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Abstract: The environmental impacts of five waste management scenarios for polylactic acid (PLA)-based bioplastics and food waste were quantified using life cycle assessment. Laboratory experiments have demonstrated the potential for a pretreatment process to accelerate the degradation of bioplastics and were modeled in two of the five scenarios assessed. The five scenarios analyzed in this study were: (1a) Anaerobic digestion (1b) Anaerobic digestion with pretreatment; (2a) Compost; (2a) Compost with pretreatment; (3) Landfill. Results suggested that food waste and pretreated bioplastics disposed of with an anaerobic digester offers life cycle and environmental net total benefits (environmental advantages/offsets) in several areas: ecotoxicity (−81.38 CTUe), eutrophication (0 kg N eq), cumulative energy demand (−1.79 MJ), global warming potential (0.19 kg CO_2), and human health non-carcinogenic (−2.52 CTUh). Normalized results across all impact categories show that anaerobically digesting food waste and bioplastics offer the most offsets for ecotoxicity, eutrophication, cumulative energy demand and non-carcinogenic. Implications from this study can lead to nutrient and energy recovery from an anaerobic digester that can diversify the types of fertilizers and decrease landfill waste while decreasing dependency on non-renewable technologies. Thus, using anaerobic digestion to manage bioplastics and food waste should be further explored as a viable and sustainable solution for waste management.

Keywords: bioplastics; disposal; LCA

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1. Introduction

Waste management options for handling bioplastics are complicated by food waste contamination. Polylactic acid (PLA)-based service ware is often discarded with food waste, which makes it difficult to recycle without separation [1,2]. Sudesh et al. expect biobased and biodegradable plastic to present a waste management challenge as production and use continue to increase [3]. In addition, there are no current systems that allow bioplastics to be recycled nationwide, which results in bioplastics being redirected to landfills alongside other municipal solid waste [4]. Sending food waste and biodegradable municipal waste to landfills is banned in many states in the US and European countries [5,6]. As food waste and bioplastics degrade, they emit greenhouse gases such as CO_2 and CH_4 that contribute to global warming [7–9].

Although bioplastics such as polylactic acid (PLA) are biodegradable they do not compost as quickly as other organics such as food waste [10]. Oftentimes, bioplastics are screened out of industrial compost facilities and sent to the landfill due to their slow degradation [4,10]. Previous research suggests that a pretreatment might enable the degradation of PLA in compost, but this is not a common practice [11].

There has been increasing interest in anaerobic digestion (AD) of food waste [12] and bioplastics, since digestion of bioplastics produces methane (CH_4) as a potential source of renewable energy [7,12,13]. Sending food waste and bioplastics to anaerobic digesters assist in meeting UN Sustainable Development Goal 6—clean water and sanitation and addressing European Union priority, building a climate-neutral, green, fair and social Europe [14,15]. However, residual bioplastics are reported to be in the digestate due to resistance to microbial activity [16–18]. A previous study used a hydropulper before anaerobic digestion to create a reduced fraction of inorganics mixed with organic slurry [19]. However, about 10% of the inorganic fraction is left in the effluent biosolids and capital cost limits implementation [20]. Thus, hydrolyzing bioplastics before anaerobic digestion and then mixing with organic waste results in more CH_4 than without treatment of bioplastics [16,17,21]. A manual picking line at the tipping area can be used to separate food waste and bioplastics before treatment [20].

Several studies have investigated the environmental impacts of managing solid organic waste through various waste management options using life cycle assessment (LCA). LCA models begin with upstream raw material extraction down to end-of-life waste removal or recycling, including all relevant inputs, emissions, credits (offsets) and outputs [22]. Bernstad et al. [23] compared the environmental impacts of incineration, composting and anaerobic digesting food waste and results showed that anaerobic digestion results in net avoidance of GHG emissions, but contributed significantly to acidification and eutrophication. Eriksson et al. [24] had similar favorable results for anaerobic digestion and found bread to have the highest potential for reducing GHG emissions due to its low carbon footprint and high energy density. Salemdeeb et al. [25] found that most of the environmental burdens from anaerobic digestion were from auxiliary materials used to control emissions. However, the environmental burden was avoided by energy recovery [25]. Although the literature is rich in studies of LCA of food waste, there are no current LCAs comparing the environmental consequences, tradeoffs, and benefits between landfilling, composting, and anaerobic digestion of food waste and bioplastics.

This study used LCA to demonstrate the environmental consequences of anaerobically digesting bioplastics and food waste compared to composting and landfilling. This study adds new knowledge to the field by exploring the efficacy of pretreatment of bioplastics to enhance anaerobic digestion and compost. The following scenarios were assessed:

Scenario 1a: Anaerobic digestion
Scenario 1b: Anaerobic digestion with pretreatment
Scenario 2a: Compost
Scenario 2b Compost with pretreatment
Scenario 3: Landfill

2. Materials and Methods

The goal of this LCA was to evaluate nine impact categories (eutrophication, acidification, ecotoxicity, global warming, ozone depletion, photochemical oxidation, human health carcinogenic, human health non-carcinogenic and respiratory effect) from Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2.1 V1.01) and the US EPA's Waste Reduction Model (WARM). The TRACI impact category fossil fuel use was substituted for Cumulative Energy Demand (CED 1.8) to account for all non-renewable and renewable resources. The CED was used to evaluate and compare normalized impacts of five different waste management scenarios for bioplastics and food waste. WARM was used to estimate the global warming potential of landfilling and composting food waste and PLA. Data were also derived from experimental work, literature and Ecoinvent 3.1.

The LCA study followed the ISO 14,040 series framework's guidelines [26]. An attributional LCA was performed only on the end-of-life for bioplastics and food waste. The functional unit was 1 kg of influent to treat bioplastic and food waste. The percent mass input from Hobbs et al.'s [21] experimental data was used in each waste management scenario (Supplementary Materials S1–S4). A pedigree matrix was used to account for the overall uncertainty of the data, including reliability, completeness, temporal correlation, geographical correlation and further technological correlation.

2.1. Description of End-of-Life Scenarios

All scenarios exclude upstream processes such as bioplastics and food waste production (Figures 1 and 2). Manual picking lines were used to separate food waste from bioplastics during pretreatment. Separating waste manually has the potential to produce higher quality material recovery [27,28] leading many private material recovery facilities to use this method as a way to reduce cost [29]. All scenarios include the construction of waste management options with a lifespan of 25 years for anaerobic digestion and compost and 100 years for landfill. Transportation was also included. Land application and power utilization are not assessed and therefore are outside of the system boundary.

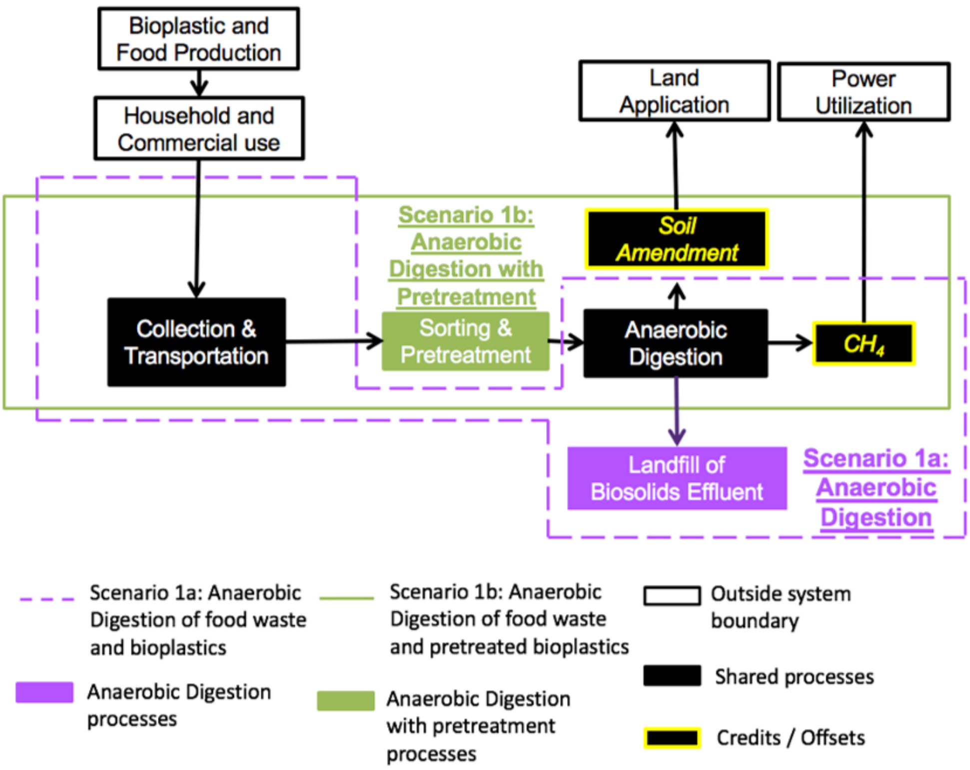

Figure 1. System boundaries for anaerobic digestion of food and PLA waste scenarios. Scenario 1a excludes pretreatment but includes landfilling of biosolid waste. Scenario 1b boundary includes pretreatment, anaerobic digestion, and co-product production.

2.2. Theory

2.2.1. Scenario 1: Anaerobic Digestion

The anaerobic digestion LCA model includes energy processes for the operation of machinery and fugitive emissions from treating food waste and PLA. The digester operates under mesophilic conditions (35–45 °C), the retention time is 22–45 days and produces two valuable products: biogas and biosolids [30]. Biogas consists of CH_4, CO_2, moisture, and trace gases such as H_2S. H_2S and CO_2 reduce biogas quality; therefore, a biogas scrubber with water solution of NaOH is used for chemical absorption of H_2S and CO_2 [30,31]. The purified CH_4 can be used for electricity cogeneration or sold as gas to a pumping station [32]. The biosolids can be substituted for fertilizer. Treatment includes storage of co-substrates, anaerobic digestion process, as well as storage after digestion, and biogas leaks through valves and pipe connections. Transportation and collection are included, and the model ends with biogas and digestate for utilization. Figure 1 shows that the system boundaries do not include power utilization from CH_4 generated and land application from biosolids.

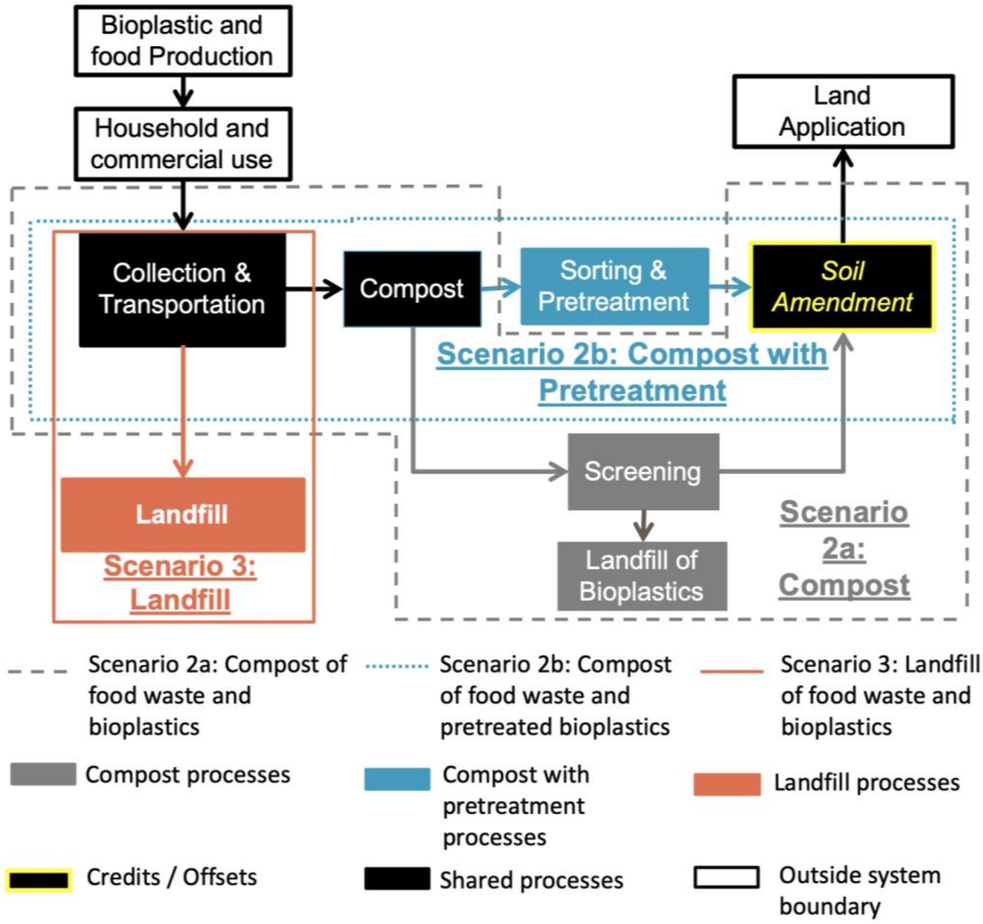

Figure 2. System boundaries for compost and landfill of food and PLA waste scenarios. Scenario 2b includes pretreatment and Scenario 2a does not.

2.2.2. Scenario 1a: Anaerobic Digestion of Bioplastics and Food Waste

Scenario 1a is based on laboratory experiments enhancing the degradation of PLA bioplastics and food waste using anaerobic digestion. Energy input data are based on operation demands. Previous experimental results found in Hobbs et al. [21] were used to determine CH_4 production and degradation of PLA. Additionally, the study demonstrated that digesting food waste and PLA results in a 53% weight reduction of PLA. Therefore, it is assumed that the digestate (0.1 kg of PLA per 1 kg of digestate) is considered contaminated and therefore sent to the landfill.

2.2.3. Scenario 1b: Anaerobic Digestion of Pretreated Bioplastics and Food Waste

The model for anaerobic digestion of pretreated bioplastics and food waste are based on laboratory experiments assessing the acceleration of PLA degradation using chemical pretreatment prior to anaerobic digestion with food waste. Requirements for operation are determined for energy inputs. The chemical pretreatment consisted of NaOH. Hobbs et al. [21] previously showed that prior to AD, bioplastic solubilizes in solution completely during pretreatment. Therefore, it is assumed that digestate can be used as a soil amendment.

2.2.4. Scenario 2: Compost

The compost scenario includes treatment of food waste and bioplastics, energy demand for operation, and process emissions such as infrastructure of the facility as well as transportation and collection. Compost experiences a 22–30 day treatment time. Composting involves the use of microorganisms to degrade organics in aerobic conditions. The composted product results in carbon sequestration when used for land applications. Fugitive CH_4 emissions from compost occur due to microbial activity during the decomposition of food waste and PLA. CO_2 emissions from composting are biogenic and are not counted in global warming potential estimation. In addition, composting is a source of N_2O, particulate matter, and NH_3. Upstream processes like bioplastic and food production and household and commercial use and land application are not included in the system boundary (Figure 2).

2.2.5. Scenario 2a: Compost of Bioplastics and Food Waste

For composting food waste and bioplastics, Scenario 2a assumed that 6.25% of the bioplastics degraded based on Hottle et al. [11]. After composting, the pile was screened for bioplastics that did not degrade, and the residual bioplastics were sent to landfill. The remaining material in the compost was used as soil amendment.

2.2.6. Scenario 2b: Compost of Pretreated Bioplastics and Food Waste

Mineral CSA (an alkaline byproduct from slag and stainless steel) degrades bioplastics when composted. Bauxite residue, a waste byproduct from the aluminum production process [33], is assumed to have similar characteristics to mineral CSA. Therefore, it was used as an alkaline pretreatment in this model. Preliminary lab trials indicate that PLA bioplastics degradation was greatly increased with an alkaline pretreatment. Therefore, this model assumed 10% pretreatment by weight is adequate to include bioplastics in the composting of food waste without post-process screening and separation. In the model, this composted material was used as a soil amendment.

2.2.7. Scenario 3: Landfill of Bioplastics and Food Waste

The landfill scenario was defined by the treatment of municipal solid waste and includes transportation, collection and equipment use. Treatment time for landfilling organic waste typically occurs between 20–30 years [34]. Landfill processes from the scenario were performed by using data from literature and Ecoinvent's treatment of municipal solid waste via sanitary landfill. In this landfill process, 60.4% of carbon in waste is biogenic and overall waste during degradability is 18.73% [35]. About 22% of the material in the landfill is considered to be compostable and leachate is treated [35]. Food waste and bioplastics undergo anaerobic decomposition releasing biogas.

The CH_4 from the biogas is captured and flared. About 20% of landfills in the US flare biogas to reduce CH_4 emissions [5]. In addition, CO2 equivalent emissions are not accounted for since they are considered to be anthropogenic emissions [34]. However, flaring produces dioxins which make up about 0.04 kg/kg of landfilled waste [35]. Treating organics such as food waste and bioplastics sequesters a small portion of carbon and prevents the release of carbon into the atmosphere [34]. All bioplastic is considered to be sequestered [34]. Only end-of-life processes were considered (Figure 2).

2.3. Calculation—Life Cycle Inventory (LCI)

The ratio of food waste to bioplastics was based on individual operation conditions for each waste management scenario, (Supplementary Materials Tables S1–S4). Life cycle inventory data for anaerobic digestion and compost scenarios are derived from peer-reviewed publications. Additional anaerobic digestion, compost, and landfill data were derived from a European database, Ecoinvent. The anaerobic digestion model was modified to include pretreatment, CH_4 and CO_2 from laboratory experiments [21].

2.4. Life Cycle Impact Assessment (LCIA)

The Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) was used for the LCIA since it is based on methodologies that represent the potential effects in the US [36]. The following eight TRACI impacts were used: eutrophication, acidification, ecotoxicity, ozone depletion, photochemical oxidation, human health carcinogenic, human health non-carcinogenic and respiratory effects. CED was included in addition to impact categories from TRACI. CED characterization factors were assigned to energy resources (i.e., non-renewable resources—fossil fuel, non-renewable resources—nuclear, non-renewable resources—primary, renewable resources—biomass, renewable resources-geothermal, renewable resources—solar, renewable resources—water, renewable resources—wind) [37]. The global warming potential impact category was assessed using WARM.

The WARM model has CO_2 equivalent emissions from food waste and PLA. The model can estimate CH_4 emissions based on the assumption that biogas collected from the landfill will be flared. In addition, the model can estimate compost emissions and offsets based on compost machinery and carbon storage [34]. Although TRACI gives US GHG emission data, the LCI is limited, which makes it difficult to replicate the LCIA. Therefore, GHG emissions from WARM were used to estimate global warming potential for composting and landfilling food waste and bioplastics. The data from Ecoinvent version 3.1 and literature were used to estimate the eight TRACI impacts.

2.5. Credits and Offsets

Credits and offsets are calculated by subtracting the avoided emissions from the TRACI impact categories, CED, and WARM global warming potential values. In scenarios 1a and 1b, credit was given since anaerobic digesters produce a renewable energy source, CH_4. In addition, since the process of extracting natural gas is avoided, the emissions associated with extracting natural gas are counted as an offset.

Biosolids, also known as digestate, are products of AD as well. Digestate from AD is rich in phosphorus, potassium, and nitrogen making it an excellent alternative to synthetic fertilizers [38]. Before digestate can be considered a soil amendment, it must comply with EPA's Federal Standards for the Use or Disposal of Sewage Sludge, 40 CFR Part 503 [39]. Therefore, digestate is commonly dewatered using a centrifuge and stabilized with quicklime before it can be applied to land or sent to a landfill [40]. In scenarios 1a and 1b, the effluent digestate is recirculated back into the digester as an inoculum to stimulate microbial activity and encourage degradation. Since the digestate is no longer centrifuged, treated with quicklime, and sent to landfill, the avoided emissions are counted as credits. Additional credit is given to scenario 1b because digestate is applied to land as soil amendments and production of synthetic fertilizer is avoided.

In scenarios 2a and 2b, soil amendments are considered Class B Biosolids (safe for land application) and in accordance with 40 CFR Part 503 [39]. Compost produces nutrient-rich soil amendments, phosphate (P_2O_5), potassium oxide (K_2OH) and nitrogen (N) [38], that can replace manufactured fertilizers. Credits are given to scenarios 2a and 2b by subtracting the avoided impact category values associated with the production of P_2O_5, K_2OH and N fertilizers. Scenario 2b avoids landfilling of bioplastic and food waste due to pretreatment and an offset is given.

2.6. Uncertainty Analysis

Uncertainty is common in LCA [41] and is often analyzed using a pedigree test of the data quality matrix. This technique of uncertainty analysis was used to evaluate waste management scenarios (Table 1). The pedigree matrix provides a qualitative numerical code for degrees of uncertainty; the lower the code, the less uncertain the data are [42]. The test data quality indicator consists of five categories assessing reliability, completeness, temporal correlation, geographical correlations and further technological correlation of data. The anaerobic digestion scenarios processes were based on measured data whereas compost and landfill scenarios were based on assumptions. Assumptions were derived from literature and Ecoinvent 3.1. The relative importance of each process was assessed by multiplying the percent impact on results and pedigree score.

Table 1. Pedigree matrix table assessing the uncertainty of data processes for scenarios.

Scenarios	Reliability	Completeness	Temporal	Geographical	Technological	Average Pedigree Processes Score
Scenario 1a (AD)						
Treatment of food waste and PLA	2	5	5	5	5	4.4
Treatment of sludge	2	5	5	5	4	4.2
Avoided production of fertilizer	4	5	5	5	4	4.6
Landfilled biosolids	4	5	5	5	3	4.4
Scenario 1b (AD with pretreatment)						
Treatment of food waste and PLA	2	4	5	5	3	3.8
Treatment of sludge	4	4	5	5	3	4.2
Avoided production of fertilizer	3	5	5	5	4	4.4
Landfilled biosolids	5	5	5	5	4	4.8
Scenario 2a (Compost)						
Treatment of food waste and PLA	4	5	5	5	5	4.8
Treatment of sludge	n/a	n/a	n/a	n/a	n/a	n/a
Avoided production of fertilizer	4	5	5	5	4	4.6
Landfilled biosolids	4	5	5	5	4	4.6
Scenario 2b (Compost with pretreatment)						
Treatment of food waste and PLA	4	5	5	5	4	4.6
Treatment of sludge	n/a	n/a	n/a	n/a	n/a	n/a
Avoided production of fertilizer	4	5	5	5	4	4.6
Landfilled biosolids	5	5	5	5	4	4.8
Scenario 3 (Landfill)						
Treatment of food waste and PLA	5	5	5	5	5	5
Treatment of sludge	n/a	n/a	n/a	n/a	n/a	n/a
Avoided production of fertilizer	n/a	n/a	n/a	n/a	n/a	n/a
Landfilled biosolids	n/a	n/a	n/a	n/a	n/a	n/a
Average Scenario Pedigree Score	3.7	4.9	5.0	5.0	4.0	4.5

3. Results and Discussion

Construction and transportation were not modeled because their impacts fell below 5% of the total impacts for each category for all scenarios [43]. Figures 3 and 4 show the potential impacts for anaerobic digestion (scenario 1a and 1b), compost (scenario 2a and 2b) and landfill (scenario 3) of food waste and PLA and their net contribution of each process.

3.1. Compost (Scenarios 2a and 2b)

The compost unit process had high environmental impacts in acidification, eutrophication, ozone depletion, photochemical oxidation, respiratory effect and cumulative energy demand (Figures 3 and 4). Edelmann et al. [44] had similar results for treating food waste; compost emissions were higher than anaerobic digestion and incineration. A study conducted in the US reports lower impact category values for global warming potential for composting PLA [45].

In most cases, the net impacts from scenarios 2a and 2b were greater than those from scenarios 1a, 1b, and 3. Composting of food waste and PLA is the largest contributor to eutrophication (Figure 3a) due to nutrient run-off (i.e., 43% nitrate and 43% phosphate aqueous emissions) during the composting process [44]. Rainfall and flooding contributions increase phosphate emissions that come in windrow sides [46]. The use of compost end product as soil amendment provides credit to net eutrophication impact. However, the credit offsets did not significantly reduce the net total impacts.

Scenario 2a has the second least contribution to ecotoxicity compared to scenarios 1a, 1b, 2b, and 3 (Figure 3c). Scenarios 2a and 2b resulted in negative emissions and more offsets compared to untreated anaerobic digestion and landfill (Figure 3d). Since composting results in carbon storage, this offsets GHG emissions. In addition, the majority of GHG emissions originate from the fermentation of the food waste and PLA which are considered biogenic and therefore emissions are not counted [34]. Amlinger et al. [47] estimated composting to contribute very little to the national GHG inventories if the composting process is controlled.

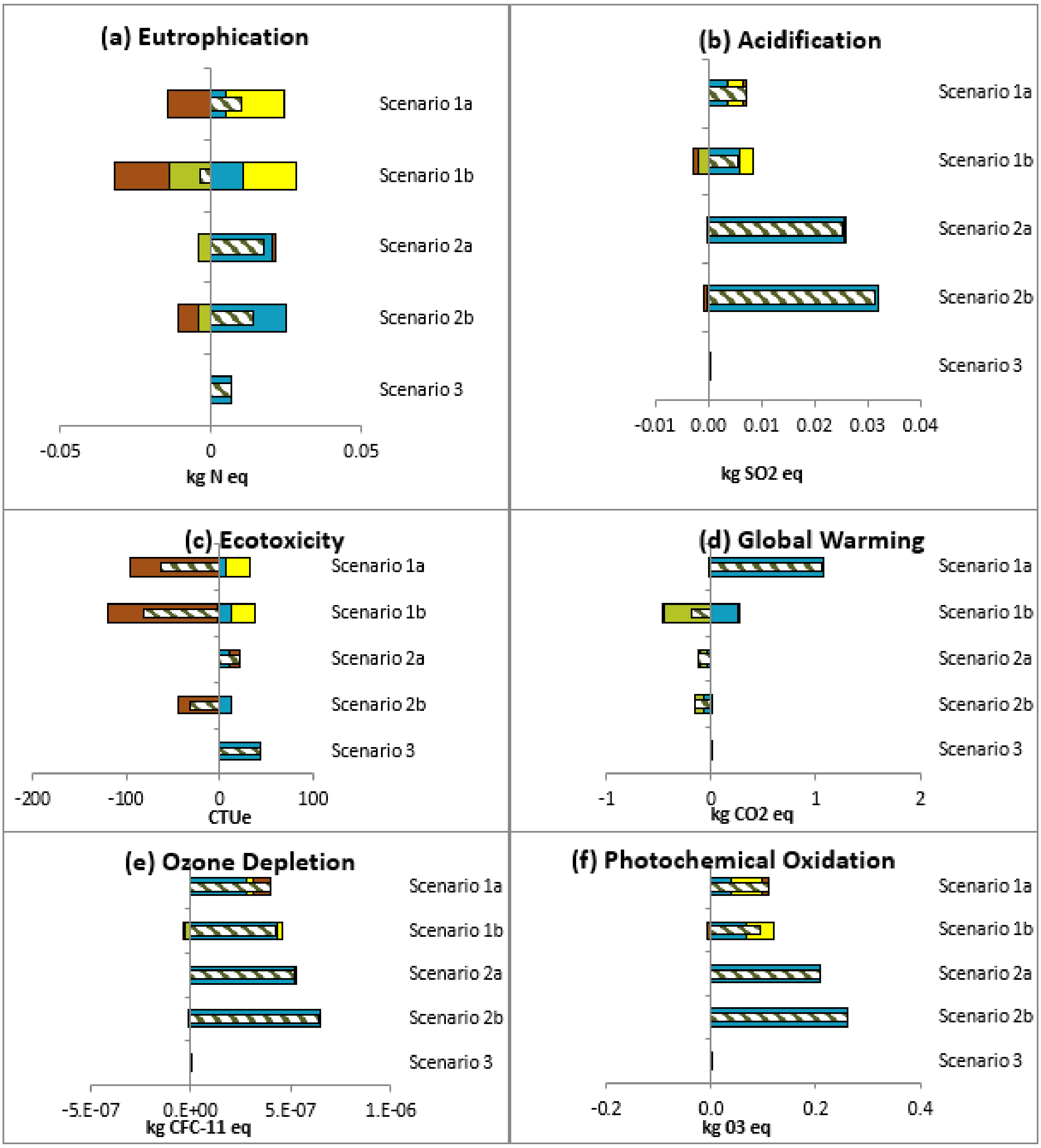

Figure 3. Six potential environmental impacts for anaerobic digestion (scenarios 1a and 1b), compost (scenarios 2a and 2b), landfill (scenario 3). (**a**) eutrophication, (**b**) acidification, (**c**) ecotoxicity, (**d**) global warming, (**e**) ozone depletion, (**f**) photochemical oxidation.

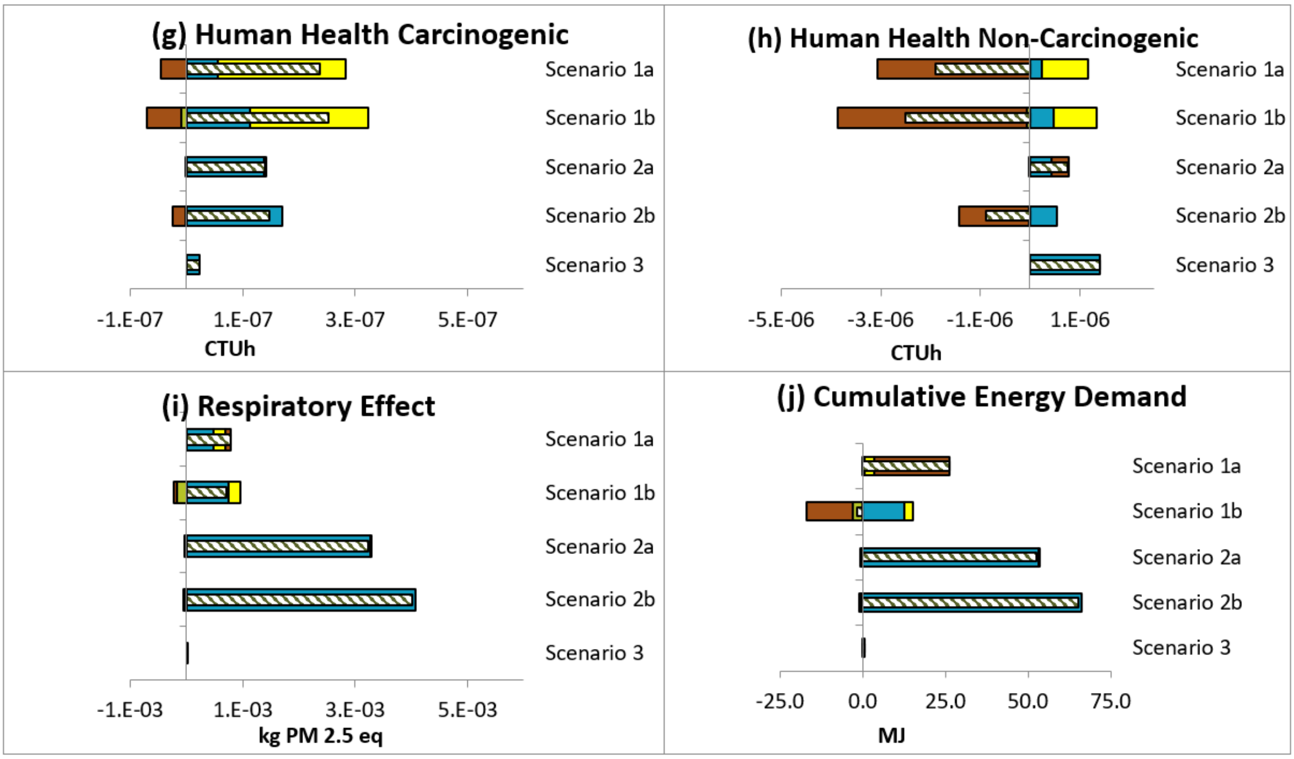

Figure 4. Four potential human health and environmental impacts for anaerobic digestion (scenarios 1a and 1b), compost (scenarios 2a and 2b), landfill (scenario 3). (**g**) human health carcinogenic, (**h**) human health non-carcinogenic, (**i**) respiratory effect, (**j**) cumulative energy demand.

Scenario 2b human health non-carcinogenic impacts are negative and are caused by credits from landfill avoidance of soil amendment (Figure 4h). Scenario 1b has the lowest potential for human health non-carcinogenic impacts due to offsets from landfilling of anaerobic digested sludge and recycling anaerobic digested slugged back into digester as inoculum.

Scenario 2a and 2b cumulative energy demand are 132–165% higher than scenario 3 (Figure 4j). Operating compost requires more than 100 kwh of electricity per ton of waste [46], whereas landfill equipment energy demands are relatively low [34].

3.2. Anaerobic Digestion (Scenario 1a and 1b) and Landfill (Scenario 3) Environmental Impacts

Results suggested that anaerobic digestion of food waste and PLA is more environmentally favorable than composting overall as shown in Figures 3 and 4. The net potential impact on eutrophication is the highest for scenario 1a due to the treatment of anaerobic digested sludge (Figure 3a). Scenario 1a and 1b contribute to eutrophication due to phosphate (84%) emissions to the groundwater. The emissions are due to pre and post-storage of materials, before digestion and after [30]. High eutrophication impacts were also seen in Mezullo et al. [47] due to the operation of the digester. Scenario 1b has a negative net impact on eutrophication because of the credit from avoided fertilizer production and landfilling of anaerobic digested sludge. Scenario 1b results in the least environmental impact for ecotoxicity, eutrophication, global warming potential, and human health non-carcinogenic (Figures 3a,c,d and 4h). This is mainly due to the avoided production of fertilizer and avoided landfilling of anaerobic digested sludge. Scenario 3 eutrophication impact is low compared to the other treatment options because landfill does not emit environmental potential compounds.

Scenario 1b had the least net global warming potential due to the pretreatment of food waste and PLA (Figure 3d). Scenario 1b has negative GHG emissions resulting from avoided landfilling of anaerobic digested sludge, avoided production of synthetic fertilizer as well as energy production from food waste and PLA. Since anaerobic digestion generates electricity there is a saving of non-renewable energy [48].

Scenario 1a and 1b resulted in negative emission potential for cumulative energy demand (Figure 4j). The cumulative energy demand is low for scenarios 1a and 1b because there was a credit or avoided emissions. In addition, biogas produced from untreated and treated food waste and PLA is purified and processed through cogeneration plants that assist in anaerobic digestion operation [32]. Scenario 1b has the lowest impact potential for cumulative energy demand because of the production of fertilizer from the anaerobic digestion process and anaerobic digested sludge credit is given since landfilling is avoided (Figure 4j).

3.3. Pedigree Matrix

The pedigree matrix showed the uncertainty of all the scenarios assessed in this study (Figure 5). The average indicator score for reliability was 3.7, meaning the average quality of data used was qualified estimation. Completeness, temporal correlation, geographical correlation, and further technological correlation indicator scores averaged 4.0 and above meaning process data for each scenario were representative data for one site, age of data unknown, data from a different location, and data assessed from laboratory scale respectively. The largest percent impacts for scenarios 2a and 2b were the treatment of food waste and PLA processes. In addition, the relative importance of scenarios 2a and 2b was the highest indicating that reducing uncertainty in these categories should be the highest priority.

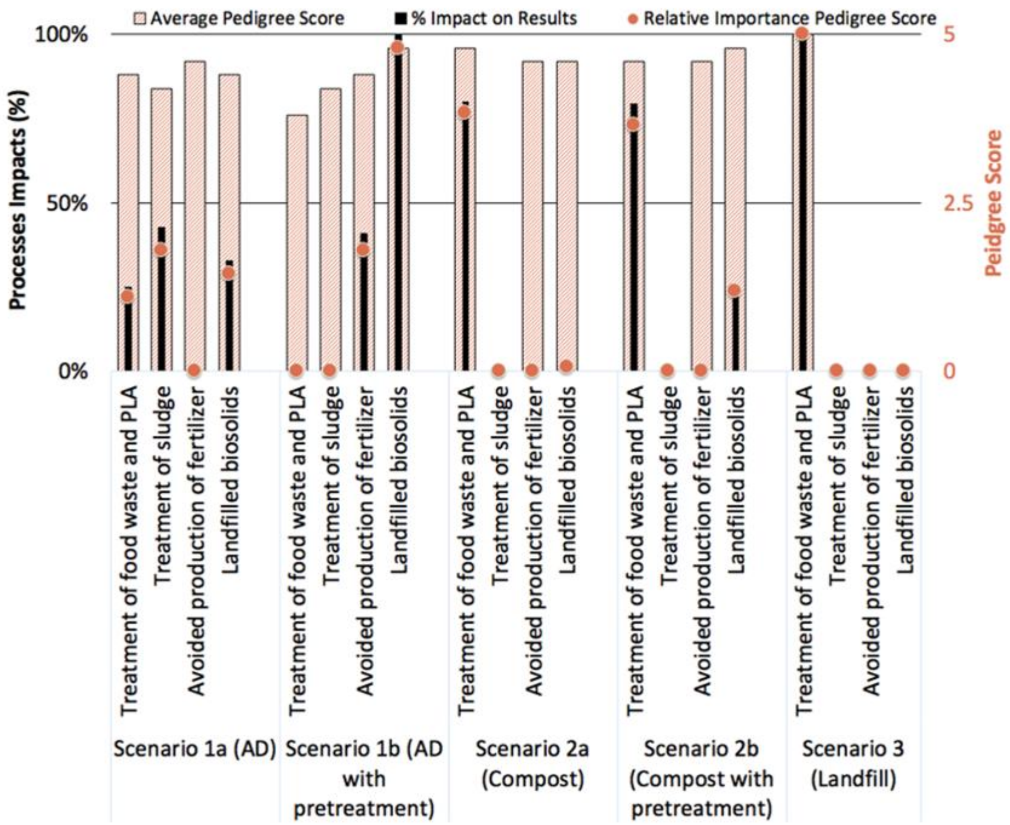

Figure 5. Average results from pedigree matrix used to assess uncertainty for processes needed to manage waste scenarios. The left axis quantifies the percent impact of each individual process in each scenario. The right axis quantifies the average pedigree score and relative importance of each process. The percentage of process impact was used to determine relative importance of each process.

3.4. Normalized Impact Assessment

Figure 6 shows the data presented in Figures 3 and 4 normalized for scenarios 1a, 1b, 2a, 2b and 3. For each impact, the results are normalized to the waste management option with the greatest overall impact. Scenario 1b is preferable in ecotoxicity, eutrophication, global warming, human health non-carcinogenic and CED compared to the other waste management alternatives. In the ecotoxicity category, scenario 1b exhibits fewer impacts than other waste management alternatives; most of this impact results from avoided impacts from landfill of digested sludge. Global warming potential, cumulative energy demand, and human health non-carcinogenic were smaller for scenario 1b due to avoidance of landfilling anaerobic digested sludge and resulting product–soil amendment.

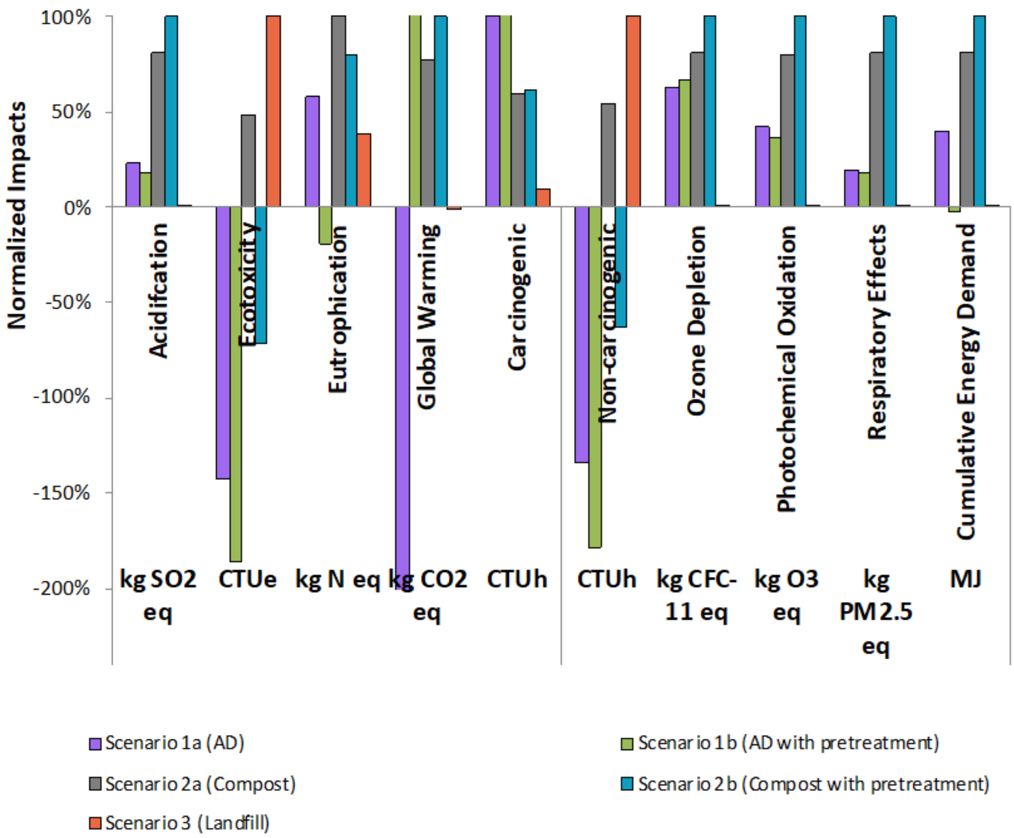

Figure 6. Life cycle environmental impacts normalized to the highest contributor for ten impact categories. (N_{eq}. = Nitrogen equivalent, $SO_{2\,eq}$. = Sulfur Dioxide equivalent, Cue = Comparative Toxic Unit for Aquatic Ecotoxicity, $CO_{2\,eq}$. = Carbon Dioxide equivalent, CFC-11 eq. = Trichlorofluoromethane equivalent, $O_{3\,eq}$. = Ozone equivalent, CTUh eq. = Comparative Toxic Unit health equivalent, CTUh eq. = Comparative Toxic Unit Health equivalent, $PM_{2\cdot5\,eq}$. = Particulate Matter 2.5 equivalent., MJ = Mega Joules).

Scenario 3 performed better in acidification, human health carcinogenic, ozone depletion, photochemical oxidation, and respiratory effect. Acidification achieved the lowest potential impact for scenario 3. Potential human health carcinogenic, ozone depletion, photochemical oxidation and respiratory effects were the lowest for scenario 3 due to smaller environmental impact from the operational process. Finally, ozone depletion scenario 3 had a lower impact compared to the other scenarios evaluated. While scenario 1b may offer some lifecycle-based human and environmental benefits, anaerobic and compost operations require specific inputs for an operation that landfill does not need.

4. Conclusions

Sending food waste and pretreated bioplastics to anaerobic digesters offers lifecycle-based environmental and human benefits for the following impact categories: cumulative energy demand, ecotoxicity, eutrophication, global warming potential and human health non-carcinogenic. Anaerobic digestion of food waste and pretreated bioplastic may provide the greatest benefit due to the relative importance of impact categories.

The landfill scenario had lower impacts than composting in all cases except ecotoxicity and non-carcinogenic. Overall, landfilling food waste and PLA resulted in the lowest impacts for five out of ten impact categories analyzed: acidification, human health carcinogenic, ozone depletion, photochemical oxidation and respiratory effect. These results are notable, as it appears landfilling food waste and PLA seems better than composting, which is counter to the commonly accepted belief that landfilling is always the worst option.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13126894/s1, Table S1. Anaerobic digestion of food waste and bioplastics (scenario 1a) inventory data for waste treatment options, Table S2. Anaerobic digestion of food waste and pretreated bioplastics (scenario 1b) inventory data for waste treatment options. Table S3. Compost of food waste and bioplastics (scenario 2a) inventory data for waste treatment options. Table S4. Compost of food waste and pretreated bioplastic (scenario 2b) inventory data for waste treatment options.

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References

1. Hopewell, J.; Dvorak, R.; Kosior, E. Plastics recycling: Challenges and opportunities. *Philos. Trans. R. Soc. Biol. Sci.* **2009**, *364*, 2115–2126. [CrossRef] [PubMed]
2. Calabrò, P.S.; Grosso, M. Bioplastics and waste management. *Waste Manag.* **2018**, *78*, 800–801. [CrossRef]
3. Sudesh, K.; Iwata, T. Sustainability of Biobased and Biodegradable Plastics. *CLEAN Soil Air Water* **2008**, *36*, 433–442. [CrossRef]
4. Meeks, D.; Hottle, T.; Bilec, M.M.; Landis, A.E. Compostable biopolymer use in the real world: Stakeholder interviews to better understand the motivations and realities of use and disposal in the US. *Resour. Conserv. Recycl.* **2015**, 134–142. [CrossRef]
5. EPA. *Food Waste Management in the United States, 2014*; EPA-Office of Resource Conservation and Recovery: Washington, DC, USA, 2016.
6. SEPA. Biodegradable Municipal Waste Landfil Ban. In *SEPA*; S.E.P. Agency: Stirling, UK, 2018.
7. Krause, M.J.; Townsend, T.G. Life-Cycle Assumptions of Landfilled Polylactic Acid Underpredict Methane Generation. *Environ. Sci. Technol. Lett.* **2016**, *3*, 166–169. [CrossRef]
8. Martin, D.; Potts, L.; Reeves, A. Small-scale simulation of waste degradation in landfills. *Biotechnol. Lett.* **1997**, *19*, 683–685. [CrossRef]
9. Lundie, S.; Peters, G.M. Life cycle assessment of food waste management options. *J. Clean. Prod.* **2005**, *13*, 275–286. [CrossRef]
10. Siracusa, V.; Rocculi, P.; Romani, S.; Rosa, M.D. Biodegradable polymers for food packaging: A review. *Trends Food Sci. Technol.* **2008**, *19*, 634–643. [CrossRef]
11. Hottle, T.A.; Agüero, L.M.; Bilec, M.M.; Landis, A.E. Alkaline Amendment for the Enhancement of Compost Degradation for Polylactic Acid Biopolymer Products. *Compost. Sci. Util.* **2016**, *24*, 159–173. [CrossRef]
12. Pilarska, A.A.; Pilarski, K.; Ryniecki, A.; Tomaszyk, K.; Dach, J.; Wolna-Maruwka, A. Utilization of vegetable dumplings waste from industrial production by anaerobic digestion. *Int. Agrophys.* **2017**, *31*, 93–102. [CrossRef]

13. Abraham, A.; Park, H.; Choi, O.; Sang, B.-I. Anaerobic co-digestion of bioplastics as a sustainable mode of waste management with improved energy production—A review. *Bioresour. Technol.* **2020**, 124537. [CrossRef]
14. UN. Sustainable Development Goals 17 Goals to Transform. Our World. Available online: https://www.un.org/sustainabledevelopment/blog/2015/12/sustainable-development-goals-kick-off-with-start-of-new-year/ (accessed on 4 February 2021).
15. European Union. European Union Priorities for 2019–2024. Available online: https://europa.eu/european-union/about-eu/priorities_en (accessed on 4 February 2021).
16. Benn, N.; Zitomer, D. Pretreatment and Anaerobic Co-digestion of Selected PHB and PLA Bioplastics [Original Research]. *Front. Environ. Sci.* **2018**, *5*. [CrossRef]
17. Hobbs, S.R.; Devkota, J.; Parameswarn, P.; Landis, A. *Environmental Implications of Food and PLA Waste Management Options 8th International Converence on Environmental Science and Technology*; American Academy of Sciences: Houston, TX, USA, 2016.
18. Hamad, K.; Kaseem, M.; Yang, H.; Deri, F.; Ko, Y. Properties and medical applications of polylactic acid: A review. *Express Polym. Lett.* **2015**, *5*, 9. [CrossRef]
19. Bozano Gandolfi, P.; Nosiglia, V.; Vitali, G. Anaerobic Digestion Of Municipal Solid Waste, Biowaste & Commercial Wastes–Examples Of: 1) Successful Revamping Of Existing Plants 2) Co-Digestion Of Biowaste And Commercial Waste with Agricultural Residues. In Proceedings of the 20 EU BC&E. ETA-Florence Renewable Energies, Milan, Italy; 2012; pp. 1468–1472. Available online: https://www.semanticscholar.org/paper/Anaerobic-Digestion-Of-Municipal-Solid-Waste%2C-%26-Of%3A-Gandolfi-Nosiglia/6f49afdcee9e2c88a6c28cd8f60ba68b59f3a034 (accessed on 1 August 2020).
20. Levis, J.W.; Barlaz, M.A.; Themelis, N.J.; Ulloa, P. Assessment of the state of food waste treatment in the United States and Canada. *Waste Manag.* **2010**, *30*, 1486–1494. [CrossRef] [PubMed]
21. Hobbs, S.R.; Parameswarn, P.; Astmann, B.; Devkota, J.; Landis, A. Anaerobic Codigestion of Food Waste and Polylactic Acid: Effect of Pretreatment on Methane Yield and Solid Reduction. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 6. [CrossRef]
22. Klöpffer, W. Life cycle assessment. *Environ. Sci. Pollut. Res.* **1997**, *4*, 223–228. [CrossRef] [PubMed]
23. Bernstad, A.; la Cour Jansen, J. A life cycle approach to the management of household food waste—A Swedish full-scale case study. *Waste Manag.* **2011**, *31*, 1879–1896. [CrossRef]
24. Eriksson, M.; Strid, I.; Hansson, P.-A. Carbon footprint of food waste management options in the waste hierarchy—A Swedish case study. *J. Clean. Prod.* **2015**, *93*, 115–125. [CrossRef]
25. Salemdeeb, R.; Bin Daina, M.; Reynolds, C.; Al-Tabbaa, A. An environmental evaluation of food waste downstream management options: A hybrid LCA approach. *Int. J. Recycl. Org. Waste Agric.* **2018**, *7*, 217–229. [CrossRef]
26. Guinée, J.B. Handbook on life cycle assessment operational guide to the ISO standards. *Int. J. Life Cycle Assess.* **2002**, *7*, 311–313. [CrossRef]
27. Dubanowitz, A.J. Design of a Materials Recovery Facility (MRF) for Processing the Recyclable Materials of New York City's Municipal Solid Waste. Master's Thesis, Columbia University, New York, NY, USA, May 2000.
28. Vrancken, C.; Longhurst, P.J.; Wagland, S.T. Critical review of real-time methods for solid waste characterisation: Informing material recovery and fuel production. *Waste Manag.* **2017**, *61*, 40–57. [CrossRef] [PubMed]
29. AlHumid, H.A.; Haider, H.; AlSaleem, S.S.; Alinizzi, M.; Shafiquzaman, M.; Sadiq, R. Performance Assessment Model for Municipal Solid Waste Management Systems: Development and Implementation. *Environments* **2019**, *6*, 19. [CrossRef]
30. Lijó, L.; González-García, S.; Bacenetti, J.; Fiala, M.; Feijoo, G.; Lema, J.M.; Moreira, M.T. Life Cycle Assessment of electricity production in Italy from anaerobic co-digestion of pig slurry and energy crops. *Renew. Energy* **2014**, *68*, 625–635. [CrossRef]
31. Tippayawong, N.; Thanompongchart, P. Biogas quality upgrade by simultaneous removal of CO_2 and H_2S in a packed column reactor. *Energy* **2010**, *35*, 4531–4535. [CrossRef]
32. Stucki, M.; Jungbluth, N.; Leuenberger, M. *Life Cycle Assessment of Biogas Production from Different Substrates*; ESU-Services Ltd.: Schaffhausen, Switzerland, 2011.
33. Power, G.; Gräfe, M.; Klauber, C. Bauxite residue issues: I. Current management, disposal and storage practices. *Hydrometallurgy* **2011**, *108*, 33–45. [CrossRef]
34. EPA. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM). In *Background Chapters*; U.S. Environmental Protection Agency Office of Resource Conservation and Recovery: Washington, DC, USA, 2016.
35. Doka, G. *Life Cycle Inventories of Waste Treatment Services*; F.r.e.d. v2.0; Swiss Centre for LCI, Empa-TSL: Dübendorf, CH, USA, 2007.
36. Bare, J.C. Traci: The tool for the reduction and assessment of chemical and other environmental impacts. *J. Ind. Ecol.* **2002**, *6*, 49–78. [CrossRef]
37. Bösch, M.E.; Hellweg, S.; Huijbregts, M.A.J.; Frischknecht, R. Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. *Int. J. Life Cycle Assess.* **2006**, *12*, 181. [CrossRef]
38. 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]
39. EPA. *Land Application of Sewage Sludge: A Guid for Land Appliers on the Requirements of the Federal Standards for the Use or Disposal of Sewage Sludge, 40 CFR Part 503*; US Environmental Protection Agency: Washington, DC, USA, 1994.

40. Pasqualino, J.C.; Meneses, M.; Abella, M.; Castells, F. LCA as a Decision Support Tool for the Environmental Improvement of the Operation of a Municipal Wastewater Treatment Plant. *Environ. Sci. Technol.* **2009**, *43*, 3300–3307. [CrossRef]
41. Ciroth, A.; Fleischer, G.; Steinbach, J. Uncertainty calculation in life cycle assessments. *Int. J. Life Cycle Assess.* **2004**, *9*, 216. [CrossRef]
42. Weidema, B.P. Multi-user test of the data quality matrix for product life cycle inventory data. *Int. J. Life Cycle Assess.* **1998**, *3*, 259–265. [CrossRef]
43. European Commission. General guide for Life Cycle Assessment-Detailed guidance. In *International Reference Life Cycle Data System (ILCD) Handbook*; Institute for Environment and Sustainability: Luxembourg, 2010; Available online: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf (accessed on 12 August 2020).
44. Edelmann, W.; Schleiss, K.; Joss, A. Ecological, energetic and economic comparison of anaerobic digestion with different competing technologies to treat biogenic wastes. *Water Sci. Technol.* **2000**, *41*, 263–273. [CrossRef] [PubMed]
45. Hottle, T.A.; Bilec, M.M.; Landis, A.E. Biopolymer production and end of life comparisons using life cycle assessment. *Resour. Conserv. Recycl.* **2017**, *122*, 295–306. [CrossRef]
46. Amlinger, F.; Peyr, S.; Cuhls, C. Green house gas emissions from composting and mechanical biological treatment. *Waste Manag. Res.* **2008**, *26*, 47–60. [CrossRef] [PubMed]
47. Mezzullo, W.G.; McManus, M.C.; Hammond, G.P. Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste. *Appl. Energy* **2013**, *102*, 657–664. [CrossRef]
48. Güereca, L.P.; Gassó, S.; Baldasano, J.M.; Jiménez-Guerrero, P. Life cycle assessment of two biowaste management systems for Barcelona, Spain. *Resour. Conserv. Recycl.* **2006**, *49*, 32–48. [CrossRef]