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Circular bioeconomy potential and challenges within an African context: From theory to practice

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ABSTRACT

A circular bioeconomy has the potential to minimize the environmental impacts of biowaste while simultaneously generating value-added bioproducts and bioenergy. Currently, most countries of the African Union lack well-defined policies, requisite infrastructure, and expertise for biowaste valorisation, thus limiting the potential development of the region. Against this background, it is necessary to deploy circular bioeconomy principles based on the awareness of the biocapacity of territories through the nexus of biowaste management and life cycle thinking. In the present study, a preliminary assessment of waste management practices in a tourist hotel in Victoria Falls in Zimbabwe is explored. The hotel produces about 3.26 tons per month of biowaste, which is often improperly disposed in non-engineered waste dumps. Furthermore, the disposal options for 1 tonne of biowaste are explored using City of Harare (CoH) as a case study. The preliminary results show composting as the most environmentally favourable option (9.6 kg CO_2 eq), followed by anaerobic digestion (56.4 kg CO_2 eq), and finally, biowaste incineration (140 kg CO_2 eq). Anaerobic digestion and composting remain the most viable biowaste disposal alternatives in Africa, due to limited expenses and expertise for construction, operation, and maintenance. However, both technologies remain under-utilized, hence, a significant portion of the source-separated biowaste is still disposed of in waste dumps and this reflects the lack of supportive institutional, regulatory and policy frameworks. Overall, these early results point to the potential to develop a circular bioeconomy in Africa, while calling for shared responsibilities among the state, market, and civil society actors to develop and adopt appropriate institutional, regulatory, policy and funding models.

1. Introduction

A sustainable circular bioeconomy is expected to contribute towards addressing current challenges like global warming, fossil resource scarcity, ecosystem degradation, food shortages and poor municipal biowaste management (Santagata et al., 2021). The circular bioeconomy is envisioned to deliver multiple bio-based products from bioresources feedstock (Mabee, 2022). In fact, the circular bioeconomy is expected to make a significant contribution to the various dimensions relating to the replacement of fossil resources without competing with food production, thus ensuring food security for all (Cristóbal et al., 2018). The circular bioeconomy concept, defined as the conversion of biowaste streams into value-added products and bio-energy, constitutes an important principle of the circular economy that will radically change

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our approach towards the management and disposal of biowaste (European Commission, 2018). It has already been adopted by a significant number of low- and middle-income countries as a new vision of development, and can be a valid path towards the achievement of the Sustainable Development Goals (SDGs) and the commitments under the Paris Climate Agreement (FAO, 2018). Currently, more than 50 nations worldwide are proposing actions and strategies to boost their economic dimension through circular bioeconomy pathways (Presidency of Council of Ministers, 2017). For example, the Chinese government launched the 12th Five-Year Plan, specifically to link its biobased economy to biotechnology with a view to promote agricultural innovation and ensuring food security to its citizens (Fan and He, 2013). Meanwhile, in South Africa, the government expects the circular bioeconomy to be a significant contributor to the country's economy by 2030 (FAO, 2018). This is to be achieved through the creation and growth of new industries that generate and develop bio-based services, products and innovations through their National Bioeconomy Strategy which was published in 2013 (Department of Science and Technology, 2013). Generally, the aim of circular bioeconomy policies for many governments is to respond to societal challenges, such as climate change, food security, energy supply and environmental improvements, which are pressing global issues even in Africa (Feleke et al., 2021; Poku et al., 2018). In most African countries, agriculture, including primary production, post-harvest agro-processing and marketing are sources of livelihoods and food security in both rural and urban areas (Gwenzi et al., 2015). Agro-processing and subsequent food preparation and consumption generate large quantities of biowastes, including food waste (Donner et al., 2020). In peri-urban and urban areas, these biowastes are often generated in centralized areas such as marketplaces, residential areas, and institutions such as hotels and educational institutions (Demichelis et al., 2019). At the same time, the generation and improper management of such large quantities of biowaste in centralized areas poses significant environmental and human health risks, including air (e.g., odours), soil and water pollution (Angouria-Tsorochidou et al., 2021). On the other hand, this creates ideal conditions for the collection, sorting, transport, and subsequent valorisation via composting, and waste-to-energy systems (Donner et al., 2020). This is particularly important given that several people in Africa lack access to energy for household and institutional heating and cooking (Mukumba et al., 2013). Thus, addressing the problem of biowaste and its pollution risks could be coupled with the provision of energy for household and institutional heating and cooking, and/or soil amendments (e.g., compost, digestate) for improving soil fertility and crop productivity. In this regard, biowaste and its pollution risks can be addressed as part of the energy-environment nexus (Angouria-Tsorochidou et al., 2021; Donner et al., 2020).

Pathways for Africa on how to use the circular bioeconomy as an effective tool for building more sustainable, more prosperous, and more inclusive societies with plenty of opportunities for new jobs and industries need more exploration (Rweyendela and Kombe, 2021). Currently, there appears to be no technological silver bullet solution to address the climate crisis and resource scarcity (Bracco et al., 2018). The low-carbon transition is primarily a societal issue and requires collective willingness to rethink our consumption patterns of goods, services, and energy (Georgantzis Garcia et al., 2021). Moreover, there remains an urgent need to chart a possible path highlighting the many factors that could lead to desirable outcomes by drawing key lessons on how to navigate catastrophes and crises such as the COVID-19 pandemic (Gwenzi, 2021). As the demand for energy and materials is expected to increase significantly in Africa in the coming decades, bioenergy derived from biomass and organic residues is expected to replace and substitute fossil-based raw materials (Abass, 2014). However, any innovation purporting to be solving one problem could run the risk of creating new problems. As such, calls towards bio-based circular economies aided by developmental innovations and technologies to boost economic growth particularly focusing on the Africa, need scrutiny. For example, a bio-based circular economy seems to promise much in terms of delivering economic growth and environmental benefits, but does not directly address social inclusion or justice and economic benefits (Birner, 2017; Sodano, 2013). Yet, circularity is expected to be inclusive by shifting from 'winner vs loser' to a 'win-win' situation towards environmental conservation, well-being and economic growth (Santagata et al., 2017). Blum et al. (2020) further cautions about the sustainability of circular practices by arguing that increased circularity does not warrant sustainability and that it requires further investigation.

Investigating the supply chain that leads to the main biomass product as well as the food generation and treatment is important when the goal is to assess the sustainability of the whole biomass value-chain. Instead, when the goal is understanding which is the most sustainable treatment process, the commonly used zero-burden approach allows to only focus on the treatment process impacts without including the waste generation impacts (Gentil et al., 2010; Allacker et al., 2014). This is because in a comparison, the amount of waste to be treated is the same and of the same kind for each investigated treatment process and because waste is not considered a co-product and therefore does not carry any allocated fraction of the upstream supply chain (Allacker et al., 2014). In the context of the present study, the focus is on the technologies for appropriate treatment of organic biowastes and residues rather than on biomass specifically grown for bioenergy. Identifying the most efficient and effective treatment technologies is of utmost importance to prevent additional sources of unsustainability along the supply chain (Santagata et al., 2021). The synergic interaction of biological, technical and social components under human control makes the implementation of circular bioeconomy challenging, especially when profits are foreseen with simultaneous links with business models (The Ellen MacArthur Foundation, 2012; WEF, 2014). A circular bioeconomy approach considers a network of biomass-based value chains to complement the circular economy, through the recovery of bio-based energy and materials which can substitute or replace non-renewable sources (Negi et al., 2021). Within this concept, biowaste acts as a feedstock for recovering bioenergy and bio-based products, and reduces the reliance on fossil energy and products (Santagata et al., 2021). Despite the intuitive environmental appeal of the circular bioeconomy concept, there is still limited evidence from Africa pertaining to how this transition can be achieved and harnessed to contribute towards industrialization (Negi et al., 2021). Therefore, this research paper intends to cover this gap by linking circular bioeconomy, life cycle assessment and waste management. The research paper first presents information on biowaste generation and its disposal at a hotel as a local scale case study representing the tourism sector which generally produces large amounts of bio-waste. Second, biowaste management practices in the City of Harare are presented as a large scale closer to life case study, where LCA and circular bioeconomy principles are applied to provide policy recommendations. Finally, results of Life Cycle Assessment (LCA) comparing incineration, composting, and anaerobic digestion are presented. A comparison of the LCA results for the three technologies is then applied to inform the selection of the best waste management option, and the development of a roadmap towards a circular bioeconomy in Africa.

1.1. Current biowaste disposal and the status of circular bioeconomy in Zimbabwe

Extremely favourable natural, climatic and soil conditions create conditions for strong development in the agricultural sector and enable the production of biomass. Zimbabwe is such a country which is endowed with enabling factors like a good climate, good soils and large tracts of arable land (Jayne et al., 2006). However, there is still an untapped potential for technological process and utilization in the agricultural sector and waste biomass exploitation (Donner et al., 2020). As such, an aggressive development strategy based on circular bioeconomy models is much needed (Ghosh and Di Maria, 2018) to overcome the basic problems related to the provision of resources for agriculture

(Ubando et al., 2021). Zimbabwe remains food insecure, a situation exacerbated by the incessant droughts resulting from climate change, poor planning and some policy inconsistencies, among others, which affect the food life cycle from a "farm to a fork" perspective (Jayne et al., 2006). Farm to fork refers to various sustainability strategies applied in the food chain from agricultural production to consumption aimed at making food systems fair, healthy and environmentally-friendly (European Commission, 2020). Whilst climate change is a natural phenomenon exacerbated by anthropogenic activities which has unpredictable impacts, poor planning and policy inconsistencies are factors authorities and policymakers can easily control. These factors affect the amount of biowaste that is generated and the subsequent management thereof. Given that Zimbabwe does not have a well-defined circular bioeconomy and biowaste management policies, opportunities to harness the biowaste fraction into biomass feedstock and useable resources are missed daily (Abass, 2014). In the absence of an integrated circular bioeconomy policy, waste management in Zimbabwe is only espoused in the Environmental Management Act, which emphasizes the need for sanitary landfills, and safe disposal of wastewater and gaseous emissions management (Environmental Management Act 20:27; Statutory Instrument 6 of 2007; Statutory Instrument 10 of 2007 and Statutory Instrument 72 of 2009). In the same Act, focus on solid waste management is largely limited to safe disposal in engineered sanitary landfills, with limited attention to harnessing the solid waste in the context of the circular bioeconomy. This legislation still applies the Polluter-Pays-Principle in pollution prevention, and fails to take advantage of recent advances in technology (e.g., biogas generation) related to the circular bioeconomy (Ntostoglou et al., 2021). Although this legislation refers to cleaner production, it is silent on opportunities and approaches through which domestic waste, in particular biowaste, can be efficiently harnessed and converted into biomass feedstock through an integrated approach (Ncube et al., 2021). This is partly explained by limited research on the circular bioeconomy in Zimbabwe, a trend also common in most African countries (Feleke et al., 2021).

This gap was exposed during the COVID-19 global pandemic which resulted in the temporal closure of many economic activities including informal vending, when many African countries effected some containment lockdowns. Such vending markets generate large quantities of biowaste which can be used a feedstock in the circular bioeconomy. The outbreak of the COVID-19 pandemic also witnessed an increase in the confiscation and destruction of agricultural produce by law-enforcement agents as they enforced national lockdowns (Fig. 1). Due to the deficiency of integrated guiding policies, there are no agreed upon biowaste management practices in Zimbabwe. More often, in urban areas all the waste is indiscriminately collected in waste receptacles for dumping at the non-sanitary landfills and dumpsites, thereby posing environmental and human health risks (Gwenzi et al., 2015). In institutions such as hotels, schools, healthcare facilities, and vegetable markets where huge volumes of biowaste are produced, waste segregation is done at the discretion of the institution (Mbasera et al., 2016). Even after segregation is done, the final dumping might be arbitrary, and often entail co-disposal of organic and non-organic solid waste, thereby defeating the purpose of waste separation and segregation in the first place (Makwara and Snodia, 2013). Given the large volumes of biowaste produced in such institutions, the conversion of the waste into a resource like energy and organic fertiliser is feasible (Monica and Zengeni, 2013). Zimbabwe faces perennial electricity problems due to persistent droughts that are affecting hydroelectricity generation, and frequent faults at the old thermal power stations which are powered by coal. Thus, transitioning towards a circular bioeconomy will present numerous opportunities especially in the bioenergy generating sector.

To start the discourse around the adoption of a circular bioeconomy policy in Zimbabwe and many other African states with similar circumstances, the authors identified opportunities that can be presented using two case studies: (1) a large hotel in the main tourist town of Zimbabwe, Victoria Falls, and (2) the City of Harare, which is the capital city. The authors also sought to contribute with scientific evidence on the potential and challenges of circular bioeconomy within an African context. Additionally, despite having several studies on municipal biowaste in Africa (Mangundu et al., 2013; Komakech et al., 2015; Nhubu et al., 2020; Adeleke et al., 2021), to our knowledge, the aspect of linking circular bioeconomy, waste management and life cycle principles is still missing in literature. Currently, the African Union does not have fully developed policies on the circular bioeconomy and as such,

Fig. 1. Photographic images showing police enforcing COVID-19 restrictions and an individual destroying confiscated organic residue (taken from a Twitter link by Dr Chipo Dendere).

related policy approaches specifically suited for Africa's needs are much needed as opposed to extrapolation of data from other regions. Finally, this paper discusses the key elements of the systemic change to the transition towards the circular bioeconomy in Africa to foster and accelerate the uptake of bio-based circular practices and promote the shift to a circular bioeconomy. In the transition to a circular economy there are winners and losers, and the proposed future research is expected to design and offer win–win solutions for Africa to maximise the net overall benefits during implementation and ensure support for regional and continental collaborations.

2. Materials and methods

To collect general information and to understand the current biowaste management practices in Zimbabwe, the authors considered two different locations and scales. A major tourist hotel located in Victoria Falls, and the city of Harare (CoH), which is the capital city of Zimbabwe. Data collection included direct field observations at the selected hotel, waste disposal sites, interviews with key informants and the review of available documents and reports. Subsequently, the collected data were synthesized into a life cycle inventory used to conduct a life cycle assessment (LCA) of different biowaste disposal options to inform policy developments towards circular bioeconomy. Restricting the focus on technologies ("gate to gate" LCA versus "cradle to gate" LCA) does not mean disregarding the production processes that lead to waste generation (agricultural, industrial and urban processes, which also need to be assessed and made more environmentally friendly) but is simply a way to reduce the complexity of the evaluation, in order to be able to suggest specific policy choices.

2.1. Assessing the potential in the hotel industry: A hotel in Victoria Falls

One of the key challenges affecting the catering industry is food waste, and addressing such a challenge at an institutional level can be considered a quick win solution, particularly in the hospitality industry (Derqui and Fernandez, 2017). Hotels produce significant quantities of biowaste but at the same time, embody the opportunity to address food waste and its disposal. The hotel considered in the present study is in the tourist town of Victoria Falls in Zimbabwe. It has 294 rooms of which 74 are family rooms with average occupancy of 70% per month. The hotel approximately occupies about 8186 m^2 of energy consuming space. The environmental policy statement of the hotel focuses on continual reduction of the environmental impact of its operations in the areas of energy, water, chemicals, resource consumption, and waste generation. The policy also advocates for green procurement, that is, purchasing locally and sustainably produced organic food and products. Currently, the Zimbabwean tourism industry has no prevailing legislation to ensure that such noble initiatives and policy statements are fully implemented. This was confirmed by the absence of procedures on biowaste treatment, documented records on waste, and energy consumption. Data at the hotel was collected over a period of 6 months for waste (food, paper, cans, glass). Food waste was mixed, and mainly composed of fruit and vegetable off-cuts and starch left-overs. The quantification of the waste used a combination of methods adapted from the International Tourism Partnership Guide and World Wildlife Fund (IHEI, 1993; WWF, 2017). This entailed daily collection of waste bins used as receptacles that were then sorted, weighed, and recorded to establish a daily bin fresh wet weight for the different waste forms. According to the International Tourism Partnership, 2014, when guests generate about 5.3 tonnes of waste monthly (calculations based on hotel occupancy), it is considered excellent. Table 1 shows the monthly average waste data that was collected from January to June 2020 at the hotel. The energy figure of 263,500 kWh is provided to give a perspective of the energy demand of the hotel and how such a demand can be met by the recovered energy from bio-waste.

Table 1
Monthly average energy and waste data at the investigated hotel in Victoria Falls.[a]

Parameter	Hotel
Energy (kWh)	263,500
Food waste (t) (as collected)	3.26
Paper (kg)	119
Plastic- PET (Kg)	53
Glass (Kg)	22
Aluminium/Tin cans (Kg)	5

[a] *Actual grid energy consumption readings were taken from the hotel's monthly energy billing. The name of the Hotel is not disclosed due to confidentiality reasons.*

Given that the investigated hotel generates 3.26 tonnes fresh weight biowaste per month, the potential for recovering renewable energy cannot be disregarded with the possibility of recovering electricity. The substitution of fossil-based electricity from the grid with biobased biogas through anaerobic digestion is a promising low carbon pathway that can be environmentally and economically beneficial (Cristóbal et al., 2018). With proper and appropriate investments, waste-to-energy projects provide a promising future too (Maqhuzu et al., 2019). In fact, according to Maqhuzu et al. (2019), in Zimbabwe, source-separated household waste including biowaste can provide about 289,300 tonnes of coal-alternative fuel with significant reductions in greenhouse gas. According to Lou et al. (2013) one tonne of food waste can potentially produce 247 m^3 methane and generate approximately 847 kWh of electricity.

2.2. Assessing the waste-to-energy potential of City of Harare (CoH) at Mbare Musika and Pomona dumpsite

Mbare Musika is the main market for organic or agricultural produce in Zimbabwe. It is the oldest and largest marketplace in Harare where farmers and vendors supply the rest of the country with fresh fruit and vegetables. The resulting organic residues are dumped outside the market causing a nuisance to the environment and public whilst waiting to be collected by city council trucks. Pomona on the other hand, is the main dumpsite in Harare, located 25 km north of the Central Business District (CBD). Most of the solid waste including organic residues collected by the City of Harare (CoH) at Mbare Musika is finally disposed at the Pomona dumpsite together with household and industrial waste. The Pomona site was first used for dumping waste in 1985, and it spreads over an area of approximately 100 ha. Many previous studies have reported the Pomona dumpsite as a non-sanitary waste dump potentially causing environmental and human health risks (Kharlamova et al., 2016; Mugadza, 2017). The site has operational staff that guides incoming vehicles on where to dump waste. The waste material is supposed to be compacted and covered daily with soil. However, due to lack of operational compactors and other machines, neither compaction nor soil coverage takes place. The site is operated by the CoH and is named as a landfill, but it is not properly engineered as a landfill. Specifically, it lacks a hydraulic liner or the impermeable layer restricting groundwater contamination, and lacks a leachate collection and treatment system, hence hereafter is referred to as a dumpsite. The data on the quantities of the municipal solid waste (MSW) was provided by the CoH through their waste management division. To understand the potential and viability of establishing a waste-to-energy plant through incineration, the authors relied on the existing pre-feasibility reports from the CoH.

The daily mass of biowaste from Mbare market exceeds 20 tons according to CoH, but this could be considered an underestimate due to poor records keeping. Of this, 70–80% is organic and if deposited to the dumpsite it decomposes under anaerobic conditions, thereby emitting substantial amounts of methane which is a potent greenhouse gas. Given that about 70–80% of the waste from urban markets is in the form of biowaste, CoH has seen it viable to establish a collection, separation, recycling, and biogas-based waste management system for Mbare

Musika to curb the solid waste management problem. The CoH has also managed to establish pilot project of biogas production in Chikurubi maximum prison, Roosevelt Girls High, and Harare Hospital. All this has been done out of necessity caused by erratic hydroelectric power supplies in the absence of supporting circular bioeconomy policies.

There are other several biogas digesters in CoH, including the Glen View Firle and Crowborough sewage treatment AD facilities. The biogas digesters were initially installed at these activated sewage treatment plants to treat sewage but not to recover energy and as such, biogas is released into the atmosphere, thereby contributing to global warming (Environment Canada, 2013). The generated biogas usually consisting of 64% CH_4 and 36% CO_2 is lost energy with enough potential to drive several other industrial operations that require large amounts of energy (Ncube et al., 2021). Besides the CoH's efforts in constructing and establishing AD plants to manage biowaste around the capital, there are other numerous practices such as industrial composting for soil conditioning being implemented. The vermiculture program in Waterfalls is one such an example, which is used to conscientize and empower local communities to derive value from biowaste through composting. At the Pomona dumpsite, which is the main waste disposal facility in Harare, a feasibility study was carried out by the CoH to determine the possibility of establishing a waste-to-energy plant. According to the feasibility study report, the Harare waste-to-energy plant will use the collected municipal solid waste (MSW) as feedstock to produce electricity. According to the CoH, the Pomona dumpsite currently receives 600–700 tons of biowaste per day with a calorific value of 7–8 MJ/kg which is suitable for an incineration plant. Despite this huge potential for recovering a renewable energy source from MSW, the major bottleneck is the lack of funds to construct such facilities. Table 2 presents the average profile of waste generated in Harare used to assess the viability of a bio-energy project, *Waste2Energy* by the CoH.

2.3. Life cycle assessment (LCA) of biowaste disposal options

This study follows the main phases of an LCA which are: (1) goal and scope setting, (2) inventory analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation in compliance with the ISO 14040:2006 (ISO, 2006), and as recommended by the International Reference Life Cycle Data System, (ILCD, 2010). The goal is to compare the impacts of disposing 1 tonne (Functional Unit) of biowaste using the three selected disposal options (anaerobic digestion (AD), municipal incineration and composting using current practice of waste dumping as the baseline. The inventory data of inputs and outputs for AD and composting options were provided by the CoH with reference to the Mbare Musika AD facility and the Hwingiri composting facility. The data were acquired through personal communications with the CoH Environmental Department, and by comparing with literature sources (Lee et al., 2007; Righi et al., 2013; Mondello et al., 2017; Salemdeeb et al., 2018). The inventory data for the municipal incineration alternative was instead adopted from Salemdeeb et al. (2018) since Zimbabwe does not have such a facility yet. The system boundary takes a "gate to gate" and a zero-burden approach by extending the analysis only from the point when waste is collected to be transported to the disposal sites (90 km radius for incineration and 20 km radius for both composting and anaerobic digestion). The incineration facility needs to be located as far away as possible from the city centre and 90 km was considered appropriate. The disposal options chosen for the analysis are the most used locally, particularly composting, and anaerobic digestion, while biowaste incineration is more difficult and requires heavy investments.

The SimaPro commercial software version 9.1.1.1 was used to analyse the inventory data and the ReCiPe 2016 Midpoint (H) was used for the interpretation of environmental impacts (Goedkoop et al., 2016). To understand the consequences of the input and emissions into the different disposal options, the environmental impacts were translated and expressed as normalized or characterized factors. The normalisation values represent the total impacts of a referenced period as sum of all total impact categories (e.g., climate change, eutrophication, etc.). Normalisation gives an indication of an impact's magnitude and can be added up using the results of the different categories since they have the same unit. Normalized impacts help support the identification of the most relevant impact categories and to ensure that the focus is put on those aspects that matter the most for communication purposes (Ncube et al., 2021). Characterized impacts are a result of the multiplication by a factor of all the inputs, which reflects their relative contribution to the environmental impact. It is a quantification of how much impact a product or service has in each impact category. Relevant impact categories were chosen based on local environmental concerns which are currently dominating discussions at policy level in Africa such as climate change, toxic chemicals posing ecotoxicity affecting human health, resource depletion, water shortages and land degradation leading to a decline in soil fertility, hence affecting productivity. The chosen categories are shown in Table 3, where units of the impact categories are expressed as equivalent of what is acknowledged as the most recognized stressor for each impact category (Steinmann et al., 2018). Subsequently, the CoH inventory data related to the treatment of 1 tonne of biowaste through anaerobic digestion, biowaste incineration and composting are shown in Table 4.

3. Results

3.1. Life cycle assessment of different disposal options

The results of the LCA comparing different disposal options for biowaste will be expressed as normalized and characterized impacts as explained in section 2.3 in Methods and Material. These data are used to support the identification of the most relevant impact categories and to ensure that the focus is put on those aspects that matter the most and for communication purposes. Fig. 2 shows the environmental normalized impacts from the chosen biowaste disposal options in this study. The impact category affected the most by the three chosen disposal options for organic residues in Zimbabwe is freshwater ecotoxicity followed by human carcinogenic toxicity (Fig. 2). Other remaining impact categories such as global warming potential, fossil resource scarcity, terrestrial acidification, particulate matter formation and water consumption were significantly low but not disregarded.

The disposal option with the highest environmental load and burden is biowaste incineration characterized by the highest environmental

Table 2
Average profile of waste generated in Harare.

	Units	Amount
Harare population approximately	Million	1,487,000
Per capita generation approximately	kg/day	0.43
Generation per month approximately	Tons	19,200
Private companies per month approximately	Tons	7200
Harare monthly generation approximately	tons/month	26,400
Harare annual waste generation approximately	tons/annual	316,800

Table 3
Selected LCA impact categories considered in the present study.

Impact category	Unit*	Abbreviation
Global warming	kg CO_2 eq.	GWP
Fine particulate matter formation	kg PM10 eq.	PMFP
Terrestrial acidification	kg SO_2 eq.	TAP
Freshwater eutrophication	kg P eq.	FEP
Terrestrial ecotoxicity	kg 1,4-DB eq.	TETP
Freshwater ecotoxicity	kg 1,4-DB eq.	FETP
Human carcinogenic toxicity	kg 1,4-DB eq.	HTP
Land use	m^{2}*a	ALOP
Fossil resource scarcity	kg oil eq.	FDP
Water consumption	m^3	WDP

Table 4
LCA inventory data to process and treat 1 tonne of biowaste through anaerobic digestion, composting and biowaste incineration.

	Materials	Unit	Anaerobic digestion	Incineration	Composting
Inputs					
	Mixed biowaste	kg	1000	1000	1000
	Process water	kg	5.49	218.5	110.8
	Woodchip	kg			0.31
	Electricity	Kwh	65	161	5.78
	Transport	tkm	20	90	20
	Diesel	kg	0.081	5.8	0.5
	Auxiliary materials	kg	0.1	10	
Outputs					
			Digestate (550 kg)		Compost (659 kg)
			Electricity (175–300 KWh)	120 Kwh	
Wastewater		m^3	320	43	
Emissions to air					
	Carbon dioxide	kg	0.26	0.003	11
	Methane	kg		0.05	0.05
	Nitrogen dioxide	kg	1.9	0.28	0.1
	Nitrogen oxides	kg	0.4	0.1	2.7
	Carbon monoxide	kg	1.5	0.16	
	Sulphur dioxide	kg	0.01	0.003	0.02
	Hydrogen chloride	kg	0.006	7.00E-06	
	Hydrogen floride	kg		5.10E-08	

Source: City of Harare, Environmental Department, 2021

load in almost five of the nine selected impact categories in Table 3. Since biowaste containing high moisture content (60–70%) requires prior drying before use in waste-to-energy systems based on incineration. The need to dry such biowaste increases the energy and environmental footprints of incineration, making the technology less attractive (Tun and Juchelková, 2019) and these LCA results have highlighted this aspect well. Anaerobic digestion is in between, followed by composting with the least environmental burden. The differences in environmental load of the three considered disposal options are a result of the infrastructure and inputs needed during construction, operations, and maintenance. Anaerobic digestion and incineration are more intensive and complicated processes, whereas composting at a local level is characterized by simple and low-cost operating procedures. To further present the relative contribution of the different disposal options to the environmental impact, each impact category was expressed as absolute characterized values as shown in Table 5.

The contribution of both biowaste incineration and anaerobic digestion options to all the impact categories appears significantly higher especially in the global warming (GWP), and terrestrial ecotoxicity (TETP) categories. Evidently, this is due to the release of biogenic emissions in both options, which are equivalent to 56.4 kg CO2 eq for AD and 140 kg CO2 eq for incineration per tonne of biowaste. Even though composting can be regarded as the least impacting from an environmental point of view, it should be noted that composting requires large land space (ALOP) (4.52 m^{2}*a crop eq per tonne of biowaste). Also, during composting, soil nutrients tend to leach into the soil, and compositing may affect the soil pH, causing terrestrial acidification (TAP) and the release of fine particulate matter pollutants (PMFP). Overall, composting is the most environmentally sound option, followed by anaerobic digestion. Biowaste incineration is the worst

Table 5
Comparison of characterized impacts of the different biowaste disposal options (functional unit-1 tonne of biowaste).

Impact category	Unit	Anaerobic digestion	Organic residue composting	Biowaste incineration
GWP	**kg CO_2 eq**	**5.64E+01**	**9.60E+00**	**1.40E+02**
PMFP	**kg $PM_{2.5}$ eq**	**4.05E-01**	**3.32E-01**	**4.06E-01**
TAP	**kg SO_2 eq**	**1.29E+00**	**1.08E+00**	**1.22E+00**
FEP	**kg P eq**	**4.24E-02**	**1.66E-02**	**7.69E-02**
TETP	**kg 1,4-DCB**	**1.16E+02**	**4.90E+01**	**3.18E+02**
FETP	**kg 1,4-DCB**	**2.21E+00**	**6.57E+00**	**4.56E+00**
HTP	**kg 1,4-DCB**	**3.57E+00**	**6.07E-01**	**6.59E+00**
ALOP	**m^2a crop eq**	**9.52E+00**	**4.52E+00**	**2.37E+01**
FDP	**kg oil eq**	**1.39E+01**	**2.70E+00**	**4.12E+01**
WDP	**m^3**	**−1.08E+01**	**1.41E-01**	**−8.70E-01**

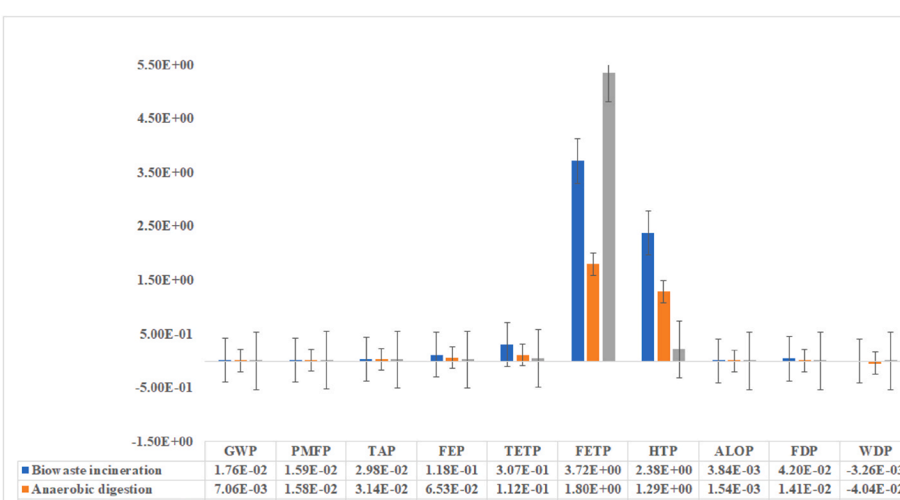

Fig. 2. Normalized impacts of the different biowaste disposal options based on a functional unit of 1 tonne of biowaste.

environmental performer, due to toxicity and the large number of greenhouse gas emissions released into the atmosphere during the incineration processes. Fig. 3 highlights the endpoint impacts in Life Cycle Impact Assessment (LCIA) so as to express the relative importance of the selected impact categories.

With respect to the overall treatment of biowaste, the endpoint weighted results in Fig. 3 indicate that human health endpoint impact category is the most affected, regardless of biowaste treatment option selected. This outcome calls for the need to apply value judgment on which biowaste treatment option is appropriate.

The combination of toxicity categories (Fig. 3) and the damage caused by other impact categories as expressed in Table 5 are responsible for largest human health impacts.

4. Discussion

The present study has provided some indications based on LCA data that the best disposal option from an environmental perspective is composting, followed by AD and lastly biowaste incineration. However, CoH is running out of land space due to other on-going development programs such as housing and the need for arable land for urban farming. In view of these competing land use needs, the option for composting is considered less appropriate (mainly considered as a temporary solution) and remains elusive. The other option is municipal biowaste incineration which was supported by the recommendations that came from the feasibility study carried out by CoH at the Pomona dumpsite. However, the LCA results have demonstrated that incineration is less favourable from an environmental point of view. In addition, the cost of constructing such a waste-to-energy incineration facility in Zimbabwe should discourage its adoption since most municipalities are struggling with budgetary constraints. Potential exceptions are cases where the waste-to-energy incineration technology is coupled to the disposal of infectious wastes from healthcare facilities.

It is important to strengthen the weak governance systems and institutions and adopt global best practices to run cities like Harare. Given frequent energy shortage, waste-to-energy should be attractive since this can feed into the grid and address the problem of poor solid waste disposal. Waste incineration has been used extensively in Europe and parts of Asia for more than half a century. It is an efficient method and a part of an efficient waste management system along with efforts to reduce, reuse and recycle. The challenges in constructing a waste-to-energy recovery facility are not only the cost, but also on ensuring the delivery of the waste to the new facility even though the costs will be higher. In addition, there is a need to train the staff for adequate operation of the facility compared to the current linear mindset of disposing at dumpsite. In Zimbabwe, the option of constructing and operating a waste-to-energy recovery plant will have to compete with other immediate needs and challenges such as waste collection and remunerations for council employees. In many cases, residents and industries are usually left to dispose waste on their own at illegal dumpsites which poses a threat to the environment and human health. Local authorities will have to be dedicated to stop dumping the waste in the old dumping sites and invest in building proper landfills or AD facilities which are cheaper to construct and operate.

Regarding the environmental performance of biowaste disposal options, several conclusions can be drawn. A recurring conclusion from literature is the general indication that landfilling is the worst environmental performer, which resulted in some directives at EU level to avoid landfilling (Sundqvist, 2006). According to Krutwagen et al. (2008) the environmental performance of the selected treatment methods remains ambiguous with less significant differences between incineration and aerobic digestion but both performing worse compared to composting. Koneczny and Pennington (2007) and Salemdeeb et al. (2018) concluded that anaerobic digestion and composting have lower environmental burden compared to incineration. According to Bernstad and La Cour Jansen (2012) these differences are due to the assumptions of the study (many of which related to the characteristics of the waste, local carbon emissions during collection, storage and pre-treatment) rather than the actual environmental impacts. This calls for more detailed guidelines in assessments and cross-study comparisons. When proposing the need for trans-disciplinary work it is essential to start out with a shared problem understanding and not just to add-up different disciplines. Regarding our study, the LCA based conclusions generated in this study are comparable to other previous studies suggesting biowaste incineration as the overall most environmentally impacting system with composting having lowest characterized values and AD standing in between (Koneczny and Pennington (2007) and Salemdeeb et al. (2018).

The LCA assessment presented in this work has some limitations based on uncertainties in the life cycle inventory given that it was taken from generalizations from various literature sources and personal communications. In addition, most of the studies use the EcoInvent database which rely on Eurocentric inventories which may be different from African inventories, thus calling for the development of specific LCI databases targeting African contexts. Indeed, the presented results highlighted some pointers towards biowaste disposal favouring composting. However, within a broader perspective, different assessment methods and solutions need to be implemented when dealing with bigger problems related to waste management and circular bioeconomy. According to Santagata et al. (2021) and Oliveira et al. (2021), multiscale and multilevel problems require the application of different assessment methods in order to bring forth similar multilevel and multiscale solutions. Another very important aspect is that the results of LCA particularly on AD are largely dependent on the type of biowaste,

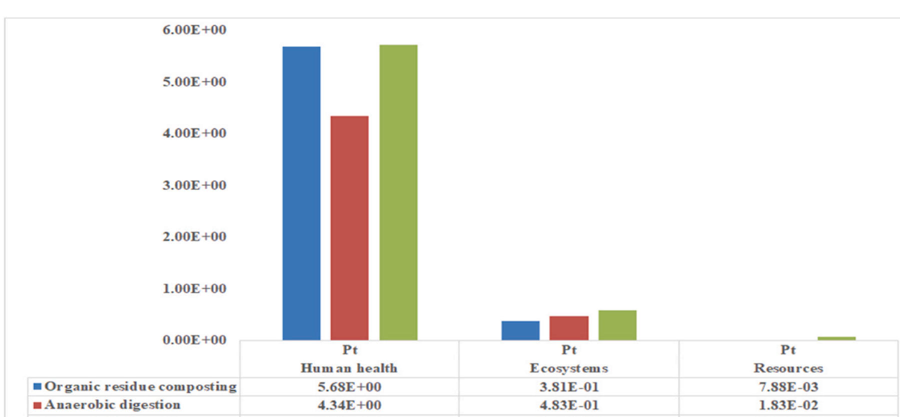

Fig. 3. Endpoint impacts and overall environmental impacts among the different biowaste treatment methods based on the functional unit of 1 tonne biowaste.

making comparisons quite difficult (Wang et al., 2021). In summary, from an environmental point of view, the option of adopting biowaste incineration compared to the other selected disposal options was less preferred due to the release of greenhouse gases and the leakage of harmful pollutants. In Zimbabwe and many other African countries, anaerobic digestion seems more preferred as it is the most practical and most invested option that meets immediate local energy needs. This further calls for the application of other assessment methods that can capture economic and social aspects, often disregarded in LCA studies.

4.1. Broader environmental policy implications of the LCA results

If Africa is serious about addressing climate change and the depletion of fossil resources, there is need for aggressive efforts to be put in place towards achieving two goals: (1) advancing the technology and policies to get to net-zero emissions by 2050, and (2) enabling people to adapt to a rapidly changing world. Moving towards a zero-carbon global economy through absolute reductions in fossil fuel usage is a sure way of mitigating climate change, and a range of environmental, social, and economic benefits would follow. The case for a circular bioeconomy for Africa is, however, less clear. Whilst some circular bioeconomy initiatives in China and Europe (McDowall et al., 2017) seem to be leading the way towards decoupling of economic growth from resource extraction, this trajectory however, does not seem to necessarily equate to reducing the rate of extraction of resources. Thus, the contribution of circular bioeconomy to the achievement of environmental objectives globally cannot be taken for granted, particularly for the global South whose economies largely depend on the extractive industries such as mining and agriculture.

Instead of continuing with the linear approach of disposing waste at dumpsites, the total biowaste collected in Zimbabwe and in many other African countries can be concurrently processed through AD, composting, or incineration options for waste to energy and material recovery thus addressing the problem of biowaste management (with biorefineries) and energy poverty. The production of new valuable bio-based materials and energy sources through the different biowaste treatment and processing options results in avoided production of the counterpart conventional products such as hydroelectricity, fossil fuels and synthetic inorganic fertilizers. Within a circular bioeconomy context, the recovered bioenergy can be used to replace grid power which relies on fossil-based fuels such as coal. Each biowaste disposal and processing option has its own environmental drawbacks as highlighted by the LCA results in terms of global contribution of the environmental service of treating the waste. Therefore, African governments need to consider these environmental implications and benefits when deciding on which option to adopt, but many of the decisions are largely influenced by operational and maintenance costs.

The amount of generated household waste is also a variable value, which is a function of population, the way and standard of living of population, settlement and its degree of development, the annual season, and other factors. The tourist industry presents an opportunity for a bioeconomy due to the significant amounts of food waste produced daily. At the investigated hotel alone, over 3.6 tonnes of food waste are produced every month. Given that there are over 50 registered food outlets (hotels and restaurants) in Victoria Falls (the tourist city) that generate biowaste, the potential for the biowaste to provide a constant feedstock material towards the recovery of bioenergy cannot be ignored. Despite this huge unexploited potential, most of the biowaste unfortunately ends up mixed at the landfills/dumpsites with other types of waste, and this often happens during the collection and disposal phase. This necessitates the need for policies to guide the municipalities, hotel, and ancillary industries towards a circular bioeconomy. In the presence of supporting policies, the hotel industry could contribute towards a circular bioeconomy by exploiting the inherent opportunities provided by biowaste. When renewable bioenergy is successfully recovered, it will reduce the current use of fossil-based electricity and ultimately reduce overhead costs related to energy consumption. The potential of converting organic residues to biofuels in Zimbabwe was explored by Maqhuzu et al. (2017) where an indication of 2.55–5.50 million Mg/yr. of crop residue and 2.99–4.99 million Mg/yr. of dung were estimated to generate an annual mean of 26.6 million GJ for crop residue and 16.9 million GJ for cow dung, respectively. Currently, the investigated hotel has written policies in place for sound environmental management but none of this is being implemented. Added to that, the hotel does not have control over the waste management process beyond its premises, thus shifting responsibility to the local municipality which in many cases is incapacitated. Given that Zimbabwe has no policies and legislation that forces hotels to be environmentally-friendly, this opens room for unsustainable practices such as the disposal of biowaste in dumpsites and even burning (Mbasera et al., 2016). The challenge of not having legislation and circular bioeconomy policies in place promotes these linear practices of take, make, and dispose without feedbacks, reuse and recycling in the hotel industry and many other sectors in Africa. It is therefore critical to develop and implement policies that promote a circular bioeconomy, in order to divert significant tonnes of biowaste residues from reaching dumpsites. There is urgent need to reduce the production and poor disposal of biowaste in the hospitality industry, cities, and the entire economy. A circular bioeconomy is difficult to define and is not only about recycling and material recovery, but also about preventive planning for overall waste reduction and provision of goods and services (Bugge et al., 2016). A circular bioeconomy should instead recommend designing preventive measures, and in so doing forcing policy and industry transformation towards waste prevention rather than recycling (relying on more waste) or treating for disposal. The promotion of preventive design within a circular economy will contribute towards the development of roadmaps and technology improvements, thereby limiting production and consumption patterns in all sectors of the economy consequently reorienting investments and creating green jobs (The Nature Conservancy, 2018; Environmental Protection Agency, 2021).

The hydroelectric power generation capacity in Zimbabwe is currently too small to meet the demand from the consumers. Load shedding is routine, coupled with occasional blackouts. The blackouts, of course, hamper the economy and disrupts people's lives especially the hotel sector which receives international travellers. To survive and continue operating, many industries including hotels are now relying on generators and biogas for cooking, heating, and lighting purposes. With the high demand for electricity in Harare and the country as whole, the current deficit is estimated at around 700 MW, with a suppressed demand of over 1200 MW. To encourage the production of renewable energy, Zimbabwe Energy Regulatory Authority (ZERA) the regulatory authority has supported the production of renewable energy sources by issuing tariff regulations for producers to be paid according to actual investments and operation costs, plus a reasonable mark up. The actual price is set on an individual basis for each producer. ZESA (Zimbabwe Electricity Supply Authority), a government owned authority, oversees most power stations and operates them through ZPC (Zimbabwe Power Company). The Kariba hydropower station located on the Zambezi River is co-owned with Zambia and has a capacity to produce and supply about 750 MW to Zimbabwe. In the west part of Zimbabwe, the Hwange thermal power station, fuelled by coal, has an installed capacity of 920 MW. There are also three other coal-fired power plants with a total installed capacity of 270 MW. However, because of lack of maintenance and water availability for the hydropower plant the real capacity is much less. The import of electricity has also been reduced during the last few years due to severe shortages of foreign currency. Thus, during peak hours, there can be a gap of up to 1600 MW to meet the demand. When introducing energy recovery from organic residues, the main problem is not the technical installations, but the cost of operation and maintenance. Waste is not any fuel that may be purchased on the market. It is crucial to ensure the inflow of feedstock material through close cooperation with hotels, restaurants, farmers, residents, and local authorities.

At the same time, the operation of the energy recovery plant must be supported at government level to ensure continuity and profitability. Since the Government of Zimbabwe appears on paper to give high priority to the energy sector to meet the demand of electricity and to have more environmental and sustainable sources of energy rather than coal, lines of credit and other incentives should be availed to private IPPs (Independent Power Producers). The easy of doing business will help expand energy recovery operations from biowaste and supply the national grid with biobased renewable energy. There are growing calls in Europe supported by policies such as the new Green Deal and the 2018 Bioeconomy strategy to expand the focus from bioenergy and biofuels to the recovery of other valuable biobased products and platform chemicals from organic residues (Bracco et al., 2018). By comparison, most African states including Zimbabwe are still struggling and currently have no such privilege to diversify due to economic hardships and technological limitations. Instead, much focus is being placed on affordable lower hanging alternatives and pathways to material and energy recovery that do not require large capital investment such as composting and anaerobic digestion. For example, the cost of a setting up a 4–6 cubic meter biogas plant is between 1500 and 2000 US$ in Zimbabwe according to CoH and Mukumba et al. (2013). The resulting digestate from the AD facility in addition to composted biowaste can be useful for improving soil fertility and ensuring food security. This is important given the prevalence of urban agriculture in Zimbabwe and other African countries.

4.2. Bioeconomy in Africa: A broader perspective

The present study was limited to a few technologies in the bioeconomy focusing on three biowaste disposal options (anaerobic digestion, composting, and incineration). Therefore, a broader approach is required in the circular bioeconomy in Africa addressing the following several aspects in the bioeconomy value-chain (Feleke et al., 2021; Poku et al., 2018).

(1) Quantifying and characterization of feedstocks

Currently limited data exists on the quantities and characteristics of feedstocks to support the bioeconomy in Africa. Thus, further studies are required to generate reliable inventories of the various feedstocks and their characteristics at national scale.

(2) Logistics and the bioeconomy

Contrary to their developed counterparts, the waste management system in LICs is poorly organized with no systematic sorting and recycling of wastes. Thus, the logistics associated with the separation, collection, storage, and transport of mingled waste could pose challenges to the adoption of the bioeconomy in Africa. Thus, adopting the bioeconomy will require a reorganization of the waste management system and awareness raising among various stakeholders, and even incentivizing waste collection and sorting. A bioeconomy-based waste management model may need to be developed and validated to achieve this.

(3) Technology needs for the bioeconomy

The present study was limited to a few technologies currently used in Zimbabwe. Thus, several other competing technologies such as pyrolysis and hydrothermal carbonization which generates synthetic gas, bio-oils, and biochar were not considered. Biochar technology is considered a carbon negative technology. LCA data comparing pyrolysis to current practices and other technologies such as AD are still lacking. Thus, further work is required to evaluate various candidate technologies to support the bioeconomy. Even in the case of AD, composting and incineration various designs exists that require further investigation to identify the most appropriate technologies for Africa.

(4) Socio-economic and scale issues in the bioeconomy

The bioeconomy could potentially create various value-chain and employment opportunities. However, data on the socioeconomics of the bioeconomy in Africa is still limited. Moreover, data on the appropriate scale of operations required to have viable bioeconomy projects are still lacking. Therefore, it is currently unclear, whether it is economically viable to develop a bioeconomy in Africa as a source of energy and other industrial products. Comparative socio-economic analysis of the circular bioeconomy projects to existing competing technologies is required to fully understand the prospects of a bioeconomy in Africa.

(5) Supportive institutional, regulatory and policy framework.

The bioeconomy is currently excluded in existing institutional, regulatory, and policy frameworks in most Africa countries. Thus, there is a need to develop a conducive institutional, regulatory and policy framework for the bioeconomy in Africa. Such frameworks require a strong evidence base which is currently missing in most African countries, pointing to the need for fundamental research on bioeconomy in Africa. It is therefore imperative to explore regional development policies to facilitate the transition to bioeconomy in Africa through the promotion of free-markets, bottom-up perspectives (start-ups) and top-down initiatives such Eco-Industrial Parks borrowing from some successive lessons from other regions such as China (Yong, 2007).

(6) Promoting local and regional integration and collaboration

The current legislations on environmental protection are mainly founded on an authoritarian and distant policy style with a negative attitude and punitive approach towards target groups of industry such as mining and agriculture which form the backbone of African economies. A paradigm shift is therefore required which encourages self-regulation instead of simply imposing legislation. Such an approach promotes cooperation amongst various actors particularly the regulatory authorities, industry, public and civil society organizations on actions intended to promote CE. Environmental management, including the mitigation of the various environmental and human health risks revealed by LCA is a shared responsibility. It entails various actors, including the public (individuals and households), the state (regulators, policymakers), markets (suppliers, consumers), and civic society (non-governmental organizations). This shared responsibility points to the need to develop appropriate models and frameworks to support a circular bioeconomy. This includes: (1) supportive institutional, regulatory and policy frameworks, (2) resource mobilization or funding models, including public-private partnership models such as build-operate and transfer, and (3) markets with appropriate pricing systems considering the environmental footprints of the products, goods, and services.

(7) Opportunities and challenges for increased circularity in Africa

The implementation of the circular bioeconomy is likely to encounter resistance from a variety of stakeholders that see their business threatened by the new paradigm. This resistance can materialise in technical, economic, social, organisational, and even geopolitical constraints that can seriously hamper circular bioeconomy development at any scale be it micro (firm level), meso (eco-industrial parks) or macro-scale (supply chain). Accurate identification and understanding of critical factors, assumptions and constraints that can affect the implementation of bioeconomy practices is therefore crucial. Issues such as job creation, empowerment of vulnerable groups, poverty alleviation and climate change need to be emphasized as they are most relevant and topical in the wider African context. In the literature, human-induced environmental impacts tend to dominate the discourse on climate change and land degradation. However, it should be noted that the human impacts are superimposed on changes driven by natural or background processes. These natural or background processes include (i) climate variability and change caused by natural processes such as volcanic activity, and (ii) natural or geological erosion and geomorphic processes responsible for the formation of landforms. Anthropogenic or human-induced processes include pollution, land degradation caused by rapid increase in human and livestock population, and greenhouse gas emissions from agriculture and industrial processes. Because the natural or background processes are largely beyond human control, public concern and mitigation efforts often focus on the human-induced impacts. Therefore, any organizational constellations, and policy mixes will need to be rational.

4.3. Conceptual framework or roadmap for circular bioeconomy in Africa

This research has been premised on an exploratory approach in a geographic region where there is lack of clarity on how to start large-scale circular economy projects. A conceptual roadmap on how to go about it within a bioeconomy framework has been proposed in Fig. 4. In the transition to a circular bioeconomy, labour and services are critical although they are disregarded by traditional LCA analysts. Also not accounted for in the environmental LCA is the flow of money (funding) to pay for direct and indirect labour costs which is much needed to achieve results in each subprocess through the interaction with other external input flows such as technology, energy, and fuels. To elaborate on this large scale, more comprehensive conceptual model, we use an energy flow diagram using the language of system symbols as proposed by Odum (2002). The purpose of these system diagrams is to highlight system boundaries, structure, and functions using pictures instead of thousand words (Brown, 2004).

To put our study into perspective, Fig. 4 represents a system that integrates the critical and necessary processes, storages and flows within a circular bioeconomy applicable to any geographic context. The diagram sets the boundary to that of an African economy which receives environmental support from renewable sources such as sunlight, deep heat, rain, and wind which are abundant to enable the production of raw materials/feedstock in this case from agricultural systems (it is possible to also consider mining as well). Agri-food products are then processed making them ready for industrial production and distribution to final consumption. By-products from each process are then collected for further recovery into useful materials and fuels before final disposal. The recovered biofuels, biochemicals and biomaterials can be fed back into upstream processes to replace or substitute fossil-based inputs which are sustained by goods, machinery, energy, and fuels coming from outside boundaries. Emissions and discharges generated from all the transformations result in loss of energy and are expressed as a heat sink according to the second principle of thermodynamics.

The proposed roadmap puts forward the development of a circular bioeconomy in Africa or its equivalent. In summary, some of the key steps and activities for a successful circular bioeconomy are outlined as follows:

1. Total solid waste estimation
2. Biowaste estimation
3. Biowaste characterization (Energy values content)
4. Laboratory/bench-type research (testing various waste-to-energy technologies).
5. Pilot scale design and evaluation of best waste to energy systems.
6. Technical, and socio-economic feasibility assessment including LCA of environmental footprints, life cycle costing and socio-economic.
7. Upscaling, dissemination, and adoption based on the findings.
8. Monitoring and evaluation plan including development of key indicators.

The bulk of African countries lacks accurate comprehensive data for the several steps highlighted in the framework. This points to the need for comprehensive research to generate the critical data and the knowledge useful to implement the circular bioeconomy should be integrated using text mining based on automatic systems to retrieve information (Spreafico and Spreafico, 2021). Yet Africa still has low research capacity in circular bioeconomy, and severe lack of research infrastructure and funding. In order to deeply understand the environmental, economic and social benefits and their impacts, further studies are needed that provide a complementary perspective by integrating different methods to achieve innovative outcomes. Studies that are purposefully oriented towards design of waste prevention instead of recycling are highly recommended.

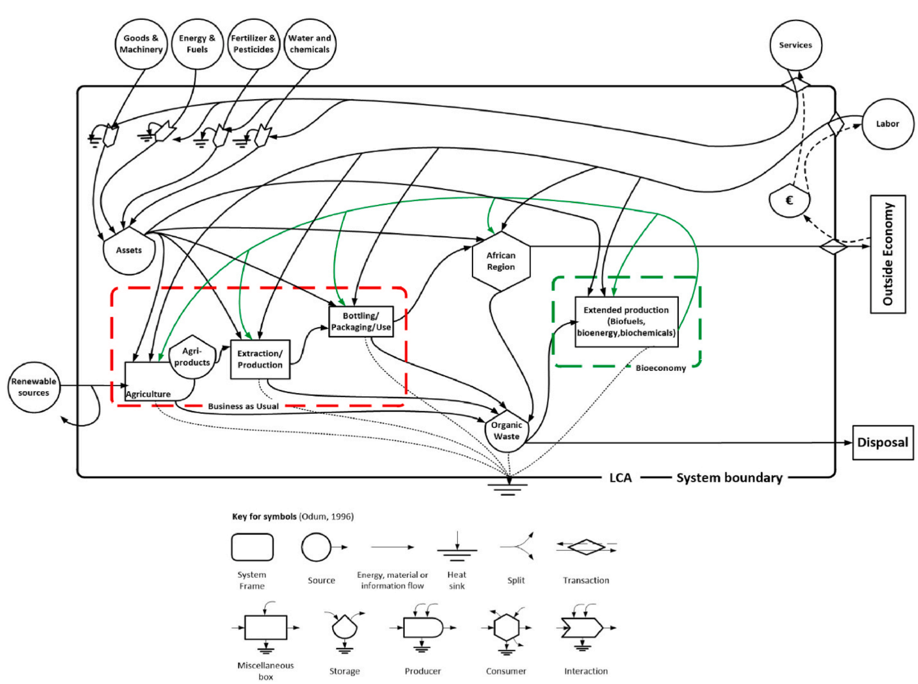

Fig. 4. Development of an interactive system model towards circular bioeconomy within a region in Africa.

5. Conclusions

The assessment of the hotel in Victoria Falls revealed and projected the possible amount of biowaste that can be produced. The organic residue is at present disposed at dumpsites often referred to as landfills in the Zimbabwean context. This current practice is known to be harmful to the environment and to human health due to the release of greenhouse gases and the leaching of harmful pollutants. Considering that the Hotel in this study is a medium sized hotel and not the only one in the tourist city of Victoria Falls which is dotted with many other smaller and larger hotels plus restaurants, we were able to postulate the industry's potential in terms of providing feedstock biomass material for a circular bioeconomy. The potential of the Hotel industry to support a circular bioeconomy in Africa is huge, coupled with the additional unaccounted household and industrial organic residues. By adopting policies that support a better transition to a circular bioeconomy we can divert millions of tons of biowaste that ends at the dumpsites/landfills. The City of Harare is already making strides towards supporting a circular bioeconomy by building AD facilities and composting facilities to process biowaste whilst at the same time recovering energy and organic fertilizer. These by-products can help support the already ailing economy through the provision of clean energy sources as well enhancing soil fertility to ensure food security. Overall, with proper policies, Africa has a potential to contribute towards the circular bioeconomy and municipalities and hotels can play leading roles in initiating this transition. The biowaste processing and disposal options are limited due to the perennial financial and technological limitations and therefore, the prominent disposal options (AD digestion and composting) remain the most practical choices. However, from a theoretical LCA perspective, the most environmentally friendly option was composting, followed by AD and lastly by biowaste incineration. Africa currently has no such ability to diversify into more advanced organic processing and recovery options due to economic and technological limitations, and focus should be placed on the available and easy to harvest lower hanging fruit technologies for now but in the long-term, the benefits of which could be used to build on other advanced material and energy recovery systems such as biorefineries. Africa needs tailor made solutions for its challenges in recovering energy and biobased materials within a circular bioeconomy context. It is often argued that the continent has always been circular, but it may not be easy to implement as proven by some insights from this study. The authors contend that there is need for more case studies and collection of raw data which can be turned into actionable insights and help inform policy. The authors intended to initiate the discourse towards exploring the potential and challenges of a circular bioeconomy in Africa and a call to arms for not missing the inherent opportunities presented by biowaste/residues.

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CRediT authorship contribution statement

Amos Ncube: Conceptualization, Writing – original draft, Methodology, Formal analysis, Investigation, Data curation, validation. **Phineas Sadondo:** Writing – review & editing, Formal analysis, Investigation, Resources, Data curation. **Raymond Makhanda:** Writing – review & editing, Formal analysis, Investigation, Resources, Data curation. **Charles Mabika:** Writing – review & editing, Formal analysis, Investigation, Resources, Data curation. **Natalie Beinisch:** Writing – review & editing, Formal analysis, Investigation, Resources, Data curation. **Jonathan Cocker:** Writing – review & editing, Formal analysis, Investigation, Resources, Data curation. **Willis Gwenzi:** Writing – review & editing, Formal analysis, Investigation, Resources, Data curation. **Sergio Ulgiati:** Supervision, Conceptualization, Writing – review & editing, Validation, Funding acquisition, Authorship has been limited to those who have contributed substantially to the work reported.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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