Article

Comparison of Potential Environmental Impacts and Waste-to-Energy Efficiency for Kitchen Waste Treatment Scenarios in Central Taiwan

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Abstract: Taiwan has a sound solid waste recycling system, and waste-to-energy is attractive under the encouragement policy and economic feasibility, especially in central and southern regions with vast agricultural wastes. The four scenarios evaluated in this study relating to current use or under consideration for kitchen waste treatment strategy in Taiwan were incineration, landfill, composting, and anaerobic digestion. These scenarios were compared through life cycle assessment to obtain the most preferable treatment solution. The analysis was based on a functional unit, i.e., 1 metric ton of kitchen waste treated, and considered all impact categories through the CML_IA baseline 2000 method. It has shown that energy recovery had enormous effects on all scenarios with the anaerobic digestion having the highest environmental performance change. A comparison between actual electricity consumption and estimated electricity generation by kitchen waste treatment through anaerobic digestion indicates that decentralized electricity generation was suitable for central Taiwan and could be considered as the energy solution in a short-term context. This study provides an experience in selecting a proper waste-to-energy method with the most negligible environmental impact.

Keywords: life cycle assessment; kitchen waste; waste-to-energy; anaerobic digestion; energy recovery; environmental impacts

1. Introduction

Fossil fuel is an irreversible energy source and is the main factor of contribution to greenhouse gas emissions. Moreover, considering that fossil-based energy will eventually be exhausted, countries worldwide seek sustainable energy, and this has led to the continuous improvement of renewable energy technology in power generation and efficiency. It has enabled countries to gradually adjust the structure of electricity generation, reduce the environmental damage potential of fossil-fuel consumption, and increase the electricity generation by renewable energy. The utilization of renewable energy sources, biomass has the considerable potential to provide bioenergy. Waste-to-energy (WTE) is an excellent alternative to fossil fuels and is also efficacious in treating waste. Except for the organic fraction from municipal solid waste and food/kitchen waste, agricultural organic wastes are thought to have the potential to provide bioenergy, i.e., biogas, hydrogen, bioethanol, and biodiesel. In Taiwan, most agricultural organic wastes such as rice husk, rice straw, fruit and vegetable residues, fishery residues, livestock, and poultry manures are treated with landfill, compost, incineration, anaerobic digestion, etc. [1]. The WTE method has proved to come with feasibility and advantages. Pipatmanomai et al. [2] and Bora et al. [3] respectively used pig dung and cow dung to produce biogas. Lal and Mohapatra [4] employed kitchen waste as the
source for biogas production, followed by its utilization in dual-fuel compression ignition engine. The research results of El-Mashad and Zhang [5] showed that adding kitchen waste into a manure digester significantly increased the biogas (particularly methane) yield. The Organization of Food and Agriculture of the United Nations reports that one-third of the food produced for human use per annum goes to waste [6].

Kitchen waste is an organic material having a high calorific value and nutritive value to microbes. The kitchen waste is derived from leftover meals, vegetables, and fruits, mainly included moisture, carbohydrates, proteins, and oils [7]. Due to the higher moisture content in kitchen waste, degradation process by anaerobic digestion is an approach to produce biogas [8–10]. Considering environmental and economic performances, anaerobic digestion is a much sustainable treatment method for biowastes. Li et al. [11] have demonstrated that Biowastes converted by anaerobic digestion can output 1–2 times more electricity than incineration [1], occupy less land-use than landfilling [12], reduce acidification and eutrophication impacts compared to composting [13]; produced biogas can be used as gaseous fuel to produce heat and electricity [14] or upgrade biomethane for serving as the transport fuel [15]. Energy supply and consumption related to climate change are the focus of environmental legislation and industrial development for pursuing sustainable energy and development in Taiwan. WTE is attractive under the policy encouragement and economic feasibility, especially for the central and southern parts of Taiwan, where regions have a large amount of organic agricultural waste. The annual kitchen waste production in Taiwan was about 650,000 metric tons with 440,000 metric tons for raising swine, 200,000 metric tons for composting, and the rest for producing biomass energy [16]. However, nowadays in Taiwan, kitchen waste is no more allowed to be used as swine feed to prevent African swine fever, and this kitchen waste needs to be treated using alternative methods. With the right technologies and approaches, kitchen wastes could become a stable, low-cost, and high-return source for producing energy. Taiwan has been a global leader in solid waste recycling but in dealing with biowastes is weak. According to the Taiwan new energy policy, conventional electricity generation is expected to be 50-30-20 clean energy mix of natural gas, coal, and renewables by 2025. It still has a gap from the 35-41-7-17 current energy mix of natural gas, coal, nuclear, and renewables.

Life cycle assessment (LCA) is a tool to transpose life cycle perspective principles into a quantitative framework that seeks to quantify all relevant emissions, consumed, or depleted resources, and the environmental and health impacts associated with the life cycle of product production [17]. Many LCA research has been implemented regarding the various kinds of biowaste reusing and treatment methods to achieve the WTE goal. More and more LCA research concerns the relevance of biowaste and biogas production, and various ways to convert energy from biogas. Poeschl et al. [18] analyzed the production and utilization of biogas in different scenarios with diverse feedstock, biogas usage, and digestate processing. Börjesson and Berglund [19] assessed the possible biogas applications from environmental and energy perspectives, focusing on greenhouse gas emissions and fossil fuel depletion. Naroznova et al. [20] assessed the global warming potential (GWP) impacts based on the treatment of individual materials found in organic household waste in Denmark and highlighted food waste treatment by anaerobic digestion allowed reducing the GWP. By comparing three different treatment systems, Bernsad and La Cour Jansen [21] carried out an LCA research and analyzed the use of the resources obtained. Their GWP results showed that biogas digestion caused the main environmental benefits, mainly when biogas was adopted as the substitute for the electricity coal power source. Usack et al. [22] and You et al. [23] used LCA results to complement techno-economic measurements and identify the weak points needing improvements. Using LCA can quantify sources of impacts throughout a life cycle for various environmental conditions, allowing environmental improvements to be determined [24,25]. Producing value-added products from kitchen waste is another main subject. Nishimura et al. [26] used kitchen waste to produce biobutanol. Adi and Noor [27] reused kitchen waste to be vermecompost. Alternatively, Li et al. [28] produced xanthan gum by pretreatment researching for kitchen waste.
A recent review article by Sindhu et al. [29] focused on value-added products conversion by kitchen waste, which also pointed to the difficulties in proper collection, storage, and bioconversion of kitchen waste valuable by-products as a significant hurdle of waste management. The treatment management and policy also considered in previous research. Hua et al. [30] discussed the emissions reducing commitment issues in developed and developing countries by comparing the renewable energy development policies and status in Australia and China. Different studies have been implemented due to the large amount produced and kitchen waste’s urgent management needs in Taiwan. Lo et al. [31] have researched the potential to provide bioenergy in biogas production from most agricultural organic wastes by anaerobic digestion in Taiwan. Tsai [32] discussed the current status of turning food waste into value-added resources in Taiwan. However, none of them aim to identify a comprehensive assessment and comparison of the impact of Taiwan’s kitchen waste treatment methods, including environmental, energy, and economic aspects, considering, in particular, both current and expected treatment methods. These points highlight the distinguishing characteristics and value of this research.

This study evaluated the environmental impacts in using four treatment scenarios including anaerobic digestion to treat kitchen waste to produce biogas for generating electricity, which became the primary strategy for treating biowaste in Taiwan. The case study was on the central region of Taiwan that has the following characteristics: (1) It is one of the leading agricultural areas with high population density and producing large amounts of biowaste and municipal solid wastes, and (2) it is also one of the leading industrial areas in Taiwan and is one of primary energy consumers. This study aims to use the LCA method to compare the potential environmental impacts at four scenarios on disposing and recycling kitchen waste in central Taiwan to identify the lowest environmental impact to support the adoption of sustainable waste treatment and opportunity for WTE and utilization as an energy development strategy.

2. Materials and Methods

2.1. Life Cycle Assessment Approach

LCA follows a standardized method that guarantees the reproducibility of results [17]. The assessment in this study was carried out through a comparative LCA: the comparison of the environmental profiles of different systems was based on equivalent functions. Three kitchen waste treatment systems currently widely used [16] were compared with one alternative hypothetical treatment scenario.

2.2. Assessment Goal, Scope Definition and Functional Unit

In assessing the potential environmental impacts in treating kitchen waste produced at central Taiwan, four scenarios (Table 1) were compared: three disposal scenarios (incineration, Scenario 1; landfill, Scenario 2; composting, Scenario 3) and one alternative scenario (biogas production by anaerobic digestion having recycling organics, Scenario 4). This assessment was to find a system with (1) relative-lower environmental impacts, (2) more sustainable practices for treating biowaste, and (3) a case of converting the waste into energy. The system boundaries and scopes of this study are shown in Figure 1; they included all activities in the kitchen waste treatment processes, from materials entrance to definitive treatment (no collection-storage section). The utilization of the products obtained from the treatment processes was not included in the system boundaries. The inventory of the foreground and background data is summarized in Table 1.

In designing different scenarios, some estimates and assumptions were made. First, the transportation of kitchen waste from production sources to collection/classification center or treatment plants was excluded in the assessment boundaries to focus on evaluating the impacts caused by different waste treatment methods and processes. Second, the treatment phase data were obtained from regular government surveys and statistical reports [1,34,35]; the energy conversion parameters were obtained from international literature and reliable
industrial indicators [36–38]. It is assumed that the kitchen waste composition at treatment plants was the same as analyzed in the baseline study. A functional unit (FU) of “1 metric ton of kitchen waste to be treated” was selected to carry out the comparison between the scenarios [39].

Table 1. Evaluation conditions about recycling energy or material and quantification of the avoided products related to the functional unit of 1 metric ton of kitchen waste treated.

| Scenario      | Unit     | Recovery | Recycled Sources | Avoided Products |
|---------------|----------|----------|------------------|------------------|
|               |          | Energy   | Material Category | Amount          | Category      | Amount          |
| 1-Incineration| kWh      | Yes      | Electricity      | 375             | Electricity   | 375             |
| 2-Landfill    | kWh      | Yes      | Electricity      | 108             | Electricity   | 108             |
| 3-Composting  | kg       | -        | Yes              | Compost         | 197           | Fertilizers     | 29              |
| 4-Anaerobic Digestion | kWh | Yes | Electricity | 405 | Electricity | 405 |

Figure 1. The system boundaries of the four scenarios studied on kitchen waste treatment.

2.3. Inventory Analysis

The inventory of the four scenarios was detailed as follows (Table 2).

In Scenario 1, the incineration of kitchen waste using a mass-burn incinerator having a heat recovery (used for electricity generation) with an energy efficiency of 19.6% was assumed. This average energy efficiency value was obtained from five incineration plants in central Taiwan: Miaoli county 20.8%, Taichung Wunshan 14.0%, Houli 21.2%, Wuri 22.5%, and Changhua Xizhou 19.3% [40]. The inventory data included substances, electricity, coal consumption, natural gas utilization during the process, and direct emissions. Scenario 2 represented the common treatment system adopted in the local context. Data related to the electricity and direct emissions due to waste treatment were the most considered; the biogas production was assumed as 30% energy recovery efficiency that obtained considering the biogas proportion and the actual efficiency. In Scenario 3, the KW was treated by composting to produce compost for being used as fertilizer; about 20% of the
initial kitchen waste quantity. Data connected to electricity and water during the process and direct emissions and leachate disposal are considered. In Scenario 4, kitchen waste was assumed to be treated by anaerobic digestion to obtain biogas for electricity generation. Data related to the system included materials, electricity, and water consumption for producing biogas and the direct emissions during treatment. The recoverable energy was 1 metric ton of kitchen waste converting into 405 kWh of electricity [36].

Table 2. Main input and output data at 1 metric ton kitchen waste treated.

| Input                  | Unit  | Scenario 1 Incineration | Scenario 2 Landfill | Scenario 3 Composting | Scenario 4 Anaerobic Digestion |
|------------------------|-------|-------------------------|---------------------|------------------------|-------------------------------|
| Electricity            | kWh   | 113                     | 645                 | 142                    | 91                            |
| Coal                   | kg    | 4.95                    | -                   | -                      | -                             |
| Natural gas            | m³    | 9.03                    | -                   | -                      | -                             |
| Chemicals-inorganic    | kg    | 8.87                    | -                   | -                      | -                             |
| Chemicals-organic      | kg    | -                       | 5.18                | -                      | -                             |
| Catalysts/auxiliary agents | kg | 1.46                    | -                   | -                      | 0.07                          |
| Output                 |       |                         |                     |                        |                               |
| Electricity            | kWh   | 375                     | 108                 | -                      | 405                           |
| Compost                | kg    | -                       | -                   | 197                    | -                             |

The kitchen waste treatment strategy in Taiwan is undergoing a transformation from swine feeding to other processes. The latest statistical data of material flow were used: the kitchen waste amount in the third quarter of the year 2020 in central Taiwan [16], also had shown in Table S1. Kitchen waste treatment might produce some co-products of recoverable energy or materials, such as the electricity from biogas or the fertilizers from composting; they were used as the “avoided products (AvPr)” [41]. The option of AvPr in assessment processes needs to be chosen when more than one product is to be the output of the whole process. AvPr helps to know how the contribution flows of the life cycle are distributed between the different product or co-product outputs, such as biogas production during biowastes treatment, and then re-using the biogas for electricity generation as energy recovery. Therefore, the AvPr option of assessment was considered to avoid repetitive evaluation of the analogous conventional products that might cause significant influence or even determine the assessment results [41,42]. Moreover, the international databases with ecoinvent database v2.0 and Agri-footprint 2.0 [43–45] were adopted to include the inventory data regarding materials and energy sources (shown in Table S2).

2.4. Life Cycle Impact Assessment

SimaPro v.8.4 software [46] was used to perform the LCA assessment. According to LCA research literatures related to the specific field of kitchen waste management, the Life Cycle Impact Assessment (LCIA) was carried out by means of CML-IA baseline 2000 methodology [47] for obtaining the environmental picture of each scenario. In the present work, for each impact category, the assessment was conducted by considering the environmental impact categories as follows: Abiotic Depletion (ADP), Acidification (AP), Eutrophication (EP), Fresh Water Aquatic Ecotoxicity (FAETP), Global Warming (GWP), Human Toxicity (HTP), Marine Aquatic Ecotoxicity (MAETP), Ozone Layer Depletion (ODP), Photochemical Oxidation (POCP), and Terrestrial Ecotoxicity (TETP). Energy Use (EU) by Cumulative Energy Demand method [48] and Land Use (LU) by CML 2001 method [47] were also used. The 2016 version of CML-IA [49] implemented in SimaPro was used. The CML Guide [50] provides a list of impact assessment categories. In the present study, the obligatory impact categories were used, and the compulsory phase of the LCA method according to ISO 14044 [17] was implemented.
3. Results and Discussion

3.1. Characterization Results with or without Considering Avoided Product (AvPr)

Table 3 summarizes the characterization results of the four scenarios. The kitchen waste treatment methods with the highest and least potential environmental loadings were landfill and anaerobic digestion. Notably, the evaluation with or without AvPr, i.e., the evaluation including or excluding energy recovery, gave a huge discrepancy in the assessment results (shown in Table S3). Moreover, for each scenario, evaluation without considering AvPr gave much higher impacts in each category than considering AvPr. The results of evaluation without considering AvPr (i.e., energy recovery) underline the fact that the potential environmental impacts of landfill (Scenario 2) were higher than those of other scenarios (incineration, composting, and anaerobic digestion) in all the impact categories. The potential environmental impacts in descending order were Scenarios 2, 1, 3, and 4. For each scenario, the degree of potential environmental impacts could be elucidated by the percentage contribution of each category (Figure 2). They ranged from 31.86% for ozone layer depletion (ODP) to 11.48% for photochemical oxidation (POCP) in Scenario 1, from 79.63% for POCP to 49.50% for ODP in Scenario 2, from 15.06% for acidification (AP) to 4.52% for global warming (GWP) in Scenario 3, and from 10.85% for terrestrial ecotoxicity (TETP) to 3.60% for GWP in Scenario 4.

| Impact Category | Unit | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|-----------------|------|------------|------------|------------|------------|
| ADP             | kg 10-eq | 0.75       | 1.57       | 2.30       | 3.14       | 0.45       | 0.72       | -2.39      | 0.51       |
| AP              | kg SO2-eq | -0.64      | 0.91       | 1.32       | 2.03       | 0.47       | 0.58       | -0.13      | 0.33       |
| EP              | kg PO2-eq | -0.12      | 0.25       | 0.63       | 1.23       | 0.11       | 0.18       | -0.03      | 0.08       |
| GWP             | kg H2 - eq | 4.93 x 10^2 | 8.31 x 10^2 | 1.15 x 10^3 | 1.27 x 10^3 | 6.31 | 1.03 x 10^2 | -2.68 x 10^2 | 8.21 |
| ODP             | kg POCF - eq | -5.93 x 10^-6 | 2.24 x 10^-5 | 2.75 x 10^-3 | 2.48 x 10^-5 | 6.18 x 10^-4 | 7.92 x 10^-6 | -3.17 x 10^-5 | 5.18 x 10^-6 |
| HTP             | kg H2 - eq | -4.10       | 40.67      | 71.06      | 98.56      | 2.77       | 25.42      | -29.31     | 14.1       |
| FAETP           | kg H2 - eq | -29.01      | 21.05      | 43.06      | 56.12      | 7.91       | 13.04      | 0.82       | 7.92       |
| MAETP           | kg H2 - eq | -6.96 x 10^4 | 4.97 x 10^4 | 9.99 x 10^4 | 1.36 x 10^5 | 1.56 x 10^4 | 2.99 x 10^4 | -1.71 x 10^5 | 1.86 x 10^4 |
| TETP            | kg H2 - eq | -0.87       | 0.51       | 1.07       | 1.43       | 0.08       | 0.23       | -0.08      | 0.23       |
| POCP            | kg C - eq | -3.52 x 10^-2 | 4.34 x 10^-2 | 2.89 x 10^-3 | 5.01 x 10^-4 | 1.63 x 10^-2 | 1.85 x 10^-2 | -1.39 x 10^-5 | 1.49 x 10^-5 |
| EU              | MJ       | -2.05 x 10^2 | 3.27 x 10^2 | 5.25 x 10^2 | 4.06 x 10^3 | 8.94 x 10^2 | 1.56 x 10^3 | -1.63 x 10^5 | 1.00 x 10^5 |
| LU              | m^2 a    | -1.04       | 1.29       | 2.07       | 3.75       | 0.27       | 0.83       | -0.31      | 0.49       |

1 Abiotic Depletion (ADP), Acidification (AP), Eutrophication (EP), Global Warming (GWP), Ozone Layer Depletion (ODP), Human Toxicity (HTP), Fresh Water Aquatic Ecotoxicity (FAETP), Marine Aquatic Ecotoxicity (MAETP), Terrestrial Ecotoxicity (TETP), Photochemical Oxidation (POCP), Energy use (EU), and Land use (LU).

In the evaluation with AvPr, the results of energy and material recovery potential by each scenario were shown in Table 3. The scenario having the highest potential environmental impacts remained the same (landfill, Scenario 2). Still, the scenario having the least impacts was utterly different. The most significant difference was incineration (Scenario 1) that has the second-highest potential environmental impact in the case not considering AvPr. The results show the high advantage of energy recovery in incineration.

Furthermore, whether including or excluding AvPr, the anaerobic digestion had the advantage of more negligible environmental impacts in all impact categories. Anaerobic digestion had the lowest impacts in abiotic depletion (ADP) and GWP categories, presenting the positive effect of sustainable resources usage. This context also responded to the Taiwanese government’s main initiative in improving the environment by reducing carbon emissions.
Figure 2. Characterization results of the four scenarios: percentage contributions to the potential environmental impacts for each characterization factors by each scenario (without the inclusion of the avoided products, AvPr). The characterization factors are: Abiotic Depletion (ADP), Acidification (AP), Eutrophication (EP), Global Warming (GWP), Ozone Layer Depletion (ODP), Human Toxicity (HTP), Fresh Water Aquatic Ecotoxicity (FAETP), Marine Aquatic Ecotoxicity (MAETP), Terrestrial Ecotoxicity (TETP), Photochemical Oxidation (POCP), Energy use (EU), and Land use (LU).

3.2. Analysis for the Scenarios Related to Energy Recovery

The evaluation results of all the scenarios having energy recovery (Scenarios 1, 2, and 4) are shown in Figure 3, and the comparison proportion data show in Table S4.

Figure 3. Comparison among the energy-recovery scenarios with considering the avoided products. The functional unit used was 1 metric ton of KW. The characterization factors are: Abiotic Depletion (ADP), Acidification (AP), Eutrophication (EP), Global Warming (GWP), Ozone Layer Depletion (ODP), Human Toxicity (HTP), Fresh Water Aquatic Ecotoxicity (FAETP), Marine Aquatic Ecotoxicity (MAETP), Terrestrial Ecotoxicity (TETP), Photochemical Oxidation (POCP), Energy use (EU), and Land use (LU).
It visualizes the characterization results and underlines the evaluation that with energy recovery, the incineration treatment (Scenario 1) could reduce significant environmental loadings. It means that Scenario 1 had the advantage of energy recovery in the incineration system by substituting conventional electricity with the energy recovered from waste treatment. The reduction of potential environmental impact in Scenario 4 was foremost due to the substitution of natural gas electricity with the electricity generated from the biogas produced from kitchen waste. Scenario 2 gave the highest potential environmental impacts within three energy-recovery scenarios. It shows that a replacement of conventional energy source with the electricity obtained in Scenario 2, landfill, did not reduce potential environmental impacts. Table 4 shows evaluation results on the energy use (EU) and land use (LU) impacts for Scenarios 1, 2, and 4. The main potential environmental benefit underlined was the avoided production of conventional electricity. Substitution by the electricity obtained through Scenario 1 gave impact reductions in EU and LU of 161% and 181%, respectively. Scenario 4 (anaerobic digestion) had environmental benefits in the EU impact category having reduction of 263% by −1634.97 MJ per FU, due to the substitution of natural gas electricity by the biogas electricity obtained from kitchen waste treatment. Anaerobic digestion also affected the impact of LU that having a 122% reduction with −0.11 m²a increased to 0.49 m²a. However, Scenario 2 had lower reduction percentages of potential environmental impacts in EU and LU, showing it had higher environmental impacts than those of Scenarios 1 and 4.

Table 4. The reduction percentage of potential environmental impacts in energy use and land use results of three energy-recovery scenarios after evaluation with avoided products.

| Impact Category | Unit | Scenario 1 Incineration | Scenario 2 Landfill | Scenario 4 Anaerobic Digestion |
|-----------------|------|-------------------------|---------------------|-------------------------------|
| Energy use      | MJ   | 161.33                  | 23.76               | 262.98                        |
| Land use        | m²a  | 180.62                  | 18.13               | 122.45                        |

These results show that the consumption and recovery of energy are the main factors dominating the selection of kitchen waste treatment methods.

3.3. Analysis for the Scenario Related to Material Recovery

Scenario 3 (composting) was the only scenario to be discussed as having material recovery. The process of composting has the bioconversion that could produce compost, and the substitute of conventional fertilizers was the immediate valuable product from kitchen waste by composting processes, which is beneficial to environmental impacts. However, even the evaluation results considering AvPr (Table 3) still show that composting is not a good strategy for treating kitchen waste. Table 3 shows that the GWP impact category after Scenario 3, considering material recovery, the emissions reduced from 103.14 to 63.17 kg CO₂-eq per FU, and the reduction rate was only about 39%. Compared with Scenario 4 (anaerobic digestion) process, after considering energy recovery, the reduction rate of GWP reached about 450%. Moreover, the LU impact that has high relevance with Scenario 3 shows a result still inferior to Scenario 1 after material recovery with impact results of 0.27 m²a and −1.04 m²a, respectively. By comparison, Scenarios 1 and 4 can reduce more potential environmental impacts than Scenario 3.

3.4. Assumed Electricity Generation by Kitchen Waste Treatment

Although the previous results show that incineration (Scenario 1) did have its advantages in energy recovery, the kitchen waste treatment via incineration requires fossil fuels during combustion operation. Considering long-term strategy for sustainable development, reducing or even eliminating the use of fossil fuels is necessary. Though the
evaluation results showed the advantages of energy recovery, incineration was not an appropriate waste-to-energy choice. Therefore, in using kitchen waste to show the feasibility of waste-to-energy, anaerobic digestion was chosen to estimate the electricity generation and evaluate the energy coverage rate in actual needs.

The estimated electricity generation from kitchen waste via anaerobic digestion in central Taiwan is listed in Table 5. On the other hand, in the same period, the Central Taiwan Science Park’s electricity consumption, which is the leading industrial area and consumes huge electricity in central Taiwan, is shown in Table 6. The electricity consumption was 3211.37 GWh based on actual working hours, and the estimated electricity generation from the biogas was 13,642 MWh. Although the electricity coverage rate was low (0.43%), from the perspective of individual bases of the Central Taiwan Science Park, this power is enough for supporting Erlin Base and Zongxing Base, or supplying 31.73% and 2.20% of the electricity required by Huwei Base and Houli Base, respectively. Moreover, based on the electricity consumption in the residential sector in central Taiwan [35], 13,642 MWh could provide 5.40% of the electricity consumption for Nantou County, 3.12% for Yunlin County, and 1.73% for Miaoli County (Table 7). The overall electricity coverage rate for the entire residential sector in central Taiwan was 0.35%. These results show that the renewable energy electricity generation based on anaerobically digesting kitchen waste has high development potential in central Taiwan.

Table 5. The assumed electricity generation based on the actual quantity of kitchen waste treated by anaerobic digestion in the third quarter of 2020 in central Taiwan.

| County and City  | July Generation Capacity (MWh) | August Generation Capacity (MWh) | September Generation Capacity (MWh) | Quarterly (MWh) |
|------------------|--------------------------------|---------------------------------|------------------------------------|-----------------|
| Taichung City    | 2705                           | 2807                            | 2755                               | 8267            |
| Miaoli County    | 575                            | 593                             | 548                                | 1716            |
| Changhua County  | 524                            | 524                             | 566                                | 1614            |
| Nantou County    | 263                            | 248                             | 248                                | 760             |
| Yunlin County    | 466                            | 405                             | 415                                | 1286            |
| Subtotal         | 4533                           | 4577                            | 4532                               | 13,642          |

Table 6. Electricity load scale and electricity consumption in the third quarter of 2020 in Central Taiwan Science Park. The quarterly electricity consumption was calculated based on the actual working days in a particular month.

| Base Area         | July (10 MW) | August (10 MW) | September (10 MW) | Whole Season (10 MW) | Quarterly (GWh) |
|-------------------|--------------|----------------|-------------------|----------------------|-----------------|
| Taichung Base     | 114.27       | 115.37         | 115.41            | 345.05               | 2542            |
| Huwei Base        | 1.96         | 1.96           | 1.92              | 5.84                 | 42.99           |
| Houli Base        | 27.67        | 27.87          | 28.56             | 84.1                 | 618.85          |
| Erlin Base        | 0.07         | 0.07           | 0.07              | 0.21                 | 1.55            |
| Zongxing Base     | 0.27         | 0.28           | 0.28              | 0.83                 | 6.11            |
| Subtotal          | 144.24       | 145.55         | 146.24            | 436.03               | 3211            |
Table 7. Electricity consumption in the third quarter of 2020 by residential sector in central Taiwan household.

| County and City     | July (MWh) | August (MWh) | September (MWh) | Quarterly (GWh) |
|---------------------|------------|--------------|-----------------|-----------------|
| Taichung City       | 647,325    | 672,106      | 700,122         | 2020            |
| Miaoli County       | 119,412    | 115,879      | 133,051         | 368             |
| Changhua County     | 249,788    | 269,875      | 269,361         | 789             |
| Nantou County       | 764,93     | 97,851       | 78,294          | 253             |
| Yunlin County       | 143,175    | 145,314      | 148,671         | 437             |
| Subtotal            | 1,236,193  | 1,301,025    | 1,329,499       | 3867            |

4. Conclusions

In treating kitchen waste, comparing with incineration, landfill, and composting, anaerobic digestion (Scenario 4) could bring the most benefits with the least potential environmental impacts and high energy recovery performance. An evaluation process considering the avoided product shows that the energy recovery would have a positive effect, reducing potential environmental impacts in treating kitchen waste or related biowastes. A high energy recovery rate can reduce more environmental impacts by reducing the environmental loadings caused by waste treatment processes. Moreover, kitchen waste treatment via anaerobic digestion would generate electricity for some actual electricity consumption. Decentralized electricity generation systems are suitable for central Taiwan and can be considered as an energy solution for the short term.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/pr9040696/s1, Table S1: The statistics amount of kitchen waste productions in the third quarter of the year 2020 in central Taiwan, Table S2: Data sources related to the international databases, Table S3: The percentage of the reduction rate of potential environmental impacts in each categorization resulting from all scenarios after evaluation with avoided products, Table S4: Comparison by proportion among the three energy-recovery scenarios of kitchen waste (KW), considering the avoided products. The characterization results per each functional unit.

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