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Sustainable valorisation of agri-food waste from open-air markets in Kampala, Uganda via standalone and integrated waste conversion technologies

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ABSTRACT

Though the magnitude of organic-rich agri-food waste arisings from open-air agri-food markets in many sub-Saharan Africa cities such as Kampala, Uganda are largely unknown, the predominant approaches to managing them, i.e., open burning and unsanitary landfilling, are unsustainable, emitting greenhouse gases, and represent an inefficient use of their intrinsic compositional and energy value. This study combined waste-to-energy (WtE) process modelling/simulation, material flow analysis and life cycle assessment to comparatively evaluate the bioenergy production, value-added material recycling opportunities and associated environmental impacts of characterised agri-food waste from three major open-air agri-food markets in Kampala City under three agri-food waste management scenarios: conventional landfilling, standalone (anaerobic digestion, AD) and integrated (hydrothermal carbonisation, HTC & anaerobic digestion; i.e., HTC-AD) technologies. Results reveal that an estimated 14.1 kt (eq. 34.8 TJ) of agri-food waste aggregated from the focus open-air markets is disposed of in an unsanitary landfill annually. Intrinsic agri-food waste compositional analyses evidence suitability for technology-based valorisation scenarios. Further, integrated HTC-AD performed better than standalone AD, marked by higher diversion of input agri-food waste from landfill (91% vs 75% for AD), recovery of diversified fuels (hydrochar and biogas) with higher energy efficiency (η_{eff} = 69% vs 45% for AD) and minimal environmental impacts. When benchmarked against landfilling, both technology-based valorisation scenarios significantly reduce (~96%) adverse environmental responses for most life cycle analysis impact assessment categories. These findings demonstrate the feasibility of addressing the interlinked challenges of agri-food waste management and associated environmental pollution whilst promoting energy/value-added resource recovery from open-air agri-food markets. This is critical and timely to support near-term decision-making on selecting appropriate decentralised WtE technology-based agri-food waste valorisation systems that can realise economic, environmental, and technical (operational and strategic) goals in the city and other similar contexts.

1. Introduction

Many sub-Saharan African cities, such as Kampala, Uganda, are characterised by open-air agri-food markets, generating enormous amounts of agri-food waste primarily managed via open-burning and unsanitary landfilling practices. Current efforts to improve waste management planning and implementation are undermined by a lack of reliable local data and an understanding of resource-appropriate technologies, posing enormous challenges for policymakers and urban planners. Moreover, the urgency to manage ever-increasing agri-food waste sustainably has become critical, particularly in urban cities, where land degradation, high levels of greenhouse emissions associated with existing waste management practices and climate change impacts are most severe.

Various waste-to-energy (WtE) interventions can strategically address these impacts, including enabling energy and value recovery from agri-food waste. As standalone conversion technologies, anaerobic digestion (AD) and hydrothermal carbonisation (HTC) are widely

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mentioned, with the former broadly implemented as a key technology for the valorisation of organic waste streams [1,2]. In sub-Saharan Africa, AD is widely deployed at different scales; however, benefits are often only partially realised partly due to feedstock supply constraints, insufficiently adapted technology and lack of viable scenarios for their commercial deployments [3]. Moreover, standalone conversion technologies are not without disadvantages: selectivity, overcoming wet heterogenous mixed waste, low conversion efficiency, end-product upgrading and a propensity to generate secondary pollutants. Integrated conversion technologies, which combine synergistically compatible conversion processes to exploit the intermediate/by-products from one conversion process by using them as raw/secondary feedstock for another, are evolving and promising to address these shortcomings [4,5]. However, irrespective of the technological approach, whether deploying standalone or integrated conversion technologies for agri-food waste valorisation, the adoption of WtE systems strongly depends, amongst other factors, on their technical feasibility and the costs associated with their implementations.

Currently, and with specific reference to Kampala (as a representative sub-Saharan Africa city), there is a paucity of data to investigate and evidence technical feasibilities and economic viability of standalone or integrated conversion technologies for sustainable agri-food waste valorisation. Data such as agri-food waste generation patterns, magnitudes and physicochemical properties, critical for selecting, designing and implementing sustainable agri-food waste valorisation systems, are limited or non-existent [1,6]. Agri-food waste generation statistics and compositional information are also limited, vital to establishing bulk flow rates of waste/residues and bioenergy production potentials within a WtE management system boundary. In addition to complementary information on agri-food waste variabilities and intrinsic elemental/chemical compositions, these are essential to inform potential inhibitory substances, inorganic ash-causing materials and devising appropriate emission controls/upgrading strategies for energy, and value-added products recovery for any technology-based agri-food waste valorisation system [7]. Also, since agri-food waste intrinsic value or hazard is at elemental levels in intermediates or by/end-products, it is crucial to understand their flow rates and concentrations within a defined WtE management boundary [7]. This is imperative from an environmental impact assessment perspective.

Furthermore, studies on how existing (e.g., standalone conversion technologies) and emerging (e.g., integrated conversion technologies) technology-based valorisation systems impact the environment compared to longstanding agri-food waste management practices are lacking. While there are a plethora of *ex-ante* approaches to evaluate WtE valorisation systems, an integrative assessment approach combining material flow analysis (MFA), WtE process modelling/simulation and life cycle analysis (LCA) (Supplementary information, SI-1 further detail this approach) with specific reference to managing agri-food waste in open-air markets has not been reported in the literature. A previous study investigating integrated HTC-AD focused on sewage sludge management [8]. Still, considerations for agri-food waste management and broader deployment in the sub-Saharan Africa context have not been reported.

In this study, agri-food waste from three major open-air agri-food markets in Kampala, Uganda, was characterised to provide primary data (thereby plugging gaps on agri-food waste physicochemical properties from agri-food markets) objectively for *ex-ante* evaluation of technology-based agri-food waste valorisation systems conceptualised based on circular economy principles. Combining MFA, LCA and process modelling/simulation, this study predicted, assessed, and evaluated changes in bulk material resource flows, bioenergy yield and associated environmental impacts under three agri-food waste management system scenarios: conventional landfilling, standalone-AD and integrated HTC-AD conversion technologies. Conventional landfilling is the predominant approach for managing agri-food waste in many sub-Saharan African cities, including Kampala, serving as a benchmark. The standalone conversion technologies selected, i.e., AD, are based on their suitability for valorising easily degradable agri-food waste streams to recover intrinsic energy (i.e., biogas) and digestate. Also, AD is acknowledged as a widespread WtE technology in sub-Saharan Africa [3]. HTC, on the other hand, is distinguished by its preferential use of wet feedstock (moisture content >50 wt% which obviates the need for energy-intensive drying before conversion treatment) to generate solid biofuel, capacity to overcome heterogeneity and proven technological credentials [9,10]. The HTC-AD (i.e., the integrated conversion technologies selected) synergistic potential has been reported as energetically favourable, offering resource looping opportunities for further energy recovery at the source [11,12]. Such is critical to address the intertwined challenge of agri-food waste management, environmental pollution, and public health risks associated with open dumping and burning whilst promoting bioenergy/bioproducts production.

2. Methodology

2.1. Agri-food waste compositional analyses

Three major open-air agri-food markets – Kalelwe, Kasubi and Nakawa markets – in Kampala city, Uganda, were selected for this study. Selected markets are among the thirteen agri-food markets serving an estimated population of 1.9 million people in the city [13]. Unlike municipal solid waste, agri-food waste generated from agri-food markets is higher in organic content, consisting of a highly heterogeneous mix of spoilt/unfit for consumption agri-food produces (mainly fruits and vegetables), crop-based residues (e.g., peelings, straws) and abattoir waste [6]. They also contain non-biogenic inorganic components, including plastics, scrap metals, and cardboard, which must be separated before conversion [14]. Factoring this, a sampling campaign[1] was conducted in each focus agri-food market to generate the primary agri-food waste compositional properties used as input data in this study. Briefly, a 25 kg representative heterogeneous mix of agri-food waste samples was collected from designated dumpsites within each market. Manual sorting and separation ensued to remove non-biogenic inorganic components. Separated samples were subsequently homogenised and dried at 105 °C for 18–24 h before using a suite of analytical techniques to characterise their physical, bromatological, elemental and biochemical properties adopting Standard Test Methods (See Supplementary Information, SI-2: agri-food waste characterisations). The outcomes of these analyses, which constituted primary input data in subsequent WtE process modelling/simulation, MFA and LCA, are presented in Section 3.

2.2. Process modelling, simulation & analysis

2.2.1. Process overview and system boundary definition

Currently, the business-as-usual agri-food waste management practice in the focus agri-food markets in Kampala follows Scenario 1 (S1_Landfill) – See Fig. 1a. Empirical evidence shows that agri-food waste arisings from individual retail stalls are discarded on designated dumps around the agri-food markets and then transported and disposed of at Kiteezi landfill, the main landfill in the city, where unsanitary conditions exist, including leachate discharge (without treatment), intentional and unintentional open-burning [15].

Scenarios 2 (S2_AD) and 3 (S3_HTC&AD) in Fig. 1b and c are conceptualised waste-to-energy (WtE) technology-based valorisation alternatives to the business-as-usual scenario. S2_AD embodies a process where a *separated, readily degradable organic fraction of agri-food waste* is

[1] Due to financial resource constraints, the sampling campaign was limited to the three case study markets and triplicate representative sampling from each market. Hence, this study could not assess the seasonal variations of agri-food waste arisings in the markets.

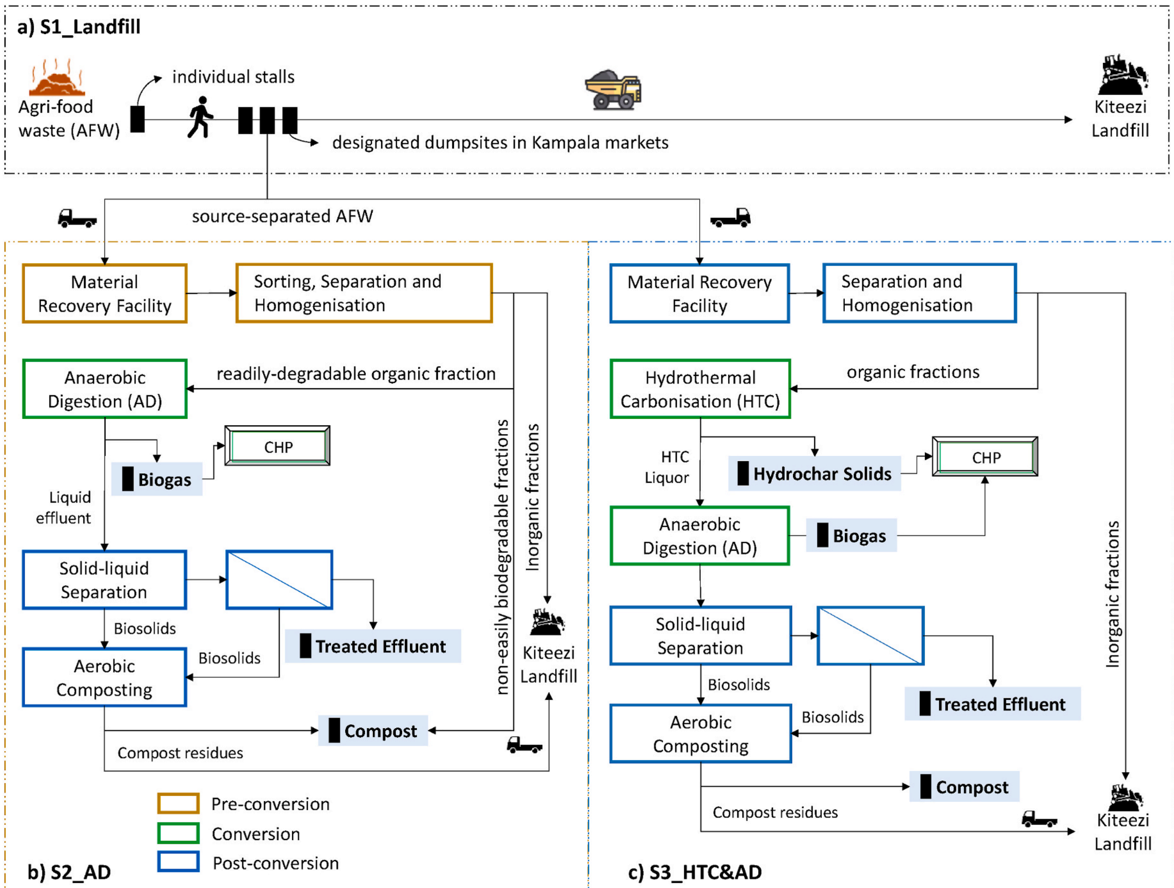

Fig. 1. A simplified block flow diagram of each scenario illustrating raw material/intermediate/product flows within interlinked processes/stages of the defined system boundary. S2_AD consists of all pre-conversion processes (separation, sorting and homogenisation) and AD treatment, while S3_HTC&AD consists of pre-conversion processes (separation and homogenisation) and HTC coupled with AD treatment. In both technology-based valorisation scenarios, however, digestate goes through post-conversion processes to concentrate nutrients, recover treated effluent, and reduce landfilling.

anaerobically digested to produce a gaseous fuel carrier (biogas), which is then combusted for heat and power recovery. S3_HTC&AD presents an integrated alternative for processing both *readily and non-readily degradable agri-food waste fractions* (thereby addressing the selectivity challenge associated with S2_AD). Under HTC conditions, agri-food waste fractions are converted to a solid-fuel carrier (hydrochar) and process liquor. The HTC liquor is then digested anaerobically to produce biogas and, in addition to solid hydrochar, is combusted for heat and power recovery.

Both WtE technology-based valorisation scenarios were informed by Uganda's Nationally Appropriate Mitigation Actions (NAMAs) commitment to the United Nations Framework Convention on Climate Change to "reduce waste generation, improve waste collection, recycling and reuse, increase efficiency and value addition prospects of agro-processing firms". Some suggested actions include using AD and integrated approaches for efficient waste management. In addition, the country's National Climate Change Policy also commit to "promote sustainable use of solid and liquid wastes for energy generation and other uses, such as fertilisers (after sorting); and proper disposal and sustainable use of waste". Hence, this study explores S2_AD and S3_HTC&AD as strategically fit approaches for advancing NAMA's objectives for sustainable waste management whilst promoting resource looping for bioenergy production/value-added product recovery with minimal environmental impacts.

2.2.2. *WtE process modelling and simulation*

The S2_AD and S3_HTC&AD scenarios described in Fig. 1 were modelled in Aspen Plus® V10, using methods described in Rajendran et al. [16] for the AD process simulation model and extending this for HTC reactions. Supplementary Information, SI-3 A&B further illustrates the process flow models for the S2_AD and S3_HTC&AD scenarios, respectively.

In summary, for S2_AD, agri-food waste is first sorted into organic and inorganic fractions, given that market wastes are unsegregated (with a mixed collection of organic wastes with plastics, metals and other solids). Only readily-degradable fractions were considered for S2_AD due to the poor biodegradability and digestibility of highly fibrous materials such as husks, shells, and kernels. This leaves the non-readily-degradable fractions in compost and the readily-degradable fractions subjected to homogenisation, pH and moisture adjustment in a buffer tank. The addition of water is not considered since the moisture content of the agri-food waste was more than 80 wt% (see Table 1). The homogenised substrate is digested in a two-stage AD reactor: AD-1 and AD-2. AD-1 models the hydrolytic conversion of complex organic macromolecules to monomeric forms, i.e., simple sugars, fatty acids, and amino acids [17]. These processes are modelled in Aspen Plus® V10 using RSTOIC block with stoichiometric equations and fractional conversion as input data (See Supplementary information, SI-4 Table A). AD-2 describes the subsequent conversion of hydrolysis products to common intermediates and finally to digestate and biogas via eight enzymatic processes: i) sugar-fermenting acidogenesis, ii) glycerol-fermenting acidogenesis, iii) amino-acid-degrading acidogenesis, iv) Long-chain fatty acid-degrading acetogenesis, v) propionate-, oleate, butyrate and valerate-degrading acetogenesis, and vi) acetoclastic methanogenesis. These reactions are defined in Aspen Plus® V10 using RCSTR block with stoichiometric equations, fractional

Table 1
LCA data inventory and boundary parameters.

Parameter	Units	S1_Landfill	S2_AD	S3_HTC&AD
Annual amount of agri-food waste collected for disposal*	t	14,144	14,144	14,144
Losses due to pre-processing of waste**	%	–	34.45	34.45
Fuel consumption via small garbage truck transportation of agri-food waste (<10 t capacity) to waste transfer facility[a]	L km^{-1}	6	6	6
Distance to transfer facility***	km	–	10	10
Fuel consumption via long-haul garbage truck transportation of agri-food waste (>25 tonne capacity) – fuel consumption[a]	L km^{-1}	–	0.33	0.33
Distance from transfer facility to Kiteezi landfill***	km	20	10	10
Landfilling (unsanitary, unlined landfill)				
Diesel Consumption in Landfill Compactor[a]	L km^{-1}	0.33	0.33	0.33
k rate[b]	yr^{-1}	0.15	0.15	0.15
Loss of VS related to loss of biodegradable carbon[c]	%	2	2	2
Time Horizon[c]	yr	100	100	100
Anaerobic Digestion				
Simulated Gas Yield as proportion of degradable carbon[#]	%		70%	70%
Simulated CH_4 in Biogas[#]	%		50.4%	53.8%
Loss of VS related to loss of biodegradable carbon[c]	%		1.89	1.89
Avoided Electricity Consumption[#]	MJ kg^{-1}		0.0038	0.0049
Avoided Heat Consumption[#]	MJ kg^{-1}		0.00058	0.0062
Gas Leak[##]	%		3	3
Solid-Liquid Separation				
Digestate Solid Fraction[##]	%		12.5	12.5
Electricity Consumption[#]	kWh kg^{-1}		0.02	0.02
Composting				
Fraction of material degraded/undegraded[c]	%		80/20	80/20
% wet weight compost/reject to landfill[c]	%		95/5	95/5
Electricity Consumption[d]	kWh kg^{-1}		0.15	0.15
Membrane Filtration				
Electricity Consumption[e]	kWh/ m^3	–	0.95	0.95
Sodium Hypochlorite[c]	kg	–	9.104E-5	9.104E-5
Transportation via long-haul garbage truck (>25 t capacity) – fuel consumption[a]	L km^{-1}	–	0.33	0.33
Distance from transfer facility to surface discharge***	km	–	5	5
Land Application[c]				
N_2 emissions to air	%	–	4.295	2.78
N_2O emissions to air	%	–	2.78	
NH_3emissions to air	%	–	7.5	7.5
NO_3 emissions to ground water	%	–	17.85	17.85
NO_3 emissions to surface water	%	–	19.58	19.58
PO_3 emissions to surface water	%	–	0.47	0.47
PO_3 emissions to ground water	%	–	0.47	0.47
CO_2emissions	%		86.75	86.75
CH_4emissions	%	–	0.05	0.05
C sequestered in soil	%	–	13.2	13.2
N plant-uptake	%	–	21.23	21.23
N soil storage	%		26.95	
P soil storage	%		14.96	
P plant uptake	%	–	84.1	84.1
Fuel consumption for transportation of fertiliser	L kg^{-1}	–	0.000015	0.000015

* – empirical data.
** – Further details in Supplementary Information, SI-4.
*** Kampala city map data.
[a] Kinobe et al., [25].
[b] average values of the range of 0.1–0.3 yr−1 reported for wet landfills in Kim and Townsend [26] and Krause [27].
[c] EaseTech default values.
[d] Zhang and Matsuto [28].
[e] average values of the range of 0.8–1.1 yr−1 reported in Krzeminski et al. [29].

conversion and kinetic parameters as input data (See Supplementary information, SI-4 Table B & C). Other AD process model inputs are presented in Table 2, including initial validation results, which show a <5% difference between the predicted AD process model used in this study and experimentally obtained values from literature.

For S3_HTC&AD, the process simulation model was expanded. The processed agri-food waste leaving the buffer tank is first subjected to HTC treatment at high-temperature and autogenous pressures to produce hydrochar and HTC liquor. First, agri-food waste undergoes sorting but excludes separation since HTC overcomes biowaste heterogeneity [9]. Then, the HTC liquor goes through AD treatment, and the resulting biogas and hydrochar are combusted for heat and power recovery. Similar to S2_AD, associated reactions are defined using stoichiometric equations, fractional conversion, and kinetic parameters, but specific equations (3,4,7,10 and 12 in Supplementary information, SI-4 Table B) in addition to Supplementary information, SI-4 Table C are added to describe substrate decomposition to intermediate products. Supplementary information, SI-4 Table D, is further included to describe the polymerisation of intermediate products to hydrochar of defined composition [7]. In both scenarios (S2_AD & S3_HTC&AD), the Non-Random Two-Liquid property method was selected to predict the thermodynamic properties of the reactants and their mixtures, assuming stead-stage operation at all stages. The Non-Random Two-Liquid property method, an activity coefficient-based model, is appropriate for this study and is well-known for phase equilibria [18]; it provides a reasonable estimation of equilibrium data, even for non-ideal liquid and partially immiscible mixtures. This is particularly important for this study, where there are several components and fluid phases, e.g. liquid and gas phases, in biogas production. While Aspen Plus® V10 databases contain most of the components used in the study, hydrochar was not included; hence the data in Medina-Martos et al. [8] was used for defining the empirical formula and deducing physical properties, citing as a non-conventional component.

In the process modelling of both technology-based scenarios, agri-food waste composition is defined using average values in empirical data, expressed as weight fractions of carbohydrates, water, protein, lipids, and inert components. Considering resource looping of products and co-products to minimise environmental pollution and disposal at landfills, post-conversion processes included solid-liquid separation [19], liquid effluent treatment via membrane filtration [20], and aerobic composting of digested/non-readily-degradable solids [21]. The membrane filtration removes colloidal, suspended, and soluble macromolecules and concentrates nutrients and minerals in separated solid fractions. A hybrid membrane filtration system (comprising ultrafiltration and reverse osmosis) is assumed to enable the recovery of clean

Table 2
AD Process model validation results.

Case	Temp. (°C)	Substrate	HRT (days)	Feed Rate	Organic Loading Rate	Total solids (%)	Volatile Solids (%)	Experimental results	Case References	Model results[b]	Difference (%)
1	55	Cow Manure	15	0.33 L day^{-1}	0.016 L VS day^{-1}	6	80	353.5 L kg^{-1}VS day^{-1}	[16]	344.7 L kg$_{VS}^{-1}$ day^{-1}	2.49
2	35	Market Waste	249	85.5–250 kg day^{-1}[a]	0.57 kg VS day^{-1}	0.23	0.63	0.41 m^3/kg^{-1}VS day^{-1}	[35]	0.428 m^3/ kg^{-1}VS day^{-1}	−4.40

[a] Average value: 170 kg day^{-1}.
[b] Current study.

water (permeate) and concentrate retentate (reject) rich in nutrients transferred for aerobic composting. Due to poor digestate dewaterability, this study assumes using a decanter centrifuge to separate solid and liquid effluent fractions of AD digestates. Other ancillary components are included in the process simulation model, e.g., pumps for moving liquids and solids from reactor to reactor and flash tanks for gas-liquid processing and separation.

2.3. Material flow analysis (MFA)

MFA was propagated using the STAN software [22] and conducted at the level of 'goods' and 'substances'. MFA aims to measure the flows and stocks of materials consumed and disposed of within complex system boundaries, enabling a comparison between the business-as-usual and technology-based scenarios to inform resource efficiency. As a mass balance approach, transfer coefficients determine the magnitude of material flows among interlinked processes within the defined system boundary in Fig. 1. At the *'substance' level,* this study quantified and evaluated intrinsic agri-food waste heavy metals transfer for all scenarios at each stage; however, the paucity of transfer coefficients data limited these analyses to select but important heavy metals: Zn, Hg, Pb, Cu, Hg, Cr, & Ni. All the transfer coefficients used for the MFA are detailed in Supplementary Information, SI-5.

2.4. Life cycle analysis (LCA) approach

The goal of this LCA was to evaluate the environmental impacts associated with the business-as-usual scenario in comparison with the two technology-based scenarios: S2_AD and S3_HTC&AD. The functional unit of the study was defined as 1 t of organic fractions of agri-food waste collected for landfill disposal. This study's LCA system boundary covers agri-food waste collection, processing, transfer/transport, treatment, and ultimate disposal. Activities relating to the installation of facilities, construction, manufacturing of machines, vehicles and equipment and essentially all capital goods/physical assets associated with processes are excluded from the system boundary. Manual labour related to sorting, separation etc., is also excluded. As multiple processes are compared, the study has taken the attributional approach using national/global averages, allocating environmental impacts between the product and co-products by weight. System expansion is performed in processes involving material or energy recovery, and product substitution has considered avoided fuel consumption and emissions. Analysis was completed using EASETECH (V3.40) [23], a computational LCA software developed at the Technical University of Denmark, widely used for modelling and analysis of waste-related processes, products, and systems. The model followed the ReCiPe2016 Midpoint methodology [24] with a hierarchist perspective that views emission contributions in a relatively short time frame, about 100 yrs. The study considered all the environmental impact categories recommended by the International Reference Life Cycle Data System guidelines. The data inventory, sources, and assumptions for all scenarios, as inputted in EASETECH [23] are summarised in Table 1. The data covers primary data, results from process simulation and inputs from secondary data, including materials consumed and co-products generated, heat and/or electricity consumed/generated, and pollutant emissions generated and avoided throughout the life cycle of the material. Normalisation and weighting of impacts are not included in this study.

3. Results and discussion

3.1. Agri-food waste composition & suitability for bio-conversion

Table 3 provides the physicochemical properties of agri-food waste aggregated from the case-study agri-food markets, including generation rates and the magnitudes of 'goods' and 'substances'. The total agri-food waste aggregated from the agri-food markets and disposed of under current management practice (S1_Landfill) is estimated at 14.1 kt. yr^{-1}. This translates to landfilling 34.8 TJ agri-food waste energy-equivalent annually, discounting inherent agri-food waste moisture content. A closer inspection of Table 3 shows no significant difference (<10%) for most of the agri-food waste physicochemical properties measured across all the agri-food markets, despite the differences in typological compositions, market locations and sampling sites of heterogeneous agri-food waste mix from each market. This is remarkable and promising for aggregating agri-food waste for realising compositional consistency critical for standardising input specifications for bioenergy conversion and resource recovery planning [30]. Meanwhile, the source of variation in the present study may relate to generation patterns (source separation practices at the point of generation), the season of collection, typological compositions, collection type, and geo-spatiotemporal factors, all identified in near-similar previous studies on food waste [31,32] and organic fraction of municipal solid waste [33]. However, this study did not investigate these factors; hence, the observed compositional variation cannot be ascertained.

While intrinsic agri-food waste organic content provides background suitability for energy conversion, quantitatively assessed evidence to support this (due in part to lack of information on agri-food waste compositional properties) is limited. This gap is addressed in this study. The principal parameters that influence thermochemical conversions and, more importantly, microbial activities/overall AD digestion process include physical (e.g., moisture content, pH, volatile solids (VS)/total solids (TS), bromatological (e.g., protein content), and biochemical (e.g., nutrients, C/N ratio) properties [34]. From Table 3, the moisture content of aggregated agri-food waste is ~83%, energetically favourable for HTC [9] and AD. Suitable feedstock for AD typically have VS in the range of 70–95% of the TS [35] and reported ranges for C/N ratios and pH for optimum AD performance are 20–30 and 6.8–7.4, respectively [34]. In this regard, aggregated pH (4.29) is lower than the optimum range, but TS, VS, and C/N ratio (21.55) are within the optimum ranges suitable for AD. When the bromatological properties of agri-food waste are assessed, according to Harun et al. [36], agri-food waste promises faster conversion rates (due to higher carbohydrate content) with minimal inhibition tendencies (low protein content). Further analysis of metal concentrations and their toxic limits shows that the feedstock is suitable for the suggested process. Karthikeyan and Visvanathan [37] and Guo et al. [38] have reported that inhibiting toxicity limits (in mg L^{-1}) for light metals ions such as Na, K, Mg, and Ca on AD methanogens are 8000, 12000, 3000, and 8000 respectively, while inhibitory

Table 3
Agri-food waste physicochemical composition, generations rates and magnitudes of 'goods' and 'substances'.

Properties	Compositions	Kasubi	Kalelwe	Nakawa	All markets	
		Mean of triplicate analyses				
Physical	Moisture, MC (%)	82.53	82.23	84.17	82.98 ± 0.99	
	Total solids, TS (%)	17.47	17.77	15.83	17.02 ± 0.99	
	Ash content, (%)	8.07	6.60	9.99	8.22 ± 1.71	
	Volatile solids, VS (%)	91.93	93.40	90.01	91.78 ± 1.71	
	pH	4.14	4.67	4.05	4.29 ± 0.29	
Energy	HHV (MJ kg^{-1})	13.7	15.21	14.97	14.48 ± 0.75	
Bromatological	Lipids (%)	4.39	4.74	3.38	4.17 ± 0.65	
	Protein (%)	7.24	7.29	8.71	7.75 ± 0.75	
	Carbohydrates (%)	66.70	66.58	63.25	65.51 ± 1.80	
Biochemical (ppm)	COD (g L^{-1})	7.93	8.01	9.53	8.49 ± 0.78	
	C (%)	31.99	27.67	29.08	29.53 ± 2.07	
	H (%)	4.91	4.09	4.03	4.31 ± 0.47	
	S (%)	0.11	0.12	0.12	0.12 ± 0.02	
	N (%)	1.49	1.31	1.31	1.37 ± 0.11	
	O (%) (by diff.)	61.50	66.81	65.46	64.59 ± 2.76	
	K (%)	1.40	1.47	1.61	1.49 ± 0.11	
						Metals (t. yr^{--1})[a]
	Zn	35.97	38.35	32.43	35.58 ± 6.02	0.50 ± 0.05
	Cu	8.67	12.63	8.53	9.94 ± 2.32	0.14 ± 0.01
	Cd	0.45	0.27	0.10	0.36 ± 0.10	0.01 ± 0.001
	Cr	3.53	2.33	1.93	2.60 ± 0.73	0.04 ± 0.004
	Mg	1883.17	2375.83	1574.83	1944.61 ± 480.5	27.51 ± 2.74
	Ni	15.85	3.90	4.07	7.94 ± 5.93	0.11 ± 0.01
	Mn	60.95	159.22	82.77	100.98 ± 45.14	1.43 ± 0.14
	Ca	5168.75	12113.75	4807.08	7363.19 ± 3778.69	104.15 ± 10.39
	Fe	1136.92	5228.58	1366.92	2577.47 ± 2046.51	36.46 ± 3.64
	Pb	7.33	10.97	2.70	7.00 ± 3.60	0.099 ± 0.01
	K	8309.16	8094.16	8672.83	8358.72 ± 2023.44	118.23 ± 11.79
	Na	687.26	457.78	946.04	697.03 ± 211.77	9.86 ± 0.98
	Hg	929.00	49.27	29.27	335.84 ± 444.95	4.75 ± 0.47
	As	64.00	40.00	0.00	52.00 ± 13.39	0.74 ± 0.07
Agri-food waste generation rates *(t yr^{-1})*[b]		3860.8 ± 1268.98	2248.8 ± 463.49	8034.4 ± 407.09		

[a] Estimated as Mass of substance = Mass of goods (t) x Concentration of substance (ppm = mg kg-1 = g t-1).
[b] Estimates are based on quarterly waste statistics as received.

concentrations (in mg L^{-1}) of prominent heavy metals such as Cu, Ni, Fe, Cd, Zn and on biogas yield are 500, 100, 2000, 1.2 and 50, respectively. When compared, these metals are significantly low in the agri-food waste obtained in this study, further supporting the suitability of the feedstock for bioenergy production.

3.2. Bioenergy production

The yield of energy products and energy efficiency, η_{eff}, of both technology-based valorisation scenarios are reported in Table 4. The

Table 4
Yield of products and energy efficiency.

		S2_AD	S3_HTC & AD
Gas Content	Water (%)	0.30	0.30
	Carbon dioxide (%)	48.87	45.54
	Methane (%)	50.32	53.02
	Ammonia (%)	0.04	0.17
	Hydrogen Sulphide (%)	0.47	0.95
Yield of Products	Daily Raw Biogas Production (m^3 day^{-1})	996.01	90.96
	Specific Gas Production (m^3 per kgVS day^{-1})	0.251	0.032
	Digestate Yield (m^3 day^{-1})	24.84	20.70
	Hydrochar Yield (t day^1)	–	0.32
	Total Energy Consumed (GJ yr^{-1})	34.02	420.77[a]
	Total Energy Generated (GJ yr^{-1})	63.04	710.41[a]
	Net Energy Generated (GJ yr^{-1})	29.02	289.64[a]
	Energy Efficiency, η_{eff} (%)	**45.41**	**68.83**
	Energy Ratio (ER)	**1.83**	**1.69**

[a] Includes energy recovery from hydrochar at 60% CHP efficiency.

results show that the yield of product for the S2_AD consists of 996 m^3 day^{-1} of raw biogas and 25 m^3 day^{-1} of digestate while S3_HTC&AD include 91 m^3 day^{-1} (raw biogas), 0.32 t day^{-1} (hydrochar, dry basis) and 20 m^3 day^{-1} (digestate). This recovery of resources mirrors the diversion of agri-food waste from Kiteezi landfill and the energy recovery potential for Kampala's major markets. Furthermore, it corroborates higher conversion efficiency and energy advantage when conversion technologies are integrated for agri-food waste processing.

Putting the results into context, the energy recovered from the S2_AD and S3_HTC&AD are significant and can potentially plug the cooking energy needs of about 3200 and 32000 traders, respectively, in Kasubi, Nakawa and Kalerwe markets, assuming fuelwood consumption rate of 220 kg cap^{-1} yr^{-1} and fuelwood HHV of 15 MJ. kg^{-1} [39,40]. Empirical evidence suggests that these markets accommodate 6000 and 20000 traders, and firewood is the primary fuel source for cooking-related trading activities such as fish smoking.

Furthermore, Table 4 shows that S3_HTC&AD had improved biomethane quality (about 7% higher than S2_AD), although the yield of the raw biogas was generally lower. The low biogas yield can be attributed to low substrate flow to the AD reactor due to the prior conversion of agri-food waste into hydrochar. Previous studies [8,41] have shown that integrating HTC and AD improves gas quality (up to 40%, depending on the process route). The improvement in gas quality is attributed to the physical breakdown of complex organic substrates and higher concentrations of volatile fatty acids (VFAs) in the HTC liquor. However, excess VFAs could adversely impact microbial growth and gas yield.

Further, the biogas yield obtained in this study is much lower than those in prior studies [35,42] where specific gas production rate varied between 0.30 and 0.88 m^3 $kgVS^{-1}$ day^{-1} for different household biogas systems, feedstock composition, organic loading rate, and process temperature. Nevertheless, the results are reliable for the WtE technology-based valorisation system described as S2_AD and S3_HTC&AD models baseline scenarios where biogas yield is not optimised, as often described for low- and middle-income countries. Low biogas yield is attributed to several factors, often relating to the organic waste's nature and processing method. Also, prolonged storage and poor collection of organic wastes are considered significant reasons for loss of energy value, and external factors such as gas leakages and pipe blockages contribute to a reduction in biogas quantity and quality produced [35].

Comparing energy efficiencies, Table 4 shows that S3_HTC&AD had a better energy performance (η_{eff} = 69%) but at a cost-on-energy ratio (ER). On the other hand, S2_AD had a higher ER (1.83) because it operates at ambient pressure and low-temperature conditions instead of the high-temperature and pressure conditions of the S3_HTC & AD. As a result, the total energy required for S2_AD was significantly lower (~34 GJ yr^{-1}) than for S3_HTC&AD (~420 GJ yr^{-1}). On the other hand, the energy generated was about 63 GJ yr^{-1} for S2_AD and 710 GJ yr^{-1} for S3_HTC&AD based on a conservative estimate of 60% CHP efficiency and 85% heat recovery efficiency. In both scenarios, the high energy value in the biogas and combined biogas and hydrochar are sufficiently large to meet the plant's parasitic energy needs, and excess electricity/heat can be used locally. However, the electricity requirement for S2_AD is 7% higher than S3_HTC&AD (8.15 GJ yr^{-1}) because of the large volume of digestate that needs to be pumped or treated.

3.3. MFA balances

Fig. 2a and b shows the MFA balances (at the level of 'goods') for the technology-based scenarios. For brevity, the substance flow balances for all the heavy metals investigated, aggregated for all agri-food markets for both technology-based scenarios, are provided in Supplementary Information, SI-6 (for S2_AD) & SI-7 (for S2_HTC&AD). Further, Fig. 2c illustrates the extent (at the levels of 'goods' and 'substances') of agri-food waste input to landfill, recovered as value-added products (solid and gaseous biofuels, compost, and treated effluents), and emissions associated with each scenario.

From Fig. 2a–c, the most obvious yet significant finding from the MFA modelling is that at the level of 'goods', both technology-based scenarios, juxtaposed with business-as-usual management practice, enable the utilisation and conversion of more than half of all agri-food waste into the recovery of value-added product. Up to 54% of the agri-food waste could be utilised and converted into valuable products under S2_AD, increasing to 78% under S3_HTC&AD. The S3_HTC&AD performed better regarding biofuel recovery, utilising and converting about 64% of input agri-food waste to recover diversified biofuels (hydrochar and biogas) compared with the S2_AD, which uses about 8% of input agri-food waste for biogas production. This performance can be ascribed to the S3_HTC&AD synergistic advantage of overcoming the selectivity (a fundamental constraint of standalone AD) and heterogeneity of agri-food waste streams, thus enabling higher throughput and value recovery potentials. Further, S3_HTC&AD enables the utilisation of intermediates/by-products, i.e., HTC process liquor, for further energy recovery via the AD treatment, thus enhancing energy carriers' diversifications and yield. Previous studies [10,11] have indicated that this integrated HTC&AD approach results in higher conversion efficiency and energy yield than standalone conversion technologies. However, the recovery of other products, i.e., treated effluent and compost under S3_HTC&AD, is significantly reduced (14% of input agri-food waste) compared with S2_AD (about 46% of input agri-food waste). What also stands out from the MFA is the extent of agri-food waste that could be diverted from landfills. Fig. 2c reveals that over 75% of input agri-food waste can be diverted from landfills under S2_AD, rising to about 91% under S3_HTC&AD. This could translate to significant environmental benefits. Moreover, net emissions are more pronounced under S2_AD; up to 32% of input agri-food waste is released as off-gases (mainly CO_2, CH_4, N_2, NO_x and VOCs) to the environment

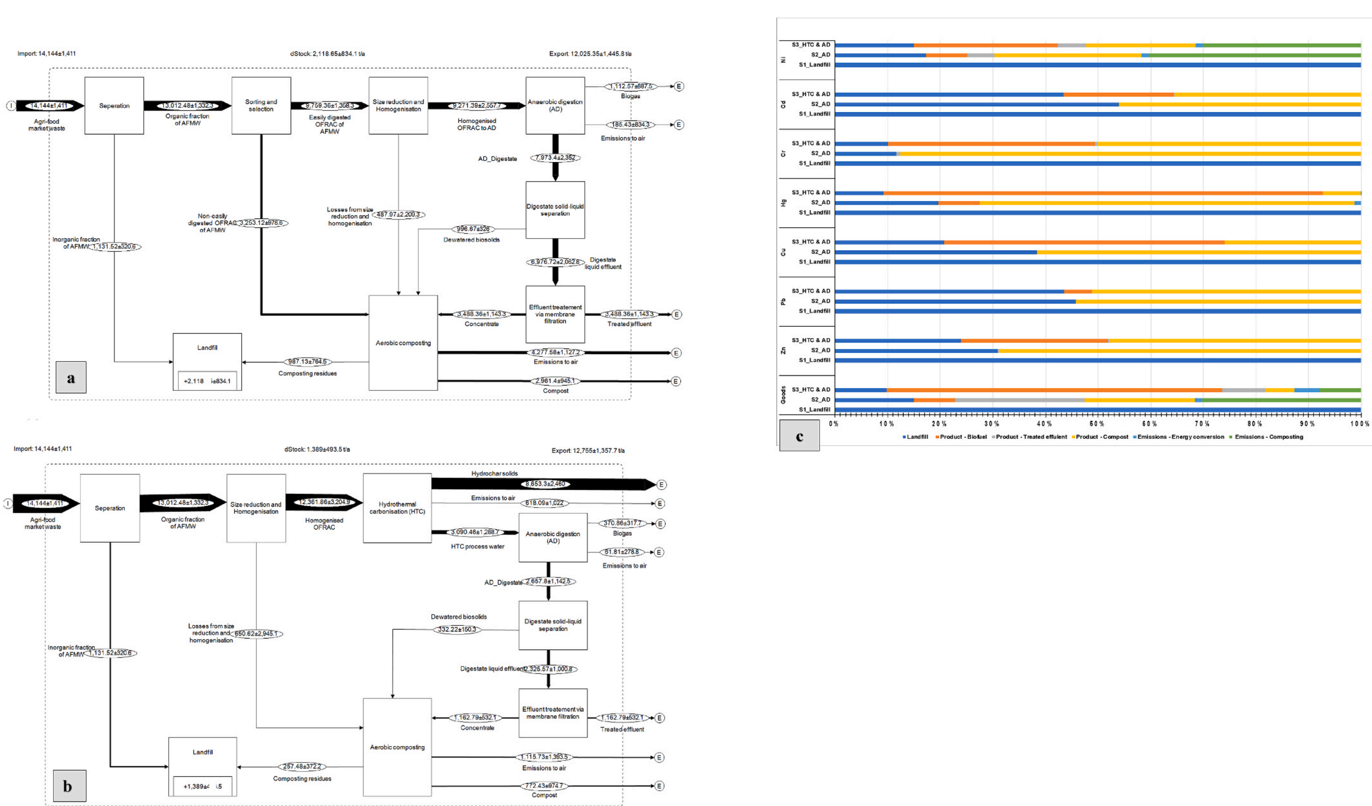

Fig. 2. MFA balances (t yr^{-1}) at the level of 'goods' for [**a**] S2_AD and [**b**] S3_HTC&AD. [**c**] Distribution of "goods" and "substances" under each scenario.

due to the concatenations of conversion and post-conversion processes vs 13% under S3_HTC&AD. Aerobic composting generated the most significant gaseous emissions regardless of the technology-based scenario and thus represents a target process for mitigating GHG emissions.

Further analysis reveals evident disruption in the fate of 'substances,' i.e., heavy metals, under both technology-based scenarios compared with the current landfilling option. There is an apparent decrease in the amount (wt.) of heavy metals landfilled under both technology-based scenarios (See Supplementary Information, SI-6 and SI-7) due to the partitioning and sequestration effects of input heavy metals during conversion and post-conversion processes. Previous studies have reported that waste conversion processes, including AD and HTC, are invaluable to binding heavy metals in their solid fractions [43,44]. Fig. 2c further reveals S3_HTC&AD as the most effective for managing heavy metals, as less than 25% of all initial heavy metals concentrations in original agri-food waste end up in landfill, except Pb and Cd (<45%). Landfilling heavy metals are inevitable; however, deploying appropriate waste management systems, including recycling options, is critical to minimising the extent of heavy metals transfer to landfills.

Regarding heavy metals in products, their distribution in gaseous energy carriers such as biogas is negligible, and their combustion poses benign toxicities compared with volatile organics such as aromatic hydrocarbons [45]. For solid hydrochar fuels, HTC is known to alter heavy metals' speciation and enhance their stability and immobilisation in hydrochar, reducing their bioavailability and eco-toxicity risk for environmental application [46]. However, due to their high melting points, heavy metals tend to remain in ash content after hydrochar combustion. Estimated heavy metals in other products – treated effluent and compost – are significantly reduced under both technology-based scenarios. This could be strategic for meeting statutory discharge concentrations/limits. The subsequent LCA section further shows the environmental advantage of recovering diversified fuels.

3.4. Life cycle impact assessment

The net environmental impacts of managing agri-food waste under S2_AD and S3_HTC&AD are summarised in Table 5, compared to the S1_Landfill, where organic fractions are sent to unsanitary landfills with no energy recovery and leachate collection. The results show significant reductions (96% or more) in adverse environmental responses for all impact categories of S2_AD and S3_HTC&AD, except for marine eutrophication, mineral resource scarcity, ionising radiation potential and most cases of ecotoxicity and human toxicity. For example, S2_AD reduced the global warming potential and ozone depletion potential to ~4.1 Mt CO_2-eq. and 2.3 kg CFC-11-eq. per annum, a 97% decrease from the current S1_Landfill. Similarly, S3_HTC&AD also reduced the annual environmental impact, but to a lesser degree; ~6.0 Mt CO_2-eq. and 2.2 kg CFC-11-eq., respectively. For both technology-based scenarios, there were net environmental savings for water consumption potential, with reductions from ~5.3 million m^3 water (S1_Landfill) to ~1.6 million m^3 water (S2_AD) and 0.8 million m^3 water (S3_HTC&AD). The decrease in mineral resource scarcity and ionising radiation potential was between 60 and 75%, while the reduction for marine eutrophication potential, human toxicity (irrespective of the type) and eco-toxicity potential (regardless of the type) were between 20 and 59%. These results show the importance of employing clean energy and waste solutions to avoid landfilling valuable agri-food waste fractions. The indicative reasons for variance in results are provided in section 3.5, supported by Fig. 3.

3.5. Contribution analysis of life cycle stages

Fig. 3a–c highlight the contribution of the different life cycle stages to net environmental impact: (a) S1_Landfill, (b) S2_AD, and (c) S3_HTC&AD scenarios. The factors contributing to the reduction in environmental performance are discussed for each scenario with a focus on i) global warming potential, ii) acidification and eutrophication, iii) ecotoxicity and human toxicity, and iv) ionising radiation and photochemical oxidant formation.

Table 5
Overall environmental impact of managing agri-food waste for all scenarios.

	Unit	S1_Landfill	S2_AD	S3_HTC & AD
Global Warming Potential	kg CO_2-eq	155544243	4121628	5959736
Fine Particulate Matter Formation	kg $PM_{2.5}$-eq	157401	841	1065
Terrestrial Acidification Potential	kg SO_2-eq	532237	3074	3596
Freshwater Eutrophication Potential	kg P-eq	122	0	0
Marine Eutrophication Potential	kg N-eq	11135	6216	6564
Mineral Resource Scarcity	kg Cu-eq	20863	4702	5184
Fossil Resource Scarcity	kg oil-eq	45541460	108619	164397
Ozone Depletion Potential	kg CFC-11-eq	67	2	2
Ionising Radiation Potential	kBq Co-60-eq	39111	15587	23484
Photochemical Oxidant Formation: Ecosystem Quality	kg NOx-eq	1198571	2780	3267
Photochemical Oxidant Formation: Human Health	kg NOx-eq	1195913	2763	3247
Terrestrial Eco-toxicity Potential	kg 1,4-DCB-eq	6232525	103914	150771
Freshwater Eco-toxicity Potential	kg 1,4-DCB-eq	268311	175923	216310
Marine Eco-toxicity Potential	kg 1,4-DCB-eq	337652	205963	253807
Human toxicity: cancer	kg 1,4-DCB	625776	405782	478094
Human toxicity: non-cancer	kg 1,4-DCB	221947871	153070404	177269177
Water Consumption Potential	m^3 water consumed	5282114	−1602072	−809655

3.5.1. Global warming potential

Global Warming Potential accounts for the distinctive properties of greenhouse gases to absorb radiation and retain absorbed heat for a given period in the atmosphere [47]. Specifically, it measures the emissions of greenhouse gases from defined processes, translating these to carbon dioxide equivalent (CO_2-eq.). In this respect, Fig. 3a shows that the primary contributor to global warming potential is landfill operation (about 92%) and the rest from venting emissions into the air. Emissions from landfill operations are generated from materials and energy used for running and maintaining the landfill site, including tailpipe emissions from diesel-powered compactors.

Considering the technology-based scenarios in Fig. 3b & c, the results show that there is a significant reduction (99% and more) in the overall contributions from landfill operations due to the reduced amount of agri-food waste; however, the environmental contributions from passive venting of landfill gas is not entirely avoided. For both technology-based scenarios, venting as a key life stage contributed more than 80% to the net environmental impact for global warming potential, corresponding to 235 t CO_2-eq. kg^{-1} agri-food waste (S2_AD) and 349 t CO_2-eq. kg^{-1} agri-food waste (S3_HTC&AD). Zero-waste approaches can avoid these emissions, e.g., source collection and segregation of organic waste, capturing landfill gas for heat and/or electricity, and sealing AD plants to avoid fugitive emissions. Agri-food waste conversion, including pre-

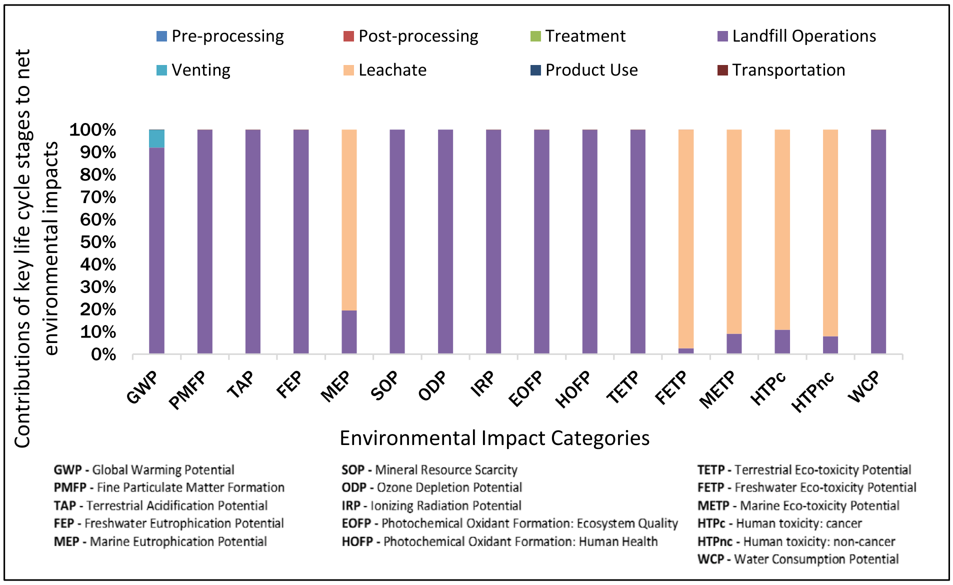

Fig. 3a. Contributions of key life cycle stages to net environmental impacts Business as Usual Scenario (S1_Landfill).

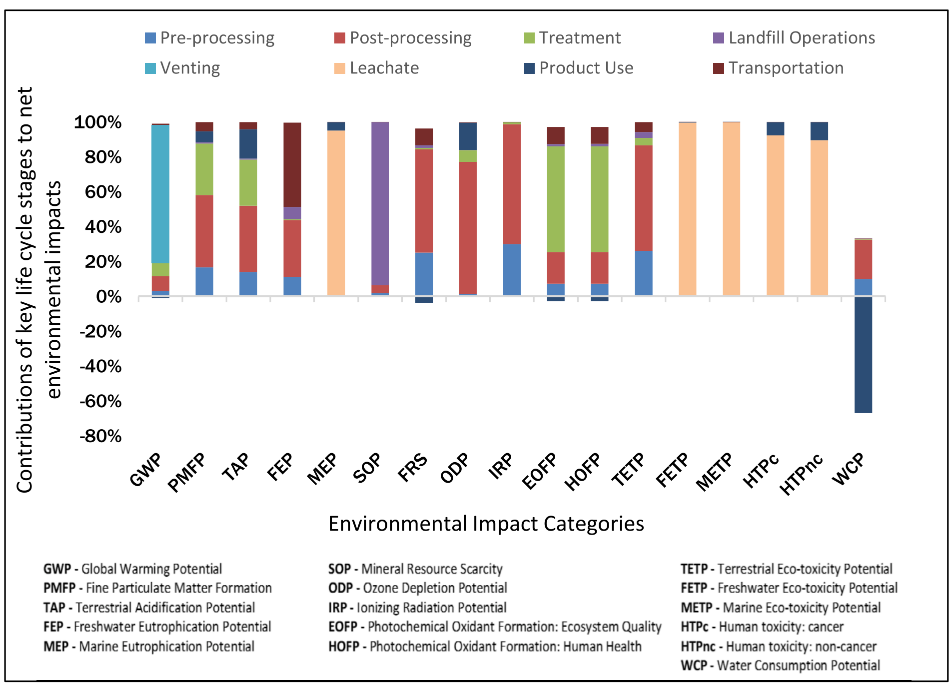

Fig. 3b. Contributions of key life cycle stages to net environmental impacts Anaerobic Digestion Scenario (S2_AD).

and post-conversion processes, also contributed to global warming potential, and emissions can be avoided by displacing fossil fuel sources with clean alternatives. In this study, using digested solids to substitute mineral fertiliser brought about a net saving of 2.6 t CO_2-eq. and 3.9 t CO_2-eq. under S2_AD and S3_HTC&AD scenarios, respectively.

3.5.2. Eutrophication and acidification

Eutrophication resulting from over-enrichment of land and/or water can lead to hypoxia (oxygen depletion), excessive algal bloom and loss of aquatic organisms and other life forms [48]. Furthermore, the decomposition of dead animals and plants, coupled with oxygen depletion and CO_2 release, can further lead to terrestrial acidification, in addition to those caused by increasing air pollutants, e.g. sulphur dioxide, nitrogen oxides and ammonia. These processes are considered in the freshwater eutrophication, marine eutrophication and terrestrial acidification impact categories. Fig. 3a shows that landfill operations also had the largest significant contribution to terrestrial acidification and freshwater eutrophication with emission contributions of 37.6 t SO_2 eq. and 8.6 kt P-eq. per kg agri-food waste, respectively. Comparing this to scenarios S2_AD (Fig. 3b) and S3_HTC&AD (Fig. 3c), it is safe to deduce that the diversion of agri-food waste from landfill had significant benefits (<1% contribution from landfill operation in all cases). However, for both technology-based scenarios, there are other contributing factors. For example, in terrestrial acidification, 14–38% (S2_AD) and 12–54% (S3_HTC&AD) of emission contributions have resulted from pre-processing, treatment and post-processing activities. However, for freshwater eutrophication, most contributions have resulted from transportation activities: 49% in S2_AD and 36% in S3_HTC&AD. These

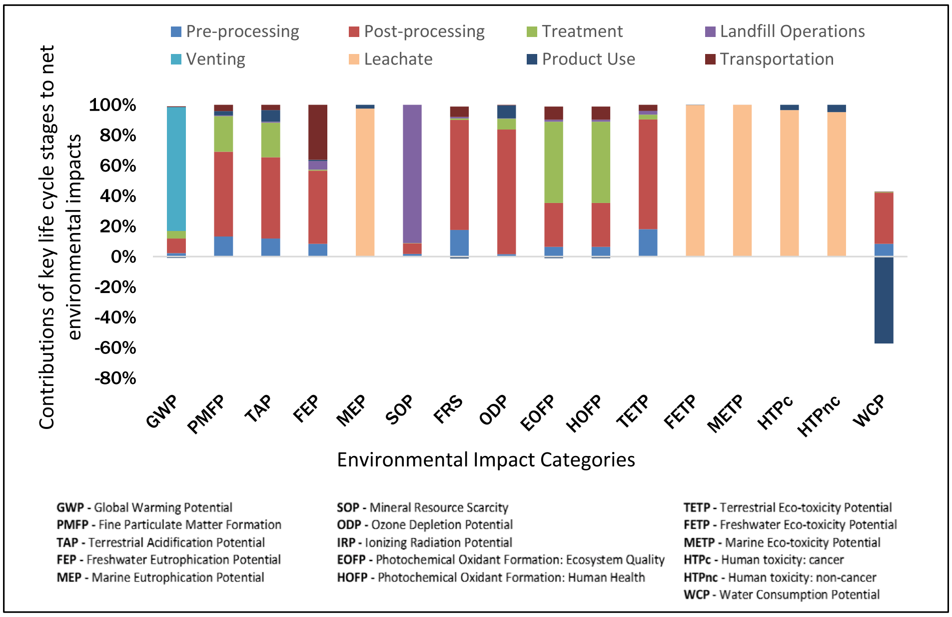

Fig. 3c. Contributions of key life cycle stages to net environmental impacts Integrated HTC-AD scenario (S3_HTC&AD).

differences in result can be attributed to the reduction in the requirement for digestate treatment in S3_HTC&AD. Comparing S2_AD and S3_HTC&AD to S1_Landfill, contributions to terrestrial acidification and freshwater eutrophication are overall limited since the overall emissions are lower and at most 0.3 t SO2 eq. per kg agri-food waste and 5.9 Mt P-eq. per kg agri-food waste.

In the case of marine eutrophication in Fig. 3a, the percolation of uncollected leachate into groundwater and subsequent runoff into surface waters had the most impact and corresponded to 80% of emission contributions. These contributions were much higher in S2_AD (~95%) and S3_HTC & AD (~98%). The reduced environmental performance can be attributed to digestate applications on agricultural soil and those resulting from landfilling of process residues. For both technology-based scenarios, net environmental savings could not be achieved; however, converting agri-food waste to energy products reduced environmental impacts. Emission contribution to eutrophication and acidification can be eliminated by avoiding nutrient discharge into surface waters through a controlled nutrient application on agricultural fields and using the best available technologies/processes for treating AD effluents and preventing release into surface waters.

3.5.3. Ionising radiation and photochemical oxidant formation

Photochemical oxidants are formed when chemical precursors, e.g. oxides of nitrogen, react with volatile organic compounds, e.g. non-methane volatile organic compounds, under sunlight-induced conditions [49]. These secondary air pollutants can lead to reduced visibility and adverse health effect. On the other hand, ionising radiation results from soil, water or air contaminated with radioactive substances. A high level of human exposure to dangerous radioactive substances can lead to damage/failure of critical organs and/or tissues. Fig. 3a shows that landfill operations are the major cause of ionising radiation potential and photochemical oxidant formation (Ecosystem quality and Human health). In contrast, Fig. 3b & c shows that emission contributions from landfill operations are minimal for S2_AD and S3_HTC & AD, primarily due to technology innovation and agri-food waste diversion. For S2_AD and S3_HTC & AD, emission contributions to ionising radiation potential were mainly from pre- and post-conversion processes, while those resulting in photochemical oxidant formation were from treatment processes, e.g. anaerobic digestion. The adverse contributions on ionising radiation potential and photochemical oxidant formation can be minimised by eliminating tailpipe emissions, e.g., via energy efficiency improvement and fuel substitution in internal combustion engines. A net environmental saving was observed on photochemical oxidant formation: ~82 kBq Co-60-eq. kg^{-1} (S2_AD) and ~37 kBq Co-60-eq. kg^{-1} (S3_HTC&AD); attributed to nutrient recovery and mineral fertiliser substitution.

3.5.4. Eco-toxicity and human toxicity

This covers aspects of terrestrial eco-toxicity, freshwater eco-toxicity, marine eco-toxicity and human toxicity, cancer or non-cancer related. Fig. 3a shows that landfilling agri-food waste contributes significantly to terrestrial eco-toxicity, and leachate percolation is the major contributor of emissions to freshwater eco-toxicity and all cases of human toxicity. Landfill operations contributed 440 t 1,4-dichlorobenzene eq. kg^{-1} to terrestrial eco-toxicity while a broad range of values between 0.5 and 1250 t 1,4- dichlorobenzene eq. kg^{-1} are observed for other eco-toxicity and human toxicity impact categories. For freshwater eco-toxicity and marine eco-toxicity, uncollected leachate contributes 18.5 t 1,4-dichlorobenzene eq. kg^{-1} and 21.7 t 1,4-dichlorobenzene eq. kg^{-1} respectively, but minimal or no effect is observed on terrestrial eco-toxicity. For human toxicity, the effect is much higher, with values ranging from 44 t 1,4-dichlorobenzene eq. kg^{-1} (human toxicity, cancer-related) and 6600 kg 1,4-dichlorobenzene eq. kg^{-1} (human toxicity, non-cancer-related). These adverse contributions are supported by landfill operations, including emissions from burning diesel fuel in landfill compactors and maintaining the landfill. Moreover, Fig. 3b & c shows that proposed technology-based scenarios can reduce terrestrial eco-toxicity by 100% or more via waste–energy conversion. However, little effect is observed for other eco-toxicity and human toxicity impact categories due to the proportion of waste residues sent to landfills and the impact of post-processing activities. The S2_AD had the lowest impact on eco-toxicity: 7.4 t 1,4-dichlorobenzene eq. kg^{-1} (terrestrial eco-toxicity), 12.4 t 1,4-dichlorobenzene eq. kg^{-1} (freshwater eco-toxicity) and 14.6 t 1,4-dichlorobenzene eq. kg^{-1} (marine eco-toxicity). It also had the lowest impact on human toxicity potential, ranging from 28 t 1,4-dichlorobenzene eq. kg^{-1} for human toxicity (cancer-related) and 10800 t 1,4-dichlorobenzene eq. kg^{-1} for human toxicity (non-cancer-related). These results are expected for the region of interest because of the heavy reliance on fossil fuel consumption for energy generation and transportation. For both technology-based scenarios, clean energy alternatives are required for pre-and post-processing activities to eliminate negative environmental contributions.

3.6. LCA sensitivity analysis

To evaluate the influence of parameter variation on environmental contributions, sensitivity analysis was completed on critical areas where emission contributions are primarily significant, e.g., pre-processing, resource conversion and post-processing activities, particularly where technical assumptions have been made. For example, this study has assumed that there is about 8 wt% loss of agri-food waste during separation, 25 wt% loss during sorting, and 5 wt% loss during homogenisation, leading to ~35% process reject. Hence, the sensitivity of data to cumulative pre-processing loss was examined in one of the cases. This study has employed a one-at-time sensitivity approach, where subsets of inputs are varied individually to ascribe cause-effect and determine outputs' sensitivity to input parameters. The lower and upper boundaries of the parameters used for the sensitivity analysis are detailed in Supplementary Information, SI-8, reflecting ±10% scenario analysis of the baseline values. Results are presented in Fig. 4a (S2_AD) and 4b (S3_HTC&AD) for variation in inputs for cumulative pre-processing loss, percentage of effluent treated via membrane bioreactor, percentage of solid-liquid separation and gas yield as a proportion of biodegradable carbon, respectively.

Fig. 4a (i – iv) & 4b (i – iv) show that a change in process input does not considerably alter the ranking of environmental outputs for most of the impact categories. The results for both technology-based scenarios are similar though varying in magnitude. Fig. 4a (i – iii) & 4b (i – iii) show that the variation in pre-processing, solid-liquid separation and effluent treatment by 10% less or more brings about a corresponding ~3%, ~20% and 3% variation in water consumption potential under S2_AD and 20%, 40% and 8% change for the case of S3_HTC&AD respectively. These results are expected due to the changes in the volume of waste treated, mainly for S3_HTC&AD, where the main advantage is the value recovery of hydrochar and reduced digestate volume. The other environmental impact categories sensitive to these inputs are ozone depletion potential (~-4.4 to 4.5%) for variation in pre-processing losses and mineral resource scarcity (5.2%) for effluent treatment via membrane bioreactor. Further assessment of Fig. 4a and b (iv) shows that the changes in biogas yield by ± 10% had the most impact on global warming potential and both cases of photochemical oxidant formation. When biogas yield changed, the global warming potential varied more than 11% under S2_AD and ~8.5% under S3_HTC&AD. These results show that factors that change biogas quality/quantity will enhance the environmental performance of both technology scenarios, and any uncertainty in parametric values will affect outcomes.

3.7. Study implications and considerations for implementation

This study has shown that up to 91% of agri-food waste arisings (under scenario S3_HTC&AD) from the case-study open-air markets in Kampala can be diverted from unsanitary landfill for energy production and value-added recovery with significant environmental benefits.

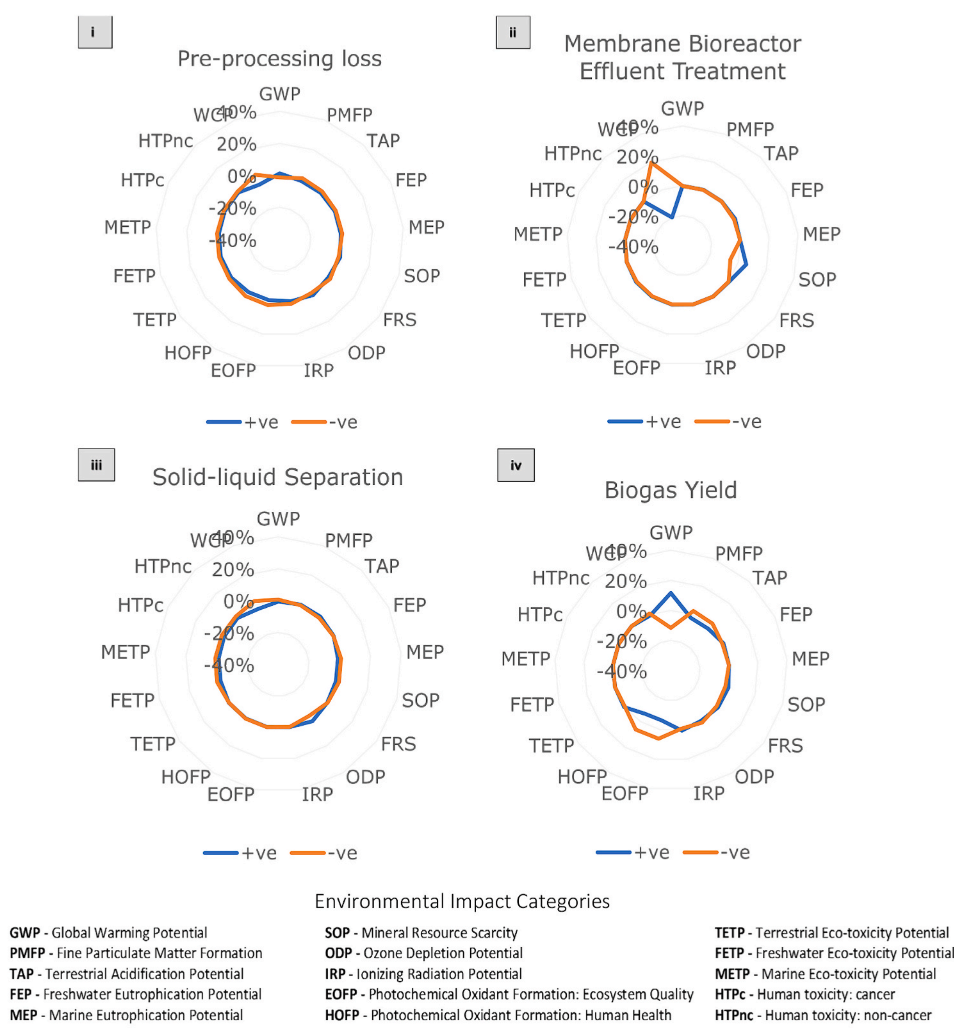

Fig. 4a. Sensitivity results for S2_AD based on variation inputs for i) cumulative pre-processing loss, ii) percentage of effluent treated via membrane bioreactor, ii) percentage of solid-liquid separation, and iv) biogas yield as a proportion of biodegradable carbon.

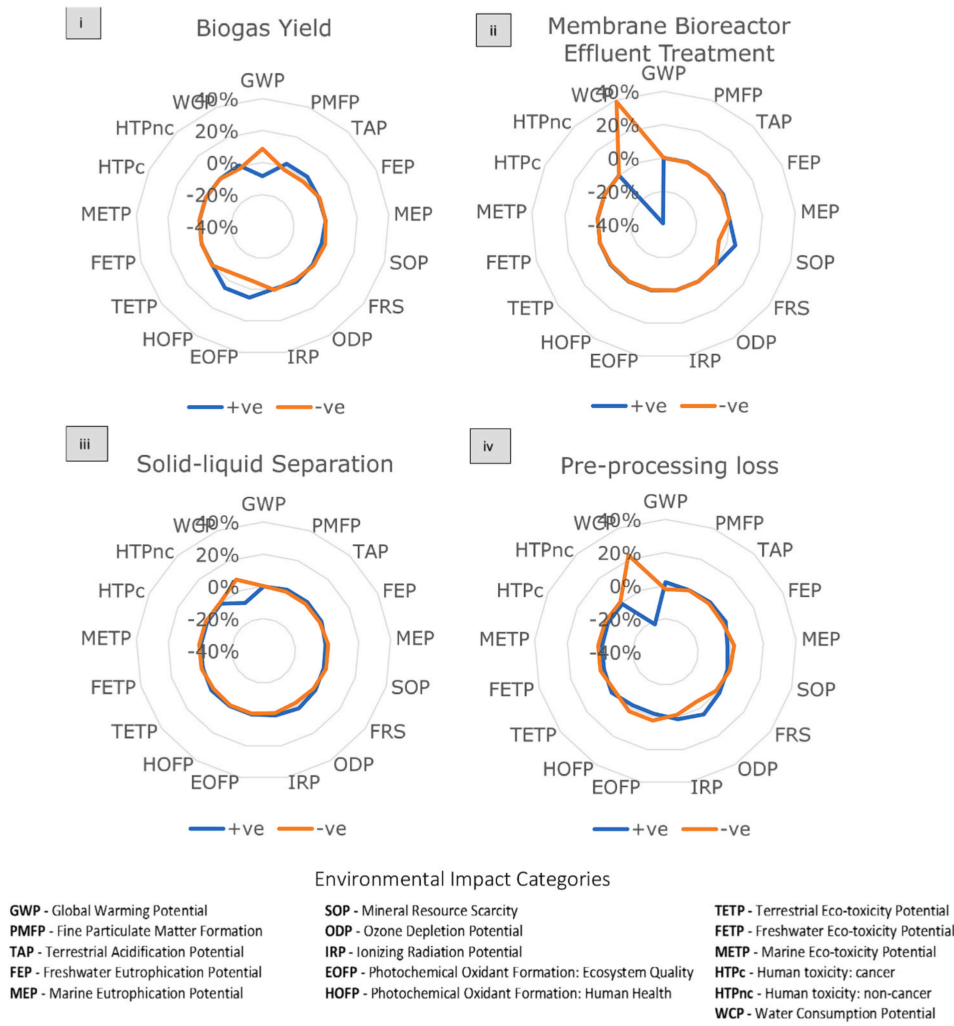

Fig. 4b. Sensitivity results for S3_HTC&AD based on variation inputs for i) cumulative pre-processing loss, ii) percentage of effluent treated via membrane bioreactor, iii) the percentage of solid-liquid separation, iv) biogas yield as a proportion of biodegradable carbon.

However, does technology innovation, transfer and adoption, particularly in sub-Saharan Africa, always translate to benefits? This remains a critical implementation question as in-depth reviews of technology adoption of small-scale anaerobic digesters in sub-Saharan Africa have itemised several challenges, ranging from financial and socio-economic to regulatory issues [50,51]. Also, evaluating technological considerations critical to sustainable WtE technology implementation in sub-Saharan Africa reveals that insufficient/low-quality feedstock represents a significant operational limiting factor. Other attributional factors include the sparse and distributed nature of waste, poor quality of segregation and lack of manpower/infrastructure to sort and separate waste efficiently [3]. In this respect, anticipated benefits promised by technology-based WtE valorisation systems (such as those investigated in this study) can only be actualised if these technical barriers are addressed.

This study further shows that there is no significant difference in agri-food waste physicochemical properties, across all agri-food markets, despite heterogeneous agri-food waste mix and differences in typological compositions, market and sampling sites; however, this is subject to spatial and temporal effects. While this study plugs the gap in the primary compositional properties of agri-food waste from open-air urban agri-food markets, more studies are needed to evaluate spatial-temporal generation patterns beyond the locations and sampling regime presented in this study, to examine wider variabilities (including typological compositions, heterogeneity, and seasonal effects) and compositional inconsistencies. Also, regarding considerations for implementations, competing uses for agri-food waste, e.g., for animal feed, need to be factored in for sustainable agri-food waste utilisation for bioenergy recovery. Other operational issues relating to inefficient/failed operation, such as clogging and under/overloading dry and fibrous materials and poor design and operation of facilities, need careful investigation or sustainable implementation.

This study's key aspect of the LCA shows that net emissions are more pronounced under S2_AD. Despite the significant reductions (96% or more) in adverse environmental responses for most impact categories, both S2_AD and S3_HTC&AD negatively impact eutrophication, resource scarcity, and ecotoxicity. These impacts are expected because land application of bio fertilisers has inherent environmental risks. These impacts can be more than projected if biogas is used inefficiently for energy generation and digestate poorly applied on agricultural fields, particularly in erosion-prone areas. For example, a study by Smith et al. [51] showed that failed AD technologies in Ethiopia and Uganda caused adverse environmental impacts due to inefficient use of biogas and digestate slurry. In other instances, over-pressurisation, gas leaks and fire explosions have been reported due to poorly maintained compost facilities, with unlined pits and open roofs. This can lead to significant environmental release of greenhouse gas emissions and nutrients leaching into underground and surface waters. In these cases, S2_AD and S3_HTC&AD could compound environmental effects rather than reduce them. To minimise such environmental impacts, implementation requires that technology-based valorisation systems be carefully designed, context-specific and adapted to local conditions, ensuring parts can be replaced locally and operators have the adequate technical ability to maintain the facilities.

Furthermore, this study has employed a one-at-a-time approach to sensitivity analysis, where subsets of inputs are varied individually while others are fixed at nominal or baseline values. This approach has been adopted by several authors [52,53] and is notably useful for identifying critical input-output relationships and priority areas for process improvement and data refinement. However, it does not account for the combined effect of several parameters and the understanding of the correlation between variables. This element can further be improved using global sensitivity analysis with specific inputs, such as the probability distribution of input parameters and their interactions, but these were not available for this study. Finally, techno-economic analyses (outside the scope of this study) that provide a viable economic basis are imperative to demonstrate the potential and benefits of WtE technology-based valorisation scenarios. This is critical to securing requisite funding mechanisms to finance beneficial WtE interventions, as reported in this study.

4. Conclusion

Open-air agri-food markets ubiquitous in sub-Saharan Africa and other similar contexts are hotspots for agri-food waste generation. Agri-food wastes are predominantly wet, unsegregated, and highly heterogenous, largely landfilled or burnt in the open. When the environmental impacts of these management approaches and intrinsic agri-food waste potential as an untapped and significant energy source are considered, there is a need to change and accelerate innovative context-sensitive interventions that mobilise and utilise them for bioenergy generation. This is critical to make significant contributions to Sustainable Development Goals 3, 7, 11 and the climate change agenda in the region.

The integrative assessment approach used in this study, combining material flow analysis, waste-to-energy process modelling/simulation and life cycle analysis, provided valuable insights into the bioenergy production potentials, value-added material recycling opportunities and environmental impacts of standalone and integrated conversion technology-based agri-food waste valorisation systems. The lack of information and published results, e.g., on compositional characteristics and life cycle analysis of agri-food waste from open-air markets or near-similar settings in sub-Saharan Africa, hampered the comparative evaluation and validation of the current study. However, deploying technology-based interventions to valorise agri-food waste, as discussed in this study, are promising alternatives to significantly minimise agri-food waste landfilling and associated environmental impacts, especially integrated HTC-AD for generating diversified biofuels with higher energy efficiency (η_{eff} ~69%), albeit with inevitable cost implications. In-depth, context-informed techno-economic analyses of both technology-based valorisation scenarios in the local (and other similar) context are critical for sustainable implementation and should inform future enquiries as a logical continuation of this study.

Credit author statement

Somorin Tosin: Methodology, Formal analysis, Investigation, Writing – Original Draft Preparation; Writing – Review & Editing; **Campos Luiza:** Writing – Original Draft Preparation; Writing – Review & Editing; **Kinobe Joel:** Investigation, Writing – Review & Editing; **Kulabako Robinah:** Investigation, Writing – Review & Editing; **Afolabi Oluwasola:** Conceptualisation; Methodology; Funding acquisition; Writing – Original Draft Preparation; Writing – Review & Editing, Supervision.

Declaration of competing interest

We declare no competing interests or relationships that could have influenced our submission.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2023.106752.

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