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Environmental impact hotspots of an integrated wet anaerobic digestion through life cycle assessment for food waste management

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Abstract. Wet anaerobic digestion (AD) is one of the most widely implemented systems that valorize food waste (FW) for biogas production. Despite the undeniable AD benefits, the environmental impact of AD could differ depending on the biogas systems used. This article examines the hotspots on environmental impact of FW management such as global warming and ozone depletion based on integrated wet AD by utilizing a life cycle assessment approach. The integrated wet AD scenario in this study is a technology that combines wet AD, aerobic windrow composting and a landfill. The scenario modelling was accomplished by applying GaBi v6.0 software with 1 ton of pre-treated FW as a functional unit, and the analysis was based on the ReCiPe (H) v1.07 characterization technique. At the midpoint level, it was observed that the integrated wet AD presented the most significant environmental impact in terms of ionizing radiation ($1.4\text{x}10^0$ kg U235-eq), followed by water depletion ($1.11\text{x}10^3$ m^3-eq), global warming ($6.27\text{x}10^2$ kg CO_2-eq), fossil depletion ($2.18\text{x}10^2$ kg oil-eq) and human toxicity ($2.89\text{x}10^1$ kg 1,4-DB-eq). The disadvantages of the integrated wet AD in global warming were associated with CO_2, CH_4, and N_2O emissions from the energy used for process treatment and fossil fuels during transportation, primarily in landfill activities, followed by wet AD and aerobic windrow composting stages. Regarding single-score indicators, integrated wet AD presented the most resource damaging impact ($3.50\text{x}10^3$ Pt), mainly due to fossil depletion. This study emphasizes the necessity of reducing the life cycle consequences related to CH_4, N_2O and NH_3 emissions throughout the decomposition process in integrated wet AD, particularly landfill activities.

1. Introduction

Throughout the decades, food waste (FW) has become a significant problem. Many stakeholders have shown interest because of its potential consequences and prospects for energy recovery [1]. From an environmental viewpoint, FW is a noticeable loss of valuable resources, as extensive resources are required for food cultivation, manufacturing, transportation, storage, selling, and preparation [2]. The global carbon footprint of FW is responsible for 4.4 Gt of carbon dioxide equivalent (CO_2 eq) per year [3]. An estimated 70% of FW is landfilled in Malaysia, while others use aerobic composting [4], [5]. In response to the environmental concerns, deterioration of important land assets and the scarcity of non-renewable resources, the Malaysian government and experts have begun investigating green disposal technology as a solution to sustainable waste management with the advantages of renewable energy sources [6]. On the other hand, the focus on the circular economy has realized that biogas and biofuel extraction and utilization provide significant potential for energy recovery and resources used from FW [7] – [9].

Anaerobic digestion (AD) is a clean technology for FW treatment since it dissolves organic materials biologically in an oxygen-free atmosphere and helps stabilize, disinfect, and deodorize waste [10]. It is a process of retrieving energy from diverse organic feedstocks with biogas (methane (CH_4) and CO_2) and producing digestate as the primary product. Currently, Germany was ranked as the world's leading biogas producer utilizing the AD technology, with a growth of 647% (2010–2013), followed by China and Italy [11]. Several modern biological plants in Malaysia have also been developed with dry AD to treat FW (i.e., Petaling Jaya, Selangor). Hoo et al. [8] discovered that about 60 Mm^3 of CH_4 (equal to 16.3 MW of energy) could be produced yearly from Malaysian FW that created in year 2010.

Due to AD's high valorization value for waste, the potential for renewable energy and the regeneration of nutrients, the assessment and reporting of its environmental impacts continue to be an important research focus. Biogas generated by AD is also anticipated to reduce greenhouse gas (GHG) emissions [12]. The majority of the comparative life cycle assessments (LCA) for environmental impact indicated a detrimental influence on the AD system were acidification and eutrophication [11]. However, the environmental results of the LCA of AD might vary depending on the biogas systems and LCA methodologies employed [13].

As reported by Brenes-Peralta et al. [1], centralized AD for FW recovery facilities can raise global warming potential (GWP) and land use compared to semi-centralized ones. The increased distance travel by waste collection vehicles and the corresponding rise in air pollution emissions, noise, and traffic were significant causes. Meanwhile, in integrated AD technologies, Al-Rumaihi et al. [14] discovered that the human toxicity for FW management was the most significant for AD combined composting (3.47×10^0 kg 1,4-DB eq). The hotspots were determined during process treatment, followed by collection and transportation of waste. Tong et al. [12] found the AD combined with composting for FW treatment was more environmentally friendly than other methods (gasification and incineration) for all environmental impacts, except for eutrophication potential (EP), GWP, and photochemical ozone creation (POCP). Composting of AD digestate produces the highest GWP releases, with almost 94% CH_4 and nitrous oxide (N_2O) [12].

Despite the LCA implementation of integrated AD as an alternative treatment technique for FW being widely used in other countries, the position of integrated AD in Malaysia is not clear. Thus, a comprehensive LCA for integrated wet AD for FW, particularly the hotspot identification for the environmental impact of the AD treatment, which is largely unknown, is necessary [11], [15]. Furthermore, it is critical to understand the perspective of the impact in every LCA study [16]. The selection of an established life cycle impact assessment (LCIA) system would not assure its conformance since most studies revealed that several of the environmental impact procedures had been neglected, as demonstrated by Ghazvinei et al. [17] and Righi et al. [18]. In certain circumstances, this results in decreased reliability of the LCA results unless the exclusion is justified correctly and in agreement regarding the research's objective and scope, even after using a well-established LCIA system.

Thus, this study assesses the whole range of environmental impact scores on FW valorization alternatives using integrated methodologies that includes wet AD, followed by aerobic windrow composting and a landfill. Its goal is to identify the hotspots relating to the phases and activities that have the most significant influence on the environment, and to develop strategies that target the major impact drivers in the integrated AD process.

2. Materials and Methods

The LCA approach based on ISO 14040/44 has been used to assess the environmental hotspot impact of the integrated wet AD FW treatment. An LCA process involves four steps: goal and scope definition, life cycle inventory, life cycle impact analysis, and result interpretation. Flowchart for the steps in the assessment of integrated wet AD for FW management is shown in Figure 1.

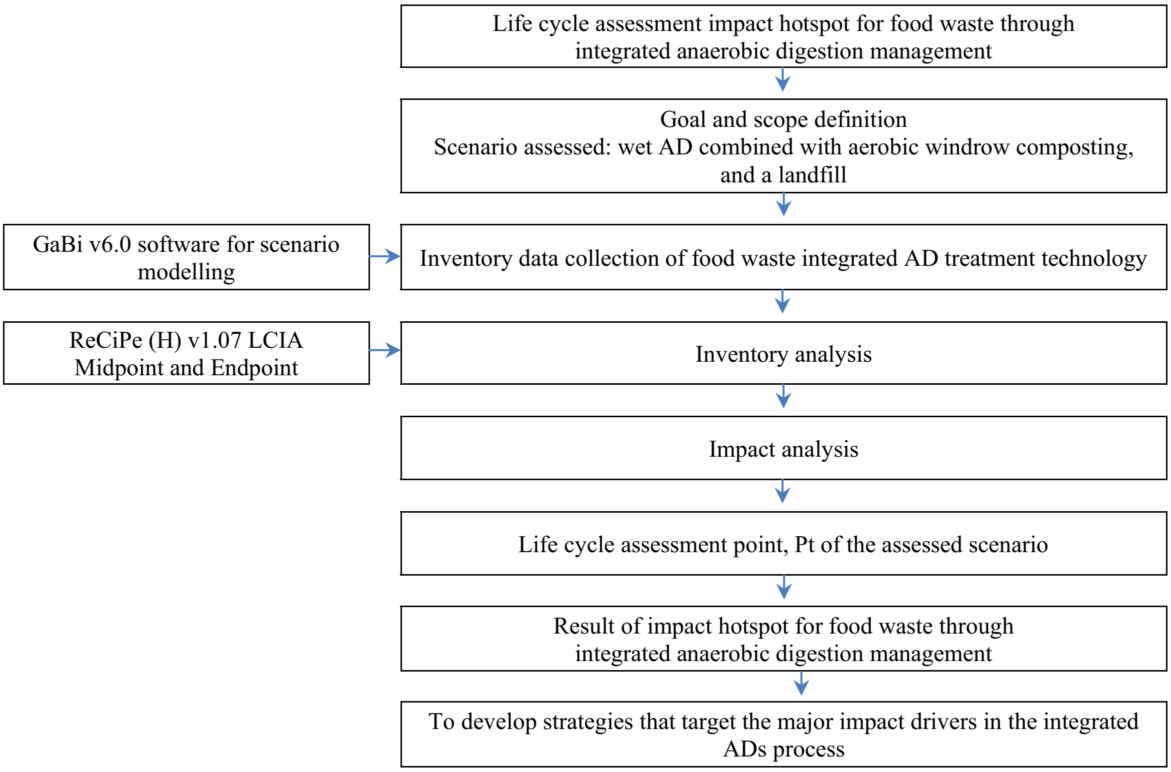

Figure 1. Flowchart for the steps in the assessment of integrated wet AD for FW management

2.1. Goal and scope definition

The principal application of this study is to discover the components of a treatment system that have the most significant influence on the environment (hot spot identification), which in this research concentrates on integrated wet AD treatment for FW management. Analysis of hotspots can reveal comprehensive information about impacts that can be used to identify potential solutions for integrated wet AD treatment for FW management while also prioritizing resources and actions around the most significant impact on its environmental impact profile. The findings of this study are essential to assist policy-makers and other stakeholders to classify, analyze, and visualize sustainability hotspots, with the knowledge and understanding drawn for ecological management of FW from agricultural and industrial sources in Malaysia.

Wet AD, aerobic windrow composting, and landfill are independent processes. When integrated, they may improve the waste management system's efficiency and achieve environmental advantages. Neither of the treatment options examined can eliminate landfilling, regardless of whether it is in the context of AD or composting. Some percentages of the waste residues of the inorganic substances in the collected waste after sorting are still transported to a landfill for disposal. However, the portion to be landfilled was reduced [18].

Seldal [19] found that optical sorting is critical to the efficacy of wet AD treatment. Consequently, a strategy encouraging separated collection of organic fractions should be taken, ideally in conjunction with policies promoting the use of bioplastic bags. At waste-to-energy facilities, Optibag plants are deployed to sort the FW. A grinder is used to open the green bags first. The waste is then carried through four mechanical pretreatment steps, each of which employs the separation process [19]. As a result, the significance of promoting bioplastic bags as a method for properly segregated collection of organic waste is emphasised in this study's objectives.

The management of 1 ton pre-treated FW has been chosen as the functional unit and the boundary systems assessed from cradle to gate. In this work, pre-treated FW is defined as soluble organic material pumped directly into the AD fermentation through four stages of mechanical pretreatment, which utilise the separation technique [19]. Upon receiving FW at the wet AD facility, the FW is then transported to the optical bags sorting, where a grinder is used to open the bags. Then, all the contaminants (plastics, metal cans, or glass bottles) bigger than 25mm are removed by metal separation using an electromagnet. Water is added to the substrate mix to reduce the dry matter content to make it suitable for the subsequent separation stage performed by wet AD technology. The FW particle size is reduced to a maximum size of 10mm through a squeezing process by a strain press machine. Finally, the last stage of the mechanical pretreatment is the hydrocyclone, which removes and washes grit and sediments smaller than 10mm.

General value chains regarding biogas functional specifications were adapted according to Seldal [19] and Ghazvinei et al. [17]. While aerobic windrows were referred to as composting plants at Tanah Sutera Development Johor Bahru and Saer et al. [20], landfill modelling was used Abba [21] and redesigned for this study's purpose. During the analysis, the process of collecting waste from business and residential locations, transportation, AD treatment phases, including the production of compost products by aerobic windrow composting, and landfilling of waste were considered within the system boundary (Figure 2). The solid material produced by the AD, known as the digestate, undergoes an aerobic windrow composting process to produce the compound to substitute for the inorganic fertilizer. This research does not indicate wastewater treatment or compost end-of-life for agricultural or land applications. The wet AD system examined for this research is a high-speed digestive system with a one-stage capacity for optimum organic waste treatment.

The integrated wet AD system will start with material collection and transportation to a treatment center. The distance from the collection center to the location of the wet AD plant was assumed to be 45km. After removing contaminants (plastics, metal cans, or glass bottles) and reducing FW size, soluble organic material is fed into the AD for a 21-day thermophilic (50–57 °C) fermentation. Dehydrated sludge with a moisture of 74% is co-composted with agricultural wastes (tree branches and leaves) for a 1-month maturation treatment using aerobic windrow composting (Sutera Folo Composting, Tanah Sutera Development, Johor Bahru). The AD plant generates electricity while 225kg of solid digested treated waste will be sold as fertilizers. Approximately $\leq 30\%$ of the remaining impurities (plastics, irons) and rejected FW from pre and post-treatment will be disposed of at a nearby conventional landfill site (Seelong Landfill site, Senai). The waste disposal in this landfill case has no gas filtering mechanism.

2.2. Life cycle inventory

Data for life cycle inventories (LCI) was collected from relevant literature and the GaBi v6.0 professional database. Table 1 displays all extractions and pollutants classified and entered into an inventory list containing input and output treatment processes. As data remains inaccessible, this research presumes all procedures for production and inventory data for the wet AD, aerobic windrow composting, and a landfill system in Malaysia are identical with countries such as Singapore, Brazil, and Italy. The assumption was founded on the similarities of these countries' solid-waste and climatic conditions [21].

2.3. Life cycle impacts analysis and type of impacts

The life cycle impact assessment (LCIA) is done in the third step of LCA research, and it converts data on elementary flows from the life cycle inventory (LCI) into environmental impact scores [16], [29]. ReCiPe v1.07 was used to evaluate the environmental hotspot impact for the hybrid wet AD scenario. ReCiPe delivers one of the most acceptable environmental impacts at mid and endpoints [30], [31]. It computes 16 midpoint indicators (Table 2), 15 endpoint indicators utilizing ReCiPe hierarchists (H) indicators, and a single score at 3-points (Table 3).

Midpoint performance indicators are problem-oriented methods that focus on a specific environmental concern, such as climate change or acidification. These characteristics may not represent the significant environmental impact of the pollutants reported in the LCI but potential impact indicators. The transformation of midpoints to endpoints facilitated the examination of the LCIA's impact.

The primary purpose of endpoint modelling is to characterize the strength or consequences of midpoint analysis. The modelling of all environmental factors is required for the endpoint characterization. As a result, endpoint metrics, also referred to as the damage-oriented method, highlight possible environmental damages at three upper accretion levels: (1) impact on human health, (2) ecosystems, and (3) scarcity of resources [32]. The normalization and weighting method used to determine the single score endpoint was the ReCiPe (H) v1.07 method embedded in the GaBi version 6.0 software.

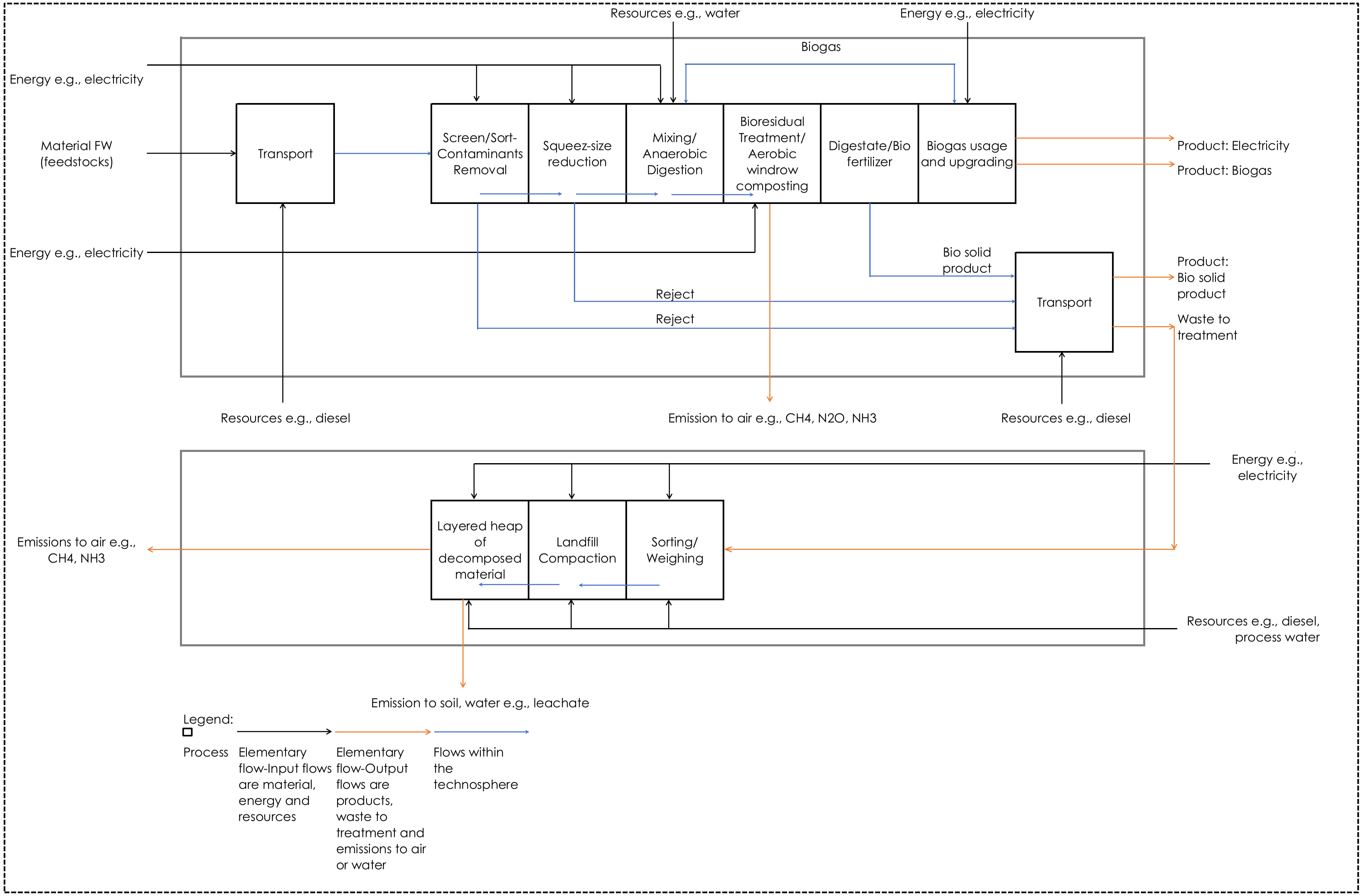

Figure 2. System boundary for the assessment of integrated wet AD for FW management

Table 1. Wet AD, composting, and landfill facility input and output inventories

Waste Treatment	Input/ Output	Flow	Amount	Unit	Source
Wet AD	**Input**				
	Material (feedstock)	FW	1	t	[a][12]; [b][17]
	Transportation	Distance	45	km	
		Truck payload	5	t	
	Energy consumption	Electricity	120(estimate)	kWh	
	Water consumption	Tap water	346[a, b]	kg	
	Resources	Diesel	30 (estimate)	l	
		Lubricant	0.25[b]	l	
	Output				
	Emission to air	CH_4	590[c]	g	[c][22], [d][18], [e][23]
		CO_2	0.5792[c]	kg	
		N_2O	0.00215[c]	kg	
		H_2S	0.00017[c]	kg	
		NH_3	0.0002[c]	kg	
	Other Waste	Plastic	0.13[d]	t	
		Iron	1.1[d]	kg	
		Rejected bio waste	0.19[e]	t	
	Energy Recovery	Electricity	178.1[e]	kWh	
	Dewatered sludge	Digestate	0.6(estimate)	t	
Windrow composting	**Input**				
	Energy consumption	Electricity	9.52[e]	kWh	[d][18], [e][23]
	Water consumption	Tap water	120[d]	kg	
	Resources	Diesel	0.64[d]	l	
	Output				
	Emission to air	CH_4	1829.7[f]	g	[e][23], [f][20]
		N_2O	0.075[f]	kg	
		NH_3	0.406[f]	kg	
	Product	Biofertilizer	225[e]	kg	
Landfill	**Input**				
	Transportation	Distance	45	km	[d][18], [g][24], [h][25] and [24], [i][26],
		Truck payload	5	t	
	Energy consumption	Electricity	667.4[g, i]	kWh	
	Water consumption	Tap water	52[d]	kg	
	Resources	Diesel	11.4 [h, i]	l	
	Output				
	Emission to air	CH_4	37849[j]	g	[g][24], [h][25] and [24], [i][26], [j](Estimated CH4 gas for Malaysia landfill data from [27], [k][28]
		CO_2	21.24[g, i]	kg	
		CO	0.0236 [i]	kg	
		N_2O	0.002[g]	kg	
		NO_x	0.25[g, i]	kg	
		HCl	0.006[g]	kg	
		HF	0.001[g]	kg	
		H_2S	0.018[g]	kg	
		SO_2	0.0381[g, i]	kg	
		Particles	0.0074[i]	kg	
	Emission to water	Total N	1003[g]	g	
		Hg	1.4[k]	mg	
		Cd	0.06[k]	mg	
		Fe	35.1[k]	mg	
		Mg	1.6[k]	mg	
		Zn	1.33[k]	mg	

3. Result and interpretation

Table 2 highlights the environmental impact of the midpoint assessment for the integrated wet AD technology evaluated relating to the management of the 1-ton FW. A positive number implies that the environmental load has risen, while a negative score implies a reduction in environmental pressure or an enhancement in the impact of sustainability. The results indicated that the integrated wet AD technology has the greatest potential for environmental improvement in several areas.

Based on environmental impact scores derived from software simulation, the highest reduction in ozone depletion, freshwater eutrophication, freshwater ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity, and marine eutrophication is observed in integrated wet AD. However, integrated wet AD poses significant adverse environmental impacts in other categories, such as ionizing radiation, water depletion, climate change, fossil depletion, human toxicity and primary energy demand. It is also found that integrated wet AD shows a moderate contribution to photochemical oxidant formation and particulate matter formation.

Table 2. Mid-point assessment from the largest to the smallest environmental impacts and inventory analysis of integrated wet AD technology analyzed

ReCiPe 1.07 Midpoint (H)	**Abbreviation**	**Integrated wet AD**	**Rank negative environmental impacts** (based on impact analysis from software)
Ionizing radiation [kg U235 eq]	IRP	1.40×10^{3}	Largest Impact
Water depletion [m^3]	WDP	1.11×10^{3}	Larger Impact
Climate change [kg CO_2 eq]	GWP	6.27×10^{2}	Larger Impact
Fossil depletion [kg oil eq]	FDP	2.02×10^{2}	Larger Impact
Human toxicity [kg 1,4-DB eq]	HTP	2.89×10^{1}	Larger Impact
Terrestrial acidification [kg SO_2 eq]	TAP	4.28×10^{0}	Moderate Impact
Agricultural land occupation [m^2a]	ALOP	2.49×10^{0}	Moderate Impact
Photochemical oxidant formation [kg NMVOC eq]	POFP	1.82×10^{0}	Moderate Impact
Metal depletion [kg Fe eq]	MDP	1.40×10^{0}	Moderate Impact
Particulate matter formation [kg PM10 eq]	PMFP	1.36×10^{0}	Moderate Impact
Marine eutrophication [kg N eq]	MEP	1.25×10^{-1}	Smaller Impact
Marine ecotoxicity [kg 1,4-DB eq]	METP	1.10×10^{-1}	Smaller Impact
Terrestrial ecotoxicity [kg 1,4-DB eq]	TETP	1.67×10^{-2}	Smaller Impact
Freshwater ecotoxicity [kg 1,4-DB eq]	FETP	1.28×10^{-2}	Smaller Impact
Freshwater eutrophication [kg P eq]	FWEP	8.61×10^{-5}	Smaller Impact
Ozone depletion [kg CFC-11 eq]	ODP	3.59×10^{-9}	Smallest Impact
Inventory Analysis: water (kg) and energy (MJ)			
Blue water consumption [kg]	BWC	1742.093	Landfill stages (77%) Wet AD (15%)
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	PED	8620.938	Landfill stages (86%) Wet AD (12%)

3.1. Midpoint assessment and hotspots identification

As illustrated in Figure 3, the impact of different components from each midpoint category is expressed in a percentage of contributions as in the evaluation criteria investigated from the wet AD, windrow composting, landfill, as well as diesel usage, collection, and transportation phases. The negative numbers seen in the data reflect benefits for the environment in the impact categories, whereas positive numbers correspond to negative environmental consequences. The anticipated effects were revealed in the findings of integrated wet AD technology, resulting in implications for the environmental performance of the value-added alternatives, as well as the deployment of centralized FW valorization methods in this study.

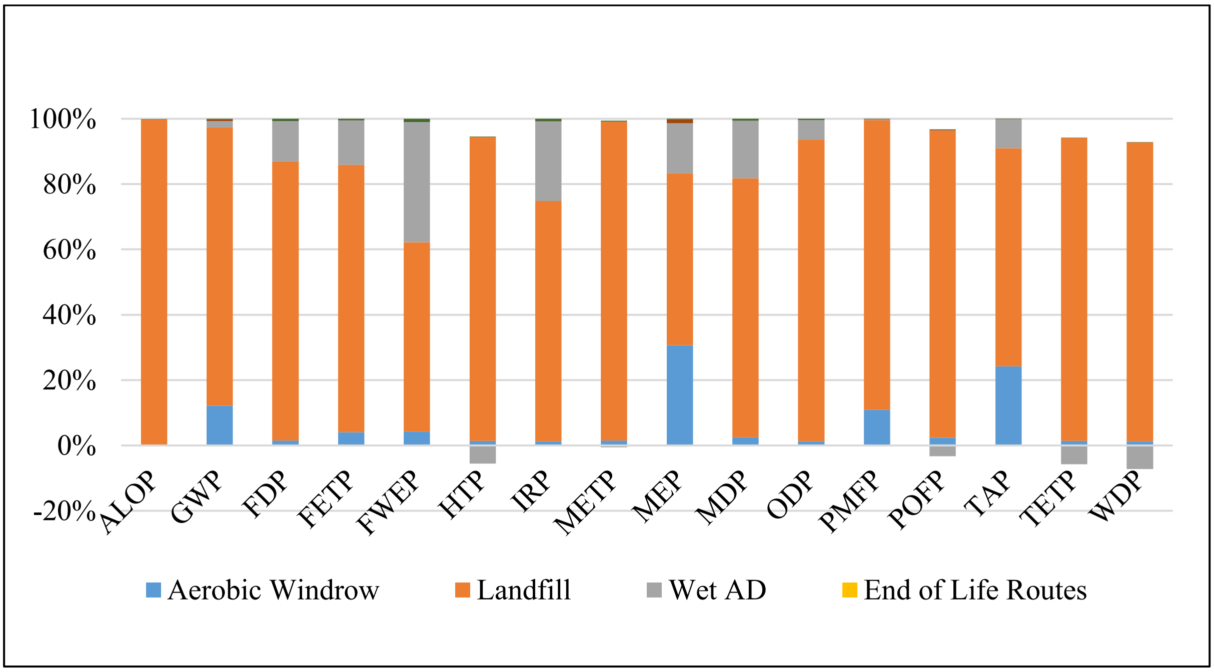

Figure 3. Integrated wet AD midpoints environmental impact scores

The majority of the environmental burdens of the proposed system are sourced from the landfill. The fermenter comes next (Fig. 3). The largest impact observed was the ionizing radiation potential (IRP) as previously highlighted in Table 2. IRP occurs when routine emissions of radioactive elements into the environment cause harm to human health. High doses of radiation may result in visually spectacular radiation burns or induce quick death through acute radiation syndrome. This category includes the generation of electricity from coal and other terrestrial sources, including naturally occurring radioactive materials that exist in rocks and soil, especially the highest found in landfill stages (74%), followed by wet AD (24%), which requires high electricity for process treatment. Based on inventories analysis generated by the software for the ionizing radiation impact category, carbon (C14) (97%), uranium (U238) (2%), and radon (1%), are the primary sources of radioactive emissions into the air identified in this integrated wet AD.

Another downside of the integrated wet AD scenario is that a substantial volume of water has to be applied during the process (Blue Water Consumption, BWC 1742.093 kg), which leads to potential water depletion. Landfill stages require the highest BWC, almost 77%, followed by wet AD stages, approximately 15% (Table 2). Dilution of the waste stream in wet AD before internal mixing activities not only requires a higher cost of water, but it also needs a high-volume reactor [12].

Concerning GWP that increases atmospheric temperature, resulting in extreme weather events (i.e., flooding and droughts), which in this scenario, CO_2 (77%), CH_4 (15%), and N_2O (7%) have the most influence on the climate change category. Anthropogenic sources, i.e., the burning of fossil fuels for transportation and other combustion processes in landfill machinery, are the main contributors to GWP [21], [16]. The CO_2 and CH_4 properties found in landfills have considerably greater negative environmental effects [32]. As shown in Fig. 3, the effects of GWP are more severe throughout the landfilling stage (85%) than of aerobic composting (12.21%). Furthermore, with the open-composting phase of wet AD dewatered digestate, CH_4 and CO_2 gases are produced, leading to GWP [20]. Composting organic materials decrease the carbon/nitrogen (C: N) ratio while sterilizing and enhancing their physical qualities. The greatest problem with composting is the release of nitrogen, mostly NH_3 and, to a smaller degree, N_2O, which adds to GWP [20].

In the FDP category, 85% of the environmental burdens are sourced from energy resources used in landfills. Wet AD requires 12% of energy resources during process treatment. The burdens that originate from the AD fermenter are mainly due to heating and energy consumption for stirring and releasing sulphur dioxide (SO_2) emissions into the air [33]. The rest is due to electricity consumption in the centrifuge for dewatering [33]. In wet AD stages, primary energy demand (PED 1025.92 MJ) was the second-highest compared to overall PED (8620.94 MJ). Fossil fuels have been extensively used for energy [21].

The fifth important potential impact is human toxicity potential (HTP). HTP is the toxicological effect on human health from the chemical emitted into the environment [16]. It includes cancerous and noncancerous substances such as heavy metals, toxic compounds, etc. Heavy metals such as arsenic, lead and mercury are found in emissions to air and fresh water, while barium, beryllium, and hydrogen fluoride cause the majority of the burdens of the HTP relating to inorganic emissions to air. In HTP, landfill emissions (30.7 kg 1,4-DB eq) were the highest contributor, followed by aerobic windrow (0.446 kg 1,4-DB eq), and the least emissions were from wet AD (-1.82kg 1,4-DB eq).

Open composting is more damaging to the digestate treatment process because of the high POCP CH_4 emissions [12]. Soil acidification, soil and water eutrophication, smog creation, and decreased air quality have all been connected to NH_3 depositions. Nitrogen oxides are the mono nitrogen oxides nitric oxide (NO) and nitrogen dioxide (NO_2) and their precursors, nitric and nitrous acid, produced during biogas combustion. Sulphur dioxide (SO_2) is a significant component of SO_x and is produced when hydrogen sulphide (H_2S)-containing biogas is burned. The other contributor to eutrophication, acidity, and photochemical oxidation potential is gaseous emissions from composting and AD processes.

There is a malodor connected with all waste treatment procedures. However, smells from landfills are the worst and have many negative consequences for humans, including health problems. These odors are produced as a result of the emission of H_2S during waste decomposition [21].

3.2. Single score endpoint assessment

In relation to single-score comparisons shown in Table 3, the integrated wet AD scenario causes significantly more impact on mineral and fossil resource degradation ($3.50x10^3$ Pt) than the overall impact of the top three accumulations. Furthermore, its impact on human health ($1.25x10^{-3}$ Pt) is greater than ecosystem quality damage ($5.00x10^{-6}$ Pt). Since the integrated scenario posed a more damaging effect on resource depletion, efficient mitigation measures are required for the integrated wet AD to overcome some of its disadvantages (Figure 4). This significant advancement will position the integrated wet AD as the most effective FW to energy management technology.

3.3. Sensitivity analysis

The sensitivity study for wet AD stages was examined in this section. To determine which factors and assumptions have the most effect on a result, a sensitivity analysis (SA) is necessary. SA is a tool for improving data collection and analysis without diminishing the accuracy of the results [14]. A 10 % change in each parameter was used to test its sensitivity. Table 4 shows the IRP, WDP, GWP, FDP, and HTP sensitivity values from integrated wet AD treatment plants.

The robustness of five variables (diesel, energy, water, distance, and payload) was examined, as shown in Table 4. When the fraction of variance exceeds 10%, the parameter is classified as sensitive. It was observed that only the electricity of the FW treatment parameter selected was the most sensitive parameter because it has a percentage change of higher than 10% based on the GWP impact group used in the sensitivity study. However, the others had a percentage change lower than 10% based on the environmental impact group. The fact that all of the parameters are less than 10% of each effect category implies that the parameters are less susceptible to the impact categories.

Table 3. Classifications of damage for integrated wet AD

ReCiPe Endpoint (H)	**Integrated Wet AD**	**Ecologically most damaging impacts** (Founded on the highest degree damages rank based on software analysis)
ReCiPe Endpoint (H), Resources (overall impact, point [Pt])	$3.50x10^{3}$	1st rank Resources Depletion
Fossil depletion [$]	$3.50x10^{3}$	
Metal depletion [$]	$4.47x10^{-2}$	
ReCiPe Endpoint (H), Human Health (overall impact, point [Pt])	$1.25x10^{-3}$	2nd rank Human Health Damage
Climate change Human Health [DALY]	$8.78x10^{-4}$	
Human toxicity [DALY]	$2.05x10^{-5}$	
Ionizing radiation [DALY]	$2.39x10^{-8}$	
Ozone depletion [DALY]	$6.30x10^{-12}$	
Particulate matter formation [DALY]	$3.53x10^{-4}$	
Photochemical oxidant formation [DALY]	$7.14x10^{-8}$	
ReCiPe Endpoint (H), Ecosystems (overall impact, point [Pt])	$5.00x10^{-6}$	3rd rank Ecosystems Degradation
Agricultural land occupation [species.yr]	0	
Climate change Ecosystems [species.yr]	$4.97x10^{-6}$	
Freshwater ecotoxicity [species.yr]	$3.58x10^{-12}$	
Freshwater eutrophication [species.yr]	$3.79x10^{-12}$	
Marine ecotoxicity [species.yr]	$2.46x10^{-14}$	
Natural land transformation [species.yr]	0	
Terrestrial acidification [species.yr]	$2.48x10^{-8}$	
Terrestrial ecotoxicity [species.yr]	$2.54x10^{-9}$	
Urban land occupation [species.yr]	0	

*Pt: Point; DALY: Disability Adjusted Life Years; yr.: Year

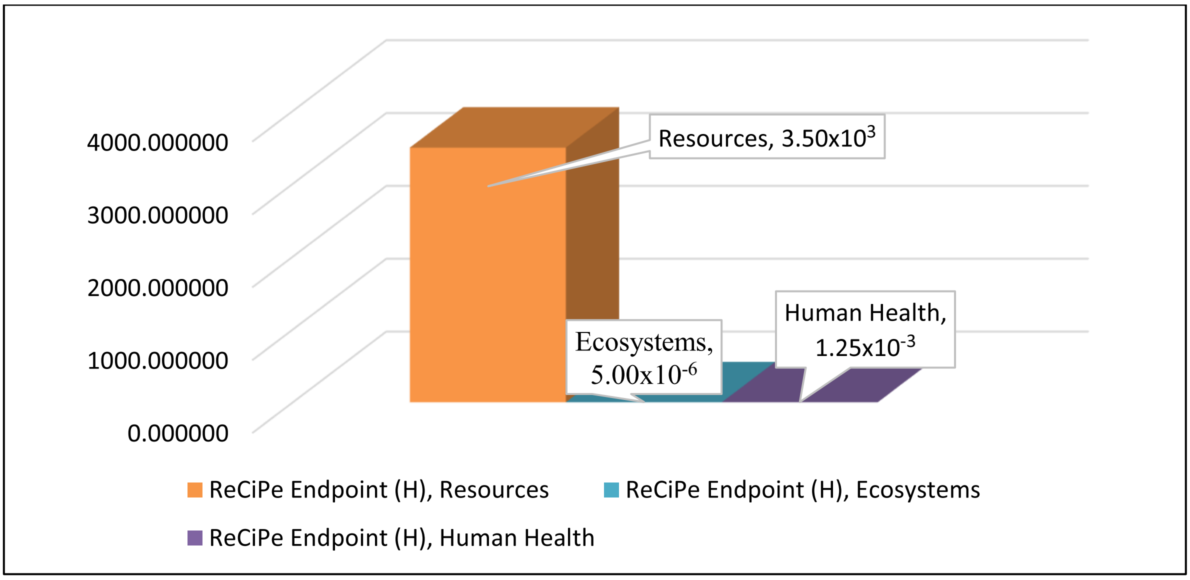

Figure 4. Single scores endpoint ReCiPe (H) v1.07 assessment for integrated wet AD

Table 4. Five impact groups sensitivity analysis for changes in wet AD stages

Percentage of Variation (%)	**Input Parameters**	**IRP kg U235 eq**	**WDP m^3**	**GWP kg CO_2 eq**	**FDP kg oil eq**	**HTP kg 1,4-DB eq**
Reference	LCIA midpoint	331	0	7.51	0	-1.82
(+/-) 10%	Diesel (%)	8.25	0	23.6	0	3.99
	Electricity (%)	1.69	0	127	0	29.1
	Water (%)	0.739	0	0.108	0	0.0552
	Distance (%)	0.0135	0	0.238	0	0.00657
	Payload (%)	0.015	0	0.265	0	0.0073

4. Mitigation strategies for integrated wet AD

Integrated wet AD mitigation strategies may involve applying suitable AD technology with biofiltration for composting and landfill gas treatment. According to Hong et al. [34], the essential element in reducing the possible effects of global warming is electricity recovery from CH_4 gas. Therefore, landfill disposal sites that can collect and process gas for energy production, which leads to a decline in cumulative GHG effects, may provide a better environmental scenario [24].

A dry AD mesophilic conducting technology with minimal water intake can be a better alternative to wet AD in organic treatments for IRP, WDP and FDP mitigation because it substantially minimizes the use of water and electricity [35]. Conversely, the local company prefers the wet AD system because of its superior methane output and volatile solids reduction rate [12]. Therefore, co-digested FW with the two types of sludges (2% total solid for primary sludge and 4% total solid for thickened active sludge) would need little or no additional water in the existing digester [36], [37]. FW co-digestion with wastewater sludge is a viable means of reducing emissions of ozone-depletion chemicals by up to 53% [7], [12]. Moreover, other advantages might be gained, such as enhanced CH_4 output and faster CH_4 production, since co-digestion makes it possible to optimize the digestive process and the synergistic effects of microorganisms by using these nutrients and bacteria in both substrates. Energy and compost production can compensate for more than half of the gross burden of POCP [12].

Saer et al. [20] proposed several techniques for controlling gaseous emissions created during composting. Emissions can be reduced by maintaining a C: N ratio greater than 25, which reduces NH_3 and N_2O emissions. When there is insufficient oxygen under anaerobic circumstances, CH_4 gas can be produced. As a result, anaerobic digestion settings will develop. The primary mitigation is to continually mix the waste piles to aerate them and avoid creating anaerobic areas in the piles. Furthermore, Amlinger et al. [38] strongly recommended the initial moisture content between 65–70% and 50–60% throughout subsequent phases [39]. Additionally, N_2O production can be reduced by keeping the temperature within 40-60°C. Finally, technology can reduce emissions by placing the organic waste mixture on perforated concrete slabs and infusing it with oxygen. This can stimulate microbial activity, reducing the occurrence of anaerobic conditions and, as a result, the creation of CH_4.

Gas treatment using biofiltration or related equipment is often recommended for digestate curing and maturing through open composting as the last-counteracting option for reducing gaseous atmospheric pollution [40]. Finally, concerning GHG emissions, AP and EP from wet AD, Ertem et al. [41] demonstrated that energy crop replacement and the optimal rate of feedstock loading (storage capability) may save up to 10-45% of GHG emissions and minimize AP and EP impact by 10%. The use of macroalgae may further reduce AP (83%) and EP (41%) [42].

5. Conclusions

This paper evaluates the environmental impact hotspot of an integrated wet AD using the LCA. The main objective is to assist decision-making processes concerning FW valorization alternatives. Therefore, it offers valuable insight into designing strategies that address the primary impact drivers in the integrated wet AD process. Although the use of integrated wet AD to treat FW has environmental consequences in all categories, the degree of the environmental load is significantly decreased owing to the possibility of energy generation when utilizing biogas as a fuel and the replacement of digestate for mineral fertilizers. However, the main findings suggest that the FW valorization through integrated wet AD has a negative impact on the ecosystem, which implies increasing ionizing radiation ($1.4\text{x}10^0$ kg U235-eq), water depletion ($1.11\text{x}10^3$ m^3-eq), global warming ($6.27\text{x}10^2$ kg CO_2-eq), fossil depletion ($2.18\text{x}10^2$ kg oil-eq) and human toxicity ($2.89\text{x}10^1$ kg 1,4-DB-eq) impact categories.

Furthermore, a centralized treatment plant would have various consequences, primarily in terms of the proportion that transportation would provide for each impact category. Thus, we can ensure the FW treatment process can be performed in situ by using an on-site composter such as dry AD for the biodegradable waste management system. By using an on-site composter such as dry AD, the transport distances and quantities are drastically reduced. Besides, the process itself requires little energy and saves the expense of transporting waste to the landfill. However, the wet anaerobic co-digestion of FW and sewage sludge could be the most viable approach for overcoming such restrictions in mono digestion. Adding FW as a co-substrate is recommended as a viable solution to increase process performance and assist in dealing with Malaysia's rising FW volume.

Different factors might have a significant influence on the impacts. These are linked to the utilization of various feedstocks for biogas production and the energy generation efficiency of the AD plant. Further investigation is necessary to explore diverse scales, operating systems, and waste streams to achieve convincing outcomes from mitigation measures.

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7. References

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