aquatic ecotoxicity potential is 0.34 kg DCB-eq (DCB: dichlorobenzene), its standardized value is $1.45 \times 10^{-13}$, and it comes mostly from wastewater treatment. The most influential factors that affect this potential produced during the wastewater treatment phase are cadmium and mercury. The main influential factor produced during the solid composting phase is cadmium. The main influencing factor produced during the collection and transportation phase is formaldehyde. These results indicate that the freshwater aquatic ecotoxicity is mainly affected by heavy metals from wastewater emission. The marine aquatic ecotoxicity potential is 53.05 kg DCB-eq, its standardized value is $2.73 \times 10^{-13}$, and it comes mostly from wastewater treatment. The most influential factors are cadmium, mercury, arsenic, and lead. In particular, the most influential factors produced during the wastewater treatment phase are cadmium and mercury. The main influential factor from the solid composting phase is arsenic. The most influential factor produced during the collection and transportation phase is lead. These results indicate that marine aquatic ecotoxicity is mainly affected by heavy metals from wastewater emissions.

The terrestrial ecotoxicity potential 0.10 kg DCB-eq, its standardized value is $8.8 \times 10^{-14}$, and it comes mostly from wastewater treatment. The most influential factors are mercury and lead. In particular, the most influential factor produced during wastewater treatment is mercury. The main influential factor from the collection and transportation phase is lead. These results indicate that the terrestrial ecotoxicity is mainly affected by heavy metals from exhaust gas and wastewater emissions. The human toxicity potential is 0.60 kg DCB-eq, its standardized value is $2.31 \times 10^{-13}$, and it comes mostly from collection and transportation and from wastewater treatment. The main influencing factors are lead, mercury, nitrogen oxides, and arsenic. In particular, the main influencing factor produced during the wastewater treatment phase is mercury. The main influential factor from the solid composting phase is arsenic, and that from the wastewater treatment phase is mercury. The main influential factor from the biogas power generation and heating phase is nitrogen oxides. These results indicate that the human toxicity is mainly affected by harmful metals from exhaust gas and wastewater emissions.

Reducing the environmental impact of restaurant food waste treatment should be addressed in terms of specific phases. During the collection and transportation phase, vehicle exhaust gas emissions containing heavy metals should be controlled. During the solid composting, anaerobic digestion, and biogas power generation phases, the emission of greenhouse gases such as carbon dioxide and methane should be controlled. In the pre-processing and biogas slurry composting phases, acid gas emissions should be controlled. During the wastewater treatment phase, the production of harmful heavy and inorganic substances should be controlled. In general, to reduce the environmental impact of the process, the amount of inorganic substances, organic substances, and heavy metals in exhaust gas and wastewater should be controlled. Exhaust gas and wastewater treatment equipment should be installed and operated across all phases to optimize the production process and to realize cleaner production.
3.4. Sensitivity Analysis

In this section, a sensitivity analysis of environmental impacts was conducted to identify the effect of chosen methods on the results of the LCA. Table 5 shows the results of the sensitivity analysis of food waste recycling, comparing the use of different LCA methods (ReCiPe1.08, IMPACT 2002+, and TRACI 2.1), considering the environmental impacts results from CML 2011 method as a reference. The larger the comparison value is, the more sensitive the method and/or data are to uncertainty in the results [45]. The results were shown to be consistent for the global warming potential category among the four methods. In terms of the acidification potential, CML2001, IMPACT 2002+, and TRACI 2.1 had consistent results. In terms of the photochemical ozone creation potential, CML2001 and IMPACT 2002+ had consistent results. In terms of the eutrophication potential and ecotoxicity potential, different methods produced different results. The main difference was inconsistent normalization units. The different results were mainly attributable to different assessment categories and different normalization values (equivalent units) in the main categories, which resulted in differences among assessment results [24]. These results indicated that the life-cycle assessment results of CML2001 are reasonable.

Table 5. Sensitivity analysis of different assessment methods.

| Category                        | Unit     | CML2001 | ReCiPe1.08 | IMPACT 2002+ | TRACI 2.1 |
|---------------------------------|----------|---------|------------|--------------|-----------|
| Acidification potential         | kg SO$_2$-eq | 0.2     | -          | 0.17         | 0.24      |
| Eutrophication potential        | kg phosphate-eq | 0.11    | -          | 0.01 PO$_1$-eq | 0.19 N-eq |
| Freshwater aquatic ecotoxicity potential | kg DCB-eq | 0.34    | 0.01       | -            | -         |
| Global warming potential        | kg CO$_2$-eq | 274.57  | 275.14     | 204.35       | 274.57    |
| Human toxicity potential        | kg DCB-eq | 0.6     | 41.54      | -            | -         |
| Marine aquatic ecotoxicity potential | kg DCB-eq | 53.05   | 1.88       | -            | -         |
| Photochemical ozone creation potential | kg ethene-eq | 0.04    | 0.03       | 0.04 C$_2$H$_4$-eq | -         |
| Terrestrial ecotoxicity potential | kg DCB-eq | 0.1     | 0.02       | -            | -         |

Table 6 shows the results of the sensitivity analysis, aimed at determining the effect of the following factors on the environmental impacts: diesel consumption during the collection and transportation stage, water consumption and electricity consumption during the pre-processing stage, aerobic composting additive during the solid composition stage, and ferric chloride consumption during the wastewater treatment stage. The third column in Table 6 shows the LCA results based on the actual data using the CML2001 model. Columns 4–8 show the results after a 5% increase in the value of the five factors.

Table 6. Sensitivity analysis of key variables.

| Category                        | Unit    | CML2001 | Diesel | Water | Electricity | Aerobic Composting Additive | Ferric Chloride |
|---------------------------------|---------|---------|--------|-------|-------------|-------------------------------|-----------------|
| Acidification potential         | kg SO$_2$-eq | 0.2     | 0.2    | 0.2   | 0.29        | 0.2                           | 0.2             |
| Eutrophication potential        | kg phosphate-eq | 0.11    | 0.11   | 0.11  | 0.12        | 0.11                          | 0.11            |
| Freshwater aquatic ecotoxicity potential | kg DCB-eq | 0.34    | 0.34   | 0.34  | 0.37        | 0.34                          | 0.34            |
| Global warming potential        | kg CO$_2$-eq | 274.57  | 274.76 | 274.65 | 277.25      | 274.57                        | 274.57          |
| Human toxicity potential        | kg DCB-eq | 0.6     | 0.61   | 0.6   | 2.49        | 0.6                           | 0.6             |
| Marine aquatic ecotoxicity potential | kg DCB-eq | 53.05   | 53.26  | 53.86  | 202.79      | 53.05                         | 53.05           |
| Photochemical ozone creation potential | kg ethene-eq | 0.04    | 0.04   | 0.04  | 0.04        | 0.04                          | 0.04            |
| Terrestrial ecotoxicity potential | kg DCB-eq | 0.1     | 0.1    | 0.13  | 0.1         | 0.1                           | 0.1             |
As shown in Table 6, marine aquatic ecotoxicity, global warming, and human toxicity are very sensitive to electricity, followed by acidification, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, eutrophication, and photochemical ozone creation. Water has an obvious effect on the marine aquatic ecotoxicity, global warming, and human toxicity. In particular, the marine aquatic ecotoxicity is mostly sensitive to water. The diesel has an obvious effect on the marine aquatic ecotoxicity, global warming, human toxicity, freshwater aquatic ecotoxicity, and terrestrial ecotoxicity. Marine aquatic ecotoxicity in particular is visibly more sensitive to diesel than other types of environmental impact. The remaining two key variables, aerobic composting additives and coagulant, showed less of an effect on various types of environmental impact, as well as low sensitivity. In summary, various types of environmental impact were here found to be sensitive to electricity, diesel, and water. Eutrophication and photochemical ozone creation showed little sensitivity to all key variables.

Electricity showed the most pronounced effect on the environment in the treatment of restaurant food waste in Lanzhou, mainly because the electric power in the city comes primarily from coal. In terms of the pollution control of the anaerobic digestion–aerobic composting technique, the input of coal power should be controlled first, and then the consumption of diesel and water should be controlled. The treatment of these three wastes should be managed diligently throughout all phases of the process. The green production process should be promoted. These results indicate that the energy structure also has an important impact on the overall environment. The optimization of energy structure should also be managed carefully.

4. Conclusions

Considering the environmental impact, the underlying threat to food safety, and the recycling potential of food waste in cities, the Chinese government made great effort to recycle food waste while reducing resource consumption and environmental impact to the greatest extent. Therefore, it is very important to analyze the life-cycle environmental impacts of certain patterns of food waste treatment to identify the best method of food waste recycling. This study assessed the life-cycle resource consumption and environmental impact of restaurant food waste treatment in Lanzhou city, which is a pilot city of food waste recycling in China. The conclusions are provided below.

Among the three methods of restaurant food waste treatment, i.e., anaerobic digestion–aerobic composting, incineration, and landfill disposal, our results showed that the anaerobic digestion–aerobic composting technique showed the least environmental impact, the landfill method had a medium impact, and incineration had the greatest impact on the environment. In particular, the latter two techniques may significantly exacerbate global warming. The anaerobic digestion–aerobic composting technique also showed better economic and social benefits. During the life cycle of the anaerobic digestion–aerobic composting treatment, the consumption of renewable and other resources was highest during the pre-processing phase. The collection and transportation and wastewater treatment phases primarily consumed hard coal and crude oil. The solid composting phases primarily consumed clay, attapulgite, and organic acid. The pre-processing phase primarily consumed water resources.

In the whole life cycle of food waste recycling, the environmental impact of global warming was found to be the most pronounced of any factor evaluated here, and terrestrial ecotoxicity had the least pronounced effect. The environmental impact in different phases showed heterogeneity. The maximum environmental impact in the collection and transportation phase is photochemical ozone creation potential. The maximum environmental impact of the pre-processing and biogas slurry composting phases is acidification potential. Wastewater treatment mostly affects marine aquatic ecotoxicity, and the remaining stages affect global warming.

Our sensitivity analysis and comparison demonstrated that the CML2001 method is a reliable means of assessing the life cycle of food waste. All environmental impacts were found to be mostly sensitive to electricity, diesel, and water. The eutrophication and photochemical ozone creation had a low sensitivity to all variables. The results of this work showed that the anaerobic digestion–aerobic composting technique has the smallest effect on the environment, especially greenhouse gas emissions,
which is consistent with the findings of previous works. The collection and transportation phase showed the least effect on the environment in the entire life cycle. In this technique, the biogas residues and biogas slurries are used for composting and have a less pronounced effect on the environment than other methods of disposal. This may provide a reference for restaurant food waste treatment in other parts of China.

Since food waste is produced in huge amounts along with rapid urbanization and a lack of good sorting at the source of municipal solid waste, recycling in a biotreatment model may contribute to the creation of new production chains and, therefore, to new markets. In the case of Lanzhou, because the production chain is incomplete (the absence of grease processing), the study did not involve the use of grease in the production of biodiesel or as a secondary pollutant of the compost product. As for most cities like Lanzhou, it is not able to process the grease due to economic and technical reasons, opting instead to trade it to cities with the ability to process it. The remote material flow between Lanzhou and the processing city was also ignored in this study. Future research should explore expanding both the system boundaries and space boundaries.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/9/17/3608/s1, Table S1: Life-cycle inventory of restaurant food waste in Lanzhou.

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