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Life Cycle Analysis of Energy Production from Food Waste through Anaerobic Digestion, Pyrolysis and Integrated Energy System

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Abstract: The environmental performance of industrial anaerobic digestion (AD), pyrolysis, and integrated system (AD sequence with pyrolysis) on food waste treatment were evaluated using life cycle assessment. The integrated treatment system indicated similar environmental benefits to AD with the highest benefits in climate change and water depletion in addition to the increased energy generation potential and the production of valuable products (biochar and bio-oil). Pyrolysis results illustrated higher impact across water, fossil fuel, and mineral depletion, although still providing a better option than conventional landfilling of food waste. The dewatering phase in the AD process accounted for 70% of the treatment impact while the pre-treatment of the food waste was responsible for the main burden in the pyrolysis process. The study indicated that the three treatment options of food waste management are environmentally more favorable than the conventional landfilling of the wastes.

Keywords: life cycle assessment; environment; End-of-Life (EOL); food waste; digestion; pyrolysis

1. Introduction

Food waste management has rapidly been influenced by local and regional policies to ensure recycling, resource optimization, and mitigation of environmental impacts. Waste management, food and energy security, climate change, and resource recovery are the primary indicators [1–3] shaping waste treatment and process adoption across the globe. The renewed acceptance of anaerobic digestion (AD) in some countries, such as Australia and member states of the European Union (EU), is closely associated with the Renewable Directives and the Waste Framework Directives for renewable energy target against 2020 [4,5], while organic waste management in developing countries is hinged on international initiatives, such as sustainable development and resource conservation [6]. The ease at which wet biomass is treated without pre-treatment to harvest energy and digestate may fundamentally be responsible for AD acceptance.

There are a large number of international developments for energy production through anaerobic digestion. About 14 Million functional small-scale digesters were developed in China and 50,000 estimated in Nepal [6]. Germany expects a 30% increase of the current 7000 small and large scale on farm AD systems by 2020 [4]. However, constraints associated with digestate utilization or disposal includes physical and chemical (heavy metals and organic pollutants) impurities; pathogens and biological matter concentrations [7]; distribution and mineralization dynamics of digestate nutrients in soil; and quality management [8]. Many studies delineated the merits of the liquid (digestate with total solid (TS) range of 0.5 to 15%) and solid (digestate with TS > 15%) residues [9] as bio-fertilizers [10,11]. Recently, energy extraction from digestate using pyrolysis is reported as another sustainable management measure [12,13] to extract energy from this bio-resistant or non-biodegradable organic product of the AD system. The soil enhancement and the other environmental potentials of the biochar (black carbonaceous residue) from the thermochemical process [14,15] are thus exploited. Supercritical water gasification of biomass is another recommended technology for the processing of biomass streams rich in water [16].

Monitoring and quantifying the inputs and outputs of the anaerobic digestion and pyrolysis treatment processes and their resultant products through a life cycle pattern expectedly enable the identification of emissions, wastes, and more environmentally sustainable options in the system [4], which consequently ensures sustainability of policy and its implementation. Life cycle assessment [17] is an established technique for environmental analysis wherein system inputs (materials, energy, and others) are adequately correlated with the outputs (product, waste, and emissions) using standard methodologies with the aim of improving the system. However, LCA of waste treatments are often based on a single treatment technique coupled with uncertainties, which make them case specific with data unconnected to specific plant or functional scenarios [18,19].

Multiple and isolated treatment options mirrored through environmental metrics for food wastes management may be a potential measure to utilize the increase in global food production. This strategy is imperative as waste management industries transit from waste treatment and disposal to being active suppliers of energy and recovered materials [20]. This study gives a novel life cycle analysis approach by evaluating and comparing the environmental performance of three end of life (EOL) management scenarios (anaerobic digestion, pyrolysis, and the integration of AD and pyrolysis) for food waste treatment processes and their resultant products with focus on the environmental benefits and burdens using selected impact categories as characterized by the LCA methodology.

2. Materials and Methods

The LCA is an established method, both technically and scientifically [21,22], and is standardized by the International Organization for Standardization ISO 14040 [23]. This method was synthesized in four interrelated phases: goal and scope definition, inventory analysis, impact evaluation, and interpretation [24,25].

The inputs and outputs of each EOL management scenario were defined, and the developed inventory was calculated using SimaPro v.8 (PRé Sustainability, Amersfoort, Netherlands) [26]. In this study, the midpoint approach is used to evaluate the environmental impact using the ReCiPe method [27], since it is one of the most recent and harmonized indicator approaches. The midpoint indicators considered in this study were climate change (CC), ozone depletion (OD), terrestrial acidification (TA), fresh water eutrophication (FE), marine eutrophication (ME), human toxicity (HTox), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TEcox), fresh water ecotoxicity (FEcox) marine ecotoxicity (MEcox), water depletion (WD), minerals depletion (MD), and fossil fuel depletion (FD).

2.1. Scope of the Analysis and Functional Unit

This study proposes environmental analysis based on the LCA method to identify impacts preventive measures and system improvement strategies necessary to improve the economic and environmental performance of an existing industrial food waste treatment process. Alternative EOL management scenarios, such as anaerobic digestion, pyrolysis, or integrated system (sequence or integration of anaerobic digestion and pyrolysis) are promoted to reduce the amount of food landfilled while obtaining valuable by-products (bio-fertilizer, biochar, bio-oil, and biogas) for other uses or applications. Therefore, it is necessary to provide a reference through which the process inputs and outputs are correlated. In this study, 1 kg of food waste was established as the functional unit. Details and characteristics of the food waste used in the modelling were described previously [13,28].

2.2. Scope of the Analysis and Functional Unit

As shown in Figure 1, the assessment focused on three different EOL scenarios to manage food waste. Considering this approach, previous stages related to the food production and use phase are not included in this analysis, since they can be considered as independent of the evaluated scenarios. Only the material and energy inputs and outputs associated with the different EOL treatment processes and the strategies for application of the generated by-product are inside the system boundaries, excluding the existing infrastructure. Moreover, in view of the assessment goal, disposal in a landfill was considered as the conventional management option.

Since electricity consumption is an important parameter, relevant consideration to account is the local energy supply mix [18]. In this case, the assessment was developed considering the Australian country energy supply mix. The distribution per sources of the electricity generation across Australia, which accounts for a high ratio of fossil fuels (86%), especially of coal (73%) and natural gas (13%), and lower ratio of alternative energies (14%), including hydropower (7%), wind power (4%), solar energy (2%), and bioenergy (1%) [29]. As a final assumption, the evaluation was carried out excluding the infrastructure impact associated to the three scenarios studied.

2.3. EOL Management Scenarios Description

An industrial one-stage anaerobic digestion (henceforth refer to as AD) plant designated predominantly for food waste treatment and the provision of electricity to the Australian national grid was compared with a parallel pyrolysis treatment and an integrated treatment process (wherein AD was sequenced with pyrolysis) for optimal energy and value added product extraction. The three food waste treatment pathways were analyzed and compared as sustainable means for further valorization of the generated food wastes.

2.3.1. Anaerobic Digestion Process

Anaerobic digestion (AD) is the microbial degradation of food waste or organics in the absence of molecular oxygen to produce bio-methane gas, liquid, and solid residues as annotated in Case A of Figure 1. The commercial one-stage AD treatment plant (1000 tonnes per week capacity) typically collects suitable solid and liquid food waste materials from the industrial, commercial, and residential sectors and converts it to energy and nutrient-rich fertilizer (digestate). The mesophilic AD system generates methane, which is converted to electricity (supplied to the Australian national grid for distribution) and heat through the combined heat and power (CHP) system. Some of the operational data of the AD process may be obtained in the previous studies [13,28], as summarized in Table 1. Part of the generated heat is used for de-watering of the digestate, control of the AD process, and feedstock sterilization when necessary. Process parameters, such as temperature and retention time (RT), are important to the AD performance [30], especially at an industrial scale. Operational cost of maintaining sludge heat for microbial activities and mixing in the reactor accounts for retention time trade-off, which results in residues with potential for energy recovery, such as those targeted in the proposed integrated system (Case C).

2.3.2. Pyrolysis Treatment Process

Pyrolysis is an endothermic process through which pre-treated (dried) food waste or bio-resistant digestate is thermally degraded for production of biogas, biochar, and bio-oil. Details of the energy distribution yield and characterization results of these products produced at industrial pyrolysis temperature (500 °C) were presented previously [13,28]. Heating rate may be defined to influence the choice of products during pyrolysis. Slow heating rate ensures higher biochar yields while fast heating rate produces higher bio-oil or biogas yields. The gas produced is expected to be co-generated (CHP) to electricity, while the resultant heat is budgeted for the food waste pre-treatment, as indicated in the schematic diagram (see Case B in Figure 1). Other related input and output data of this scenario are presented in Table 1.

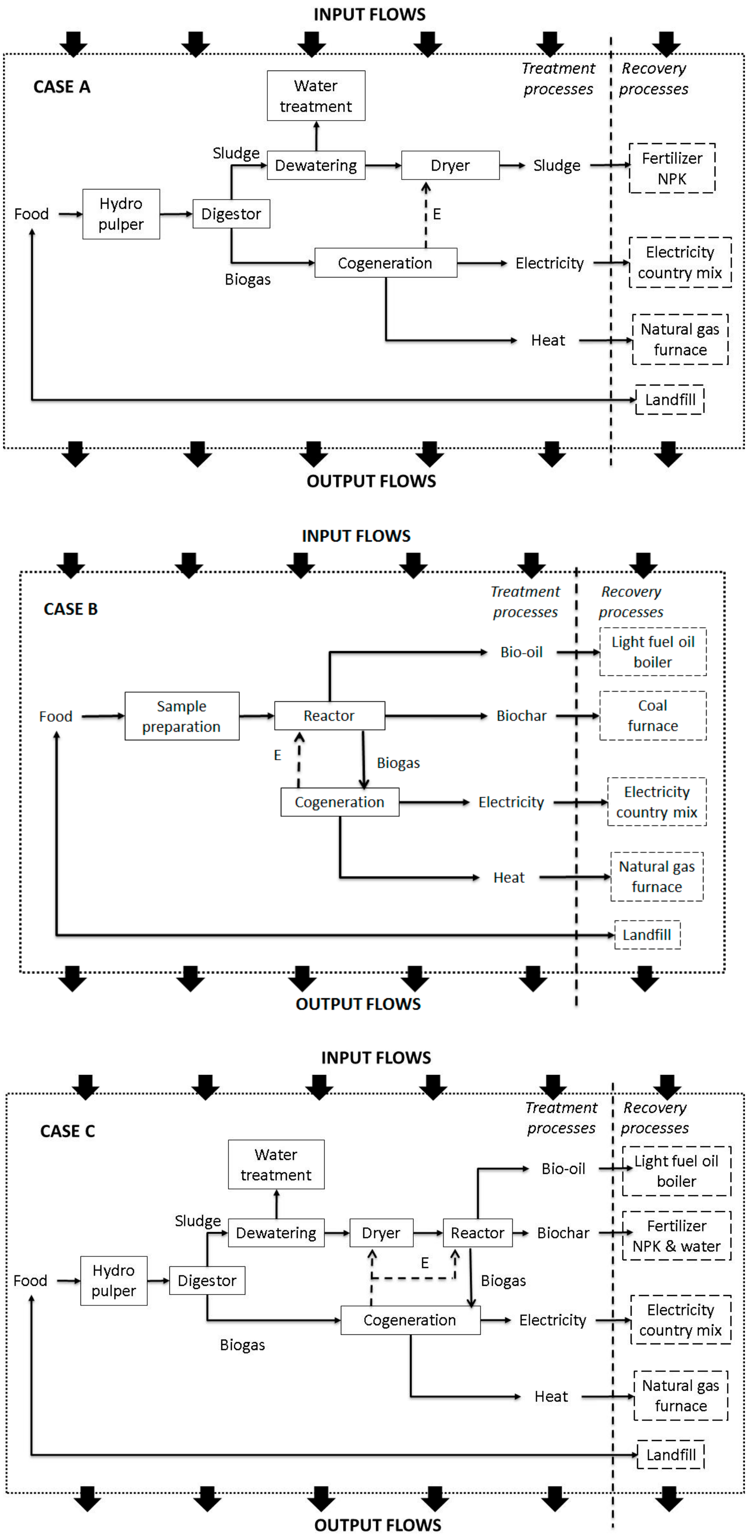

Figure 1. System boundaries of the three end of life (EOL) management scenarios including the definition of the treatment and recovery processes. Case A: Anaerobic digestion; Case B: Pyrolysis; and, Case C: Integrated or sequenced anaerobic digestion and pyrolysis system.

2.3.3. Integrated Treatment Process

The integrated treatment process implied sequence or combining both anaerobic digestion and pyrolysis processes, as shown in Case C of Figure 1. The summary of the inputs and outputs are also provided in Table 1.

2.4. Life Cycle Inventory

The Life Cycle Inventory [31] includes the energy and materials involved in analysis of the EOL scenarios. These data were obtained by combination of different sources; mainly from a functional industrial one-stage anaerobic digestion food waste treatment plant in Sydney, laboratory tests, methods, and analysis of samples, as reported previously [13,28], and standardized by the Eco-invent 3.1 database [32]. Material and energy consumption associated with the waste treatment processes involved in the pyrolysis and the proposed integrated management scenarios were obtained from the laboratory experiments [13,28]. Since the industrial scale pyrolysis provides the inert condition simulated by N_2 in the laboratory scale, nitrogen was therefore excluded in the evaluation while maintaining other data obtained through the pyrolysis trials. On the other hand, data supported by Eco-invent database [32] after validation was selected to characterize the modeling and use of the by-products and the conventional landfill scenario.

Table 1 shows the most relevant data included in the Life Cycle Inventory (LCI) considering the case studies and system boundaries defined in Figure 1. Additionally, it is necessary to take into account the materials and energies saved or conserved through the recovery or recycling of the useful products generated by the treatment processes, as included in the description of the EOL management scenarios (Figure 1). For instance, in case A (digestion), the material saved by using the digestate as a conventional fertilizer and the grid electricity saved were included in the evaluation. In case B (pyrolysis), besides the grid energy saved, fossil fuel consumption was treated as potential saving, since bio-oil was considered as a substitute for light fuel oil in boilers and biochar was characterized as substitute for coal in industrial furnaces for heat production. This assumption was predicated on the physicochemical properties of the pyrolyzed raw food waste, as detailed in previous studies [28].

In case C (integrated digestion and pyrolysis system), similar recovery actions for electricity generated from bio-oil alongside the cogeneration, while the biochar produced in this scenario was considered as a conventional fertilizer due its nutrients and water retention potential (consequently, saving irrigation water) and equally replace digestate function as bio-fertilizer were assumed. Finally, it is important to note that the heat generated in the CHP (indicated in the Figure with dotted arrow lines) are not considered as inputs since they are within the boundaries under consideration, as shown in the illustrated system boundaries (see Figure 1).

2.5. Cut-off Criteria

All of the relevant environmental impacts were incorporated in the study through the following cut-off criteria:

i Materials: In this study, flows lower than 1% of the cumulative mass of the inputs and outputs are excluded due to their environmental irrelevance, which predicates on the type of flow of the LCI. However, this sum of the neglected material flows does not exceed 5% of the mass, energy or environmental relevance.

ii Energy: Flows <1% of the cumulative energy of all the inputs and outputs (depending on the type of flow) of the LCI model, are excluded from this analysis. Their environmental relevance is equally not a concern.

These criteria were established based on a thorough analysis of the system with adequate evaluation of energy and mass balances of the processes involved.

Table 1. Main inputs and outputs related to anaerobic digestion (Case A), Pyrolysis (Case B) and Integration of Anaerobic Digestion (AD) and pyrolysis (Case C).

	Main Inputs		**Main Outputs**	
CASE A	Food waste Water Electricity Caustic soda	1 kg 0.569 kg 0.008 kWh 0.005 kg	Electricity from biogas (CHP) Heat * Organic fertilizer	0.240 kWh 0.369 kWh 0.030 kg
CASE B	Food waste	1 kg	Electricity from biogas (CHP) Heat * Biochar Bio-oil	0.026 kWh 0.020 kWh 0.097 kg 0.181 kg
CASE C	Food waste Water Electricity Caustic soda	1 kg 0.569 kg 0.136 kWh 0.005 kg	Electricity from biogas (CHP) Heat * Biochar Bio-oil	0.242 kWh 0.365 kWh 0.013 kg 0.016 kg

Note: * Heat remained after covering the energy require along the process.

3. Results and Discussion

3.1. Case A: Anaerobic Digestion (AD)

The environmental impact results of industrial one stage anaerobic digestion treatment as EOL management scenario are summarized in Table 2. The negative values observed in the results represent environmental benefits in the analyzed impact categories, while positive values refer to the environmental impacts. The results demonstrate that case A achieved environmental benefits along the whole value chain of this EOL management scenario.

Although the food refuse treatment process entailed environmental impacts for all of the indicators, these impacts were compensated through the energy generated by the biogas and the digestate substituting for grid electricity and synthetic fertilizer, thus, enabling large enough conventional EOL disposal to balance the rest of the contributed impacts. The environmental impacts and benefits associated with specific phases and stages of AD treatment process are shown in Figure 2. The most impacting stage for all of the indicators is the dewatering process, which accounts for more than 70% of the total impacts associated with the AD treatment process.

In the AD process, ozone depletion (OD) rose to about 84% (Figure 2) to indicate the highest impact category. The inclusion of wastewater treatment in the dewatering stage may have accounted for the overall impacts. On a broader perspective, the electricity consumption associated with the wastewater treatment related the most relevant impact, while the OD indicator was specifically influenced by the use of sodium hydroxide. High quantities of tetra-chloromethane (CFC-10) emissions are involved during NaOH production, which are factored for its use in the wastewater treatment. In addition, although the dryer energy demand was sourced from the heat generated by the CHP, this equally includes impacts associated with wastewater treatment, which consequently accounted for an average of 11% of the impacts. Similarly, the hydro-pulper stage impacts were indicated to be driven by electricity and water used during the phase. The microbial digestion phase delineated the least impact due to low electricity demand of this treatment phase.

Table 2. Environmental impacts for anaerobic digestion of food waste (Case A).

Impact Category	Unit	AD Treatment Process	Use of By-products and Avoided Landfill	Total
Climate change	g CO_2 eq	144.22	−901.38	−757.16
Ozone depletion	µg CFC-11 eq	4.79	−5.24	−0.45
Terrestrial acidification	g SO_2 eq	0.57	−1.90	−1.33
Fresh water eutrophication	g P eq	0.22	−0.42	−0.21
Marine eutrophication	g N eq	0.06	−2.94	−2.88
Human toxicity	g 1,4-DB eq	2.33	−12.85	−10.52
Photochemical oxidant formation	g NMVOC	0.34	−1.10	−0.75
Particle matter formation	g PM10 eq	0.17	−0.56	−0.39
Terrestrial ecotoxicity	g 1,4-DB eq	0.01	−0.03	−0.02
Fresh water ecotoxicity	g 1,4-DB eq	0.01	−0.18	−0.17
Marine ecotoxicity	g 1,4-DB eq	0.02	−0.22	−0.20
Water depletion	l	327.29	−918.85	−591.56
Minerals depletion	g Fe eq	0.50	−0.99	−0.49
Fossil fuel depletion	g oil eq	37.55	−125.48	−87.94

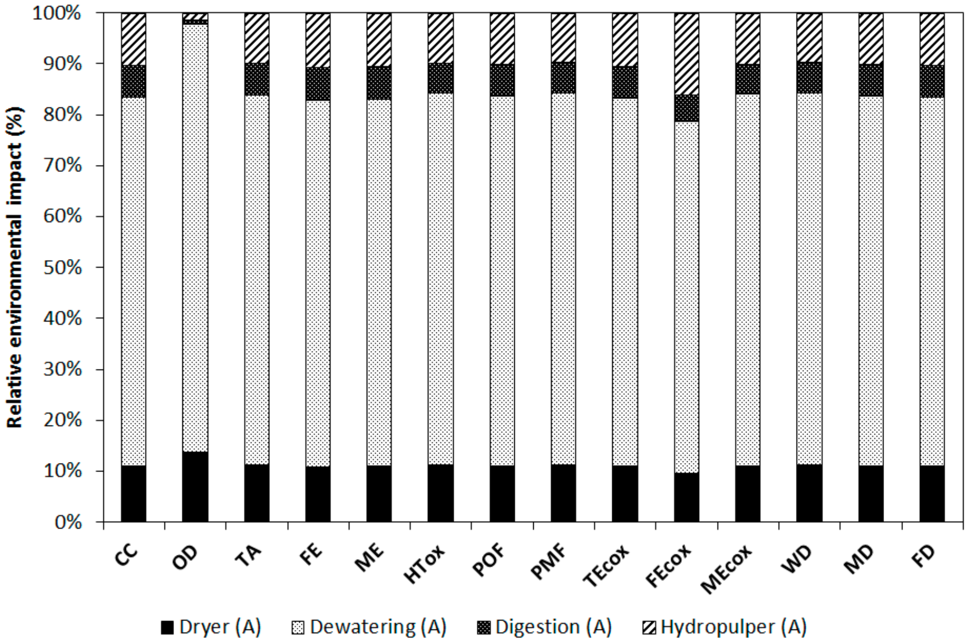

Figure 2. Environmental impacts for the industrial one stage anaerobic digestion treatment process.

Figure 3 shows the environmental benefits obtained by the application of the AD by-products and the avoided landfilling implications. In this case, recovery process performance was predicated on the indicator choice. Some indicators, such as TA, FE, POF, PMF, TEcox, WD, and FD, were specifically affected by the Australian electricity production that would be avoided considering the electricity production by biogas cogeneration. Nevertheless, other indicators reflected the fertilizer role of digestate, for example OD, HTox, MEcox, and MD were more sensible to the fact that synthetic fertilizer production can be avoided by the use of digestate produced during the AD treatment system. Particularly averted is the high impact associated with urea and phosphate production, which is one of the main material inputs during the manufacturing of synthetic NPK fertilizers. Additionally, the conventional EOL scenario (landfill avoidance) had a significant relevance for the environmental categories CC, ME, and FECox. The excess heat generated during the cogeneration stage is another benefit when recycled into the system or deployed in industrial furnaces, thus avoiding natural gas consumption. No relevant contribution was provided by the intervention to any of the environmental categories.

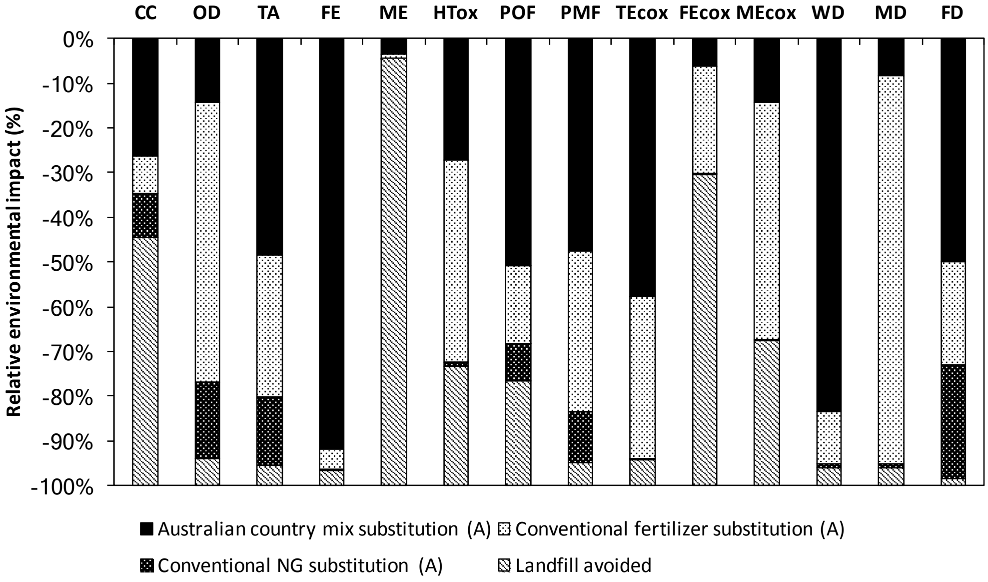

Figure 3. Environmental impacts for the recovery processes included in Case A.

3.2. Case B: Pyrolysis

The environmental impact results obtained by the midpoint analysis using the ReCiPe method for pyrolysis treatment process are summarized in Table 3. In this scenario, the results showed different behavior depending on the analyzed indicators. Prominent environmental impacts were indicated, especially on WD and FD, followed by MD, TA, FE, PMF, POF, and TEcox, while, CC, OD, ME, HTox, FEcox, and MEcox of this EOL management scenario delineated environmental benefits along the whole value chain. The neutralizing effect of the energy and materials produced during the thermochemical treatment may be attributed to the aforementioned impact categories. Regarding food refuse pre-treatment and its carbonization (pyrolysis) stages moisture removal accounts for the total impact in all of the analyzed indicators, particularly due to the associated electricity consumption. Recycling the heat generated during electricity production equally compensated for some of the system energy demand.

On the other hand, Figure 4 shows the environmental benefits obtained from the use of the by-products (biogas, bio-oil, and biochar) generated in this scenario and the avoided landfilling implications. Similar to Case A, it was found that variation in the performance of the indicators is a function of the considered product utilization choice. The benefits from the use of the biochar when substituting for coal in industrial applications and the avoided conventional landfill disposal had the highest impact in most of the indicators. For example, coal replacement with biochar influenced specifically TA, FE, HTox, POF, PMF, TEcox, and MD categories accounting for relative benefits from 43% (TEcox) to 72% (PMF) while the averted landfill disposal had high relevance in CC, ME, FEcox, and MEcox with relative benefits ranging from 61% to 99%. The other options considered for the utilization of the obtained by-products only show the predominant relevance in three of the analyzed categories that is the WD in case of electricity generation from biogas through the CHP, which prevents grid electricity consumption. Similarly, the OD and FD were improved in case when bio-oil is used to substitute for light fuel oil in boilers due to the impacts avoided and associated to the fossil fuel production.

Table 3. Environmental impacts for pyrolysis of food waste (Case B).

Impact Category	Unit	Pyrolysis Treatment Process	Use of By-products and Avoided Landfill	Total
Climate change	g CO_2 eq	683.11	−809.08	−125.97
Ozone depletion	µg CFC-11 eq	2.82	−14.63	−11.82
Terrestrial acidification	g SO_2 eq	2.61	−1.19	1.43
Fresh water eutrophication	g P eq	1.07	−0.10	0.96
Marine eutrophication	g N eq	0.29	−2.84	−2.56
Human toxicity	g 1,4-DB eq	10.27	−12.59	−2.32
Photochemical oxidant formation	g NMVOC	1.59	−1.39	0.20
Particle matter formation	g PM10 eq	0.76	−0.45	0.31
Terrestrial ecotoxicity	g 1,4-DB eq	0.04	−0.01	0.03
Fresh water ecotoxicity	g 1,4-DB eq	0.03	−0.14	−0.11
Marine ecotoxicity	g 1,4-DB eq	0.10	−0.12	−0.02
Water depletion	l	1457.88	−164.09	1293.79
Minerals depletion	g Fe eq	2.32	−0.14	2.18
Fossil fuel depletion	g oil eq	178.34	−81.38	96.97

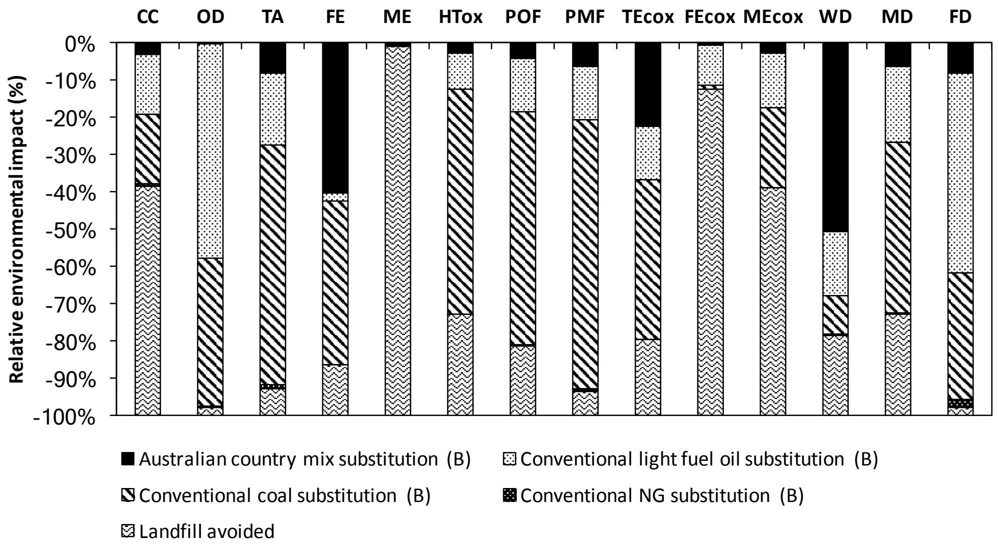

Figure 4. Environmental impacts for the recovery processes included in Case B.

3.3. Case C: Integrated system

The environmental impacts related to the integrated food waste EOL management scenario wherein AD treatment is sequenced by pyrolysis are summarized in Table 4. This EOL management scenario revealed the environmental benefits throughout the considered environmental categories, except for OD with an impact along the entire value chain. Expectedly, material and energy (since more combustible biogas is produced) substitution through by-products coupled with conventional EOL disposal compensate for the impacts associated with this food waste treatment process.

Table 4. Environmental impacts for integrated system of anaerobic digestion followed by pyrolysis (Case C).

Impact Category	**Unit**	**Integrated Treatment Process**	**Use of By-products and Avoided Landfill**	**Total**
Climate change	g CO_2 eq	144.22	−865.66	−721.44
Ozone depletion	µg CFC-11 eq	4.79	−3.88	0.91
Terrestrial acidification	g SO_2 eq	0.57	−1.57	−1.00
Fresh water eutrophication	g P eq	0.22	−0.42	−0.21
Marine eutrophication	g N eq	0.06	−2.92	−2.87
Human toxicity	g 1,4-DB eq	2.33	−9.74	−7.41
Photochemical oxidant formation	g NMVOC	0.34	−1.01	−0.67
Particle matter formation	g PM10 eq	0.17	−0.46	−0.29
Terrestrial ecotoxicity	g 1,4-DB eq	0.01	−0.02	−0.01
Fresh water ecotoxicity	g 1,4-DB eq	0.01	−0.17	−0.16
Marine ecotoxicity	g 1,4-DB eq	0.02	−0.16	−0.14
Water depletion	l	327.29	−882.02	−554.73
Minerals depletion	g Fe eq	0.50	−0.64	−0.14
Fossil fuel depletion	g oil eq	37.55	−110.17	−72.63

In the integration scenario (case C), pyrolysis assumes the processing of the dried digestate. Moreover, the biochar produced is expected to replace the agronomic role of digestate due to the char NPK nominal properties and its water retention capacity. Therefore, the relative global impact contribution of the system stages was analyzed, as depicted in Figure 5. Again, the dewatering process constitutes more than 65% of the impacts in all of the indicators included in this study. The main reason is related to the wastewater treatment included in the dewatering stage. However, the rest of the process had a distributed impact to the environmental categories. Hydro-pulper and drying components of the integrated system provided impacts of around 10–16%, respectively, while the environmental impacts of the digestion process are less than 6% of the impacts across different indicators.

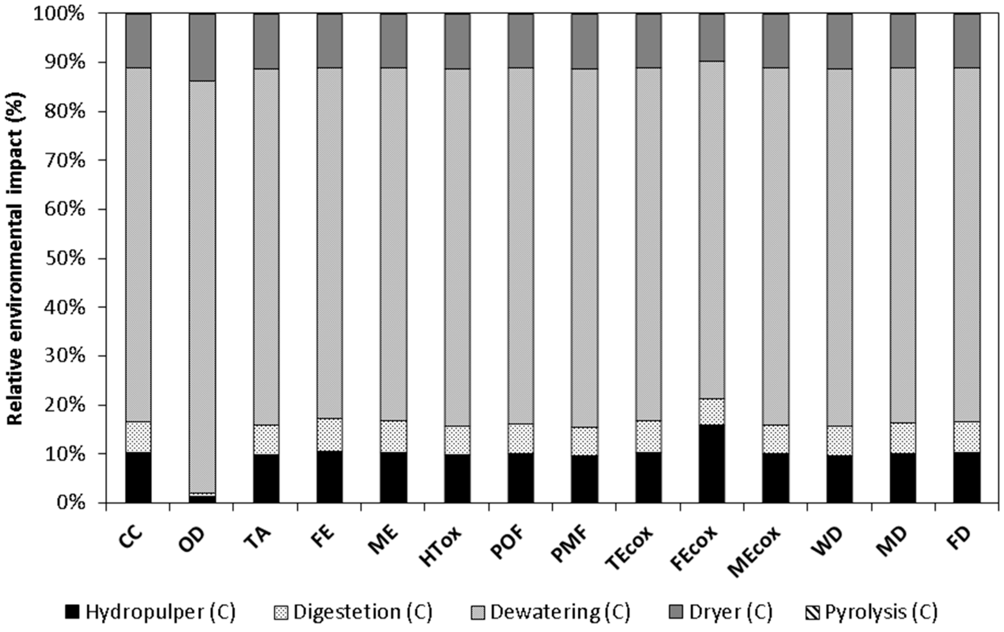

Figure 5. Environmental impacts for the treatment processes included in Case C.

The environmental benefits obtained by utilizing the by-products generated in this scenario and the avoided landfill are shown in Figure 6. The two main relevant factors that accrue in this treatment option offer the highest environmental gains in electricity generation (through the CHP from the biogas produced consequently the mix electricity consumption is avoided) and the avoided landfill use. The Australian electricity production has an important impact from the coal consumption affecting the indicators such as TA, FE, HTox, POF, PMF, TEcox, WD, and FD, which were avoided to imply benefits for the process. Additionally, the benefits from the avoided landfill use were profound for ME, FEcox CC, and MEcox due to the associated treatments. The avoided conventional fertilizer production by using the biochar equally accounts for about 80% and 30% of the total impacts for MD and OD, respectively. Since NPK fertilizer was considered in the assessment, the MD was particularly affected by the potassium chloride, while the urea production had an important influence on the OD indicator.

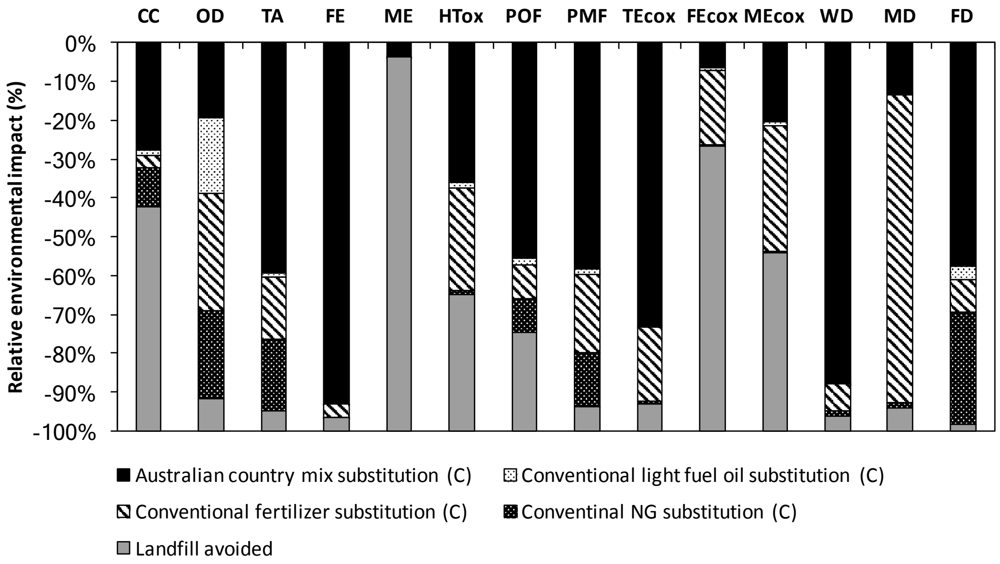

Figure 6. Environmental impacts for the recovery processes included in Case C.

3.4. Comparison of the Analyzed EOL Management Scenarios

The overall environmental performance of the scenarios related to the entrenched environmental impacts were compared and equally related to the conventional landfill option, as shown in Table 5. Although some indicators showed impacts in cases of B and C, the results evinced that all of the case studies were environmentally better options than the conventional landfilling of the food wastes as indicated by all of the impact categories. The degree of impacts in some of the EOL management scenario, such as pyrolysis, when compared to the conventional landfilling, the latter impacts are significant with 4000% higher FE and FD against the former.

Comparatively, out of the three scenarios, Case B was the least environmentally favored with overall environmental impacts for FD, FE, PMF, TEcox, MD, POF, TA, and WD categories (see Table 5). The integrated scenario C only exhibited an overall environmental impact for ozone depletion (OD), while the AD treatment process indicated environmental benefits in all of the impact categories. Case C and Case A indicated similar environmental performance in all the categories even though the latter expressed slightly higher environmental gains. However, the feasibility and the environmental viability of the two are reflected in the results.

The results obtained in this study were further related to previous studies. For example, similar trends were reported by [33] during the evaluation of different municipal solid waste management scenarios using a comparative LCA approach in Iran. The latter study included anaerobic digestion, landfilling combined with composting, incineration, incineration combined with composting and anaerobic digestion combined with incineration. The results obtained for climate change varied from 800 kg CO_2 eq per tonne in case of landfilling to −250 kg CO_2 eq per tonne in case of digestion combined with incineration posited as the most eco-friendly scenario. Similarly, higher environmental benefits (above 1000 kg CO_2 eq per tonne) were reported by Rajaeifar et al. [34] considering also the digestion and incineration treatment options. In the extended study by Parkes et al. [20] wherein ten different integrated EOL scenarios were evaluated through four impact categories, around −30 to −1100 kg CO_2 eq per tonne was reported for CC, which was similar emission trend to this study. The latter study equally reiterated that not a single management system performed the best in all of the impact categories. The relevance of recycling and recovery of energy and materials included in the EOL management scenarios were also addressed by Xu et al. [35] focusing on biogas from food wastes. Similar to the results depicted in this study, the results presented by Xu et al. [35] equally indicated that the environmental benefits achieved in the overall treatment processes are pivoted on the utilization and recovery of the generated energy.

Table 5. Comparison of the three EOL management scenarios and the conventional landfill management.

Impact Category	Unit	Case A	Case B	Case C	Landfill
Climate change	g CO_2 eq	−757.16	−125.97	−721.44	498.27
Ozone depletion	μgCFC-11 eq	−0.45	−11.82	0.91	0.32
Terrestrial acidification	g SO_2 eq	−1.33	1.43	−1.00	0.08
Fresh water eutrophication	g P eq	−0.21	0.96	−0.21	0.01
Marine eutrophication	g N eq	−2.88	−2.56	−2.87	2.81
Human toxicity	g1,4-DB eq	−10.52	−2.32	−7.41	3.41
Photochemical oxidant formation	g NMVOC	−0.75	0.20	−0.67	0.26
Particle matter formation	g PM10 eq	−0.39	0.31	−0.29	0.03
Terrestrial ecotoxicity	g1,4-DB eq	−0.02	0.03	−0.01	0.00
Fresh water ecotoxicity	g1,4-DB eq	−0.17	−0.11	−0.16	0.12
Marine ecotoxicity	g1,4-DB eq	−0.20	−0.02	−0.14	0.07
Water depletion	l	−591.56	1293.79	−554.73	34.98
Minerals depletion	g Fe eq	−0.49	2.18	−0.14	0.04
Fossil fuel depletion	g oil eq	−87.94	96.97	−72.63	1.86

4. Conclusions

This study investigated the environmental impacts and benefits of three treatment scenarios for food waste management, anaerobic digestion, pyrolysis, and integrated anaerobic digestion followed by pyrolysis. The results revealed the integrated system provides similar overall benefits and impacts with AD. The coal based Australian electricity mix impact was significantly avoided in the AD and integrated treatment processes, whereas it was accounted for the impacts associated to pyrolysis, especially in the feedstock pre-treatment. The impacts assigned to pyrolysis were predicated by the electricity mix configuration, while AD and integrated system were constrained by the use of NaOH. The alternative means of moisture removal (pre-treatment of food) and replacement of NaOH during wastewater treatment may substantially reduce the associated impacts applicable to the scenarios. The uncertainties were minimized (using real time industrial data) owing to the importance of food waste management.

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Nomenclature

EOL: End of Life
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
CC: Climate Change
OD: Ozone Depletion
TA: Terrestrial Acidification
FE: Fresh water Eutrophication
ME: Marine Eutrophication
HTox: Human Toxicity
POF: Photochemical Oxidant Formation
PMF: Particulate Matter Formation
TEcox: Terrestrial Ecotoxicity
FEcox: Fresh water Ecotoxicity
MEcox: Marine Ecotoxicity
WD: Water Depletion
MD: Minerals Depletion
FD: Fossil fuel Depletion
AD: Anaerobic Digestion
MSW: Municipal Solid Waste
CHP: Combine Heat and Power

References

1. Edwards, J.; Othman, M.; Burn, S. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. *Renew. Sustain. Energy Rev.* **2015**, *52*, 815–828. [CrossRef]
2. Wang, X.; Guo, F.; Li, Y.; Yang, X. Effect of pretreatment on microalgae pyrolysis: Kinetics, biocrude yield and quality, and life cycle assessment. *Energy Convers. Manag.* **2017**, *132*, 161–171. [CrossRef]
3. Ling-Chin, J.; Roskilly, A.P. A comparative life cycle assessment of marine power systems. *Energy Convers. Manag.* **2016**, *127*, 477–493. [CrossRef]
4. Evangelisti, S.; Lettieri, P.; Borello, D.; Clift, R. Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. *Waste Manag.* **2014**, *34*, 226–237. [CrossRef] [PubMed]
5. Vega, G.C.C.; Hoeve, M.T.; Birved, M.; Sommer, S.G.; Bruun, S. Choosing co-substrates to supplement biogas production from animal slurry—A life cycle assessment of the environmental consequences. *Bioresour. Technol.* **2014**, *171*, 410–420. [CrossRef] [PubMed]
6. Wilkinson, K.G. A comparison of the drivers influencing adoption of on-farm anaerobic digestion in Germany and Australia. *Biomass Bioenergy* **2011**, *35*, 1613–1622. [CrossRef]
7. Al Seadi, T.; Lukehurst, C. Quality Management of Digestate from Biogas Plants Used as Fertiliser. IEA Bioenergy, 2012. Available online: http://task37.ieabioenergy.com/files/daten-redaktion/download/publi-task37/Digestate_Brochure_Revised_12-2010.pdf (accessed on 4 December 2015).
8. Alburquerque, J.A.; de la Fuente, C.; Ferrer-Costa, A.; Carrasco, L.; Cegarra, J.; Abad, M.; Bernal, M.P. Assessment of the fertiliser potential of digestates from farm and agroindustrial residues. *Biomass Bioenergy* **2012**, *40*, 181–189. [CrossRef]
9. Li, Y.; Park, S.Y.; Zhu, J. Solid-state anaerobic digestion for methane production from organic waste. *Renew. Sustain. Energy Rev.* **2011**, *15*, 821–826. [CrossRef]
10. Alburquerque, J.; de la Fuente, C.; Canpoy, M.; Carrasco, L.; Nájerab, I.; Baixauli, C.; Caravaca, F.; Roldán, A.; Cegarra, J.; Bernal, M.P. Agricultural use of digestate for horticultural crop production and improvement of soil properties. *Eur. J. Agron.* **2012**, *43*, 119–128. [CrossRef]
11. Tambone, F.; Scaglia, B.; D'Imporzano, G.; Schievano, A.; Orzi, V.; Salati, S.; Adani, F. Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. *Chemosphere* **2010**, *81*, 577–583. [CrossRef] [PubMed]

12. Monlau, F.; Sambusiti, C.P.; Antoniou, N.; Barakat, A.; Zabaniotou, A. A new concept for enhancing energy recovery from agricultural residues by coupling anaerobic digestion and pyrolysis process. *Appl. Energy* **2015**, *148*, 32–38. [CrossRef]
13. Opatokun, S.A.; Strezov, V.; Kan, T. Product based evaluation of pyrolysis of food waste and its digestate. *Energy* **2015**, *92*, 349–354. [CrossRef]
14. Bogusz, A.; Oleszczuk, P.; Dobrowolski, R. Application of laboratory prepared and commercially available biochars to adsorption of cadmium, copper and zinc ions from water. *Bioresour. Technol.* **2015**, *196*, 540–549. [CrossRef] [PubMed]
15. Cely, P.; Gascó, G.; Paz-Ferreiro, J.; Méndez, A. Agronomic properties of biochars from different manure wastes. *J. Anal. Appl. Pyrolysis.* **2015**, *111*, 173–182. [CrossRef]
16. De Blasio, C.; Järvinen, M. Supercritical Water Gasification of Biomass. In *Encyclopedia of Sustainable Technologies*; Abraham, M.A., Ed.; Elsevier: Oxford, UK, 2017; pp. 171–195.
17. Rios, R.; Stragliotto, F. M.; Peixoto, H. R.; Torres, A.E.B.; Bastos-Neto, M.; Azevedo, D.C.S.; Cavalcante, C.L., Jr. Studies on the adsorption behavior of CO_2-CH_4 mixtures using activated carbon. *Braz. J. Chem. Eng.* **2013**, *30*, 939–951. [CrossRef]
18. Laurent, A.; Bakas, I.; Clavreul, J.; Bernstad, A.; Niero, M.; Gentil, ME.; Hauschild, M.E.; Christensen, T.H. Review of LCA studies of solid waste management systems–Part I: Lessons learned and perspectives. *Waste Manag.* **2014**, *34*, 573–588. [CrossRef] [PubMed]
19. Laurent, A.; Clavreul, J.; Bernstad, A.; Bakas, I.; Niero, M.; Gentil, ME.; Christensen, T.H.; Hauschild, M.E. Review of LCA studies of solid waste management systems–Part II: Methodological guidance for a better practice. *Waste Manag.* **2014**, *34*, 589–606. [CrossRef] [PubMed]
20. Parkes, O.; Lettieri, P.; Bogle, I.D.L. Life cycle assessment of integrated waste management systems for alternative legacy scenarios of the London Olympic Park. *Waste Manag.* **2015**, *40*, 157–166. [CrossRef] [PubMed]
21. Patel, B.; Guo, M.; Izadpanah, A.; Shah, N.; Hellgardt, K. A review on hydrothermal pre-treatment technologies and environmental profiles of algal biomass processing. *Bioresour. Technol.* **2016**, *199*, 288–299. [CrossRef] [PubMed]
22. López-Sabirón, A.M.; Royo, P.; Ferreira, V.J.; Aranda-Usón, A.; Ferreira, G. Carbon footprint of a thermal energy storage system using phase change materials for industrial energy recovery to reduce the fossil fuel consumption. *Appl. Energy* **2014**, *135*, 616–624. [CrossRef]
23. Morero, B.; Rodriguez, M.B.; Campanella, E.A. Environmental impact assessment as a complement of life cycle assessment. Case study: Upgrading of biogas. *Bioresour. Technol.* **2015**, *190*, 402–407. [CrossRef] [PubMed]
24. Gnansounou, E.; Vaskan, P.; Pachón, E.R. Comparative techno-economic assessment and LCA of selected integrated sugarcane-based biorefineries. *Bioresour. Technol.* **2015**, *196*, 364–375. [CrossRef] [PubMed]
25. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* **2004**, *30*, 701–720. [CrossRef] [PubMed]
26. PRé Consultants. SimaPro 7 LCA software. 2010. Available online: https://www.pre-sustainability.com/simapro (accessed on 4 March 2016).
27. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; Schryver, A.D.; Struijs, J.; van Zelm, R. *A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, Report I: Characterisation*; Ministry of Housing, Spatial Planning and Environment: Amsterdam, The Netherlands, 2009.
28. Opatokun, S.A.; Kan, T.; Al Shoaibi, A.; Srinivasakannan, C.; Strezov, V. Characterization of Food Waste and Its Digestate as Feedstock for Thermochemical Processing. *Energy Fuels* **2015**, *30*, 1589–1597. [CrossRef]
29. Origin Energy. Elecricity Generation across Austrialia. 2015. Available online: https://www.originenergy.com.au/blog/about-energy/energy-in-australia.html (accessed on 29 January 2016).
30. Cao, Y.; Pawłowski, A. Sewage sludge-to-energy approaches based on anaerobic digestion and pyrolysis: Brief overview and energy efficiency assessment. *Renew. Sustain. Energy Rev.* **2012**, *16*, 1657–1665. [CrossRef]
31. Viotti, P.; Di Genova, P.; Falcioli, F. Numerical analysis of the anaerobic co-digestion of the organic fraction from municipal solid waste and wastewater: Prediction of the possible performances at Olmeto plant in Perugia (Italy). *Waste Manag. Res.* **2004**, *22*, 115–128. [CrossRef] [PubMed]

32. Weidema, B.P.; Bauer, C.; Hischier, R.; Mutel, C.; Nemecek, T.; Reinhard, J.; Vadenbo, C.O.; Wernet, G. *Overview and Methodology: Data Quality Guideline for the Ecoinvent Database Version 3*; Swiss Centre for Life Cycle Inventories: St Gallen, Switzerland, 2013.
33. Rajaeifar, M.A.; Tabatabaei, M.; Ghanavati, H.; Khoshnevisan, B.; Rafiee, S. Comparative life cycle assessment of different municipal solid waste management scenarios in Iran. *Renew. Sustain. Energy Rev.* **2015**, *51*, 886–898. [CrossRef]
34. Schott, A.B.S.; Andersson, T. Food waste minimization from a life-cycle perspective. *J. Environ. Manag.* **2015**, *147*, 219–226. [CrossRef] [PubMed]
35. Xu, C.; Shi, W.; Hong, J.; Zhang, F.; Chen, W. Life cycle assessment of food waste-based biogas generation. *Renew. Sustain. Energy Rev.* **2015**, *49*, 169–177. [CrossRef]