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A Comparative Life Cycle Assessment of Dry and Wet Anaerobic Digestion Technologies for Food Waste Management

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ABSTRACT

Anaerobic digestion (AD) is especially useful in the treatment of organic waste sources, such as food waste (FW) since AD can support the generation of clean energy while preventing the hazards of uncontrolled GHG pollution originating from landfills. However, the potential environmental impacts of dry AD and integrated wet AD treatment are largely unknown, particularly in Malaysia. Thus, this study aimed to compare the potential environmental impacts of four FW treatment technologies in Malaysia: landfill (Sc0), dry anaerobic digestion (Sc1), wet anaerobic digestion combined with windrow composting (Sc2), and wet anaerobic digestion combined with windrow composting and landfill (Sc3). The scenario modelling was performed via GaBi v6.0 software using 1 ton of pre-treated FW as a functional unit, with the analysis of environmental impact scores being based on the ReCiPe (H) v1.07 characterization method. At the midpoint assessment, the Sc1 produced extensive improvements in 12 mid-point impact categories, being the most environmentally favoured FW treatment method compared to the other options in critical categories such as global warming, depletion of fossils and agricultural land occupation. The Sc1 mesophilic conducting reactor in this study used less energy for heating, without generating waste water while requiring a small operating area. Sc3 had the lowest environmental performance since the emissions into the air from windrow composting and landfill were discharged completely without any form of treatment like capturing or flaring. Finally, through the single score analysis, Sc1 was regarded as an appropriate FW treatment technology with the least damaging impact on resource depletion, human health, and ecosystems in comparison to all scenarios. This was accomplished through relatively low power demands for the operation, shorter road transport distances, and a substantial reduction in the amount of waste and electricity generation. These analyses provide a useful framework for understanding the important characteristics of anaerobic treatment despite the divergent challenges faced by the different processes.

Keywords: Food waste; environmental management; anaerobic digestion, life cycle assessment; global warming

INTRODUCTION

Food waste (FW) is a global issue that is gaining attention due to its environmental, social, and monetary consequences (Elginoz et al. 2020, Brenes-Peralta et al. 2020). If the current trends continue, FW in Asian countries is expected to rise rapidly from 2.78 billion tons to 4.16 billion tons by 2025 (Ren et al. 2018). In 2018, approximately 16,700 metric tons of FW were produced daily in Malaysia (Suzannah, 2018). The economic growth for the past two decades or more has increased income and thus drastically changed the food consumption habits of Malaysian households (Jereme et al. 2016). FW comes from food preparation wastes and unconsumed food (Jereme et al. 2016). Malaysia, like many other countries, uses extensive landfills to dispose FW (Woon et al. 2021) while the FW recycling rate is low at only 5% (Lim et al. 2016).

Landfill can no longer support the rapidly increasing municipal solid wastes (MSW), challenging its sustainable disposal management. Landfilling the FW in large volumes will adversely affect human health and cause tremendous environmental and sanitary problems like greenhouse gas (GHG) emissions, leachate production, air pollution, underground water contamination, and degradation of valuable land resources (Bong et al. 2017). However, it is also significant to shift FW management into clean energy and sustainable development (Zhu et al. 2018). The potential for biomethane (BMP) production from FW has been identified as one of the key benefits to add value to FW (Zhu et al. 2018). This value can be increased through the development of effective waste management technologies.

Converting FW to renewable energy is an appealing option for Malaysia (Woon et al. 2021). The climate change, depletion of non-renewable resources, and the spike in petroleum prices have prompted the Government of Malaysia (GoM) to reconsider the strategy to be more successful, including the choice to invest in renewable energy resources as a superior energy source in the global energy mix. As stated by Hoo et al. (2017), about 60 Mm^3 of CH_4 (equal to 16.3 MW of energy) can be produced yearly in Malaysia based on the FW produced in 2010.

Despite Malaysia's relative abundance of fossil fuels, the nation has committed to become carbon neutral by 2050 (Hamid, 2021). Under the National Renewable Energy Policy, GoM aims to cut the carbon emission intensity of GDP by 40% by 2030 compared to the 2005 levels and to raise the renewable energy mix to 20% by 2025.

Referring to the revamped enabling policy for carbon trading, converting FW to biogas using anaerobic digestion (AD) can enhance the nation's climate change governance (Ibrahim, 2021). The current waste disposal legislation has shifted the waste management schemes from linear to circular (Hanum et al. 2019; Kumaran et al. 2016). In a circular economy, waste does not exist, and products and raw materials are reused as long and as intensely as possible. Waste has become the new raw material.

As a result, several municipalities in Malaysia have shown a growing interest in resource recovery, and waste to energy technology by generating AD biogas from organic waste. A good example is the Petaling Jaya City Council, which has been using the dry AD continuous batch method (Cowtec. technology).

AD is particularly effective in the treatment of organic waste sources since it helps generate clean energy while reducing the threats of uncontrolled GHG pollution from landfills (Papageorgiou et al. 2009). AD would decrease the organic components of MSW by almost 70% before it is transported to a landfill, thereby reducing the mass and contaminants of methane (CH_4) and leachate (Ghosh, 2016).

The AD method can be divided into three main modes based on the total solid (TS) quality preserved in the digester: the dry AD, TS above 15%; semi-dry AD, TS within 15% and 10%; and wet AD; TS of less than 10% (Rocamora et al. 2020; Tong et al. 2018). Dry and wet AD is a biochemical process to produce biogas via microbial conversion of organic matter that occurs in an oxygen (O_2) free environment (Gumisiriza et al. 2017). The operational phases include pre-treatments, removal of non-digestible stuffs, shredding, digestion, recovery of biogas, and treatment of residues. In general, the chemical progression involves four consecutive stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

In contrast to wet ADs, continuous dry AD systems do not have internal mixing, and the fresh substrate and digestate are combined outside the reactor before the feed. The favoured materials for dry and wet AD are comprised of FW, agro-wastes (AW), and manure, to name a few, that normally contain over 70% humidity (Thengane 2018). Moreover, the biogas generated contains approximately 50–70% CH_4 which could be exploited as an energy source. The CH_4 concentrations from dry AD, for example, ranged from 0.2 to 0.6 m^3/kg of volatile solids (VS) based on raw materials and specifications (Karthikeyan et al. 2013). The treated sludge from the digester may be used as a nutrient to support plant growth (Kumar et al. 2017). Biogas generated by AD is also anticipated to offer great potential to reduce GHG emissions (Tong et al. 2018). Thus, the assessment and reporting of its environmental impacts continue to be an important research focus.

Hence, quantifiable evaluation approaches, such as the life cycle assessment (LCA) method, would enable the quantification and comparison of environmental implications across the stages of a FW treatment's life cycle, including raw material acquisition, processing, transportation, consumption, recycling, and final disposal (Woon et al. 2021).

Numerous environmental impact studies that use the LCA tool are applicable to wet digestion. On the other hand, although the popularity of dry AD has increased in recent years, there is still a lack of knowledge for environmental impact assessment compared to wet AD (Rocamora et al. 2020; Angelo et al. 2017).

In addition, the emissions and energy requirements of different AD systems vary. It is critical to employ LCA as a systematic tool to evaluate and verify the environmental feasibility of FW treatments, especially for regional disparities (Righi et al. 2013). Choosing the best FW treatment that employs AD technologies might be challenging, and the LCA methodology is especially beneficial for analysing the possible environmental implications of two or more different solutions (Brenes-Peralta et al. 2020).

Thus, constructive evaluation of the FW treatment for biogas production state and its effects on the ecosystem through the assessment of life cycles is essential.

LITERATURE STUDIES

RESULT OF RELATED STUDY REVIEWED

A non-exhaustive number of literature sources (Table 1) have summarized the various types of technologies performed on FW management systems utilizing AD. As shown by Table 1, the cohesions of the LCA done were largely identified in the goals and scope description. The research was undertaken to support a decision because a number of studies demonstrated that the primary utilization of LCA was to inform decision-making or governance groups about the ecologically-sound preference in addition to helping assess various possibilities for a bio-based waste management in a specific area (Brenes-Peralta et al. 2020; al Rumaihi et al. 2020). While under anaerobic conditions, the emphasis is on material recovery and sustainability practices (Woon et al. 2021; Elginoz et al. 2020).

TABLE 1. Summary of life cycle assessment of anaerobic digestion for food waste treatment studies reviewed

Ref.	State	Feedstock	Technology assessed	Summary LCA studies of AD				Environment advantageous options
				Functional unit	LCA software	LCIA	Assess impact category	
(Woon et al. 2021)	Malaysia	Food waste	L_O, L_{SER}, C_W, AD_E, AD_G, AD_F	Per one tonne of FW (wet basis).	SimaPro 9.0	Eco-indicator 99	C, R_o, R_{io}, CC ETP, AP, EP	AD_E
(Elginoz et al. 2020)	Sweden	Food Waste (Lab scale)	AD, AD_L, L	Management of 1 ton food waste	GaBi version 8.7 Ecoinvent v3.0	CML 2001 January 2016 version	AP, EP, FAETP, GWP, HTP, ODP, POCP, TETP	AD
(Al-Rumaihi et al. 2020)	State of Qatar	Food waste	C_W, AD_W	1 ton of FW	SimaPro7 (Version 7.1.0)	CML baseline 2000 (v2.03) Midpoint method	ADP, ADP-FF, GWP, ODP, HTP, POFP, AP, EP	AD + windrow composting
(Brenes-Peralta et al. 2020)	Costa Rica, Latin America	Food waste	AD_{Centr}, AD_{SCentr}, $C_{TakakuraCentr}$, $C_{TakakuraSCentr}$.	117.3 t of FW per year	SimaPro (Version 9.0.0.49)	ReCiPe 2016 midpoint method	GWP, LU, TA, FE, M-RS, F-RS, WC	AD semi-centralized (continuous load digester).
(Slorach et al. 2020)	UK	Food waste	AD	Treatment of 1 ton of household FW	GaBi	ReCiPe v1.08	GWP, FD, MD, FET, MET, TET, HT, FE, ME, TA, PMF, POF, OD, ALO, ULO, NLT, IR, WD	AD
(De Laurentiis et al. 2020)	City of Gothenburg, Italy	Food waste	L, C, Inci, AD	500t of fruit saved from being wasted	SimaPro 8.5, eco invent 3 databases	Environmental Footprint (Version 2.0)	The transport distances, the electricity used, and the amount of paper used (expressed as number of leaflets)	AD
(Tong et al. 2018)	Singapore	Food waste	Inci, AD_{com}, AD_{inci}, AD_{gas}	1000 ton of FW	GaBi software 2017	CML 2001	AD-E, AD-F, AP, EP, FAET, GWP, HTP, MATP, ODP, POCP, TTP	AD + windrow composting.
(Lam et al. 2018)	Hong Kong	Food waste		The management of 1t FW/15years lifetime of the operation of facilities	SimaPro 8.3	ReCiPe Endpoint	Resources, Ecosystem, Human Health	Centralized organic waste treatment (AD + Dewatering + Composting)

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(Angelo et al. 2017)	Rio de Janeiro, Brazil	Food waste	L, AD_L, MRF-AD_L	1 ton of source selected OFMSW	EASETECH Denmark eco invent 3.0	ILCD	GWP, ODP, PM2.5, IR, POF, EU-FW, EU-M, AP, EU-L, ET, AR, HT-C, HT-n C	Dry AD + Landfill Scenario a2: 20% separate collection of organics for anaerobic digestion. Landfilling of residual waste. Use of biosolids as fertilizer on farmland. And Scenario a3: 50% separate collection of organics for anaerobic digestion. Landfilling of residual waste. Use of biosolids as fertilizer on farmland.
(Ghazvinei et al. 2017)	Campus National University of Malaysia	SW of the campus	RDF, C_W, AD, Inci, Integrated	1t of SW of the campus	SimaPro 7.3	Eco-Indicator 99	GWP, OD, EP	Scenario 5 Incinerate (30%) Compost (20 %) AD (30%) Recycle (20%)
(Fusi et al. 2016)	Lombardy, Northern Italy	Tomato waste, Maize silage, Slurry, Co-digestion of the feedstocks	AD	Generation of 1 MWh of electricity to be fed into the grid	GaBi LCA software v6.11	CML 2001	ADP (elements), ADP Fossil, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, TETP.	AD animal slurry (Plant 5), and AD slurry + agricultural waste + small amount of maize silage (Plant 1).
(Lauer et al. 2016)	Germany	Plant biomass, Animal slurry	AD	1 kWh (electricity) emission	Umberto 5.6, eco invent 2.2 database	Mid-point	GWP	Plant A - AD additional CHPUs increases the overall efficiency of biogas

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(Martinez-Sanchez et al. 2016)	Denmark	Food waste	AD	The management of annual food waste 82 generated by Danish households: 1,500,000 single-family housing (SFH) and 1,000,000 multi-family housing (MFH) units	EASETECH LCA model	ILCD midpoint	GW, POF	AD
(Eriksson et al. 2015)	Uppsala, Sweden	Food waste, Packaging waste	AD	Removal of 1 kg of FW including packaging from the 4 supermarket of Uppsala city	Calculation ISO2006a,2006b Swedish National Food Database	SNFA 2013	GWP	AD
(Ebner et al. 2015)	U.S.A.	Co-digestion of food waste and cattle slurry	AD	1 ton of feedstock (wet)	eco invent v.2.2.	IPCC 2007 Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) 100-year	GWP	AcoD-Anaerobic co-digestion
(Styles et al. 2015)	U.K.	Food waste, Cattle slurry, Maize, Grass silage, Miscanthus. Co-digestion of the above	AD	1 year of farm operation	LCAD eco invent 2010	CML 2010	GWP, AP, EP and RDP	Slurry and FW
(Xu et al. 2015)	China	Food waste	AD	The management of 1t volatile solid (VS)	eco invent 2010 Monte Carlo model	ReCiPe mid-point IMPACT2002+ TRACI	GWP, ODP, TAP, FEP, MEP, HTP, POFP, PMFP, TETP, FETP, METP, IRP, ALOP, ULOP, NLTP, WDP, MDP, FDP.	S-2 (AD of FW)
(Seldal, 2014)	Norway	Food waste, Organic waste	AD	1-ton Dry Matter (Food Waste Resource) mixed organic waste entering RBA value chain of Romerike biogas Plant	ARDA	ReCiPe (midpoint-hierarchist)	GWP, ODP, TAP, FEP, MEP, HTP, POFP, PMFP, TETP, FETP, METP, IRP, ALOP, ULOP, NLTP, WDP, MDP, FDP.	AD

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(Zhu, 2013)	Netherlands	Grape seed oil, Food waste, Whey and Manure from dairy farms (co-digested)	AD	Annual production of grape seed oil	SimaPro 7	CML 2001	ADP, AP, EP, GWP100, ODP, HT, EF, ET, EM, EM-S, EF-S, Malodor's air	AD co-digestive
(Righi et al. 2013)	Emilia-Romagna Region (NE Italy)	OFMSW + dewatered sewage sludge and	L, AD_C, AD_L, Integrated WWTP+L+C	The management of 3000 t of biodegradable waste fractions	GaBi 4	CML	GWP, AP, EP, ODP, POCP	AD_C (Integrated AD combined with aerobic composting post-treatment)
(Poeschl et al. 2012)	Germany	Plant biomass, Animal slurry, Industrial waste + other	AD	1 ton of feedstock mixture	SimaPro 7.2, eco invent v2.1	ReCiPe Midpoint (H) and ReCiPe Endpoint (H/A) LCIA methodologies (Version 1.04, March 2010)	GWP, ODP, TAP, FEP, MEP, HTP, POFP, PMFP, TETP, FETP, METP, IRP, ALOP, ULOP, NLTP, WDP, MDP, FDP.	Co-digestion of Municipal Solid Waste (MSW) with agricultural and food industry residues
(Dressler et al. 2012)	Germany	Maize -Plant biomass	AD	1 kg of fresh matter of maize, 1 kWh of electricity	GaBi 4.4 GEMIS	CML mid-point	GWP, AP, EP, FED	Cultivating maize and using waste heat from the CHP at biogas plant in Celle Lower Saxony, Germany.
(Jin et al. 2010)	China	Food waste	AD	1 ton of food waste	SimaPro 8.0	CML 2001 midpoint	GWP100, HTP, FAETP, AP and EP	Scenario AD -energy consumption (EC) of an integrated food waste-based biogas system and its Subsystems

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(Rozieana et al. 2023) *this study*	Malaysia	Food Waste	Dry AD, Wet AD + windrow, Wet AD + Windrow + Landfill, Landfill	1 ton of pre-treated food waste	GaBi v6.0	ReCiPe v1.07 Midpoint, endpoint, Single score	ALOP, GWP FDP, FETP FWEP, HTP IRP, METP MEP, MDP ODP, PMFP POFP, TAP TETP, WDP	Sc1-Dry AD

FW: Food Waste; KW: Kitchen Waste; YW: Yard Waste; SS: Sewage Sludge; NA: Not Applicable; OFMSW: Organic Fraction Municipal Solid Waste LCIA: Life Cycle Impact Assessment; CML: Centrum voor Milieu Kunde Leiden; IPCC: Intergovernmental Panel on Climate Change, ReCiPe: RIVM and Radboud University, CML, and PRE' Consultants; EDIP: Environmental Design of Industrial Products; TRACI 2: Reduction and Assessment of Chemical and Other Environmental Impacts; ILCD: International Reference Life Cycle Data System, AP: Acidification potential; EP: Eutrophication potential (EU-Fresh, EU-Marine,AP,EU-Land); GWP: Global warming potential; POF: Photochemical ozone formation; ODP: Ozone depletion potential; FEU: Fossil energy use; ETP: Eco toxicity potential; REU: Renewable energy use; EU: Energy use; ADP: Abiotic depletion potential; HH: Human health; HTP: Human toxicity potential; HM: Heavy metals; HT(w): Human toxicity (water); HT(s): Human toxicity (soil); HT(a): Human toxicity (air) HT-Carc,HT-non Carc; ET(wc): Eco toxicity (water chronic); ET(wa): Eco toxicity (water acute); ET(s): Eco toxicity (soil); LU: Land use; WU: Water use; RU: Resource use. PM2.5: Particulate Matter; IR: Ionising Radiation; AR: Abiotic Resources S: Smog, FF: Fossil fuel used, AD: Abiotic depletion, ADFF: Abiotic depletion (Fossil Fuel), HT: Human toxicity, FWaEcotox: Fresh water aquatic eco toxicity, MAEcotox: Marine aquatic eco toxicity, TEcotox: Terrestrial eco toxicity, POP: Photochemical oxidation potential

The findings in Table 1 demonstrated the AD systems used (depicting Figure 1 as a reference), and the areas represented by the studies varied greatly (e.g., Europe, Middle East, USA and Asian countries). Furthermore, the different AD technologies entailed different problems and possibilities that influenced the results (Brenes-Peralta et al. 2020; Tong et al. 2018, Righi et al. 2013). The different facilities chosen for each type of treatment method ranged from the least favourable to the most favourable FW management options in terms of factors affecting the environment.

FIGURE 1. Various types of AD treatment for FW

There are various critical reviews: acidification potential (AP) related to electricity and fuel intake for waste treatment; ammonia (NH_3) contaminants by methanogen and denitrification actions; and global warming potential (GWP) caused by CO_2 pollution from fossil fuel used in transportation and processing plants (Angelo et al. 2017; Righi et al. 2013).

Therefore, the environmental results of the LCA of ADs might vary depending on the biogas systems and LCA methodologies employed (Fusi et al. 2016). As stated by Brenes-Peralta et al. (2020), a centralized AD for FW recovery facilities can raise global warming potential (GWP) and land use when compared to those that are semi-centralized. The increased distance travelled by waste and the corresponding rise in air pollution emissions, noise, and traffic have been identified as significant causes.

Meanwhile, in integrated AD technologies, Al-Rumaihi et al. (2020) discovered that the human toxicity impact category for FW management was the most significant for AD combined with composting (3.47 x 10 kg 1,4-DB eq). The hotspots were determined in AD during process treatment, followed by collection and transportation.

A study conducted by Tong et al. (2018) has found that the AD followed by composting for FW treatment was more environmentally friendly than other scenarios (gasification, and incineration) for all environmental impacts, except for eutrophication potential (EP), GWP, and photochemical ozone creation (POCP). The highest GWP releases are produced by composting AD digestate, with nearly 94% CH_4 and nitrous oxide (N_2O) (Tong et al. 2018).

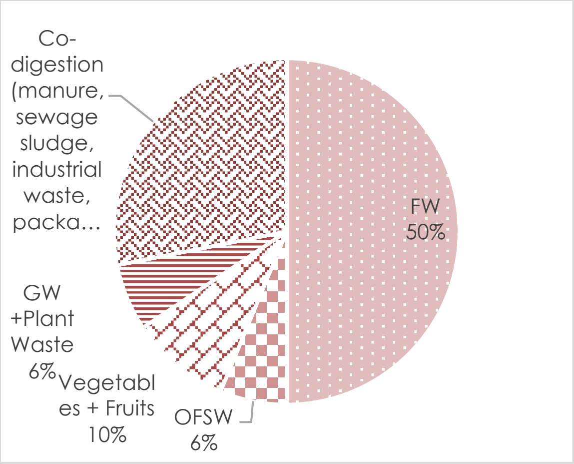


FIGURE 2. The most prevalent kind of feedstock source used for anaerobic treatment in previous LCA studies

As shown by Figure 2, the FW is by far the most widely considered feedstock in AD treatment. Carbohydrates, proteins, lipids, and traces of inorganic compounds are the main content of food waste composition (Palaniveloo et al. 2020). The nitrogen in FW was mainly organic nitrogen, which could be found in various molecular forms such as proteins, peptides, nucleic acids, amino acids, chitins, etc. While according to Aqeela et al. (2021), FW characteristics have moisture content of 66.4%, pH value 4.7, electrical conductivity 9.3 mS/cm, nitrogen 3.1%, phosphorous 1.5%, potassium 0.2%, and carbon 52.2%. Besides that, another considered feedstock in AD treatment is preceded by co-digestion of green waste and animal slurry (Figure 2). Present study proves there was improvement in biogas production in co-digestion of agro-wastes with cattle manure by using glycerol as co-substrate biogas from sugarcane bagasse (Kamarudin et al. 2018).

The functional unit (FU) is primarily determined by either a unit of biogas feedstock or an energy unit (biogas, heat, or electricity). The FU is commonly stated in waste

LCAs in four ways: (i) unitary (e.g., Al Rumaihi et al. 2020; Brenes-Peralta et al. 2020), (ii) generation-based (e.g., Fusi et al. 2016), (iii) input-based, and (iv) output-based (e.g., Lauer et al. 2016). The unitary functional unit gets progressively more preferred in the papers studied, indicating a greater theoretical or conceptual goal for the LCA.

The FU is crucial to permit comparisons amongst LCA studies of comparable cross-study types. The FU is defined by the type of function or service provided by the system or items, and is created to offer a baseline that pertains to both inputs and outputs. Therefore, it must be quantifiable. Eventually, it prefers mass or volume for composting, but the AD biogas technologies correspond to the power, distance, mass, volume, or hectare utilised for land. For example, the FU in the LCA composting or AD biogas generation studies vary: tonne, kg, Mg, m^3, MJ, kWh, MWh, ha, and km.

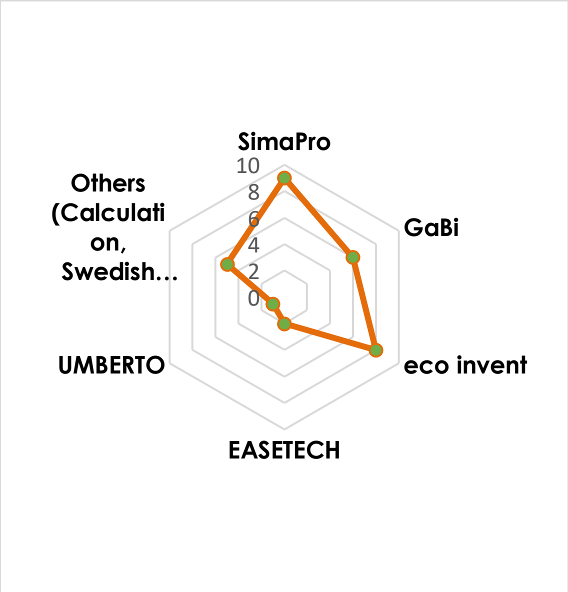


FIGURE 3. Databases for LCA reviewed studies in FW treatment plant by AD

From the cases reviewed in Table 1, SimaPro was the most extensively used LCA software as can be seen in many studies, for example by Woon et al. (2021), Al Rumaihi et al. (2020) and Brenes-Peralta et al. (2020); followed by GaBi (Elginoz et al. 2020; Slorach et al. 2020), EASETECH (Angelo et al. 2017), and eco invent (Figure 3). Users may use SimaPro and GaBi's databases and impact assessments for a number of industrial and commercial applications, such as water footprint, carbon footprint, eco-design product, performance indicator identification, and environmental product certification. More open data in datasets provide good visualization to represent the assessment results.

The largest difference between studies, nonetheless, is perceived in the number of impacts recognized and the techniques used to evaluate them. The most recent biogas reports have either centred on climate change or recognized a limited yet significant impact. To approximate the impacts, most research focused on the secondary foreground data or used minimal primary data.

The choice of a complete LCIA system does not assure its correct implementation since most previous research has revealed that some of the impact categories have been neglected. In certain situations, this means that, although it uses a well-known LCIA system, the LCA's results are less credible unless such exclusion is well warranted and consistent with the purpose and scope of the research.

The missing categories of impact as described were shown in prior research, for example in Brenes-Peralta et al. (2020); Ghazvinei et al. (2017); Lauer et al. (2016); Styles et al. (2015); Eriksson et al. (2015); and Ebner et al. (2015). Excluding certain impact categories results should be avoided or recorded when applicable.

The former researches cover almost all established LCIA processes, including Eco Indicator 99, CML 2001, Impact 2002+, and ReCiPe. Midpoint LCIA approaches such as ReCiPe (Brenes-Peralta et al. 2020), EDIP, and Impact 2002+ give more evaluation and comparison categories as opposed to CML (Elginoz et al. 2020) as shown in Table 2 for references.

These and other variations, such as co-product credits, have resulted in very different findings across research, making it impossible to compare them and make generalizations about biogas' environmental viability (Fusi et al. 2016).

EMERGING LCA FOR AD TECHNOLOGY IN MALAYSIA, ITS CHALLENGES AND IMPROVEMENT NEEDED FOR FW MANAGEMENT

In Malaysia, an approach to LCA in waste treatment is being used and showing considerable improvements in recent years. Saheri et al. (2012) examined the MSW comparison between open landfill and sanitary landfill for LCA solid waste research in Malaysia. Ghazvinei et al. (2017) assessed MSW on campus while Keng et al. (2020) performed community-scale aerated static pile composting for FW.

To date, an increasing number of works have been done on the environmental impact assessment of bioenergy production, especially from palm oil mills effluent (Aziz et al. 2020). Choong et al. (2009) investigated the energy recovery from wood waste while Woon et al. (2021) analysed and differentiated the LCA study's environmental range of possible FW valorisation technologies for several valued commodities, focusing on Malaysia's local conditions.

According to Tenaga Nasional Berhad (TNB), Malaysia's current power emission factor is 0.54 t CO_2-eq/MWh (Woon et al. 2021). The quantity of power generated through FW valorisations is predicted to eliminate 880 Kt CO_2-eq/year, or 0.4% of Malaysia's total CO_2-eq emissions (the number of CO_2-eq emissions was 250 Mt in 2018).

TABLE 2. The impacts assessment related to LCIA mid-end points analysis in LCA researches

Method	Version of the method used in this assessment (GaBi v9.2.1 database)	Midpoint/Endpoint	Number of Categories considered
CML 2001	CML 2001-Jan 2016	Midpoint	12
Impact 2002+	Impact 2002+	Midpoint/ Endpoint	15 4
EDIP 2003	EDIP 2003	Midpoint	19, 7
Eco-indicator 99*	Eco Indicator 99*	Endpoint	11
TRACI 2	TRACI 2.1	Midpoint	11
ReCiPe Midpoint	ReCiPe 2016 v.1.1 Midpoint (H)	Midpoint	19
ReCiPe Endpoint	ReCiPe 2016 v.1.1	Endpoint	19, 3 (aggregate)
Ecological Scarcity 2006*	Ecological Scarcity 2006*	Endpoint	7
Environment Footprint	Environment Footprint 2.0	Midpoint	19
IPCC	IPCC AR5	Midpoint	5
ILCD	ILCD	Midpoint	14

* (SimaPro) extracted from Cavalett et al. (2012) and Abu et al. (2021)

Many studies throughout the world use the LCA technique to assess the environmental implications of valorising FW to multiple value-added commodities, including biofertilizer, power, cooking gas, and biogas car fuel (Woon et al. 2021; Elginoz et al. 2020; Brenes-Peralta et al. 2020).

Although the LCA implementation of AD as an alternative treatment method for FW can be seen recently, its condition in Malaysia is unclear. In particular, the dry AD and integrated wet AD treatment's environmental impacts are largely unknown due to a variety of reasons, including that the research and development effort in this area has not kept up with the pace of technological advancements (Hanum et al. 2019). Moreover, the management and maintenance of the AD plant would necessitate highly skilled engineers and technicians, which might be inadequate in Malaysia since AD is still not an acknowledged practice in this country (Ali et al. 2012).

Due to the different AD technologies, the damaging emissions related to the AD technologies' treatment vary, bringing a variety of issues and possibilities that have affected the outcomes (Brenes-Peralta et al. 2020). The different facilities selected for each form of treatment system vary from the least desirable to the most desirable FW management alternatives in terms of environmental effectiveness, harmful impact to human health, high energy consumption, depletion of natural resources, and others. Although dry AD has grown in popularity in recent years, there is scarce information on environmental impact score evaluation as compared to wet AD (Rocamora et al. 2020; Angelo et al. 2017).

Therefore, this study aimed to make comparisons between dry AD systems, integrated wet ADs, as well as baseline practice-landfill on the environmental sustainability of FW treatment by considering their life cycle's environmental impacts. In order to achieve more convincing outcomes from the treatment methods and proposed mitigation measures, an LCA-based environmental assessment research framework for FW treatment alternatives through AD technologies could be established to assist the proactive decision-making process for sustainable development.

The novel aspects of the work compared to the previous studies performed in the Malaysian context include: (i) comparing the LCA of several real scale AD technologies for FW treatment alternatives; (ii) introducing a real scale dry AD single-stage, continuous-batch process for FW treatment; and (iii) using the comprehensive ReCiPe (H) LCIA method to analyse the full environmental impact scores: 16 midpoints and 15 endpoints and single scores to determine damage to the environment at three higher accumulation levels: (1) impact on human wellbeing, (2) biodiversity, and (3) scarcity of resources.

For this study, the scenarios of a real-scale AD facility, aerobic windrow composting, and landfill were evaluated because a particular waste data, which is typically difficult to obtain, was already available from previous research, and partly because the infrastructures for all scenarios exist and could be used to collect site-specific data. Furthermore, the findings have the potential to improve the efficiency and sustainability of FW treatment alternatives through AD technologies, which are being used as a green waste management technique as well as an alternative renewable energy source in Malaysia.

METHODOLOGY

MATERIAL AND METHODS

The environmental profiles and the comparative analysis were performed utilizing LCA methodology, standardized by ISO 14040:2006 and ISO 14044:2006. LCA is an empirical evaluation of the environmental performance of treatment systems over their entire life cycle, including the consumption of resources, production, usage, and disposal. The LCA methodology comprises of four phases: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation (see Figure 4).

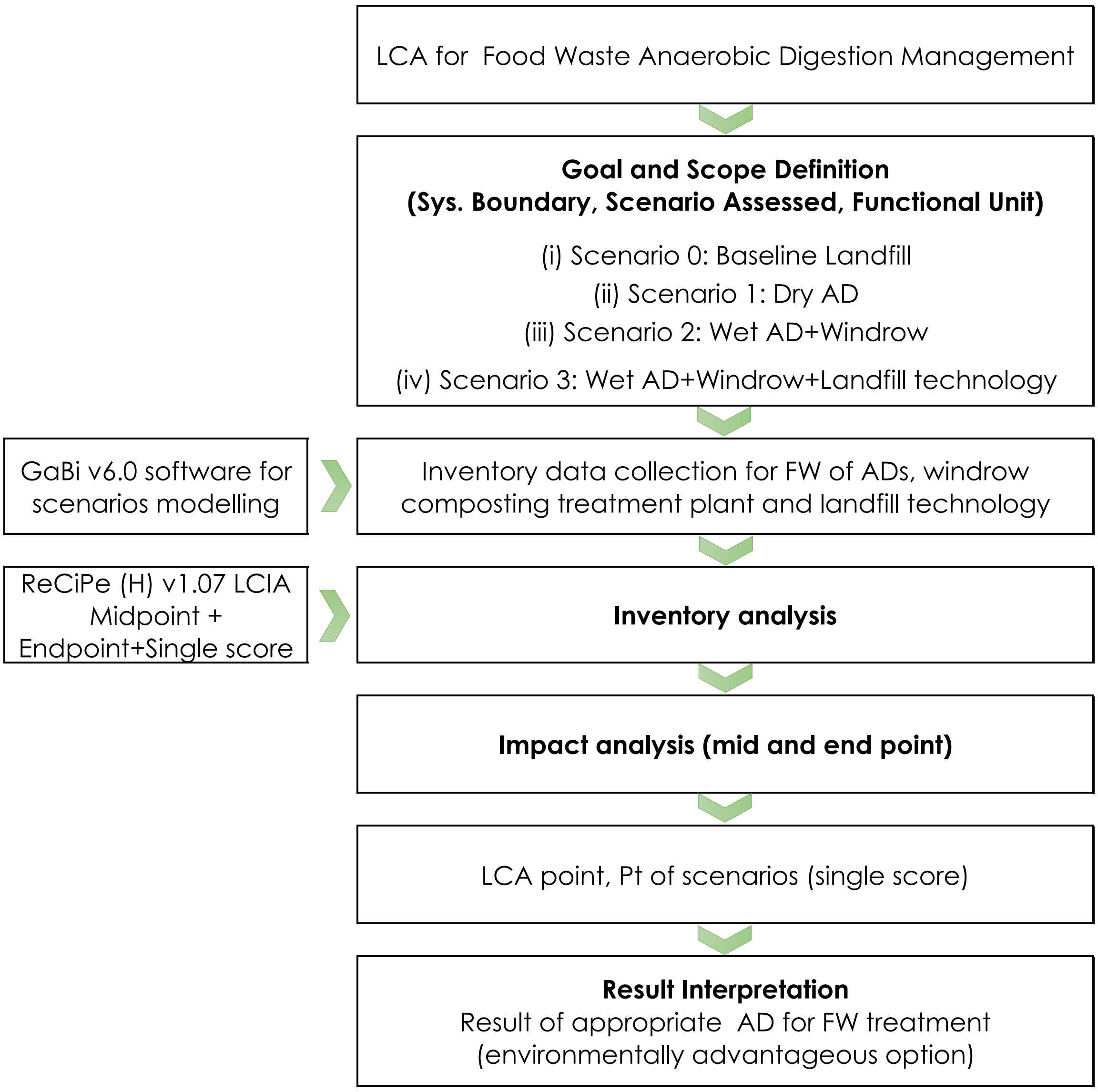


FIGURE 4. Flowchart for the steps in the assessment of AD technologies for FW management

CASE STUDY

A FW treatment plant located in Petaling Jaya city, Selangor, Malaysia, was chosen as a case study. According to the data derived from the Petaling Jaya City Council (PJCC) for 2017-2020, the inhabitants produced an average of 97,274.32 kg FW per year. The PJCC has considerable success in FW treatment with substantial funding assistance from the Department of National Solid Waste Management. PJCC has taken an important step in introducing a number of FW management programs under Agenda Petaling Jaya 21 to alleviate FW problems in Petaling Jaya (Lim et al. 2016). The home composting scheme for FW between households between June 2008 and November 2009 was developed by PJCC. The PJCC set up a trial composting facility for Shence Greentech Sdn. Bhd. in 2013 (Lim et al. 2016). Later in 2017-2019, PJCC installed a large-scale dry AD for FW treatment (Cowtec. CTM-100, CH Green Sdn. Bhd., Kuala Lumpur, Malaysia) capable of converting FW into liquid fertilizer and biogas. The dry AD plant was funded entirely by the State government and self-sustaining, operating a carbonization unit and a small-scale hydroponics farm in addition to the AD process. This facility, which was constructed in 2017 by CH Green Sdn. Bhd. and managed by PJCC, has collected around 0.5-1t of FW each day from commercial properties and business hubs as well as nearby residential areas. The dry AD plant operating days are 7 days a week.

GOAL AND SCOPE DEFINITION

The study aimed to determine the existing FW management practice's impacts on the environment through the comparison of dry and integrated wet AD technologies, as well as landfill scenarios from the context of the LCA. The vision is to evaluate and communicate the most appropriate FW management solution based on the least possible pollutions for Petaling Jaya City Council Malaysia, and potentially generalizing the result of this research to other States as well. The intended audience for this work is AD plant managers, LCA practitioners and researchers, research institutions, solid waste management departments, and the Government of Malaysia. The scenario's description is presented in the next sub section under the scenarios assessed.

SYSTEM BOUNDARIES

System boundaries are assessed from cradle to gate as shown in Figure 5(a). The general value chains regarding biogas functional specifications were adapted according to real scale dry AD at Petaling Jaya city, Selangor Malaysia; wet AD as per Woon et al. (2021) and Seldal (2014) while the aerobic windrow was referred to Ghazvinei et al. (2017), and the landfill modelling was by Abba (2014) and redesigned for this study's purpose. The phases of transportation, feed-stock, biogas, and bio fertilizer production were included in system boundaries. The distance from the city to the dry AD site was 1 km. The entire distance travelled by the trash truck was taken into account as 45 km, and the same site assumed the wet AD facility, windrow composting, and landfill sites. No consideration was given to wastewater treatment and disposal of the compost for agriculture purposes. The electricity/biogas and compost produced by the dry and wet AD scenario were credited with the subtraction of energy and mineral fertilizer. Input flows were materials, energy, and resources. As illustrated by Figure 5(b), output flows were products, waste to treatment, and emissions into the air, water, and soil.

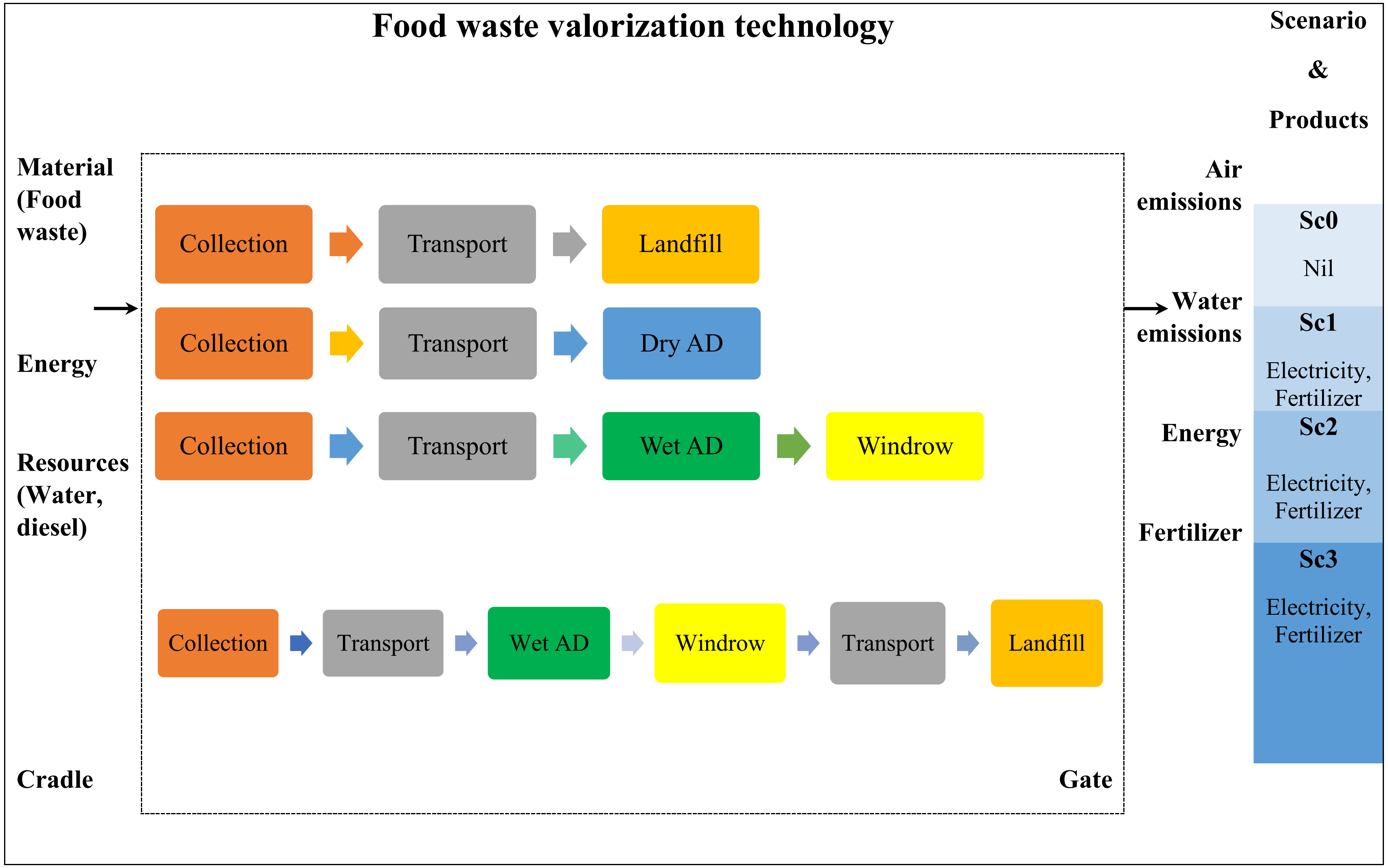
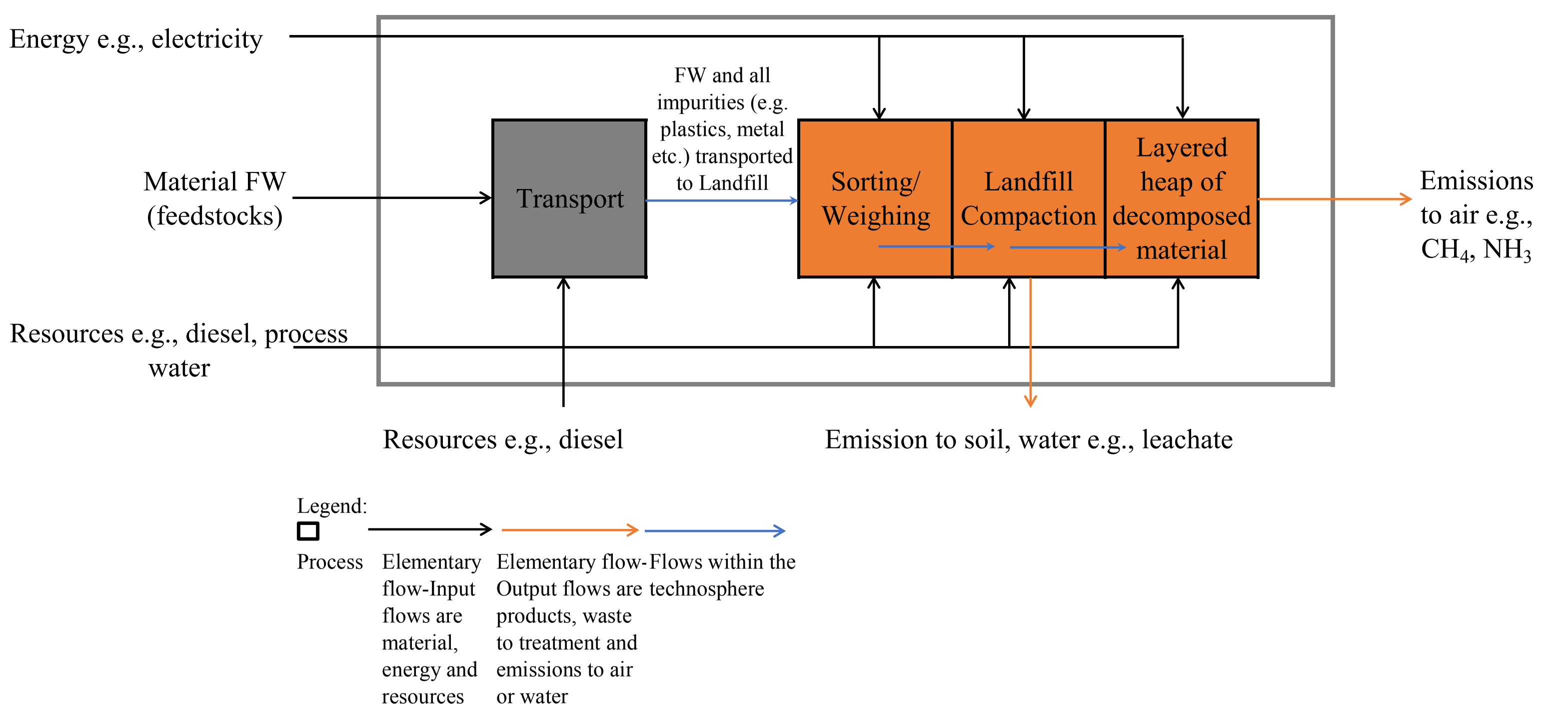


FIGURE 5 (a). System boundaries for FW valorization technology

(i) ***Sc0***



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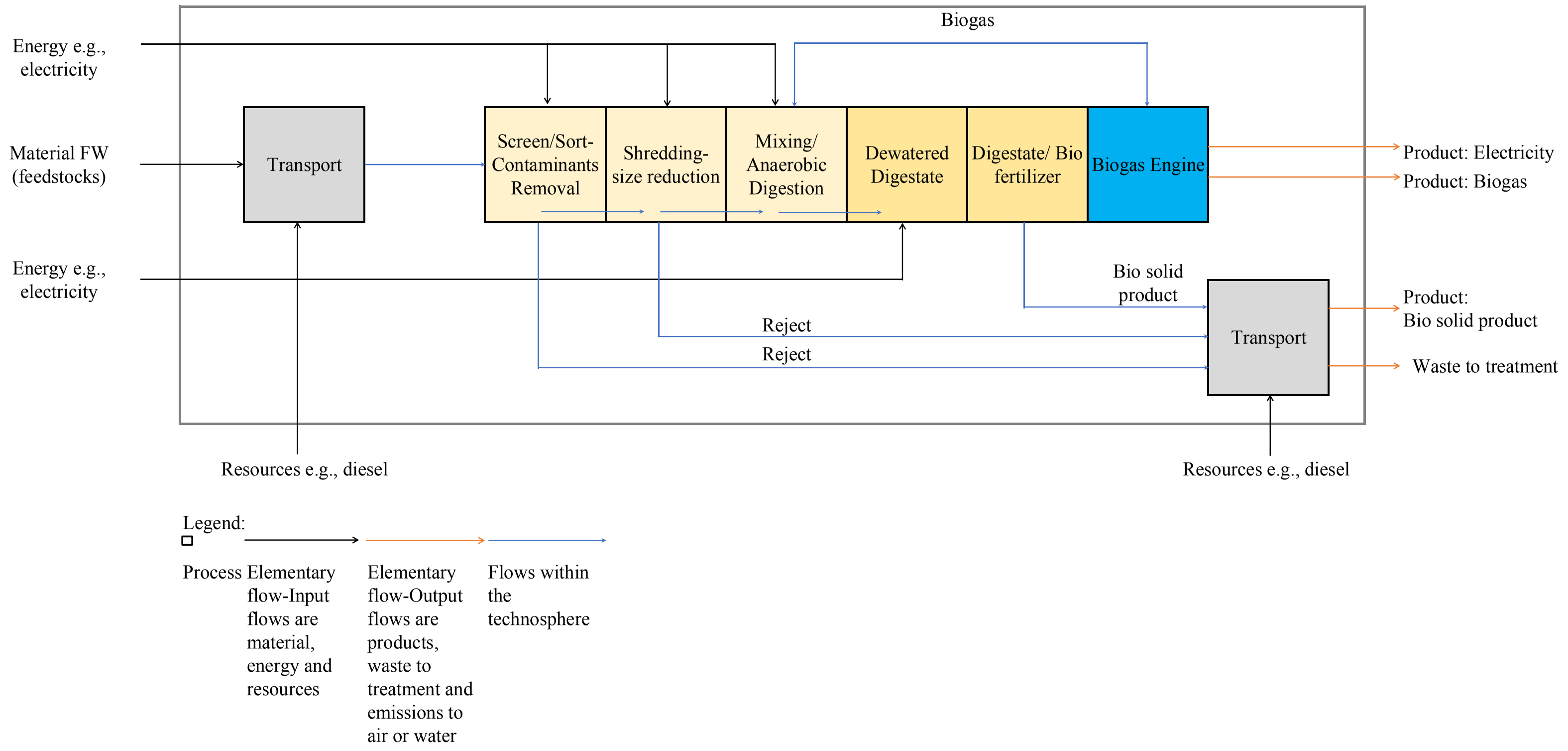
(ii) Sc1



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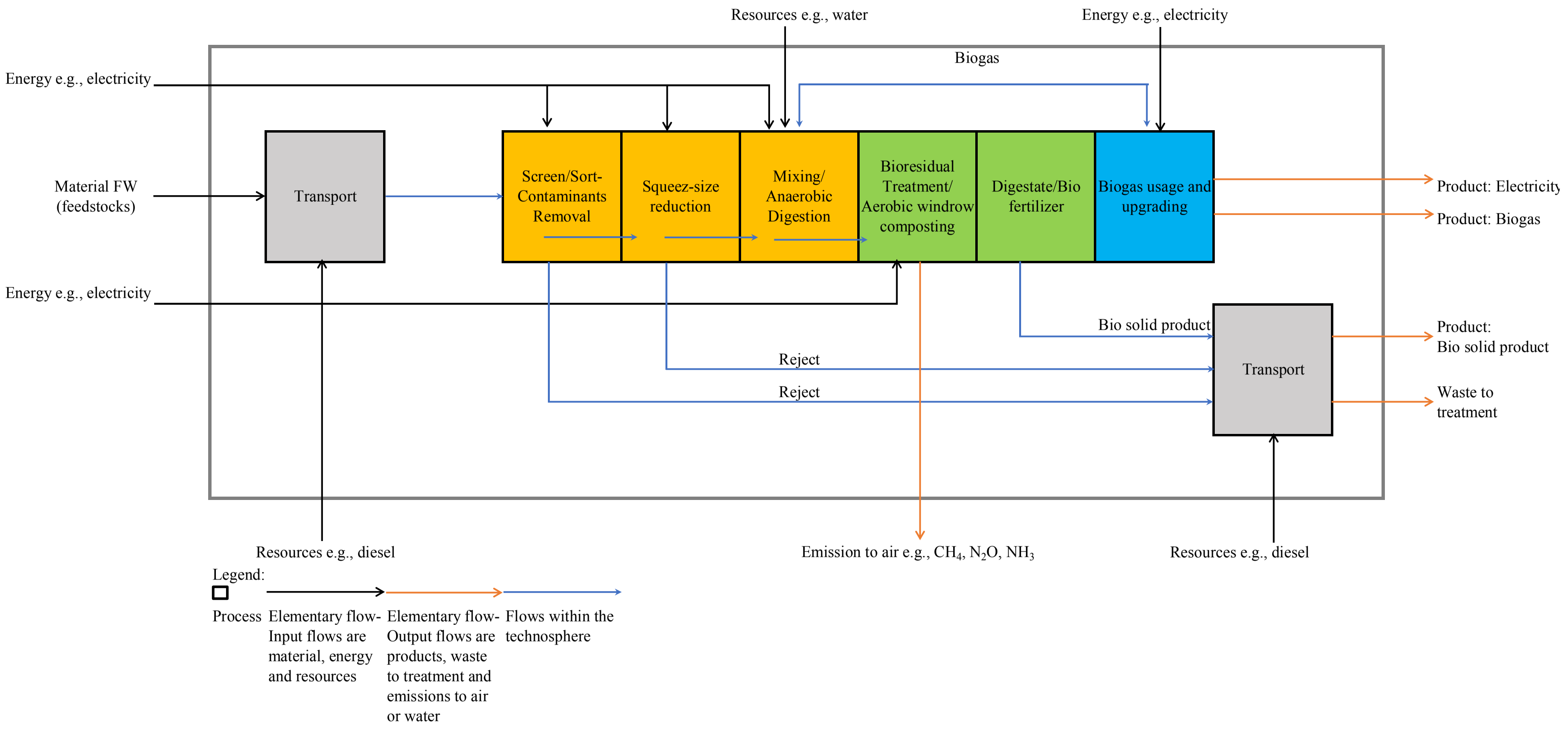
(iii) Sc2



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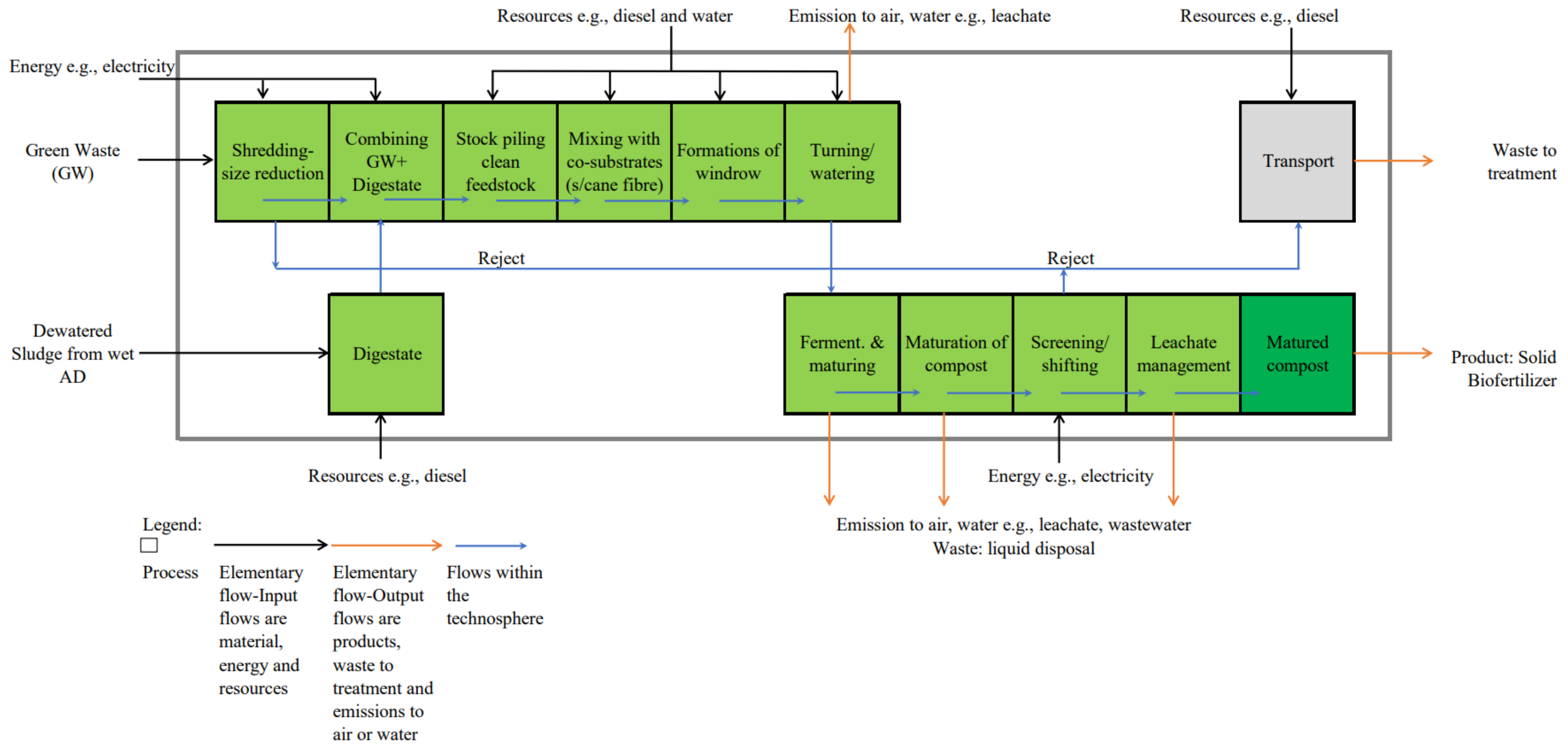
(iii) Sc2_bioresidual treatment using windrow composting



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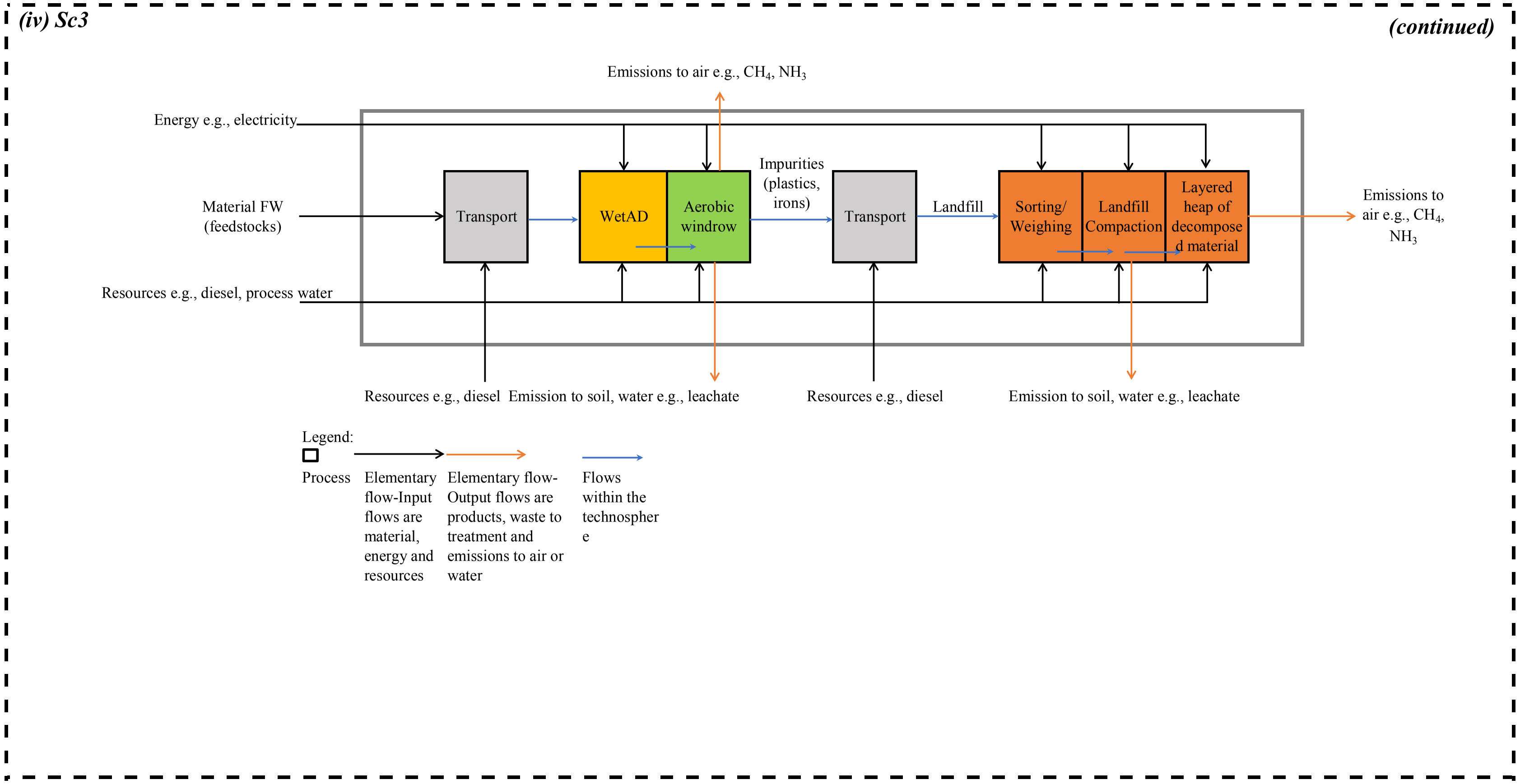

FIGURE 5 (b). Elementary flows (input and output) and flows within the techno sphere for the assessment of FW management (i) Sc0-Landfill, (ii) Sc1-Dry AD, (iii) Sc2-Integrated wet AD and aerobic windrow composting and (iv) Sc3-integrated wet AD with aerobic windrow composting and landfill

SCENARIOS ASSESSED

Sc0: Baseline Scenario-Landfill without energy recovery and without the use of landfill gas or leachate treatment. The landfill scenario defined the strategic practices employed through the past decade. In this case, FW was deposited in a landfill without energy recovery and without the use of landfill gas or leachate treatment. Landfill gas was unrestrainedly discharged into the atmosphere. The estimated distance travelled by the collection truck from the waste generation point to the Jeram, Selangor landfill site plant was 45 km. The average garbage load was 5.0 t and the truck trip from the collection point to the landfill for biodegradable waste was twice-weekly. Even though landfill treatment of biodegradable waste was currently discouraged, this scenario has been included in the LCA study to provide a comparison and to determine the extent of the environmental benefits that can be obtained by adopting effective waste management strategies.

Sc1: Dry AD-Scenario 1, the first scenario dry AD, the present FW management system was analysed. A dry AD system started with material collection and transportation to a composting centre. Upon arrival, the feedstock materials comprised of FW were pre-treated by employing simultaneous screening to separate the organic wastes from the solid fraction containing impurities like plastics, metals, and others. The biodegradable waste was then shredded to the required size. The maximum dimension of feedstock materials was best between 1 mm long and 2 mm wide. This dry AD was a single-stage high-dry solid batch continuous anaerobic digester (Cowtec. technology). It was fitted with a power source, a 3000 kg capacity mixing and composting tank, a horizontal propeller, a gas scrubber unit, and a discharge pump. No water addition was conducted since it fully utilized the moisture content of the fresh FW substrates. The hydraulic retention time (HRT) was 30 days at a mesophilic temperature ranging from 30 to 35 degrees Celsius (°C). The total solids (TS) content was 25%, and the carbon to nitrogen (C/N) ratio was 10-35:1. The plant used biogas, which had a processing capacity of 2.76-5.52 kg/day. The method was a closed system, with air emissions more likely to be emitted at the end of the process when the compost was discharged, without the generation of leachate. Meanwhile, organic fertilizers, as well as biogas/electricity, were produced as products of this system. The energy in the gas was converted into electricity and consumed by the treatment plant. The digestion residue was passed through a dewatering system, after which the liquid fraction was collected. The dewatered digestate could produce approximately 600kg of solid digested matter per ton of treated FW, which was then composted and sold as a dry fertilizer.

Sc2: Wet AD with windrow composting-Scenario 2, the wet AD scenario combined with windrow composting. The wet AD assessed in this study was a biogas digester with microorganisms at a mesophilic temperature (around 35 °C) (Jouhara et al. 2017). The complex FW was hydrolyzed and fermented into short-chain organic matters, then further decomposed by methanogens to produce biogas. The biogas consisted of 62% CH_4, 32% biogenic CO_2, and 6% of other gas components such as NH_3, VOCs, O_2, and N_2. The biogas was collected through a blower and sent to a gas turbine. In this scenario, the biogas was used to generate electricity. It should be noted that the biogas was required to undergo a biogas upgrading process (i.e., water scrubbing) to purify the biogas to 98% CH_4 before being used as cooking gas (Woon et al. 2016). The transport distance between the wet AD plant and FW collection sites was estimated at 45km. Thus, the average distance travelled by the waste trucks was assumed to be 45 km. Once delivered to the plant, the FW was first fed into a screener which would reject any large pieces of plastic and other non-biodegradable materials, such as glass bottles and metal cans. Simultaneous squeezing was then employed to reduce the particle size of the waste. Water addition was conducted. The highest concentration of putrescible material was pumped into the anaerobic digester for an average of 3 weeks of mesophilic (35 °C) fermentation. The digestion residue was passed through a dewatering system, after which the liquid fraction was reused on-site and drained to the nearby wastewater treatment plant. Finally, the digestate underwent an aerobic windrow process to produce the compound that would be used by the conventional composting process to substitute for the inorganic fertilizer. The dewatered digestate, with a water content of 74%, was co-composted with horticultural wastes (tree trunks, branches, and leaves) for an average of 4 weeks of maturation treatment. The electricity produced (334.29 kWh) was used by the treatment plant and about 225kg of the solid digested matter was sold as a dry fertilizer.

Sc3: Scenario 3-Wet AD, aerobic windrow composting, and landfill were independent processes. However, when integrated, they might improve the waste management system's efficiency and achieve environmental advantages. Neither of the treatment options examined could entirely eliminate landfilling, regardless of whether it was in the context of AD or composting. Some percentages of the waste residues of the inorganic substances in the collected waste after sorting were still transported to a landfill for disposal. However, the portion to be landfilled was actually reduced (Righi et al. 2013). The integrated wet AD system in this scenario was the same as in Sc2. However, the remaining approximately 30% of impurities (i.e., plastics, irons) and rejected FW from pre- and post-treatment would be disposed of at a nearby conventional landfill site. The waste disposal in this landfill case had no gas filtering mechanism.

FUNCTIONAL UNIT

In LCA, the purpose of the functional unit is to provide a reference to which the inputs and outputs are able to be related. Dry AD, wet AD combined windrow composting, wet AD combined windrow composting and landfill, as well as landfill methods were used to treat 1 metric ton of FW with equal amounts of FW of the same composition in all systems. The functional unit selected was the management of 1 metric ton of FW in Petaling Jaya city, Selangor Malaysia. The characteristics of FW considered in this study is depicted in Table 3.

TABLE 3. Characteristics of FW

Food waste proportions 13.1%			Bulking agent
Vegetable waste	Fruit waste	Meat waste	Dry leaves
1.1%	4.9%	7.1%	86.9%

*Adapted from Lim et al. (2019)

LIFE CYCLE INVENTORY

For life cycle inventory, in this step, all extractions and emissions were classified and put in an inventory list that included all inputs and outputs of the treatment examined (Table 4). The secondary data obtained from the Petaling Jaya City Council Office (Selangor), on-site observation, and published scientific literature, such as Angelo et al. (2017); Ghazvinei et al. (2017); and Mendes et al. (2004), were used for this analysis, as well as the GaBi v6.0 Professional database.

The data could be separated into two processes: the foreground system that integrated pollutants associated with dry and wet AD, aerobic windrow composting and landfill for FW treatment systems considered in the analysis; and the background system that incorporated diesel and energy specifications into the foreground system and the generation of electricity and mineral fertilizers. The foreground data came from the owner's treatment plant and digester provider while the background data came from the generic GaBi Professional v6.0 database, which was used to model and evaluate the environmental burdens of all systems, dry and wet AD, aerobic windrow composting and landfill. All energy requirements originated from Malaysia's national electricity grid.

Since local Malaysia data is still unavailable, this study assumed the manufacturing processes and inventory data of all scenario processes were similar between Malaysia and other regions such as Singapore, and Brazil. The assumption was founded on the similarities of these countries' solid-waste and climatic conditions (Abba 2014).

TABLE 4. Input and output inventories for landfill, dry AD, wet AD and windrow composting

Technologies	Waste Treatment	Flow	Amount	Unit
Landfill	**Input**			
	Material (feedstock)	FW	1	t
	Transportation	Distance	45	km
		Truck payload	5	t
	Energy consumption	Electricity	667.4[a, b]	kWh
	Water consumption	Tap water	52[c]	kg
	Resources	Diesel	11.4[d, b]	l
	Output			
	Emission to air	CH_4	37849[e]	g
		CO_2	21.24[a, b]	kg
		CO	0.0236[b]	kg
		N_2O	0.002[a]	kg
		NO_x	0.25[a, b]	kg
		HCl	0.006[a]	kg
		HF	0.001[a]	kg
		H_2S	0.018[a]	kg
		SO_2	0.0381[a, b]	kg
		Particles	0.0074[b]	kg
	Emission to water	Total N	1003[a]	g
		Hg	1.4[f]	mg
		Cd	0.06[f]	mg
		Fe	35.1[f]	mg
		Mg	1.6[f]	mg
		Zn	1.33[f]	mg

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Dry AD	**Input**			
	Material (feedstock)	FW	1	t
	Transportation	Distance	>1[g]	km
		Truck payload	1	t
	Energy consumption	Electricity	98.16[g]	kWh
	Resources	Diesel	0.007	l
	Output			
	Emission to air	CH_4	500[h](estimate)	g
		O_2	0.1[h](estimate)	kg
		H_2	0.2[h](estimate)	kg
		NO_3	0.2[h](estimate)	kg
	Energy Recovery	Electricity	87.84(estimate)	kWh
	Valuable materials	Compost	950g	kg
Wet AD	**Input**			
	Material (feedstock)	FW	1	t
	Transportation	Distance	45	km
		Truck payload	5	t
	Energy consumption	Electricity	120(estimate)	kWh
	Water consumption	Tap water	346[i, j]	kg
	Resources	Diesel	30 (estimate)	l
		Lubricant	0.25[j]	l
	Output			
	Emission to air	CH_4	590[k]	g
		CO_2	0.5792[k]	kg
		N_2O	0.00215[k]	kg
		HF	0.00017[k]	kg
		H_2S	3.095[l]	kg
		Particles	0.0002[k]	kg
		Biogenic CO_2	85.445[l]	kg
		N_2	5.098[l]	kg
		O_2	1.942[l]	kg
		H_2	0.061[l]	kg
	Other Waste	Plastic	0.13[m]	t
		Iron	1.1[m]	kg
		Rejected bio waste	0.19[n]	t
	Energy Recovery	Electricity	334.29[e]	kWh
	Waste	Unstabilized Digestate	0.85	t

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Windrow composting	**Input**			
	Material (feedstock) unstabilized digestate from wet AD	FW	1	t
	Transportation	Distance	<1	km
		Truck payload	1	t
	Energy consumption	Electricity	110[j]	kWh
	Water consumptio n	Tap water	120[m]	kg
	Resources	Diesel	9.641[m, j]	l
		Lubricant	0.5[j]	l
		Anti-odour	20[j]	l
	Output			
	Emission to air	CH_4	1455[m, j]	g
		CO_2	430[j]	kg
		CO	0.6[j]	kg
		N_2O	0.1[j]	kg
		NH_3	10.04[m, j]	kg
		H_2S	0.02[m]	kg
		VOC	36.5[j]	kg
		NMOC	0.01[m]	kg
	Emission to water	Total N	3452[j]	g
		BOD_5	1964[j]	g
		COD	6392[j]	g
		Phenol	0.6[j]	g
		Free chlorine	0.1[j]	g
		Sulphide	3.9[j]	g
		NH_3	2934[j]	g
		PO_4	19.4[j]	g
		Leachate	0.28[j]	t
	Valuable materials	Compost	225[n]	kg

a(Mendes et al. 2004), b(Forti et al. 2004), c(Righi et al. 2013), d(Hong et al. 2006), e(Johari et al. 2012), f(Agamuthu & Fauziah, 2008), g(Dry AD plant, PJ), h(Angelo et al. 2017), i(Tong et al. 2018), j(Ghazvinei et al. 2017), k(Carnevale et al. 2015), l(Anukam et al. 2019), m(Righi et al. 2013), n(JB Aerobic Windrow Composting plant)

LIFE CYCLE IMPACT ASSESSMENT METHODOLOGY AND TYPES OF IMPACT

The third step of the LCA assesses the significance of the potential environmental impacts resulting from an inventory analysis. In particular, inventory data is categorized and translated into specific equivalence units for each classification of effect (e.g., global climate change, human pollution, acidification, etc.) to be summarized for each category of the indicator (Hauschild et al. 2017).

The impact study was performed using the LCA software GaBi v6.0 and ReCiPe hierarchists (H) v1.07 as the LCIA method was used to assess the environmental burden and advantages in this analysis. There are two common methods for calculating characterization factors: at the midpoint level and at the endpoint level. In GaBi Professional v6.0 package software, ReCiPe (H) was constructed with 16 midpoint indicators, 15 endpoints indicators, and a single score of 3 points, and in the analysis for this study, all environmental impact scores were included.

Midpoint metrics, often known as problem-oriented approaches, are based on a single environmental concern, such as climate change or acidification. Since the midpoint groups have lower uncertainty associated with them, it can be more difficult to interpret, for example global warming-radiative forcing and smog creation-photo oxidant formation. These characteristics did not represent the final consequences on the environmental pathway of the emissions listed in the life cycle inventory, but were potential impact indicators. Converting midpoints to endpoints simplified the analysis of the effects of the LCIA. Endpoint modelling consisted basically of characterizing the severity or consequences of midpoint impacts. This characterization at the endpoint level required modelling of all environmental mechanisms.

Endpoint metrics, generally referred to as the damage-oriented approach, show an environmental impact at three higher accumulations levels: (1) impact on human wellbeing, (2) biodiversity, and (3) scarcity of resources. In order to construct a single score indicator, various LCIA methods, such as IMPACT 2002+, Ecological Scarcity 2006, and Eco-indicator 99 (H), have distinct normalization and weighting factors, and these parameters have a significant influence on the output of the single score. The ReCiPe, however, has been designated as the optimal endpoint approach for assessing environmental impacts based on mature characterization models (Cavalett et al. 2013; Poeschl et al. 2012).

RESULT AND DISCUSSION

Table 5 summarizes the environmental impact scores for the treatment of 1-ton FW for the four cases considered. The interpretation of positive value denotes an additional burden on the environment while negative value reduces environmental pressure or enhances sustainability impacts. The ReCiPe (H) LCIA technique was used to compute 16 midpoints indicators, 15 endpoint indicators, and a single 3-point score. Table 5 and Table S1 *(Supplementary)* provide all of the values. The first eight midpoint impacts were discussed in the text-section while the other eight midpoint impacts were explained in the Supplementary material *(Figure S2 continued-supplementary)*.

The results indicated that Sc1 had the greatest potential for environmental improvement in all areas except Human toxicity (HTP), Marine ecotoxicity (METP), Terrestrial ecotoxicity (TETP), and Water depletion (WDP). The highest reduction in HTP, METP, TETP, and WDP was found in Sc2. However, Sc3 posed significant negative environmental impacts in the categories of Global Warming (GWP), TAP, Ozone Depletion (ODP), and Primary Energy Demand (PED). It was also found that Sc3, Sc0, Sc2 showed a higher contribution to ionizing radiation (IRP).

TABLE 5. Total environmental impacts of the four scenarios considered using ReCiPe (H) midpoint analysis per ton treated FW

ReCiPe 1.07 Midpoint (H)	Acronym	Baseline Landfill Sc0	Dry AD Sc1	Wet AD + Windrow Sc2	Wet AD + Windrow + Landfill Sc3	Environment. most preferred option
Agricultural land occupation [m^{2}a]	ALOP	2.49E+00	2.40E-03	1.96E+00	4.45E+00	Sc1
Climate change [kg CO$_2$ eq]	GWP	5.34E+02	4.94E+01	1.40E+04	1.45E+04	Sc1
Fossil depletion [kg oil eq]	FDP	1.72E+02	3.66E+00	2.63E+01	2.01E+02	Sc1
Freshwater ecotoxicity [kg 1,4-DB eq]	FETP	1.05E-02	1.52E-04	2.13E-03	1.27E-02	Sc1
Freshwater eutrophication [kg P eq]	FWEP	4.99E-05	1.56E-07	6.47E-03	6.52E-03	Sc1
Human toxicity [kg 1,4-DB eq]	HTP	3.02E+01	4.58E-01	-3.18E+00	2.71E+01	Sc2
Ionising radiation [kg U235 eq]	IRP	1.03E+03	5.50E+00	1.06E+03	2.11E+03	Sc1
Marine ecotoxicity [kg 1,4-DB eq]	METP	1.09E-01	1.65E-03	-4.61E-03	1.05E-01	Sc2
Marine eutrophication [kg N eq]	MEP	6.57E-02	2.52E-02	9.43E-01	1.01E+00	Sc1
Metal depletion [kg Fe eq]	MDP	1.11E+00	1.15E-02	6.30E-01	1.75E+00	Sc1
Ozone depletion [kg CFC-11 eq]	ODP	3.32E-09	4.15E-11	6.80E-10	4.02E-09	Sc1
Particulate matter formation [kg PM10 eq]	PMFP	1.20E+00	8.27E-02	3.14E+00	4.35E+00	Sc1
Photochemical oxidant formation [kg NMVOC]	POFP	1.83E+00	3.37E-02	5.97E+00	7.81E+00	Sc1
Terrestrial acidification [kg SO$_2$ eq]	TAP	2.86E+00	5.34E-01	2.48E+01	2.77E+01	Sc1
Terrestrial ecotoxicity [kg 1,4-DB eq]	TETP	1.75E-02	2.61E-04	-1.69E-03	1.58E-02	Sc2
Water depletion [m^3]	WDP	1.18E+03	1.83E+01	-1.73E+02	1.01E+03	Sc2
Inventory (water intake and energy used for treatment)						
Blue water consumption [kg]	BWC	1.35E+03	1.97E+01	3.10E+02	1.66E+03	Sc1
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	PED	7.46E+03	1.57E+02	1.10E+03	8.64E+03	Sc1

MIDPOINT ENVIRONMENTAL IMPACT ASSESSMENT

According to the mid-point impact analysis based on the results of Figure 6, Sc1 was the best treatment facility because the dry continuous system required only a small space for operations with land use (ALOP, 2.40E-03 m^{2}a). Sc1 also had a small reactor, with little to no wastewater discharged and less heat needed as opposed to an equivalent of single-stage wet digestion system (Van et al. 2020).

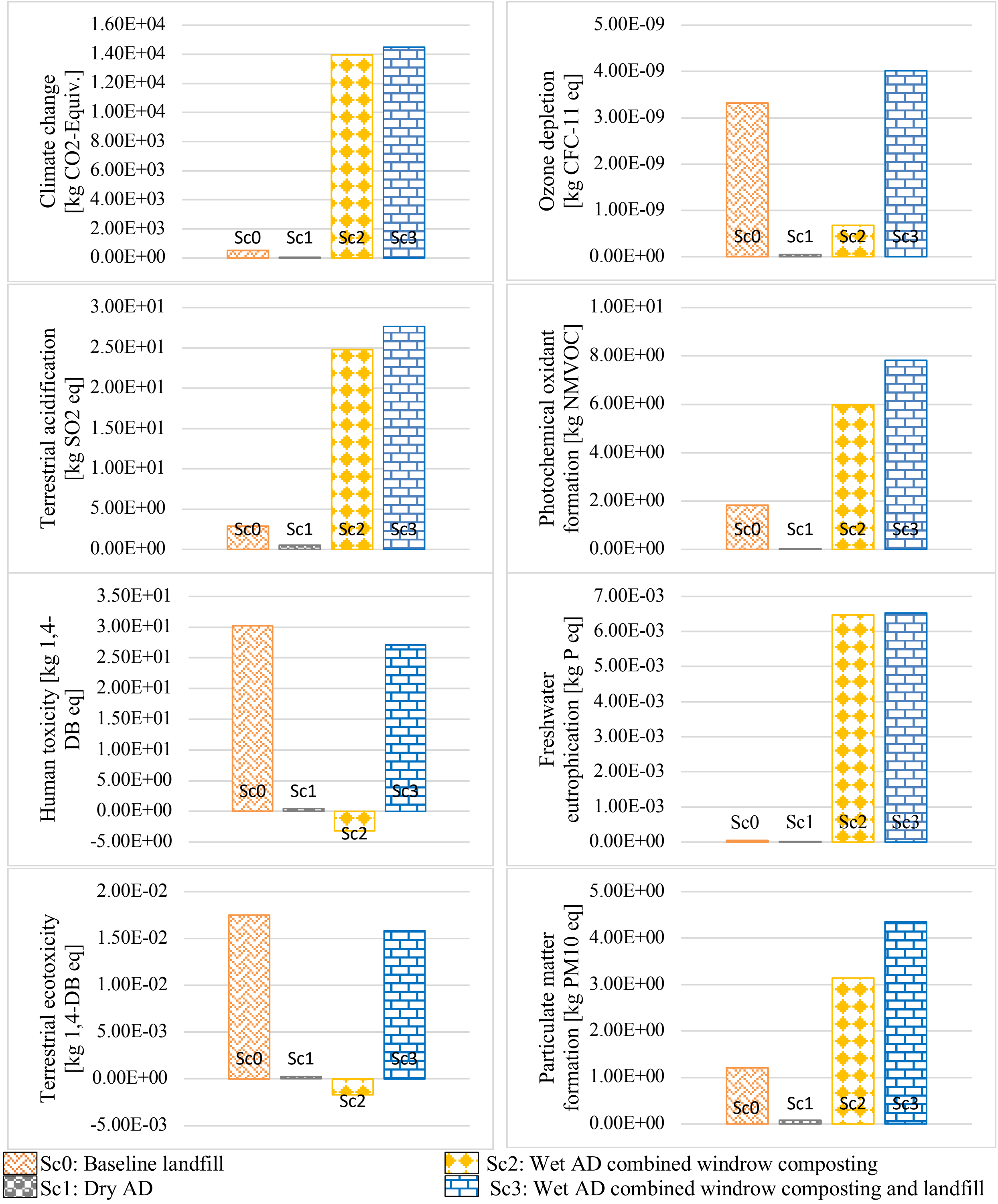

FIGURE 6. Results of 8 midpoint impact categories analyzed using ReCiPe (H) v1.07 generated by the four FW disposal and treatment scenarios

On the other hand, Sc3, as well as Sc0, required a wider area for operating and needed to be located far from a populated area. As a result, there was a significant increase in the volumes carried, as well as the distance travelled by road to digestion facilities. Another downside of Sc3 was that a substantial volume of water had to be applied during the process of wet AD treatment and landfill activities (Blue Water Consumption, BWC 1.66E+03kg).

Landfill machineries and dilution of the waste stream before internal mixing activities in wet AD stages require not only higher energy usage (PED 8.64E+03 MJ) and the cost of water, but also a high-volume reactor. Moreover, the dilution of waste will also lead to a reduction in the yield of biogas and more waste (Tong et al. 2018). Sc1 showed the best performance in the BWC (1.97E+01kg) category since this system fully utilized moisture content derived from FW substrates.

The GWP category measures emissions of GHGs that warm the earth by energy absorption, adversely affecting environmental, human health, and material well-being. Sc1 (4.94E+01 kg CO_2 eq) outperformed all other alternatives in this category because of the environmental benefits from compost production in addition to biogas and electricity generation. For the Sc1 system and mesophilic operating conditions considered in this study, biogas electricity can help reduce GHG emissions relative to a fossil-intensive electricity mix (Fusi et al. 2016).

Sc3 was the most significant contributing factor to the risk of global warming (1.45E+04kg CO_2 eq) in every case. The phases of aerobic windrow composting and landfill activity add the most to the GWP in the Sc2 and Sc3 scenarios as GHGs (mostly CO_2, CH_4, N_2O) are generated and discharged completely with no form of treatment, such as capturing or flaring.

Furthermore, the increased resource demand, such as the use of diesel and lube oil by landfill machines and equipment, is attributed to this high level of emissions. As wet AD dewatered digestate undergoes the open-composting treatment phase, CH_4 and CO_2 gases are released. As a result, the gas treatment for digestate curing and maturing produced by wet AD (via bio filtration or similar technologies) is frequently proposed as a last resort to reduce gaseous pollution to the atmosphere (Sánchez et al. 2015).

ODP estimates the ozone-depleting compound pollution, which lowers the concentration of stratosphere ozone and increases the amount of UV-B radiation reaching the Earth's surface. Increased UVB radiation intensity on Earth's surface will harm human health and destroy our ecosystems. The negative consequences of ODP were the most substantial in all landfill scenarios, whether Sc3 or Sc0 (4.02E-09 kg and 3.32E-09 kg CFC-11 eq), mainly from the emissions of a group of very stable industrial halocarbon gases used as solvents or refrigerants (the chlorinated CFCs or freons), or fire extinguishers (the brominated halons) (Hauschild et al. 2017). This is because, in nearly all Malaysian landfills, mixed MSW is deposited without first being pre-treated (Abba, 2014). Meanwhile, the majority of the ODP burden in the wet AD scenario was due to the digestion mechanism, primarily because of the high fermentation water demand (6.80E-10 kg CFC-11 eq). The pollutant is derived greatly from the background processes such as power generation for the treatment process and tap water of the wet AD scenario cases (Tong et al. 2018).

POFP refers to the reaction of anthropogenic airborne pollutants with sunlight, which results in the formation of reactive substances (predominantly ozone) and the increase in ground ozone levels. This produces smog, a chemical compound that causes respiratory diseases and disorders in humans, as well as habitat loss and crop damage. Sc3 contributed far more to the POFP (7.81E+00 kg NMVOC) than Sc2 (5.97E+00 kg NMVOC) due to the high concentrations of VOCs, CO, and NO_X. The significant man-made emissions of VOCs are derived from road traffic and the use of organic solvents. CO is emitted from combustion processes with insufficient O_2 supply. These include road traffic and various forms of incomplete combustion of fossil fuels. NO_X is also emitted from combustion processes in transport, and energy systems. In AD scenarios, the emissions from biogas engines created a POF potential, and the exhaust gas emissions represented the largest part of the effect in all situations (Tong et al. 2018). Sc1 would seem to be the most favoured (3.37E-02kg NMVOC) in this impact category.

When the three AD technologies were compared, integrated wet AD scenarios (Sc3, and Sc2) indicated a poorer environment for TAP (2.77E+01kg and 2.48E+01

SO_2 eq, respectively). Out of 100%, 95% of acidification from both integrated wet AD (Sc3, and Sc2) is derived primarily from the background processes such as power generation during the treatment process. TAP relates to the emission of acidifying compounds, which alter the pH of the receiving medium and cause damage to the ecosystem, as well as living organic and inorganic materials contained therein. Landfilling had the third greatest effect on acidification (2.86E+00 kg SO_2 eq) relative to Sc1 (5.34E-01 kg SO_2 eq). Concentrations were higher in landfill sites, especially in Sc3 and Sc0 due to possible liner leaks (Abba, 2014). Landfill liners are typically designed to collect 70% of leachate and lose 30% due to leaks, which are often a concern, particularly as liners age (Cherubini et al. 2009). The use of electricity and diesel for the whole wet AD treatment, such as in the Sc3 and Sc2 processes, also contributed considerably to this acidification impact.

The findings showed that, similar to freshwater eutrophication potential (FEP), nitrogen-containing inorganic compounds were the major contributors in TAP, with biogas/syngas combustion in a gas engine and digestate post-composting being the maximum polluting steps. Electricity substitution plays an important role in lessening the acidification impact in each scenario by avoiding the emission of SO_x and NO_x from fossil fuel-based power plants. This substitution compensates for the emission of NO_x and NH_3 during waste treatment, and results in a net environmental saving in all the scenarios (87.84 kWh Sc1 and 334.29 kWh wet AD).

Both integrated wet ADs impacted the freshwater eutrophication (FEP). Sc3 (6.52E-03 kg P eq) was the highest and Sc2 was the second highest (6.47E-03 kg P eq) because of N_2O pollution from vehicles during the transportation phase. Due to the obvious higher overall N content in landfill leachate, the nutrient enrichment was greater in Sc3. The Sc1 (1.56E-07 kg P eq) had the lowest FEP. Meanwhile, the integrated wet ADs, Sc3 followed by Sc2 (3.14E+00 kg PM10 eq), had the highest emissions of PMFP compared to Sc1 (8.27E-02 kg PM10 eq).

PMFP, which consists of respirable particles (PM_{10}) with an aerodynamic diameter of less than 10 μm, coarse particles (PM10–2.5) between 2.5 and 10 μm, fine particles ($PM_{2.5}$) less than 2.5 μm, and ultrafine particles (UFP) less than 100 nm, has mainly toxicity-related health effects (Hauschild et al. 2017). Primary PM refers to particles that are directly emitted, e.g., from road transport or power plant activities. Secondary PM refers to organic and inorganic particles formed through reactions of precursor substances including NO_x, SO_x, NH_3, and semi-volatile and volatile organic compounds (VOC). The Sc0 had the third highest impact on PMFP (1.20E+00 kg PM10 eq) in this comparative study.

With regard to human toxicity potential (HTP), this impact was the lowest for electricity generated by Sc2 (-3.18E+00 kg 1,4-DB eq) and highest for Sc0 (3.02E+01 kg 1,4-DB eq). For Sc3, the main contributor was the production of the emissions from biogas combustion.

Meanwhile, for ecotoxicity potentials (such as METP and TETP), the lowest METP was estimated for Sc2 (-4.61E-03kg 1,4-DB) and the highest for Sc0 (1.09E-01 kg 1,4-DB eq). The landfill operations were the main contributors to this impact for Sc0. Sc1 had lower MAETP and TETP due to the efficiency associated with economies of scale as these impacts were mainly influenced by the plant operation. Similar to HTP, the best option for TETP was Sc2 (-1.69E-03 kg 1,4-DB eq), but as for TETP, Sc0 had the highest impact (1.75E-02 kg 1,4-DB eq). The main hotspot was grid electricity used for landfill because of the emissions of beryllium and hydrogen fluoride in the life cycle of electricity generation (Fusi et al. 2016).

SINGLE SCORE BY ENDPOINTS ReCiPe LCIA METHODOLOGY ANALYSIS

Based on the single score ReCiPe endpoint analysis as shown in Table S1 *(supplementary)*, Sc1 seemed to be the most promising method of FW treatment for long term sustainability, particularly for avoiding loss of resources (Resource's Scarcity, 4.44E+01Pt). It also had more positive impacts compared to the other three scenarios, as it caused the least damage to both human health (9.28E-05 Pt) and ecosystems (3.94E-07 Pt) as shown in Figure 7. This was determined by a significant decrease in both mileage and quantities on road transportation, relatively low demands on operational energy, and energy/resources preservation against compost produced by the digestible substance.

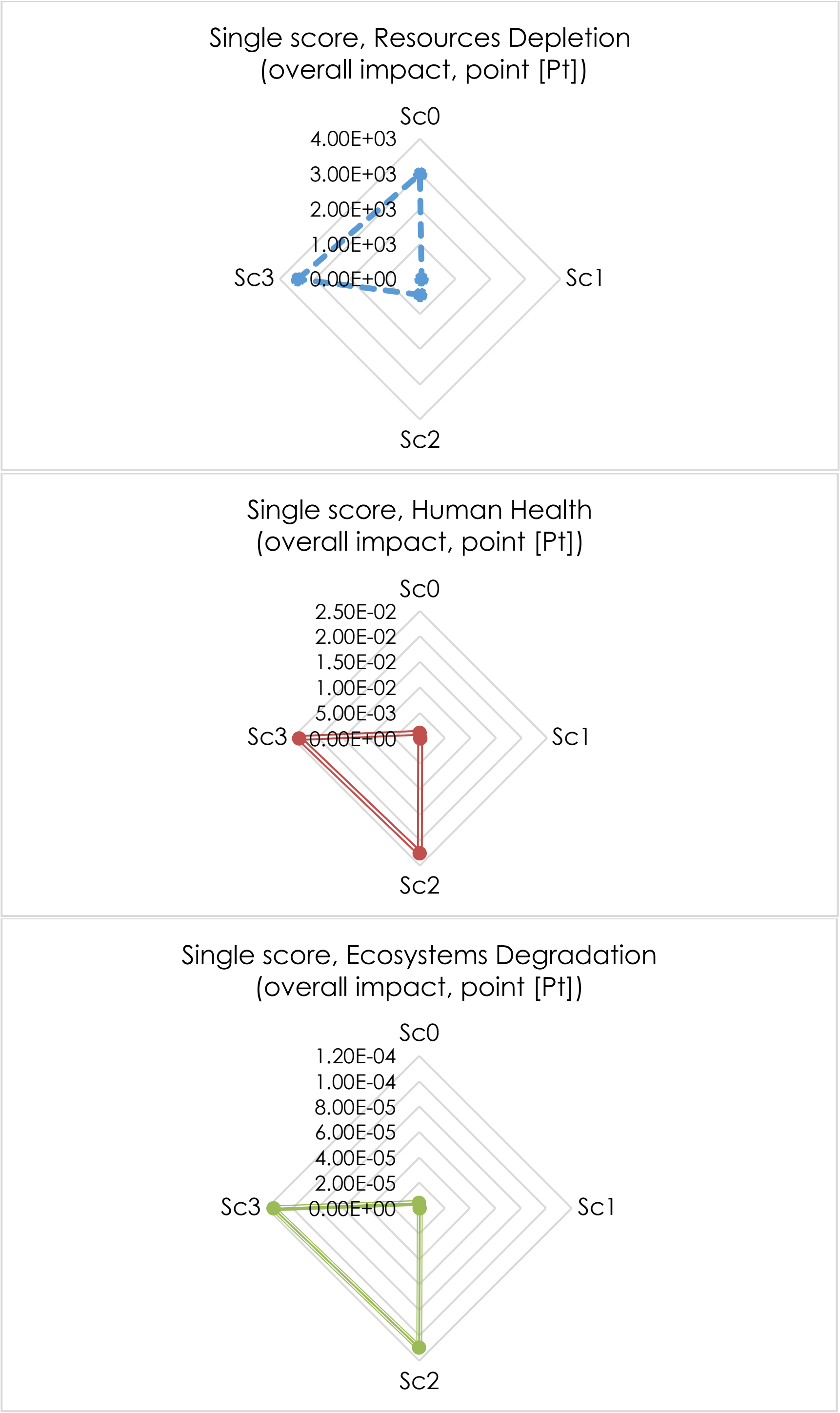

FIGURE 7. Comparative single-score endpoint results for Sc0, Sc1, Sc2 and Sc3

Despite the potential for increased green energy efficiency, conducting wet AD under integrated conditions (i.e., Sc3) has disadvantages, such as greater energy consumption for continuous mixing (Resources Scarcity, 4.48E+02 Pt) (Table S1-*supplementary*) and a prerequisite for more vigilant process management as the microorganisms are most responsive to shifts in environmental factors (Visvanathan, 2006). As opposed to thermophilic processes, mesophilic processes are often predominantly invulnerable to NH_3 as the proportion of fatty acids (FA) present in the medium changes with temperature (Hansen et al. 1998).

This mesophilic conducting reactor (Sc1) is proven to be harmless for the methanogenic bacteria since the thermophilic will rise temperature in the ADs, which can increase the FA accumulation from 0.75 to 2.6 g/l. It is shown by a drop in specific volume growth from 1 to 0.67 as the FA concentration rose from 1.1 to 1.3 g/l (Hansen et al. 1998). The requirement for extra stringent process control to preserve stability renders thermophilic AD less common while greater efficiency for mesophilic assets may be achieved if the process is thoroughly explored (Rocamora et al. 2020). Sc3 is the least favoured treatment method with a loss of resources (3.48E+03 Pt), followed by Sc0, because it inflicts the greatest damage in terms of resource depletion resulting from fuel and energy consumption during the treatment.

Figure 7 also demonstrates fewer damaging impacts of Sc0 on human health (2.29E-04 Pt) and ecosystems (1.15E-06 Pt) when compared to both wet ADs (Sc3, 2.37E-02 Pt and Sc2, 2.26E-02 Pt). Sc3 caused the greatest damage to the ecosystem (1.15E-04 Pt) and human wellbeing (2.37E-02 Pt). Previous research indicates that aerobic windrow and landfills are a major contributor to global warming (Al-Rumaihi et al. 2020; Abba, 2014; Cherubini et al. 2009). The emissions of CH_4 from landfills followed by windrow composting have the greatest impact on climate change. NO_x can affect breathing and may increase the risk of respiratory infections.

Concerning the single score, the relative contribution of the respiratory categories in PMF in the ReCiPe endpoint (H)-this method category is related to emissions of particulate, SO_x, NH_3, and NO_x with some small differences in characterization steps and all of them are expressed in Disability Adjusted Life Years (DALY), at the endpoint level. When compared to dry AD, both wet ADs (Sc3 and Sc2) in the PMFP category (1.13E-03 and 8.18E-04 DALY) had the highest values that represented harmful impacts on human health safety and decreased environmental benefits *(Table S1-supplementary)*.

Furthermore, landfilling, such as the one used in the current design, emits a lot of NO_x from transportation trucks and landfill equipment. As there are no facilities for gas and leachate treatments, the degradation of waste material itself produces sulphur-based compounds. The presence of polluting compounds, such as CO, N_2O, and H_2S is found in both leachates and emissions (Abba, 2014).

The recent surge in the warming of the Earth's atmosphere is mostly due to the effects of ozone depletion originating from landfill treatment. Other implications include a reduction in harvest crops (due to photosynthesis disruption), tumour signs (skin cancer and eye diseases), and a decrease in sea plankton. All landfill scenarios have also been shown to have a severe acidification impact. Acidification in landfills is primarily due to NO_x and NH_3 emissions (Abduli et al. 2011).

Besides that, the water used in the wet AD system such as Sc3 and Sc2 was already listed as the possible environmental hotspot for ODP (7.05E-12 DALY and 1.20E-12 DALY respectively) *(Table S1-supplementary)* in this study, and supported by the previous study as well (Tong et al. 2018). Wet AD is known as an effective and stable method of treating FW, characterized by high solubility and fast acid release. Researchers have shown that the addition of water can aid the distribution of volatile fatty acid (VFA) to methanogens by acidic bacteria (Nagao et al. 2012).

This does not only prevent a pH decrease and inhibition of methanogen microbes induced by VFAs accumulation, but also speed up the process of hydrolysis, leading to an improved CH_4 output and decreased VS rate (Liotta et al. 2014). Water also participates in the pre-treatment to reject inorganic impurities by separating the wet density.

Finally, FW's slurry of water reduces the viscosity of the substratum flow and enables the use of cheap centrifugal pumps in transport and handling (Lissens et al. 2018). All these considerations justify the local company's adoption of the wet AD method. Nevertheless, the comparatively high-water usage necessary to accomplish the low solid state is an ecologically significant problem for wet AD, and literature reviews indicate that water usage for water AD plants ranges from 0.37 to 1.1m^3 per ton of organic waste (Tong et al. 2018).

Sc1, alternatively, uses less water in comparison. Angelonidi and Smith (2015), however, commented that, at times, high water additives were also given for dry AD processes, equivalent to 15% and 40% of the overall digester food mass. In this LCA report, 50% of the water demand was expected to be supplied from the digester with recycled water.

RESULTS COMPARISON WITH LITERATURE

When the results were compared to the literature, there were differences in the order of magnitude in all of the impact categories (Table 6). Variations resulted from the establishment of system boundaries, specification of treatment facilities, efficiency of specific plants, feedstock properties, and allocation or replacement methods. As there was no demand for district heating in Malaysia, the excess heat from the biogas CHP had not been absorbed, resulting in an inadequate discovery of the benefits of biogas (Hanum et al. 2019).

As discussed in Table 1, the results of an LCA on a waste management plan are divergent and heavily influenced by expectations and local constraints (Tong et al. 2018). To ensure the high reliability and integrity of the LCA studies, thorough documentation of the findings and the whole dataset is needed.

Considering the conceptions of global warming (referred to as "Global Warming" in CML, TRACI, EDIP, and Impact 2002+ and "Climate Change" in ReCiPe Midpoint; the same character reference was taken from the IPCC), it should have been noticed that all of the impacts can indeed be contrasted because they are measured in kilograms of CO_2 equivalent (kg CO_2 eq).

In Sc1 comparison with Angelo et al. (2017) from Brazil, this study (Sc1) presented lower GWP, ODP and POFP since it was a closed system and not integrating the landfill into the system boundary. Meanwhile, for the wet AD combined windrow composting treatment, the study conducted by Tong et al. (2018) from Singapore had the highest GWP due to the large-scale volume of treatment it handled (1000t) with a thermophilic reactor, which requires more energy and water to operate if compared with the Sc2. They did, however, generate a significant amount of electricity, and the electricity/biogas and compost generated by the wet AD scenario are credited with reducing energy and mineral fertilizer use. As a result, TAP for this analysis was significantly reduced.

Finally, Abduli et al. (2011) from Tehran, Iran showed that landfill was the best environmental scenario with the minimum GWP since it had a mechanism for gathering and monitoring gases used to produce energy while the assessed landfill procedure in this analysis (Sc0) was the second-best environmental scenario due to the absence of this system.

TABLE 6. Comparison of impact scores per treating 1 ton waste from this and other similar LCA studies

Impact Category	Unit	Sc1: Dry AD	Integrated Dry AD	Sc2: WetAD+ comp.	WetAD+ comp.	Sc0: Baseline Landfill	Landfill
		This study	(Angelo et al. 2017)	This study	(Tong et al. 2018)	This study	(Abduli et al. 2011)
LCIA		ReCiPe	ILCD	ReCiPe	CML 2001	ReCiPe	Eco-Indicator 99
GWP	kg CO_2-eq	4.94E+01	4.00E+02	1.40E+04	9.41E+04	5.34E+02	3.80E−01
TAP	kg SO_2-eq	5.34E-01	-	2.48E+01	-1.69E+02	2.86E+00	-
FEP	kg P eq	1.56E-07	-	6.47E-03	-	4.99E-05	-
FETP	kg 1,4-DB eq	1.52E-04	-	2.13E-03	-1.13E+04	1.05E-02	-
HTP	kg 1,4-DB eq	4.58E-01	-	-3.18E+00	-2.55E+04	3.02E+01	-
ODP	kg CFC-11 eq	4.15E-11	7.00E-05	6.80E-10	-	3.32E-09	-
POFP	kg NMVOC	3.37E-02	4.00E-01	5.97E+00	-	1.83E+00	-
TETP	kg 1,4-DB eq	2.61E-04	-	-1.69E-03	-3.36E+02	1.75E-02	-

According to Table 6, the midpoint studies performed by Tong et al. (2018) employed CML techniques and demonstrated not only promising evidence of terrestrial acidification reduction, but also improvement in this impact category compared to Sc2. Because of variations in spatially related characterization variables and different model features followed by each method, the results for acidification are not convergent, and hence, the wet AD combined composting by Tong et al. (2018) and landfill by Abduli et al. (2011) scenarios cannot be compared.

CML (acidification, as kg SO_2 eq), ReCiPe (terrestrial acidification, as kg SO_2 eq), EDIP (acidification as square meter), TRACI (acidification as H+ moles eq), and Impact 2002+ have been used to illustrate the distinctions between terrestrial acidification (as kg SO_2 eq) and aquatic acidification (kg SO_2 eq) (Cavalett et al. 2013). Another form of environmental impact that can also be compared with various techniques was ozone layer depletion (called "Ozone Depletion" in ReCiPe, TRACI, and EDIP and "Ozone Layer Depletion" in CML and Impact 2002+, represented in kilograms of chlorofluorocarbons equivalent) (kg CFC-11 eq) (Cavalett et al. 2013).

This quantitative analysis is indeed not possible with impacts like eutrophication and toxicity, which have different indicators for different ecological components based on the approach used.

SENSITIVITY ANALYSIS

Sensitivity analysis (SA) aims to examine how model variables and parameters, assumptions, and input values impact the outputs of the research and its findings. SA is a tool for simplifying data collection and interpretation without negotiating the reliability of a result. The sensitivity study for dry AD was examined in this section. To evaluate the sensitivity of each parameter, 10% of variations in parameter input were used. The sensitivity results for GWP, ODP, POFP, TAP, FEP, PMFP, HTP and TETP from Sc1 plant are depicted in Table 7. As seen in Table 7, four parameters (diesel, electricity, water, and distance) were tested for robustness. The parameter is deemed as sensitive when the percentage of variation is greater than 10%. Electricity or energy used for FW treatment is considered to be the most sensitive parameter based on the eight impact groups used for the sensitivity study, with only terrestrial acidification (7.76%) having the lowest percentage of change of less than 10%. The other parameters were less than 10% of each impact category, indicating they were less sensitive to the impact categories.

TABLE 7. Eight impact groups sensitivity analysis for changes in dry AD

Percentage of Variation (%)	Input Parameters	GWP kg CO$_2$ eq	ODP kg CFC 11 eq	POFP kg NMVOC eq	TAP kg SO$_2$ eq	FEP kg P eq	PMFP kg PM10 eq	HTP kg 1,4-DB eq	TETP kg 1,4-DB eq
10%	Diesel	0.00%	0.02%	0.01%	0.00%	0.32%	0.00%	0.00%	0.00%
	Electricity	15.80%	92.80%	79%	7.76%	61%	21.20%	94.70%	94.80%
	Water	0%	0%	0%	0%	0%	0%	0%	0%
	Distance	0.05%	0.23%	0.19%	0.01%	3.26%	0.03%	0.04%	0.03%
Reference	LCIA midpoint	49.4	4.15E-11	0.0337	0.534	1.56E-07	0.0827	0.458	0.000261
-10%	Diesel	0.00%	-0.02%	-0.01%	0.00%	-0.32%	0.00%	0.00%	0.00%
	Electricity	-15.80%	-92.80%	-79%	-7.76%	-61%	-21.20%	-94.70%	-94.70%
	Water	0%	0%	0%	0%	0%	0%	0%	0%
	Distance	-0.05%	-0.23%	-0.19%	-0.01%	-3.26%	-0.03%	-0.04%	-0.03%

RECOMMENDATIONS

It is suggested to enhance the analysis conducted on AD FW treatment plants to provide better outcomes. This could be done by identifying a system with more processes to achieve a more accurate result, thereby requiring additional processes with more stable inputs and outputs. Furthermore, the value chain could be compared with the related studies conducted. LCA practitioners are highly advised to do both the material flow accounting (MFA) and the LCA for a more precise prediction (Seldal 2014).

Moreover, appropriate databases could be selected to model the study system, for example by using waste-related LCA software technologies for a more accurate simulation of waste systems. In waste treatment schemes, for example, ORWARE (organic waste research), IWM-2 (integrated waste management II), WISARD (waste – integrated systems for assessment of recovery and disposal), WRATE (waste resources assessment tool for the environment), and EASEWASTE (environmental assessment of solid waste systems and technologies) are among the recommended software (Kulczycka et al. 2015).

Concerning the AD solutions to organic waste disposal, biodegradable matter can be treated efficiently in a single-stage dry and a single-stage wet high-rate digestion system (Van et al. 2020). Both systems can reduce water usage and energy costs substantially. Nevertheless, a dry, continuous system is more desirable for the high generation of organic wastes in a city with less space because it has a small reactor, inexpensive pre-treatment, reduced wastewater discharge, well-implemented composting, and lower heat consumption (Van et al. 2020).

Likewise, Sabri et al. (2018) conducted single-stage (MR-1) and two-stage (MR-2) investigations in two similar 1L anaerobic sequencing batch reactors (ASBR) with effective capacities of 800 mL and operating at 37 °C under mesophilic conditions. This study shows that semi-continuous anaerobic sequencing batch reactor CH_4 production from sago mill effluent is viable in both single and two-stage systems under mesophilic conditions (Sabri et al. 2018).

The recommendations to reduce AD's impacts on the environment are by introducing an on-site composter and decentralized management system. The primary goal of using an on-site composter, such as dry AD, is to ensure that the composting process can be performed in-situ, and to save the cost of transporting waste to a landfill (Brenes-Peralta et al. 2020; Righi et al. 2013). Poeschl et al. (2012) acknowledged this fact and demonstrated that small-scale AD technologies were a good potential solution for reducing environmental effects.

In addition to social benefits, greater public acceptance of waste treatment facilities and better citizens' awareness of waste management issues can be gained (Brenes-Peralta et al. 2020; Righi et al. 2013). Regardless of whether the FW treatment system is dry AD or wet AD, the operating processes that require power or fuel usage must be optimized to decrease the overall environmental effects of the process. Optimization of inoculum to substrate ratio, composition, and scale of feedstock is among the important parameters in effective AD operations. An investigation by Lim et al. (2019) strongly recommended that 23.18% of vegetable waste, 34.34% fruit waste; 36.46% meat waste; and 6.01% cow manure with composite convenience of 0.977 were optimal composition treatment settings for dry AD with dry leaves. The composed desired strength was close to unity and it demonstrated that all responses have been effective in the settings. The developed regression models were experimentally validated, with predicted responses being obtained in acceptable ranges for C/N ratio (21.2-21.8), and pH 7.92-7.99. Finally, the negative issues associated with landfill can be avoided if gas extraction and application are integrated into the landfill. Landfill liner designs often state that liners collect 70% of leachate, and those liners must be replaced as they age (Cherubini et al. 2009).

FUTURE RESEARCH DIRECTION

The LCA on FW treatment studies analysed in this study are identical; ADs exert both the environmental burden and the GWP credits. GHGs are released by AD plants as a result of organic matter degradation, including the use of electricity and fuels in the waste disposal operations. LCA can lead to a better definition of environmental impact categories for AD systems, but it also establishes the possibility of ignoring considerations, such as the inherent conflict of costs and social consequences from the evaluation. Although LCA is helpful, it is inadequate for making sound decisions about design, production, or organizational improvements (Curran et al. 1996).

LCA may not monetize impacts and it has largely ignored the approval appraisal of multi-stakeholder interest, which includes State and Regional governments, waste management professionals, environmentalists, residents, retail owners, and food-related sectors (both small and large). However, that is not to say that the LCA impact analyses, which do not monetize impacts or address societal acceptance, are without value. The impact of monetizing on the life cycle is critical to LCA's fullest potential as a decision-making mechanism.

The reason is simple, it should translate inventory and effect analyses into metrics (dollars and cents) that business organizations would understand. By defining specific method and product change goals, the transition from carbon inventory to forecasts of environmental and health threats offers crucial details. All of these process and product development considerations require the core financial rationale to justify the desired reform.

The public approval is a qualitative metric that is affected by the region's degree of growth and waste management technology. Technological advancements will find it more difficult to enter a market with certain high levels of confusion and fear of negative effects on humans and the ecosystem. Since public approval is a qualitative quality which cannot be calculated, it is recommended that a 9-level scale (1-worst, 9-best) to be used to assess this set of parameters in the multi criteria-analytical hierarchy process (AHP) phase (Brenes-Peralta et al. 2020).

As a result, a comprehensive framework incorporating various related variables in assessing FW treatment approaches through the integration of LCA, life cycle costing, and multi-criteria needs to be established in order for the decision-makers to make good decisions while taking into account the unique strengths and weaknesses of every judgment (Zhou et al. 2019). To get a full picture of the impacts of FWM, social (respiratory illnesses, etc.), economic (diesel prices, etc.), and psychological (abnormal sounds, etc.) elements must be addressed for further evaluation and ultimate decision-making (Khandelwal et al. 2019).

CONCLUSION

The comparison between the environmental impacts of the four FW management strategies in Malaysia has been conducted according to the ReCiPe LCIA method. The findings of the LCA revealed that the Sc1 scenario produced extensive improvements in the 12 mid-point impact categories and the single score ReCiPe endpoint analysis method of treatment, particularly for avoiding loss of resources, with the least damaging impact on ecosystems and human health relative to all three scenarios.

This is made possible by the significant reduction in road transport distances and volumes, comparatively low energy requirements for operation, and preservation of energy as well as resources, mostly from compost produced by the digestible material. Meanwhile, Sc0 is considered the second-best option, and the third is Sc2, and the last option with significant negative environmental impacts for FW treatment alternatives is Sc3.

Even though there is a similar comparable finding for environmental impact categories using AD as an effective biotechnological method of managing FW, whether dry or wet, more studies are needed to address some of the drawbacks associated with the high overall amount of processed solid material.

Optimization of inoculum to substrate ratio, composition and scale of feedstock, liquid recirculation, bed compaction, and usage of bulking agents are some of the parameters that require further study in batch dry AD to minimize localized inhibition effects and prevent process instability. More considerations must be paid to the relationship between feedstock composition, organic loading rate, and mixing regimes for continuous-batch dry AD systems.

Besides that, it is important to provide a comprehensive picture of the impacts of FW management by AD treatment, and further assessment of final decision-making factors, such as social (i.e., public acceptance) and economic (i.e., life cycle costing) factors must be addressed.

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DECLARATION OF COMPETING INTEREST

None

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