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Mitigating greenhouse gas emissions from municipal solid waste in Sub-Saharan Africa via sustainable waste management: An economic benefit assessment

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ABSTRACT

Municipal solid waste (MSW) management is a major challenge for cities worldwide, particularly in Africa. This study used an emission-reduction framework to assess the economic benefit of sustainable MSW management in Sub-Saharan Africa (SSA) over a 60-year period (2000–2060). Two waste-to-energy (WTE) methods, sanitary landfills and anaerobic digestion, were used to assess the potential electricity generation from MSW under four waste collection scenarios. The assessment was compared to the potential economic damage from cumulative methane (CH4) emissions under business-as-usual waste management practices for the same period. The results show that energy recovery from current MSW generation forecasts can contribute to 100–245 kWh per capita electricity generation between 2025 and 2060, depending on the WTE technology employed. The net present value (NPV) of WTE technologies is less than half the dollar cost of the potential economic damage from methane emissions. These results have significant policy implications for increasing access to sustainable and clean energy in SSA countries. Given that the current average per capita electricity generation in SSA is 158 kWh and that several countries in the area are experiencing energy problems, MSW electricity generation offers untapped economic development prospects. These findings highlight the economic advantages of effective waste management in SSA to mitigate future environmental and climate change consequences of greenhouse gas emissions. Furthermore, this study underscores the need for stakeholders to develop cost-effective and sustainable waste management strategies to avoid possible future economic and environmental damage in SSA.

1. Introduction

Municipal solid waste (MSW) is a pressing global issue (Tsai et al., 2020; Di Foggia and Beccarello, 2021; Vergara and Tchobanoglous, 2012), with less than half of the world's population having access to adequate waste management. The increase in worldwide MSW generation, which is now at 1.3 billion tons per year and is expected to reach 2.2 billion tons by 2025 (S. Kaza et al., 2018), endangers the environment and hinders socioeconomic development (Sherien et al., 2016; Miezah et al., 2015). As a response, sustainable waste management systems and policies are being rolled out across municipalities worldwide.

Integrated waste management systems (ISWM), ideally incorporating waste reduction, reuse, recycling, and energy recovery (waste-to-energy (WtE)), have been identified as economically feasible and critical for public health, greenhouse gas (GHG) reduction, and promoting a green, circular economy (Di Foggia and Beccarello, 2021; Larson et al., 2021; Mateus et al., 2021; Zhao et al., May 2021; Heidari et al., 2019; Kurniawan et al., 2021; Liu et al., 2022; Farzadkia et al., 2021). The 2030 Agenda for Sustainable Development of the United Nations prioritizes effective MSW management to decrease cities' environmental footprint (United Nations 2015; Zhang et al., 2021). However, in developing countries, waste management systems and recycling technologies are often lacking, resulting in indiscriminate disposal in uncontrolled landfills, rivers, or open burning.

This inadequate waste management results in an increase in the concentration of GHGs (mainly CH_4) in the atmosphere, leading to negative externalities that affect the well-being of all parties involved,

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without its impact being reflected in the market prices of goods consumed. The accumulation of such negative externalities in the long-term results in harmful environmental pollutants. When combined with pollution from other sources, these could escalate to levels where the resultant economic damage could become irreversible (David et al., 2020).

In developing countries, there is a limited allocation of resources towards investment in waste treatment, since the primary emphasis is placed on waste collection (Wilson, 2007; Ikhlayel and Nguyen, 2017). The low collection rate of 44% for MSW poses substantial environmental and public health risks (United Nations Environment Programme 2021; Adusei-Gyamfi et al., 2022). Furthermore, it is worth noting that while around 70% of the waste generated in Africa has the potential for recycling, the actual percentage of waste that undergoes recycling measures is very low, amounting to less than 4% (Adusei-Gyamfi et al., 2022). Recognizing the difficulty and cost of managing MSW, several local governments are moving toward becoming zero-waste cities (Di Foggia and Beccarello, 2021; Zhao et al., May 2021).

Building on the significant energy recovery potential of MSW, several studies have highlighted the potential economic benefits of managing the substantial waste generated in Sub-Saharan Africa (SSA) [(Scarlat et al., 2015; Ayodele et al., 2017), p., (Ogunjuyigbe et al., 2017; Longfor et al., 2023)]. The underlying premise is that these countries could harness MSW as a renewable energy source to alleviate their energy crisis. Typical approaches to evaluating the economics of MSW management involve analyzing current or envisaged waste management practices to identify socially, economically, and environmentally viable alternatives. Common methods include life cycle assessment (LCA), life cycle costing (LCC), social cost-benefit analysis (SCBA), internal discounted rates, and various tools to measure the socioeconomic benefits, environmental cost benefits, and overall economic development potential of efficient MSW management systems (Sharma and Chandel, 2021; Carlsson Reich, 2005; Miyata et al., 2013). In the SSA context, previous studies have conducted cost-benefit analyses of recycling and examined the electricity generation potential of different waste-to-energy (WTE) technologies (Scarlat et al., 2015; Ayodele et al., 2017; Ogunjuyigbe et al., 2017; Longfor et al., 2023; Somorin et al., 2017).

This research deviates from conventional approaches by providing a cost-benefit analysis of waste management via the implementation of an emission reduction strategy. The theoretical framework suggested in this research is consistent with the notion that the long-term cost of energy recovery from waste disposal is lower when compared to the management of accumulated municipal solid waste (Beede and Bloom). Furthermore, the research investigated the prospective economic benefits, quantified as net present value, associated with the implementation of sustainable waste management strategies in SSA across different waste management scenarios and waste generation forecasts.

The primary objective of this study is to address three distinct research questions: (1) What are the economic, social, and environmental costs of potential cumulative methane emissions over the next four decades under current waste management practices in SSA? (2) To what extent can the adoption of proper waste management strategies alleviate these costs? (3) What are the potential economic benefits that may be derived from the implementation of proper waste management practices in SSA?

This research is a valuable contribution to the existing body of literature about the environmental and economic benefits of sustainable MSW management on a global scale, with a specific focus on SSA. To the authors' knowledge, this study is the first to attempt to forecast waste management practices at the national level and throughout the SSA region for many decades ahead. As a result, it offers distinctive perspectives on the prospective consequences of existing waste management strategies. This study presents a theoretical framework for analyzing the economic impact of emission reduction from MSW in developing countries with limited waste management data. From a policy perspective, the study presents an analysis of the potential long-term economic, social, and environmental benefits that may be derived from implementing effective MSW management strategies in 44 SSA countries. The rest of this paper is structured as follows. The review of the literature is presented in Section 2. Section 3 describes the study methodologies and data that were employed. The data analysis and findings are presented in Section 4. Section 5 concludes with a discussion of the results and their implications.

2. Literature review

Recently, the economic and environmental benefits of sustainable waste management practices through waste-to-energy (WTE) conversion have been increasingly recognized (Tsai et al., 2020; Di Foggia and Beccarello, 2021; Liu et al., 2022; Ogunjuyigbe et al., 2017; Slorach et al., 2019; Wang et al., 2021). The appeal lies in the dual benefits of sustainable waste management: it not only provides a rich source of renewable energy but also mitigates greenhouse gas emissions. While there are multiple approaches to sustainable MSW management, this study focuses on economic and environmental benefit analysis through an emission reduction strategy lens.

An early study on the economic benefits of MSW management was conducted by Beede and Bloom (Beede and Bloom). They demonstrated a positive correlation between the generation of MSW and per capita income, highlighting that the least efficient MSW management systems are typically found in developing countries. These inefficient systems pose a severe threat to the local environment and public health. Interestingly, the authors found that proactive community interventions in handling MSW are far less costly over time compared to rectifying future damage caused by MSW. Callan and Thomas (Callan and Thomas, 2001) proposed an economic benefit model for MSW management that accounts for economies of scale and scope in a multiple output cost structure between recycling and disposal activities. They argue that economies of scope in MSW management offer financial incentives for municipalities to undertake joint action on waste management. Ibáñez-Forés et al. (Ibáñez-Forés et al., 2019) used comprehensive indicators and metrics to assess the socioeconomic performance of MSW management systems in Brazil, highlighting untapped economic and environmental benefits. Liu et al. (Liu et al., 2022) found that higher tax incentives boost the economic impact on waste recycling enterprises, potentially increasing revenue by 33.5% by 2030. Medina-Mijangos et al. (Medina-Mijangos et al., 2021) used a social cost-benefit analysis (sCBA) to perform a techno-economic analysis of MSW systems, revealing a potential private benefit of 49.94 euros per ton and a total benefit of 87.73 euros per ton.

Other studies focused on the energy recovery potentials of sustainable waste management systems. Scarlat et al. (Scarlat et al., 2015) found that electricity generation from waste in several African urban areas could reach 112 TWh by 2025 under full waste collection scenarios. A similar study found incineration and landfill gas to energy (LFGTE) to be the most viable technological options for energy recovery in several Nigerian cities (Ogunjuyigbe et al., 2017).

Furthermore, studies have explored other benefits of sustainable waste management systems, such as energy savings, improved air quality, and carbon emission reduction. Farzadkia et al. (Farzadkia et al., 2021) showed that recycling up to 80% of paper and glass could improve energy savings by 3.5 to 5.5 times and reduce air pollutant emissions by 3.5% or more. Liu and Li (Liu and Li, 2023) demonstrated that construction waste recycling offers significant economic benefits and that carbon trading can reduce carbon emissions by 100.66% in a scenario-based analysis. In a related research, Liu et al. (Liu et al., 2023) discovered that contractors had a high proclivity to pick the resource sorting option, with a considerable decrease in total carbon emissions at 25CNY/t. Zhang et al. (Zhang et al., 2022) analyzed the carbon mitigation and economic benefits from carbonation of construction waste, concluding that the production process should be adjusted to enhance emissions control and economic benefits.

This review underscores the extensive economic and environmental advantages of sustainable MSW management systems worldwide. The key issue addressed in this study corresponds with previous research that explored the benefits of sustainable waste management, specifically the potential for energy recovery and carbon emission reduction. However, our study differs from existing literature in several ways.

Firstly, it introduces a prospective approach to forecast and characterize MSW in various Sub-Saharan African (SSA) countries over several decades. This provides a quantitative understanding of country-level waste generation and the potential for energy recovery. Secondly, it uses two waste-to-energy (WTE) recovery technologies to compare the economic benefits (in terms of electricity generation potential) of these wastes with the economic and environmental damage (in terms of CH_4 emissions) caused by unsustainable waste management practices in these areas. Lastly, it assesses the net benefits (in terms of discounted USD) saved from adopting basic sustainable waste management practices, factoring in the net present value (NPV) of investing in WTE recovery and potential economic damage. This systematic, future-focused analysis offers policymakers robust insights into current and prospective sustainable waste management strategies.

3. Data and methodology

This research presents a cost-benefit assessment of MSW management in SSA. The study adopts a material flow analysis (MFA) approach to quantify the flows of MSW in SSA countries. MSW generation, CH_4 emissions from uncontrolled landfilling, electricity generation potential, and the associated socioeconomic costs and benefits were estimated for a time period, 2000–2060, for which relevant parameters such as MSW composition, MSW collection rates, landfill rates, etc. are available. The limited availability of waste management-related data for Sub-Saharan African countries prompted the authors to use data on waste collection and landfill rates from the World Bank (S. Kaza et al., 2018) and UNEP (UNEP 2018).

3.1. Framework of analysis

In the "business as usual" (BAU) scenario, municipal solid waste is dumped in open dumps or uncontrolled landfills (see Fig. 1a). The biodegradable fraction of the MSW (i.e., organic waste and paper/cardboard) decomposes over time and generates GHGs, mainly CH_4 and CO2. While the CO2 generated from biodegradable materials is considered climate neutral, the accumulation of CH_4 tends to trigger global warming over time, and the negative externalities of waste management under the BAU scenario account for the economic damage to various countries. The sustainable alternatives aim at recovering energy from MSW with various WTE projects (sanitary landfills and anaerobic digestion). In these scenarios, MSW is converted into an energy-rich gas made up of methane and carbon dioxide, and the methane component is burned to produce electricity. Electricity sales could benefit both the economy and the environment over time. The net benefit of both scenarios forms the main basis of this study (see Fig. 1b).

3.2. Data and methods

3.2.1. Country population, GDP, and area

The demographic population of SSA includes people living in all 44

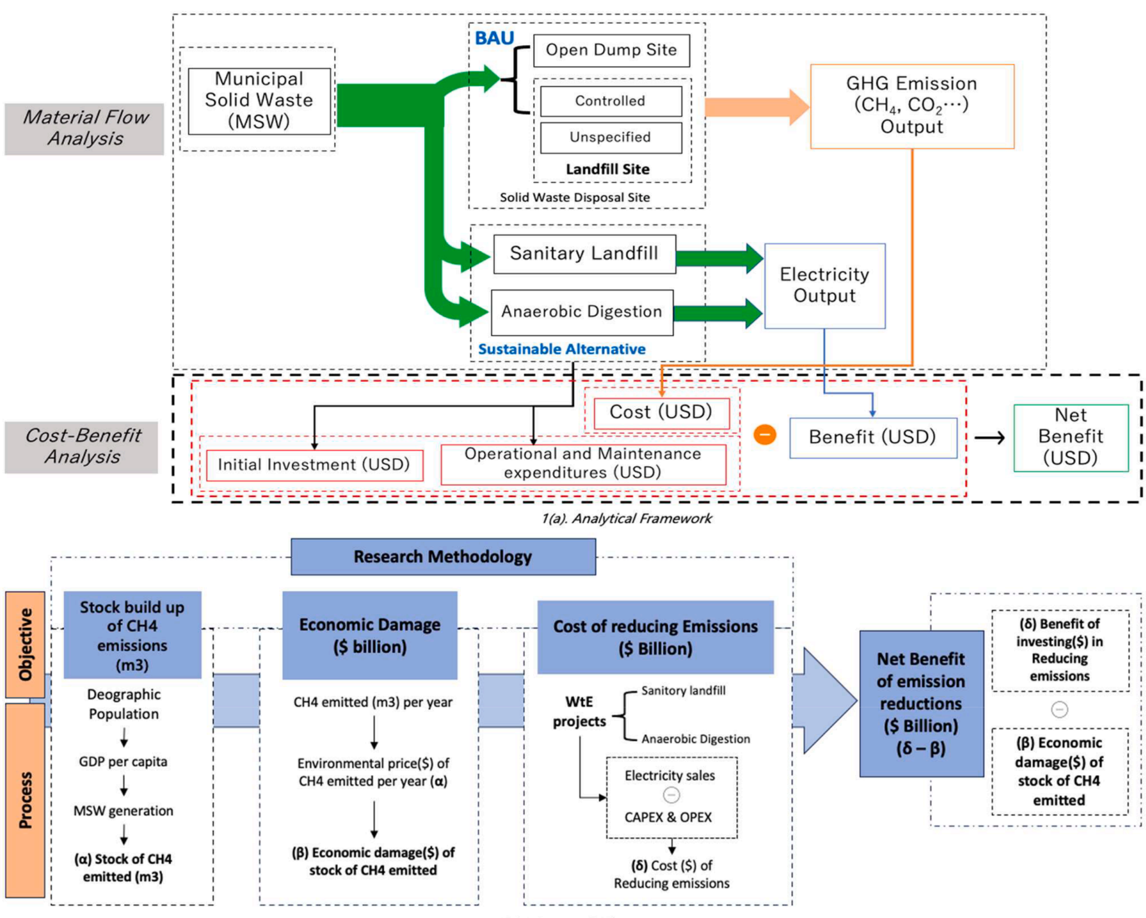

Fig. 1. (a): Analytical Framework; 1(b) Technical Roadmap.

countries constituting the region. The demographic population of all SSA countries from 2000 to 2060 was taken from the United Nations (United Nations 2022). From 2000 - 2021, the Sub-Saharan region's population increased from 621 million to 1 billion inhabitants, which is expected to increase to 2.4 billion in 2060 and 3.6 billion in 2100 (United Nations 2022). Gross domestic product (GDP) per capita is another important parameter, and SSA country-specific GDP per capita from 2000 to 2026 was retrieved by the International Monetary Fund (IMF 2021; AfDB 2011).

3.2.2. MSW generation

The MSW generation of a country is affected by multiple drivers. Advanced models have been developed to simulate the demographic, socioeconomic, and geographical variables for MSW generation in cities, regions, and countries (Kawai and Tasaki, 2016; Karadimas and Loumos, 2008; Beigl et al., 2008; Kontokosta et al., 2018). There exists a positive correlation between waste generation, economic growth and urbanization (Hoornweg and Bhada-Tata, 2012). For example, OECD countries generate 660 million tons of waste per year on average, accounting for roughly half of the world's waste due to high economic growth, compared to SSA and East Asia, which generate 62 million tons and 270 million tons of waste, respectively (Hoornweg and Bhada-Tata, 2012; OECD 2020).

This study looked at the relationship between population growth and GDP growth from 2000 to 2060 to figure out the MSW generation rates per person per year in SSA countries. This relationship is shown in Eq. (1).

$$w_{c,t} = 1647.21 - 419.73\ln G_{c,t} + 29.43\ln\left(G_{c,t}\right)^2 \quad (1)$$

where $w_{c,t}$ is the proxy MSW generation per capita in country c in year t (kg/person/yr) and $G_{c,t}$ is the country's GDP per capita in year t (in USD expressed in 2014 terms).

The total MSW generation was estimated using the population growth and per capita generation rates, as shown in equation 2.

$$W_{c,t} = Pop_t \times w_{c,t} \times 365 \times \frac{1}{1000} \quad (2)$$

Where $W_{c,t}$ is the total MSW generation in country c in the targeted year t (tonnes), Pop_t is the country population in year t, 365 is number of days in a year, and 1000 is the kg to tonnes conversion factor.

This work focuses on the organic fraction of MSW (OFMSW) and its decomposition in landfills. We used the following equation (Eq. 3) to figure out how much food and paper waste was sent to landfills in each SSA country from 2000 to 2060:

$$m_{j,c,t} = W_{c,t}\cdot lf_{c,t}\cdot s_{j,c,t},\ \forall\, c \in C,\ t \in \{2000, \ldots, 2060\} \quad (3)$$

where $m_{j,c,t}$ is the mass of waste material j (food or paper waste) disposed of in landfills in country c in year t (tonnes year^{-1}), $lf_{c,t}$ is the landfill rate in country c in year t (% of total MSW), and $s_{j,c,t}$ is the share of waste material j contained in the MSW generated in country c in year t (% wet mass).

The landfill rate and the share of OFMSW are both highly uncertain parameters due to a lack of data. Based on The World Bank data[4], we assumed a uniform share of OFMSW across all countries, i.e., 43% of MSW is food waste and 10% is paper waste. For the landfill rate, we defined four scenarios that cover the large uncertainty surrounding this parameter (Table 1).

3.2.3. LFG generation

The decomposition of biodegradable materials (e.g., food and paper) in landfills is a slow process. Consequently, LFG generation and its collection for energy recovery, occur over a potentially infinite period of time. A common recommendation is to consider a time horizon of 100 years after waste disposal (Sauve and Van Acker, 2020; Lee et al., 2017; Wang et al., 2020; Manfredi and Christensen, 2009). The volume of CH_4 generated by one tonne of waste material over 100 years following its disposal in landfills can be estimated with a first-order decay equation (Eq. (4)):

$$q_{j,y,c} = \sum_{k\in K}\left(1 - moist_j\right)\cdot vs_j\cdot bmp_j\cdot\left(e^{-k_{j,c}\cdot(y-1)} - e^{-k_{j,c}\cdot y}\right),\ \forall\, j \in J, y \in \{1, \ldots, 100\}, c \in C \quad (4)$$

where y is the year after waste disposal and ranges from one to 100, $q_{j,y,c}$ is the volume of CH_4 generated by one tonne of waste material j in year y following waste disposal in country c (Nm^3 CH_4tonne^{-1} wet material), $moist_j$ is the moisture content of waste material j (tonne dry material tonne^{-1} wet material), vs_j is the volatile solids content of waste material j (% dry mass), bmp_j is the biochemical CH_4potential of waste material j (Nm^3 CH_4tonne^{-1} volatile solids), and $k_{j,c}$ is the decay rate of waste material j in country c (year^{-1}).

The physicochemical properties of food and paper waste used to estimate LFG generation are presented in Table 2. The decay rate varies across countries based on climatic conditions. The IPCC provides values for the decay rate based on the mean annual precipitation (MAP) (IPCC 2006). The decay rate of food waste ranges from 0.085 year^{-1} if MAP < 1,000 mm year^{-1} to 0.400 year^{-1} if MAP > 1,000 mm year^{-1}, while for paper waste this range goes from 0.045 year^{-1} if MAP < 1,000 mm year^{-1} to 0.070 year^{-1} if MAP > 1,000 mm year^{-1}. We matched each country to its specific decay rates based on MAP values facilitated by the World Bank (Table A.2 in Appendix A).

The total volume of CH_4 generated by a landfill in a given year was calculated based on the CH_4 generated from the waste materials disposed of in that year plus the CH_4 generated from the waste materials disposed of in the previous years. For example, the total volume of CH_4 generated in the country in 2020 is the sum of the CH_4 generated from the waste disposed of in 2000 plus the CH_4 generated from the waste disposed of in 2001, and so on until the year 2020 is reached.

Table 1
Scenarios of landfill rate assessed for sub–Saharan Africa countries.

Scenario	Description
100%	This scenario assumes that 100% of the MSW is diverted to landfills. Consequently, this scenario calculates the maximum volume of methane that could be generated by landfills in each country.
24%	This scenario assumes a uniform landfill rate across all countries equal to the average landfill rate for Africa as provided by the World Bank (S. Kaza et al., 2018).
44%	This scenario uses the MSW collection rate as a proxy for the landfill rate. Therefore, we assumed a uniform landfill rate across all countries equal to the average MSW collection rate for Africa as provided by the World Bank (S. Kaza et al., 2018)
Country-specific	This scenario uses country-specific MSW collection rates as a proxy for the landfill rate. Since this information is rather scarce, we could find country-specific MSW collection rates for 29 countries (Table A.1 in Appendix A). For the remaining 15 countries, we assumed an average collection rate of 44%.

Table 2
Physicochemical properties of waste materials.

Property	Units	Food waste	Paper waste	References
Moisture	% wet mass	60	10	(S. IPCC 2006)
Volatile solids	% dry mass	83	84	(Götze et al., 2016; Krause et al., 2016)
Biochemical CH_4potential	Nm^3 CH_4 tonne^{-1} volatile solids	390	225	(Krause et al., 2016)
Decay rate				
MAP < 1000 mm year^{-1}	year^{-1}	0.085	0.045	(S. IPCC 2006)
MAP > 1000 mm year^{-1}	year^{-1}	0.400	0.070	(S. IPCC 2006)

3.2.3.1. Electricity generation through LFG combustion. Once generated, the LFG can be partially collected and burned in engines to generate electricity. The amount of electricity generated by the combustion of the LFG in each year in each country was calculated as shown in Eq. (5).

$$E^{LFG}_{c,t*} = \sum_{t \in T} Q_{c,t} \cdot \alpha \cdot \beta \cdot \varepsilon^{LFG} \cdot \theta, \ \forall \ c \in C, t^* \in \{2000, \ldots, 2100\} \quad (5)$$

where $E^{LFG}_{c,t*}$ is the electricity generated through LFG combustion in country c in year t^* (kWh year^{-1}), $Q_{c,t}$ is the volume of CH_4generated by landfills in country c in year t (Nm^3 year^{-1}), α is the LFG collection efficiency (% vol.), β is the LHV of methane (35.8 MJ Nm^{-3}), ε^{LFG} is the electrical efficiency of engines used for LFG combustion (% LHV), and θ is the parameter that converts MJ to kWh (i.e., 3.6 MJ kWh^{-1}). We assumed an average LFG collection efficiency of 50% for all the countries. This is a conservative assumption based on the values reported in the literature (Manfredi and Christensen, 2009, IPCC 2006, Barlaz et al., 2009). For the electrical efficiency of engines, we calculated an average value of 33% based on several studies (Slorach et al., 2019, Wang et al., 2020, Manfredi and Christensen, 2009, Anshassi et al., 2021, Manfredi et al., 2010, Kirkeby et al., 2007).

3.2.3.2. Electricity generation by anaerobic digestion. Anaerobic digestion (AD) was assessed as an alternative to LFG collection and combustion. In this regard, we assumed that food and paper waste are diverted from landfills to AD and that the resulting biogas is burned to generate electricity. The amount of electricity generated was calculated as shown in Eq. (6).

$$E^{LFG}_{c,t*} = \sum_{t \in T} Q_{c,t} \cdot \alpha \cdot \beta \cdot \varepsilon^{LFG} \cdot \theta, \ \forall \ c \in C, t^* \in \{2000, \ldots, 2100\} \quad (6)$$

where $E^{AD}_{c,t*}$ is the electricity generated through biogas combustion in country c in year t^* (kWh year^{-1}) and ε^{AD} is the electrical efficiency of engines used for biogas combustion (% LHV). We assumed an average engine's electrical efficiency of 35%.

3.2.4. Economic damage

The stocks of CH_4 emissions in the environment build up over time and compromise the quality of the environment. In time, this pollutant endangers human wellbeing and prosperity worldwide. Unlike goods and services traded in the marketplace, environmental quality does not have a direct "price" for the well-being of citizens. However, there is a growing need to quantify the benefits of a clean environment so that humans can be held accountable for economic decisions (Pindyck and Rubinfeld, 2015). The price of the environmental quality of a country cannot be estimated directly in a marketplace; thus, its monetary value has to be calculated. In this study, we used estimated environmental prices from CE Delf (the Bruyn et al., 2018) (Table 3). The monetary value of a clean environment was estimated on the basis of the assessed damage arising as a result of emissions and other changes in the Earth's natural capital (the Bruyn et al., 2018).

The environmental price of CH_4 emissions from organic wastes were assessed as follows (Eq. (7)),

$$E_d = Q_{c,t} \times E_p \quad (7)$$

where E_d is the environmental cost of methane emitted into the environment due to MSW management (USD), $Q_{c,t}$ is the annual volume of CH_4emitted (kg emission), E_p = Environmental price of emission ($\$_{2015}$/kg emission).

3.2.5. Cost of emissions reduction

To figure out if it makes economic sense to reduce emissions from MSW by using WTE, the discounted present values of the annual benefits are used to figure out the policy's net present value (NPV).

The revenue (cash inflow) of the and sanitary landfill or anaerobic digestion project is generated from the sales of electricity generated to the energy market. It was assumed that there is no market for the sale of compost; thus, no income was estimated for this by-product. Data on cash outflow (capital and operational expenditures) for both sanitary landfills and anaerobic digestion were derived from GIZ (GIZ et al., 2017) (See Table 4).

The difference between the present cash inflows and cash outflows within an economic lifetime yields the Net Present Value, NPV (Eq. 8).

$$NPV = \sum_{y=1}^{n} \frac{C_{E,y}}{(1+R)^y} - C_0 \quad (8)$$

Where, $C_{E,y}$ = Annual net benefit of the cost-reducing emissions, C_o= the initial cost of investment for the biogas project, and R = Social rate of discount, 2%.

4. Results

4.1. MSW generation and WTE potential in SSA: overall findings

his section presents the results of MSW generation, waste-to-energy (WTE) potential, environmental and economic damage assessment, and net-benefit assessment of sustainable waste management in 44 SSA countries using two WTE technologies. Future waste generation up to 2060 was forecasted based on historical data using the model described in Section 3.2.2. The results for all SSA countries are summarized in Table A.3 (in Appendix A). The analysis includes total waste generated (Panel A), methane gas potential (Panel B), and electricity potential from sanitary landfills (Panel C) and anaerobic digestion (Panel D) under four scenarios: 100% landfill rate, 24% landfill rate, 44% average collection rate, and country-specific collection rates (Table 1). The results suggest a huge potential for energy recovery from MSW in SSA based on current and projected waste generation in all four scenarios. It is noteworthy that remarkably similar results (trends) were shown by both the 44% collection rate and country-specific collection rate in all panels. The forecast for both scenarios is shown in Fig. 2, where it can be observed that the output from country-specific collection rates, although relatively higher, shows a similar trend to the 44% collection rate often reported in MSW literature for SSA countries. The subsequent analysis used the country-specific collection rate.

The results in Table 6 demonstrate that SSA countries can effectively utilize the waste generated annually to generate millions of MWh of electricity. For instance, under sanitary landfill WTE technology, the results show that SSA countries could generate more than 20 million MWh of electricity by 2060, even under current country-specific collection rates. Similarly, Fig. 3 shows that the electricity generation potential of anaerobic digestion could reach 58 million MWh by 2060.

Table 3
Environmental price for average GHG emissions ($2015/kg emission).

Pollutant		Lower (US $)	Central (US $)	Upper (US $)
Methane	CH_4	0.507	1.943	1.965
Carbondioxide	CO_2	0.015	0.0632	0.0632

Source: (the Bruyn et al., 2018).
* The values include VAT and increases by 3.5% per annum relative to 2015 values.

Table 4
CAPEX and OPEX of waste-to-Energy technologies.

Technology	CAPEX (USD/tonne)	OPEX (USD/tonne)
Sanitory landfill	1.26	0.55
Anerobic digestion	17.7	14.3

Source: (GIZ et al., 2017).
Note: Original values were expressed in Euro/tonne, but these values to converted to USD/tonne with 2021 values.

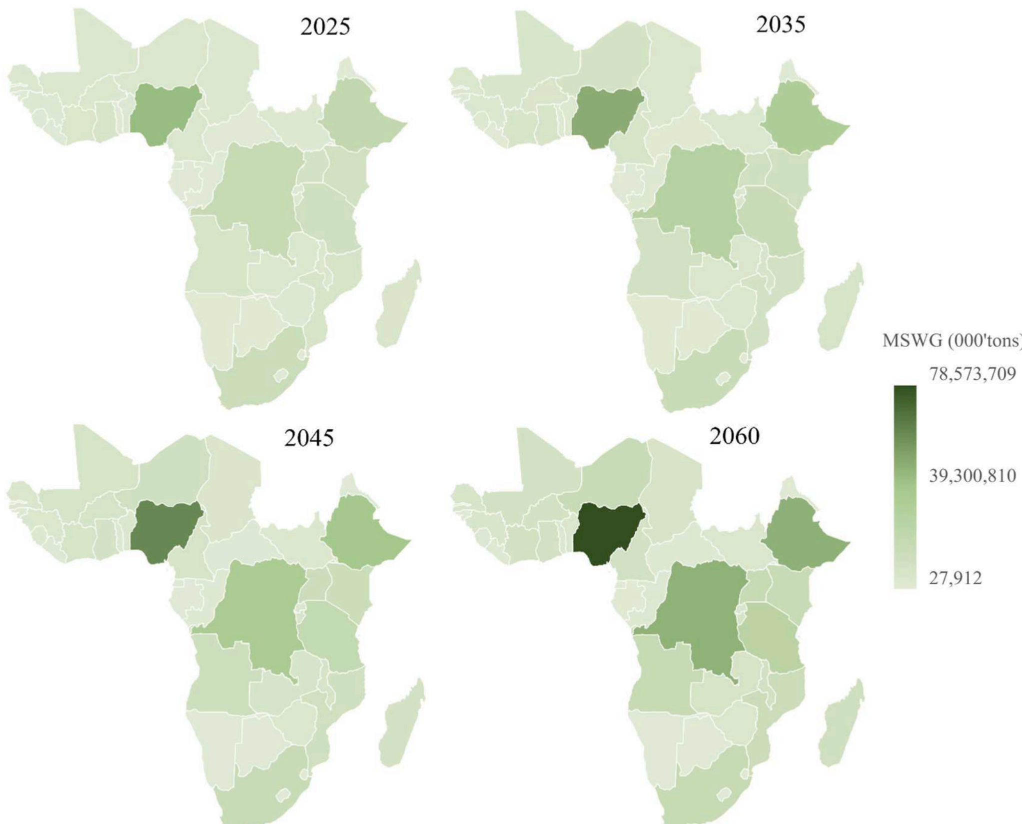

Fig. 2. Map showing MSW generation forecast: 2025~2060 (source: Authors projection based on economic and population data).

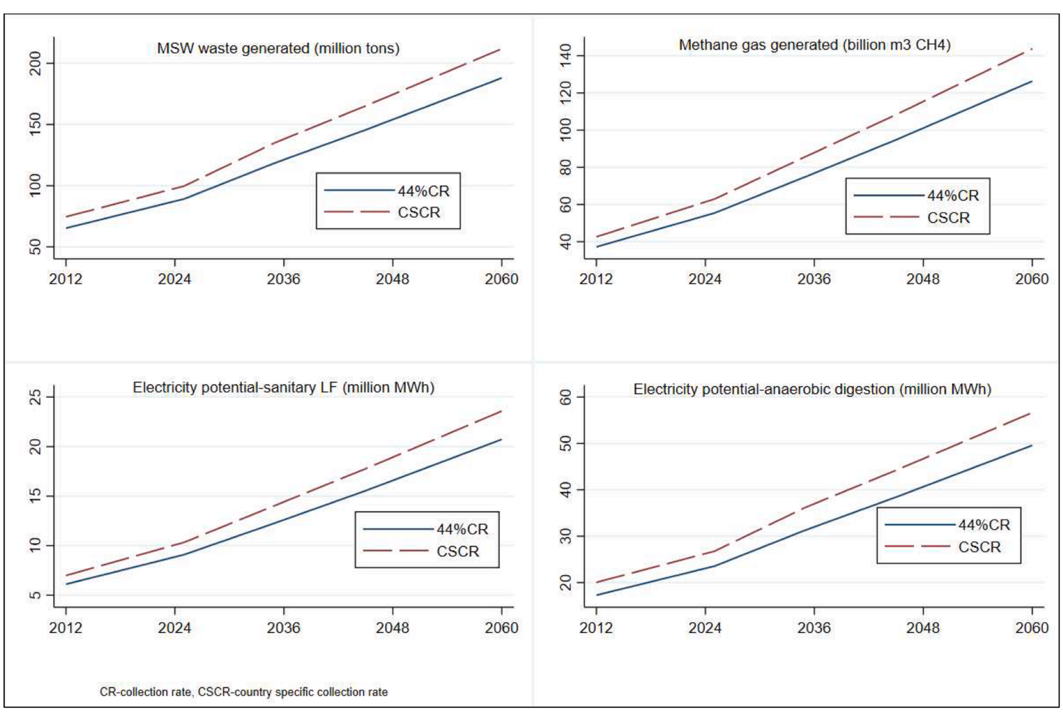

Fig. 3. Comparing average collection rate and country specific collection rate.

These findings demonstrate that electricity generation from MSW could improve per capita electricity consumption by 10–23 kWh by 2060, depending on energy recovery technologies.

4.2. Waste generation and the energy potential in SSA: country-specific findings

This section examines country-level waste and electricity generation potential based on forecast data. Table 6 presents the electricity potential for both technologies (Panel A. sanitary landfill, Panel B. anaerobic digestion) in descending order of magnitude, from countries with the highest potential to countries with the lowest potential. Under sanitary landfill technology evaluation, the top 20 countries are highlighted, each having the potential to generate about 0.2 MWh to 3.3 million MWh between 2035 and 2060. Whereas, for anaerobic digestion, these top 20 countries could also generate between 0.4 MWh and 8.5 MWh of electricity between 2035 and 2060. However, in terms of per capita electricity contribution, the top 20 countries with the highest per capita generation from waste using both technologies (Panel B, Table 6). Most of the top 20 countries appear to contribute significantly to per capita electricity generation using waste. For instance, Guinea could contribute between 100 kWh and 244 kWh per capita generation between 2035 and 2060 using either of the energy recovery technologies. Namibia stands to reap between 18 kWh and 48 kWh per capita generation from waste alone between 2035 and 2060, using either of the energy recovery technologies. Overall, the results show that SSA countries have huge potential for energy recovery from waste using relatively cheap energy recovery technologies such as sanitary landfills and anaerobic digesters.

4.3. Economic damage under BAU versus NPV of sustainable waste management adoption in SSA

4.3.1. Overall findings

A major incentive for MSW management is reducing its impact on climate change. Improper waste management has been a significant source of CH_4 emissions, a substance with high global warming potential. In this section, we analyze the economic damage resulting from current waste management practices and compare the results with sustainable waste management scenarios for all SSA countries. This enables us to examine the benefits, in net present value, of adopting sustainable waste management practices in each country.

Fig. 4 shows a graph of the potential damage from CH_4 emissions resulting from current waste management practices in SSA countries. Overall, the results show that significant economic damage from CH_4 emissions will cost billions of dollars to undo if the current practice of MSW disposal is allowed to continue. This economic damage appears to double every decade from 2025 to 2060. While all SSA countries show potential damage, some countries show potentially significant damage of over billions of dollars in costs. However, our analysis of the cost of WTE recovery technologies shows that only a fraction of the cost of economic damage is sufficient to mitigate or recover the methane emissions responsible for such huge economic costs. Fig. 5 compares the potential economic damage and NPV of investing in these two waste-to-energy recovery technologies. The findings show that significant economic damage from methane emissions could be mitigated between 2025 and 2045 if sanitary landfills or anaerobic digestion are used to recover energy from waste generated in the same period. In addition, Fig. B.1 (Appendix B) compares the cumulative damage and NPV from the two waste-to-energy technologies. This figure demonstrates that the NPV of sanitary landfills is approximately half of the economic damage, whereas the NPV from anaerobic digestion is merely one-third of the cost of damage from MSW.

4.3.2. Country specific findings

Fig. 6 presents the country-level comparative results of economic damage and NPV of WTE recovery technologies. The first panel presents the results for sanitary landfills, whereas the second panel shows the results of anaerobic digestion. In the Figure, the total annual economic damage is compared to the total annual net present value for adopting a

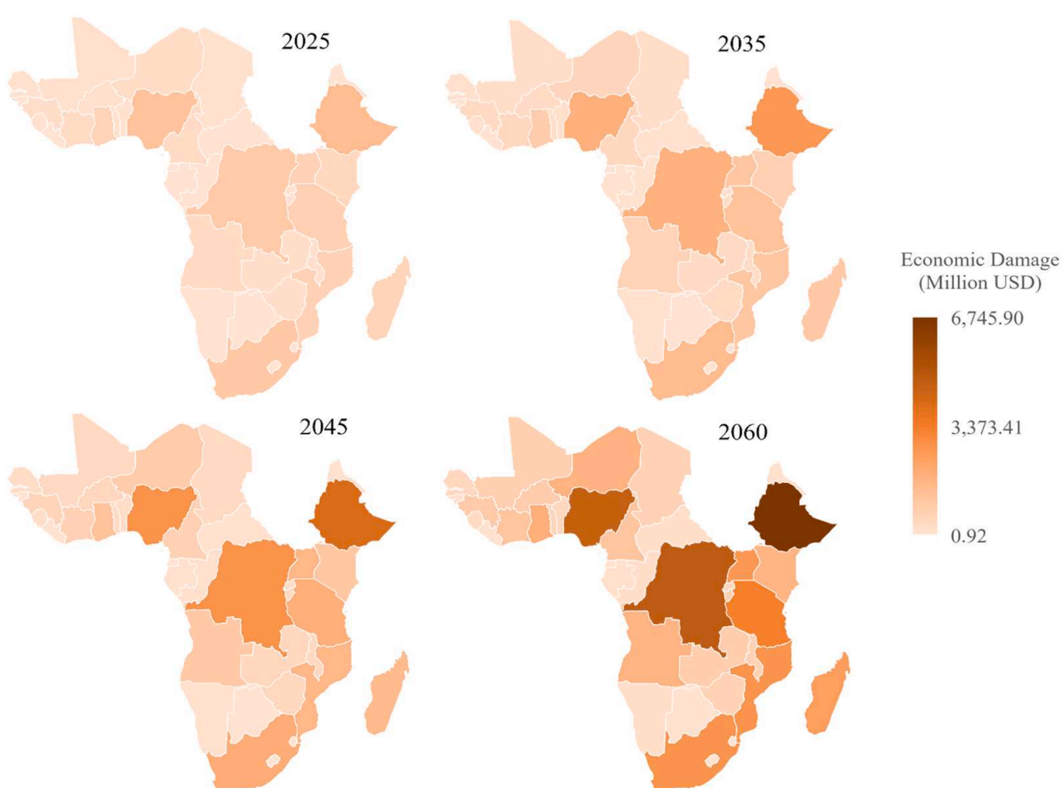

Fig. 4. Potential economic damage from MSW generation and management under BAU, 2025 - 2060.

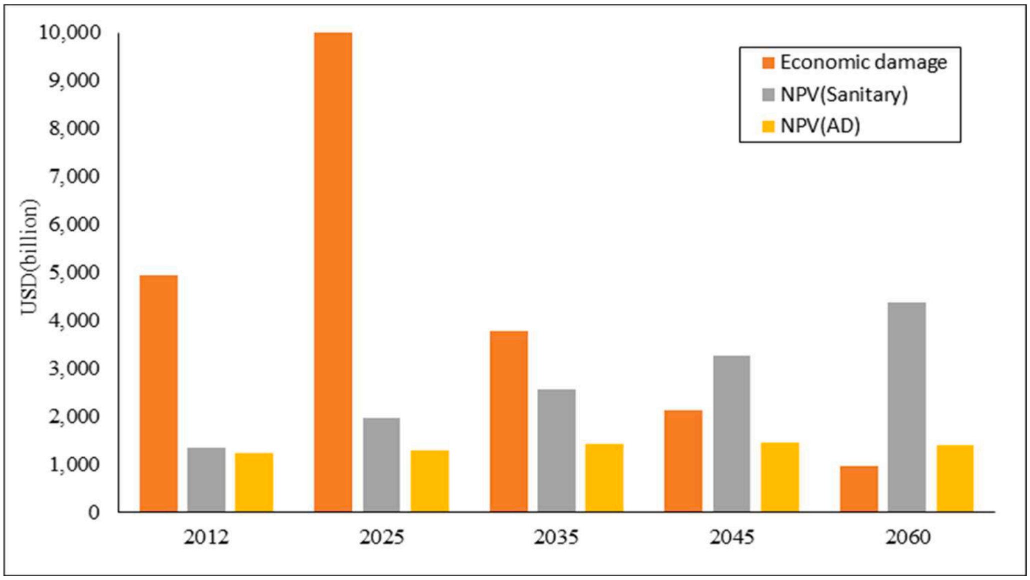

Fig. 5. Economic damage and NPV of two WTE recovery technologies for SSA countries.

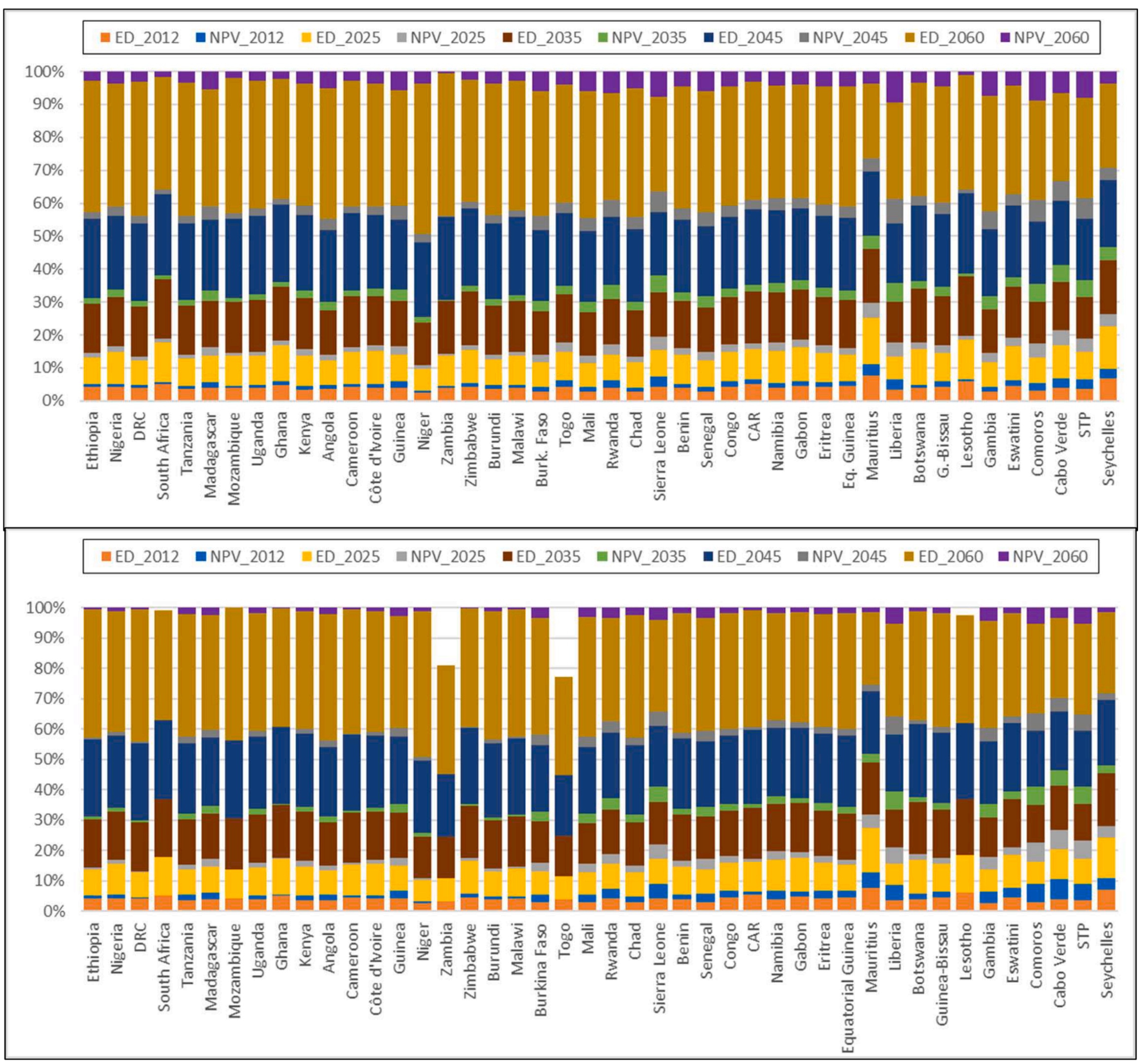

Fig. 6. Comparing economic damage cost and cost of investing in WtE: SA-first panel, AD- second panel.

sustainable waste recovery method in all SSA countries.

As shown in Fig. 6, in all countries, years, and waste recovery technologies, the results show that the cost of mitigation was less than a quarter of the damage caused by emissions from MSW. Only five countries, namely, Lesotho, Mozambique, South Africa, Togo, and Zambia, did not show viable energy recovery with anaerobic digestion. This provides a compelling and significant incentive for these countries to adopt at least one of the energy-recovery technologies presented here.

4.4. Net benefit of waste-to-energy recovery under sustainable waste management adoption in SSA

This section examines the net benefits of WTE recovery for both technologies. The results shown in Fig. B.3 (Appendix B) suggest that SSA countries could save billions of dollars in net benefits resulting from methane emissions while simultaneously improving per capita energy for their vast populations. Based on these results, the net benefits tend to increase over the years, which suggests that adopting proper waste management will result in huge potential net benefits. Although the economic damage assessment focuses on methane, which directly impacts emissions, the actual impact of the net benefit could be much larger if other benefits, such as improved health of citizens resulting in controlled and proper waste management, are considered.

Fig. B.3 (Appendix B) shows the country-level net benefits of both WtE recovery technologies in order of decreasing magnitude from left to right. The results show that the top 10 countries with the highest net benefit potential for waste-to-energy recovery using sanitary landfills are Ethiopia, South Africa, the DRC, Nigeria, Mozambique, Ghana, Tanzania, Uganda, Zambia, and Madagascar. Similarly, these countries also showed the highest potential for waste-to-energy recovery using anaerobic digestion, except for Zambia.

5. Discussion and policy implications

5.1. Waste generation and energy recovery potential forecast

Forecasts up to 2060 reveal significant waste-to-energy (WTE) recovery potential across all 44 examined African countries. These countries show a high potential for energy recovery from MSW using WTE technologies across all waste collection rate scenarios. This study opted for country-specific collection rates, which showed similar results to the often-cited 44% average collection rate (Scarlat et al., 2015; S. Kaza et al., 2018). According to the research, these countries could generate between 20 and 58 million MWh electricity from MSW alone by 2060 (see Table 5). This translates to around 100–230 kWh per capita, giving significant untapped economic growth prospects, particularly considering some of these countries' current energy challenges. Furthermore, owing to specific characteristics, some countries have a higher WTE recovery potential. From 2035 to 2060, the top twenty countries may produce between 0.2 and 3.3 million MWh and 0.4 and 8.5 MWh (Table 6; Fig. B.3, Appendix B), greatly increasing their per capita electricity generation from waste. For instance, Guinea could generate between 100 and 244 kWh per capita using either of the energy recovery technologies between 2035 and 2060, whereas Namibia could generate between 18 and 48 kWh per capita using similar energy recovery technologies during the same period.

5.2. Economic damage assessment and net benefit

Adopting sustainable MSW management can significantly reduce emissions and their climate impact. This study finds that current waste management practices could lead to substantial economic damage from CH_4 emissions, potentially costing billions of dollars. This damage is projected to double every decade from 2025 to 2060. Some countries, due to their specific waste generation potential, could face damages costing trillions of dollars (see Fig. 4). However, the cost of establishing waste-to-energy (WTE) recovery alternatives, is a fraction of the economic damage cost, suggesting that these options could mitigate the methane emissions responsible for these costs. Between 2025 and 2045, substantial economic losses from methane emissions may be avoided if sanitary landfills or anaerobic digestion were employed for energy recovery. The entire economic damage caused by CH_4 emissions might reach 24 trillion USD by 2060 (see Fig. B.1., Appendix B), whereas the net present value (NPV) of anaerobic digestion and sanitary landfills are around 30% and 50% of this amount, respectively (see Fig. 6).

In all countries and with all waste recovery technologies, mitigation costs were less than a quarter of the damage costs from emissions. Sustainable MSW management could provide net benefits and compelling incentives to adopt one of the energy-recovery technologies, potentially saving between 98 and 1006 billion USD in damage costs (see Fig. B.2, Appendix B). These results are consistent with prior research on the potential emission reductions from sustainable waste management (Liu and Li, 2023; Liu et al., 2023; Zhang et al., 2022).

5.3. Policy implications

MSW landfills are the third greatest source of GHG emissions due to increasing MSW disposal rates and inadequate management practices.

Table 5
Overall organic waste and electricity potential in SSA.

	2012	2025	2035	2045	2060
Panel A. Mass of MSW considered in the different scenarios (tonnes/year)					
100% LF	148,298,079	202,603,574	269,373,145	330,961,366	427,295,753
24% LF (avg.)	35,591,539	48,624,858	64,649,555	79,430,728	102,550,981
44% collection rate (avg.)	65,251,155	89,145,573	118,524,184	145,623,001	188,010,131
country-specific collection	74,582,111	99,656,717	135,083,753	165,178,893	211,883,526
Panel B. Methane gas potential (m^3 CH_4)					
100% LF	8459,008,143	12,589,933,356	17,014,521,148	21,544,150,713	28,710,614,171
24% LF (avg.)	2030,161,954	3021,584,006	4083,485,076	5170,596,171	6890,547,401
44% collection rate (avg.)	3721,963,583	5539,570,677	7486,389,305	9479,426,314	12,632,670,234
country-specific collection	4261,663,058	6293,923,946	8564,747,775	10,832,221,125	14,374,667,545
Panel C. Electricity potential from sanitary landfill (MWh)					
100% LF	13,879,823	20,657,982	27,917,993	35,350,361	47,109,333
24% LF (avg.)	3331,157	4957,916	6700,318	8484,087	11,306,240
44% collection rate (avg.)	6107,122	9089,512	12,283,917	15,554,159	20,728,106
country-specific collection	6992,679	10,327,280	14,053,324	17,773,869	23,586,434
Panel D. Electricity potential from anaerobic digestion (MWh)					
100% LF	39,245,085	53,484,171	71,073,295	87,323,162	112,740,700
24% LF (avg.)	9418,820	12,836,201	17,065,611	20,961,235	27,046,633
44% collection rate (avg.)	17,267,837	23,533,035	31,286,953	38,428,930	49,585,494
country-specific collection	20,042,555	26,754,426	36,188,568	44,221,710	56,658,859

Table 6
WtE electricity potential (MWh) for SSA countries, 2012 - 2060.

Panel A. Electricity potential Sanitary landfill						Anaerobic digestion					
Country	2012	2025	2035	2045	2060	Country	2012	2025	2035	2045	2060
Ethiopia	985,486	1300,250	1921,203	2508,608	3314,040	Ethiopia	2976,347	3565,170	5885,149	7000,967	8557,691
Nigeria	706,747	1111,313	1359,174	1695,755	2250,192	Nigeria	1867,108	2844,537	3211,035	3970,026	5182,859
South Africa	563,895	890,917	1060,110	1191,380	1334,966	South Africa	2358,117	2530,004	2707,072	2895,907	3074,985
DRC	628,126	829,217	1298,008	1692,554	2321,245	DRC	1492,427	1968,742	3160,116	4024,339	5387,694
Tanzania	430,232	622,830	885,062	1149,850	1607,724	Tanzania	1056,894	1509,200	2136,824	2731,922	3754,612
Uganda	365,037	561,464	781,976	980,655	1269,257	Uganda	907,242	1355,070	1874,760	2298,650	2901,454
Mozambique	365,253	557,364	764,903	979,713	1328,968	Mozambique	885,263	1297,437	1837,483	2314,348	3077,434
Ghana	351,641	523,372	620,505	736,405	909,395	Ghana	911,070	1278,822	1443,122	1692,037	2055,839
Madagascar	367,141	516,705	712,676	892,987	1184,040	Kenya	838,425	1250,442	1467,355	1721,397	2057,542
Kenya	222,329	391,306	517,845	640,653	814,135	Madagascar	911,456	1216,234	1701,229	2094,139	2727,975
Angola	216,021	298,627	435,395	580,684	842,103	Angola	616,162	725,965	1058,683	1391,765	1983,654
Côte d'Ivoire	165,085	266,599	322,004	400,574	531,641	Niger	486,347	715,362	1207,307	1657,630	2470,987
Cameroon	173,292	261,729	332,932	412,905	540,757	Côte d'Ivoire	418,899	667,711	759,714	936,775	1225,016
Niger	130,600	230,966	364,739	531,561	844,990	Cameroon	441,004	640,539	788,023	964,536	1241,420
Guinea	142,002	189,578	262,464	329,957	436,168	Zimbabwe	364,289	460,301	547,126	639,755	754,028
Zimbabwe	102,422	158,995	199,690	241,823	302,203	Guinea	350,716	454,374	627,122	774,301	1003,399
Zambia	103,849	158,007	218,030	280,968	386,548	Burkina Faso	325,123	450,847	651,850	820,951	1092,871
Burkina Faso	89,405	149,488	213,749	284,703	401,762	Zambia	264,339	384,821	524,786	665,384	898,919
Malawi	92,062	132,659	185,613	234,270	310,469	Mali	270,785	382,486	548,789	698,248	933,609
Burundi	93,819	132,443	196,446	253,902	349,977	Chad	226,711	342,059	482,096	603,724	795,022
Mali	72,291	123,806	178,493	240,062	341,957	Burundi	227,108	315,302	475,298	602,408	813,732
Chad	61,169	109,843	157,902	209,978	294,103	Malawi	239,537	314,615	444,483	550,464	714,728
Togo	78,834	108,996	145,745	180,244	234,213	Senegal	192,156	289,084	354,809	440,623	579,159
Senegal	49,140	88,942	121,167	156,342	215,423	Togo	197,302	259,372	345,692	420,562	536,811
Rwanda	66,731	88,261	125,418	152,900	191,942	Benin	145,443	210,903	270,606	336,845	445,153
Benin	57,376	86,236	113,512	143,276	192,540	Rwanda	157,403	207,171	297,917	355,029	435,399
Sierra Leone	58,266	75,862	99,841	118,098	142,449	Sierra Leone	134,942	178,044	233,952	271,019	319,715
Congo	37,826	50,448	65,319	81,684	108,668	Namibia	120,564	137,777	157,294	180,974	213,301
Namibia	27,729	46,918	58,295	69,462	85,780	Congo	105,213	122,047	154,895	191,358	250,657
CAR	37,261	44,196	59,997	72,672	90,218	Gabon	72,870	100,895	112,763	132,851	162,412
Gabon	27,193	40,821	48,393	57,681	71,761	CAR	87,210	99,804	141,357	167,918	204,074
Eritrea	18,969	26,630	34,819	43,460	56,437	Botswana	59,403	80,546	80,122	90,174	101,610
Botswana	13,587	24,948	30,459	35,470	42,156	Eritrea	60,773	71,306	98,997	118,151	145,091
Liberia	14,538	19,815	27,379	33,809	43,606	Liberia	35,136	46,727	65,131	78,862	99,731
Eq. Guinea	16,362	19,406	28,658	36,045	46,825	Eq. Guinea	46,626	46,099	68,900	84,585	107,198
Mauritius	15,245	19,073	17,611	17,225	16,056	Mauritius	39,185	44,569	37,693	36,322	33,291
Gui-Bissau	12,080	16,428	22,164	27,131	34,666	Lesotho	35,292	39,101	43,998	47,143	50,498
Lesotho	10,630	14,770	17,353	19,437	21,839	Gambia	27,944	38,989	52,486	65,121	84,066
Gambia	6941	12,665	17,582	22,967	31,541	Gui-Bissau	30,061	38,794	52,461	63,092	79,052
Eswatini	6276	9671	11,451	13,352	16,168	Eswatini	25,221	27,390	29,772	34,204	39,612
Comoros	4468	7663	9999	12,320	15,777	Comoros	17,333	23,230	28,114	33,085	40,243
Cabo Verde	2713	4462	5220	5763	6295	Cabo Verde	10,566	13,673	13,024	13,747	14,161
Seychelles	1292	1649	1676	1717	1703	Seychelles	3240	4099	3665	3704	3604

Panel A. Per capita electricity contribution Sanitary landfill						Anaerobic digestion					
Country	2012	2025	2035	2045	2060	Country	2012	2025	2035	2045	2060
Guinea	88.48	85.81	96.35	100.72	106.26	Guinea	218.52	205.66	230.22	236.36	244.45
Namibia	12.63	16.91	17.92	18.56	19.45	Namibia	54.93	49.66	48.36	48.37	48.37
Gabon	15.54	16.41	16.12	16.31	16.60	Seychelles	34.99	40.67	35.29	35.28	35.29
Madagascar	16.43	16.40	17.84	18.16	18.48	Gabon	41.65	40.56	37.57	37.57	37.57
Seychelles	13.95	16.36	16.14	16.35	16.67	South Africa	44.63	40.28	39.34	39.34	39.34
Mozambique	14.69	15.49	16.35	16.63	16.96	Madagascar	40.79	38.60	42.59	42.59	42.59
Ghana	13.53	15.21	15.01	15.20	15.44	Ghana	35.05	37.17	34.92	34.92	34.92
Mauritius	12.16	14.94	13.93	14.14	14.38	Mozambique	35.61	36.06	39.27	39.27	39.27
South Africa	10.67	14.19	15.40	16.18	17.08	Mauritius	31.26	34.91	29.82	29.82	29.82
Eq. Guinea	15.87	11.85	13.61	13.94	14.29	Botswana	29.13	31.37	26.93	26.93	26.93
Togo	11.64	11.71	12.55	12.76	12.99	Zimbabwe	27.78	28.57	28.48	28.48	28.48
Uganda	10.56	10.74	11.69	11.96	12.26	Eq. Guinea	45.22	28.16	32.72	32.72	32.72
Ethiopia	10.63	10.02	11.99	13.16	14.22	Togo	29.13	27.86	29.78	29.78	29.78
Zimbabwe	7.81	9.87	10.39	10.76	11.41	Ethiopia	32.10	27.48	36.73	36.73	36.73
Botswana	6.66	9.72	10.24	10.59	11.17	Uganda	26.25	25.91	28.03	28.03	28.03
Burundi	10.15	9.62	10.96	11.17	11.40	Niger	27.33	24.56	29.16	29.16	29.16
Tanzania	9.14	9.04	9.79	9.95	10.12	Comoros	23.95	24.07	24.16	24.16	24.16
Côte d'Ivoire	7.66	8.92	8.52	8.60	8.73	Cabo Verde	20.91	23.40	20.58	20.58	20.58
Cameroon	8.07	8.72	8.83	8.94	9.10	Burundi	24.56	22.91	26.51	26.51	26.51
Sierra Leone	8.68	8.61	9.51	9.71	9.93	Eswatini	23.37	22.38	21.24	21.24	21.24
CAR	8.40	8.28	9.12	9.30	9.50	Côte d'Ivoire	19.44	22.34	20.11	20.11	20.11
Congo	8.39	8.09	8.30	8.40	8.53	Tanzania	22.46	21.89	23.63	23.63	23.63
DRC	9.10	7.96	9.45	9.68	9.91	Cameroon	20.53	21.33	20.89	20.89	20.89
Comoros	6.17	7.94	8.59	9.00	9.47	Kenya	18.91	20.85	20.09	20.09	20.09
Niger	7.34	7.93	8.81	9.35	9.97	Sierra Leone	20.10	20.22	22.29	22.29	22.29

(*continued on next page*)

Table 6 (*continued*)

Panel A. Per capita electricity contribution Sanitary landfill						Anaerobic digestion					
Eswatini	5.81	7.90	8.17	8.29	8.67	Congo	23.33	19.58	19.68	19.68	19.68
Angola	8.60	7.76	8.38	8.50	8.65	DRC	21.62	18.91	23.01	23.01	23.01
Cabo Verde	5.37	7.64	8.25	8.63	9.15	Angola	24.54	18.87	20.38	20.38	20.38
Zambia	7.18	7.45	7.86	7.99	8.14	Burkina Faso	19.62	18.79	20.96	20.96	20.96
Eritrea	5.84	6.89	7.46	7.81	8.26	CAR	19.66	18.70	21.49	21.49	21.49
Lesotho	5.28	6.63	7.18	7.50	7.87	Eritrea	18.70	18.44	21.22	21.22	21.22
Kenya	5.01	6.52	7.09	7.48	7.95	Zambia	18.27	18.15	18.93	18.93	18.93
Benin	5.90	6.24	6.43	6.52	6.63	Chad	17.73	18.04	19.60	19.60	19.60
Burkina Faso	5.40	6.23	6.87	7.27	7.70	Lesotho	17.51	17.55	18.19	18.19	18.19
Malawi	5.98	6.07	6.62	6.75	6.89	Mali	16.95	16.33	17.81	17.81	17.81
Rwanda	6.33	6.05	7.00	7.16	7.33	Benin	14.95	15.26	15.32	15.32	15.32
Chad	4.78	5.79	6.42	6.82	7.25	Senegal	14.34	15.17	14.64	14.64	14.64
Mali	4.52	5.29	5.79	6.12	6.52	Malawi	15.56	14.39	15.86	15.86	15.86
Nigeria	4.23	4.76	4.61	4.65	4.73	Rwanda	14.92	14.21	16.62	16.62	16.62
Senegal	3.67	4.67	5.00	5.20	5.45	Gambia	14.67	14.02	14.65	14.65	14.65
Gambia	3.64	4.56	4.91	5.17	5.50	Nigeria	11.16	12.19	10.89	10.89	10.89
Liberia	3.52	3.48	3.86	3.94	4.02	Liberia	8.50	8.21	9.19	9.19	9.19
Gui-Bissau	1.13	1.09	1.16	1.15	1.13	Gui-Bissau	2.82	2.59	2.74	2.67	2.58

Methane, a powerful greenhouse gas with a warming potential 25 times that of CO_2 (EPA), is a significant contributor to climate change. As a result, limiting methane emissions from landfills is critical for mitigating climate change.

In SSA, a greater majority of landfills are uncontrolled, resulting in methane emissions entering the atmosphere. However, this study shows that energy generation from methane can significantly offset economic damage. By 2060, landfill gas electricity generation could produce enough power for approximately 1.7 million homes across SSA, also creating job opportunities linked with the construction and operation of energy recovery plants.

Landfill rates vary widely throughout SSA, with some countries, such as Cabo Verde and Mauritius, exceeding 90%. It is a practical approach to divert MSW from landfills to Anaerobic Digester (AD) facilities for energy production. AD biogas might be utilized to power homes or as a car fuel in public transportation. The absence of gas grids in SSA makes biogas systems a plausible regional endeavor, enabling its transition to a sustainable circular economy.

WtE utilization involves various sectors and actors, including regional authorities, waste managers, and energy producers. Effective policies require stability and continuity, especially for projects requiring large, long-term investments. Governments could adopt green budgeting for sustainable MSW projects, a step already taken by certain African countries like Cote D'Ivoire, Senegal, and South Africa. This can be applied to all other countries within the region to boost sustainable waste management projects and increase the share of renewables in the electricity grid.

However, municipalities often focus solely on waste collection and disposal, without substantial investment in waste treatment and energy recovery. To transition to sustainable waste management in SSA, public-private partnerships (PPP) could be adopted, where waste recovery projects are government-owned but privately managed. Thus, releasing institutional shackles and increasing operational flexibility.

6. Conclusion

Waste management challenges are escalating in Sub-Saharan Africa (SSA), posing environmental, social, and economic threats. It's essential to recycle the organic component of MSW to advance a cradle-to-cradle economic model of waste management. SSA lags in implementing sustainable waste practices, with neglect adversely affecting the region's environment and economy. Several energy recovery technologies for MSW exist, such as sanitary landfills, anaerobic digestion, and incineration. However, their limited use reflects a lack of awareness about alternatives to mitigate the environmental and economic crises caused by poor waste management.

This study sheds light on the negative impacts of improper waste management in SSA and provides comprehensive guidance on mitigation strategies. The results suggest that SSA countries can transition to sustainability through innovative policies and incentives promoting energy recovery and recycling. Such policies should foster an environment conducive to private investment in waste management, yielding economic, social, and environmental benefits, (Table A1, Table A2, Table A3, Fig. B1, Fig. B2, Fig. B3).

This research's limitations include a lack of waste management data for most SSA nations, that required the use of regional data from reliable sources. Additionally, there's no consensus on the social discount rate for estimating the NPV of government projects. In this case, secondary data from the literature were used to assess the economic viability of energy recovery projects in SSA countries. Future studies should explore innovation policies for self-sustainable energy recovery projects in SSA and how to incorporate industrial symbiosis principles in planning to transform by-product streams into profitable activities.

CRediT authorship contribution statement

Nkweauseh Reginald Longfor: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Resources. **Joseph Jr. Aduba:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization, Resources. **Ioan-Robert Istrate:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – review & editing, Visualization, Resources. **Xuepeng Qian:** Writing – review & editing, Supervision, Resources.

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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Appendix A

Table A.1
Country-specific municipal solid waste (MSW) collection rate. Due to the lack of data, we could find country-specific collection rates for 29 countries, whereas for the remaining 15 countries (indicated with an asterisk) we assumed the average collection rate for Sub-Saharan countries as provided by The World Bank (44%).

Country	MSW collection rate	Country	MSW collection rate
Angola*	44.00%	Kenya	47.50%
Benin	37.50%	Lesotho*	44.00%
Botswana*	44.00%	Liberia	20.00%
Burkina Faso	47.00%	Madagascar	89.00%
Burundi	41.00%	Malawi	30.00%
Cabo Verde*	44.00%	Mali	41.00%
Cameroon	51.50%	Mauritius*	44.00%
CAR*	44.00%	Mozambique	82.00%
Chad*	44.00%	Namibia	93.00%
Comoros	60.00%	Niger	60.00%
Congo*	44.00%	Nigeria	25.00%
Côte d'Ivoire	48.00%	Rwanda	35.50%
DRC*	44.00%	Senegal	36.00%
Equatorial Guinea*	44.00%	Seychelles*	44.00%
Eritrea*	44.00%	Sierra Leone	45.00%
Eswatini*	44.00%	South Africa	69.00%
Ethiopia	69.00%	STP*	44.00%
Gabon	57.00%	Tanzania	55.00%
Gambia	35.00%	Togo	70.00%
Ghana	83.00%	Uganda	65.00%
Guinea	76.00%	Zambia	45.00%
Guinea-Bissau*	44.00%	Zimbabwe	69.75%

Table A.2
Country-specific mean annual precipitation (MAP) and the corresponding decay rate for food and paper waste. Based on IPCC data[52], the decay rate of food waste ranges from 0.085 $year^{-1}$ if MAP < 1000 mm $year^{-1}$ to 0.400 $year^{-1}$ if MAP > 1000 mm $year^{-1}$, while for paper waste this range goes from 0.045 $year^{-1}$ if MAP < 1000 mm $year^{-1}$ to 0.070 $year^{-1}$ if MAP > 1000 mm $year^{-1}$. We matched each country to its specific decay rates based on MAP values facilitated by The World Bank[1].

Country	MAP (mm $year^{-1}$)	Decay rate		Country	MAP (mm $year^{-1}$)	Decay rate	
		Food waste	Paper/cardboard waste			Food waste	Paper/cardboard waste
Angola	1010	0.400	0.045	Kenya	630	0.085	0.045
Benin	1039	0.400	0.045	Lesotho	788	0.085	0.045
Botswana	416	0.085	0.045	Liberia	2391	0.400	0.045
Burkina Faso	748	0.085	0.045	Madagascar	1513	0.400	0.045
Burundi	1274	0.400	0.045	Malawi	1181	0.400	0.045
Cabo Verde	228	0.085	0.045	Mali	282	0.085	0.045
Cameroon	1604	0.400	0.045	Mauritius	2041	0.400	0.045
CAR	1343	0.400	0.045	Mozambique	1032	0.400	0.045
Chad	322	0.085	0.045	Namibia	285	0.085	0.045
Comoros	900	0.085	0.045	Niger	151	0.085	0.045
Congo	1646	0.400	0.045	Nigeria	1150	0.400	0.045
Côte d'Ivoire	1348	0.400	0.045	Rwanda	1212	0.400	0.045
DRC	1543	0.400	0.045	Senegal	686	0.085	0.045
Equatorial Guinea	2156	0.400	0.045	Seychelles	2330	0.400	0.045
Eritrea	384	0.085	0.045	Sierra Leone	2526	0.400	0.045
Eswatini	788	0.085	0.045	South Africa	495	0.085	0.045
Ethiopia	848	0.085	0.045	STP	3200	0.400	0.045
Gabon	1831	0.400	0.045	Tanzania	1071	0.400	0.045
Gambia	836	0.085	0.045	Togo	1168	0.400	0.045
Ghana	1187	0.400	0.045	Uganda	1180	0.400	0.045
Guinea	1651	0.400	0.045	Zambia	1020	0.400	0.045
Guinea-Bissau	1577	0.400	0.045	Zimbabwe	657	0.085	0.045

[1] https://data.worldbank.org/indicator/AG.LND.PRCP.MM?locations=ZG.

Table A.3
Economic damage and NPV of waste management adoption (million USD).

	Economic damage (million USD)						NPV from Sanitary landfill						NPV from Anaerobic digestion				
Country	2012	2025	2035	2045	2060	Country	2012	2025	2035	2045	2060	Country	2012	2025	2035	2045	2060
Ethiopia	698.09	1386.88	2581.07	4064.69	6745.90	Ethiopia	160.43	212.54	286.23	378.44	504.68	Madagascar	140.01	144.43	165.73	167.35	161.98
Nigeria	500.64	1185.36	1826.00	2747.63	4580.38	Nigeria	136.12	214.64	263.40	328.87	436.99	Tanzania	138.58	152.97	177.75	186.45	190.41
DRC	444.95	884.47	1743.83	2742.44	4725.01	Madagascar	115.80	163.10	216.39	271.39	360.18	Nigeria	128.05	150.81	139.65	141.64	137.39
South Africa	399.45	950.28	1424.22	1930.39	2717.39	DRC	101.20	133.60	198.98	260.13	357.65	Ethiopia	112.09	103.79	140.55	137.16	124.58
Tanzania	304.76	664.33	1189.05	1863.10	3272.60	Tanzania	69.98	101.36	150.42	195.43	273.25	Uganda	93.71	110.76	126.50	127.39	119.26
Madagascar	260.07	551.13	957.46	1446.91	2410.17	Angola	58.18	80.90	114.65	153.04	222.18	Angola	75.60	68.86	82.37	88.84	94.08
Mozambique	258.74	594.50	1027.62	1587.43	2705.18	South Africa	56.40	91.96	98.04	111.19	125.75	Kenya	63.98	73.77	71.01	68.34	60.69
Uganda	258.58	598.87	1050.56	1588.95	2583.64	Uganda	56.11	86.40	122.75	154.02	199.40	Guinea	62.01	62.10	70.32	71.22	68.58
Ghana	249.09	558.24	833.63	1193.20	1851.12	Guinea	48.94	65.37	87.56	110.17	145.78	DRC	56.21	57.32	75.47	78.85	78.43
Kenya	157.49	417.38	695.71	1038.05	1657.21	Ghana	47.42	70.74	76.97	91.49	113.21	Burkina Faso	54.97	58.93	69.89	72.21	71.42
Angola	153.02	318.52	584.94	940.88	1714.14	Kenya	46.01	81.75	103.86	129.14	165.00	Sierra Leone	44.72	45.61	49.17	46.73	40.96
Cameroon	122.76	279.17	447.28	669.03	1100.74	Mozambique	42.05	64.28	79.18	101.69	138.37	Mali	43.69	47.71	56.15	58.61	58.23
Côte d'Ivoire	116.94	284.36	432.60	649.05	1082.18	Côte d'Ivoire	33.23	53.70	62.41	77.69	103.24	Rwanda	37.56	38.22	45.09	44.08	40.16
Guinea	100.59	202.21	352.61	534.63	887.84	Sierra Leone	31.55	41.07	53.31	63.10	76.15	Senegal	33.97	39.51	39.78	40.53	39.58
Niger	92.51	246.36	490.01	861.29	1720.02	Burkina Faso	29.26	49.25	68.20	91.17	129.10	Côte d'Ivoire	28.73	35.40	33.04	33.42	32.47
Zambia	73.56	168.54	292.92	455.25	786.84	Rwanda	27.96	36.99	51.89	63.31	79.55	Chad	27.82	32.44	37.51	38.54	37.71
Zimbabwe	72.55	169.59	268.28	391.83	615.15	Cameroon	26.32	39.83	47.86	59.45	78.01	Niger	25.84	29.38	40.67	45.81	50.74
Burundi	66.46	141.27	263.92	411.40	712.40	Togo	25.55	35.36	33.44	40.74	51.53	Zimbabwe	20.27	16.12	11.71	8.71	3.47
Malawi	65.21	141.50	249.36	379.59	631.98	Niger	23.48	41.92	61.02	89.63	143.60	Benin	15.60	17.48	18.40	18.79	18.45
Burkina Faso	63.33	159.45	287.16	461.30	817.81	Mali	22.77	39.32	55.14	74.43	106.44	Burundi	15.58	16.72	20.67	21.49	21.57
Togo	55.84	116.26	195.80	292.05	476.75	Burundi	18.79	26.55	37.99	49.19	67.91	Namibia	14.79	13.07	12.24	11.55	10.12
Mali	51.21	132.06	239.80	388.97	696.07	Senegal	16.32	29.81	39.97	51.70	71.43	Liberia	14.63	15.04	17.20	17.09	16.05
Rwanda	47.27	94.14	168.49	247.74	390.71	Chad	16.28	29.48	40.91	54.65	76.90	Cameroon	13.20	14.82	14.96	15.02	14.36
Chad	43.33	117.16	212.14	340.23	598.66	Zimbabwe	15.53	24.35	28.35	34.13	42.19	Ghana	13.18	14.30	13.24	12.74	11.50
Sierra Leone	41.27	80.92	134.13	191.35	289.96	Benin	14.28	21.50	27.66	34.94	47.01	Congo	12.91	11.58	12.05	12.21	11.89
Benin	40.64	91.98	152.50	232.15	391.92	Malawi	13.42	19.50	26.65	33.71	44.77	Eritrea	7.46	6.76	7.70	7.54	6.88
Senegal	34.81	94.87	162.78	253.32	438.50	Congo	10.20	13.67	17.23	21.56	28.71	Gabon	7.25	7.76	7.12	6.88	6.25
Congo	26.80	53.81	87.75	132.35	221.20	Liberia	9.31	12.69	17.62	21.77	28.10	Malawi	7.17	7.28	8.44	8.57	8.27
CAR	26.40	47.14	80.60	117.75	183.64	Namibia	7.55	12.89	15.24	18.21	22.56	Gambia	6.89	7.43	8.20	8.35	8.01
Namibia	19.64	50.04	78.32	112.55	174.61	Zambia	7.34	11.23	4.58	6.71	11.02	Mauritius	6.63	5.83	4.04	3.20	2.18
Gabon	19.26	43.54	65.02	93.46	146.07	CAR	7.13	8.47	11.03	13.38	16.64	Comoros	6.55	6.78	6.74	6.50	5.88
Eritrea	13.44	28.40	46.78	70.42	114.88	Gabon	6.59	9.91	11.33	13.51	16.83	Eq. Guinea	5.72	4.37	5.36	5.40	5.08
Eq. Guinea	11.59	20.70	38.50	58.40	95.32	Eritrea	5.08	7.19	9.07	11.36	14.81	CAR	5.31	4.70	5.46	5.32	4.80
Mauritius	10.80	20.34	23.66	27.91	32.68	Mauritius	5.04	6.32	5.73	5.61	5.23	Botswana	4.53	4.75	3.88	3.58	3.00
Liberia	10.30	21.14	36.78	54.78	88.76	Eq. Guinea	4.41	5.26	7.55	9.51	12.38	Guinea-Bissau	3.69	3.68	4.08	4.03	3.75
Botswana	9.63	26.61	40.92	57.47	85.81	Guinea-Bissau	3.27	4.46	5.85	7.16	9.16	Cabo Verde	3.18	3.18	2.48	2.15	1.65
Guinea-Bissau	8.56	17.52	29.78	43.96	70.57	Gambia	2.92	5.39	7.38	9.66	13.30	Eswatini	3.09	2.60	2.32	2.18	1.88
Lesotho	7.53	15.75	23.31	31.49	44.45	Botswana	2.77	5.19	6.15	7.19	8.58	STP	1.38	1.54	1.46	1.45	1.38
Gambia	4.92	13.51	23.62	37.21	64.20	Comoros	2.68	4.61	5.91	7.29	9.35	Seychelles	0.50	0.49	0.36	0.30	0.21
Eswatini	4.45	10.32	15.38	21.63	32.91	Eswatini	1.66	2.61	3.00	3.50	4.26	Lesotho	−0.85	−0.73	−0.68	−0.59	−0.47
Comoros	3.17	8.17	13.43	19.96	32.11	Cabo Verde	1.34	2.23	2.57	2.85	3.11	Mozambique	−0.88	−0.99	−1.16	−1.19	−1.18
Cabo Verde	1.92	4.76	7.01	9.34	12.81	Lesotho	0.83	1.18	1.26	1.43	1.62	South Africa	−20.57	−17.06	−14.97	−13.14	−10.37
STP	0.93	2.07	3.15	4.65	7.59	STP	0.70	1.03	1.27	1.55	2.01	Togo	−48.76	−58.23	−71.12	−77.43	−83.13
Seychelles	0.92	1.76	2.25	2.78	3.47	Seychelles	0.40	0.51	0.51	0.52	0.52	Zambia	−68.71	−79.81	−90.88	−90.71	−83.66

Appendix B

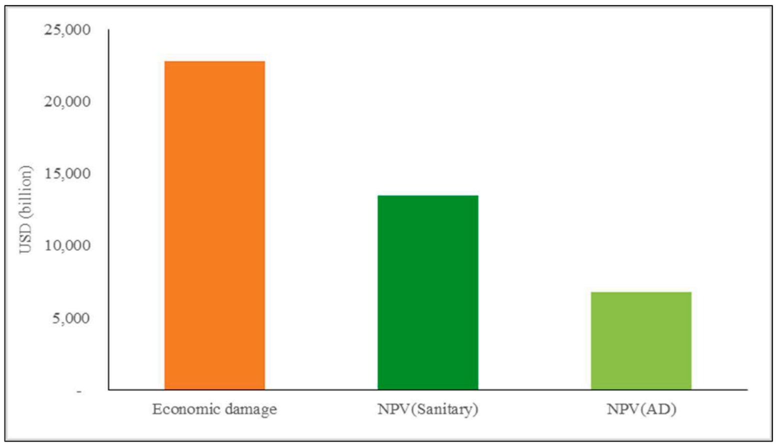

Fig. B.1. Cumulative economic damage versus NPV two WtE recovery technologies for SSA countries (2012 ~ 2060).

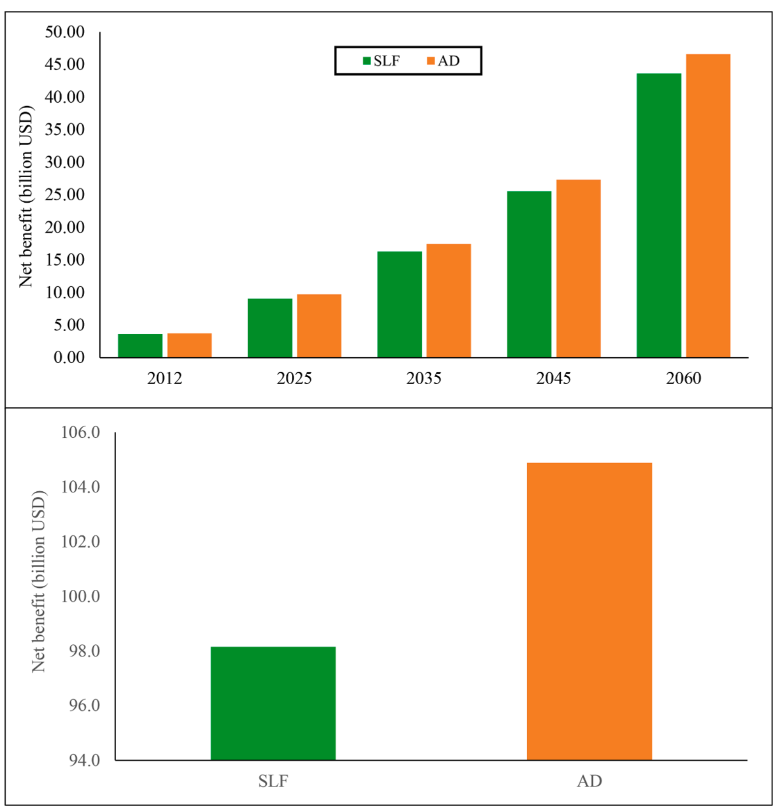

Fig. B.2. Net benefits of adopting sustainable waste management using two WtE recovery technologies.

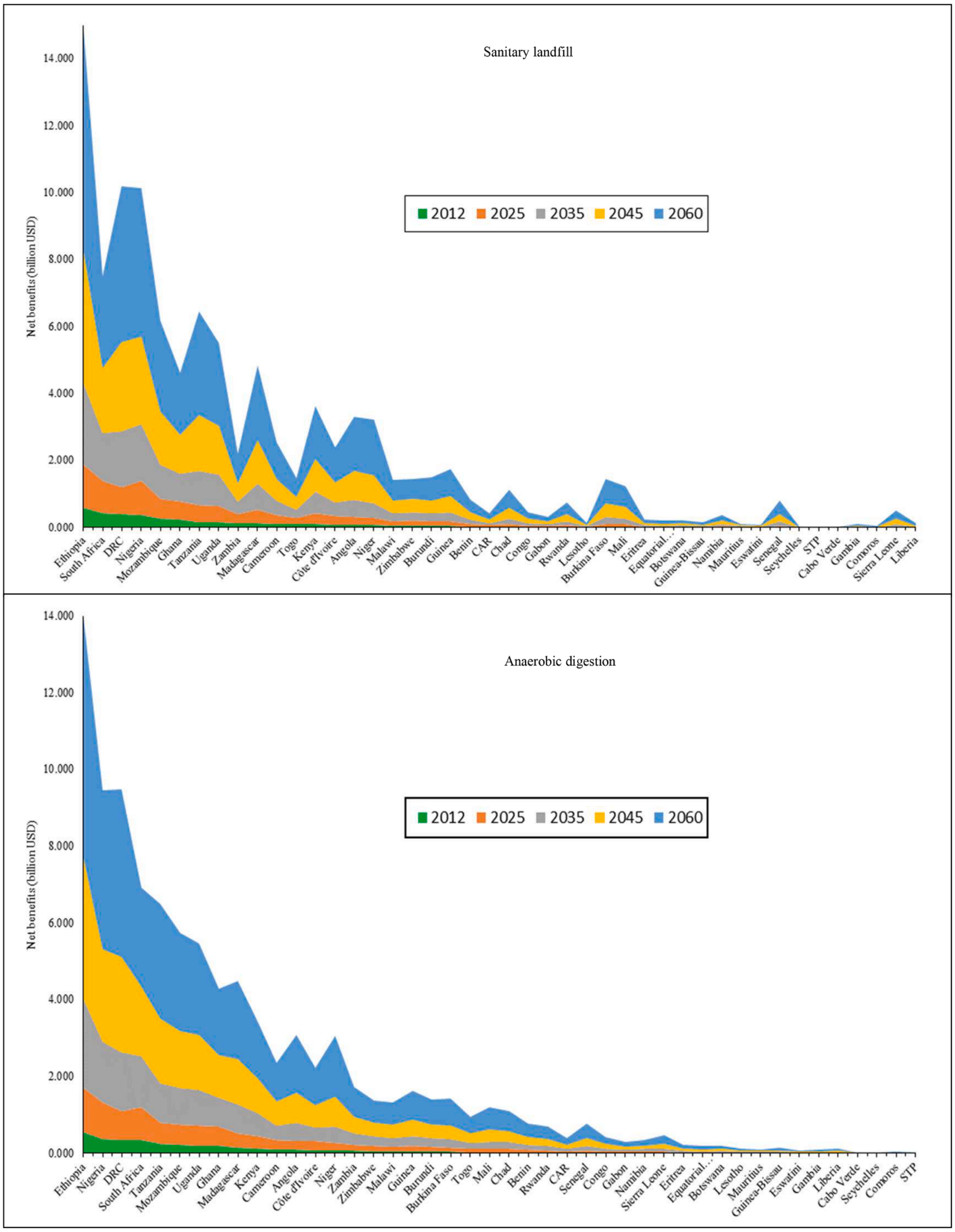

Fig. B.3. Net benefits of adopting sustainable waste management using two WtE recovery technologies (country level results.

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