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Green Technology & Innovation

Journal homepage: gtijournal.com

Technical article

Zero Waste Disposal (ZeWAD): A Case Study with Economic Assessment

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ABSTRACT

Sustainable waste management systems are urgently needed in developing countries to replace conventional landfilling systems. This study aims to conduct a Material Flow Analysis and economic feasibility assessment of a Zero Waste to Landfill Disposal (ZeWaD) system in Ghana. The system integrates source segregation, three onsite treatment technologies: anaerobic digestion, recycling and incineration, export of excess recyclables to external industries and import of special waste for incineration. Results show a high diversion rates from landfill (100%) and incineration (77%) which needs improvement. Waste composition averaged 39.3% organics, 49.73% plastics, 9.3% paper, and 0.62% other materials. Also, incineration generated the highest direct revenue, exceeding US$2,500 per year, mainly from treatment of special external waste. Compared with the pre-ZeWaD disposal cost of US$962 per year, the system achieved an annual net benefit of US$2,901 through direct revenues and avoided disposal costs. The financial feasibility assessment produced an internal rate of return of 36% and a payback period of 5 years, indicating strong economic viability. Overall, ZeWaD presents a flexible integrated modular design with linkages to external value chains. Although demonstrated at the institutional level, it presents preliminary evidence of a potential for further research, targeting wider adoption while supporting the Sustainable Development Goals (SDGs) and Ghana's climate mitigation agenda.

ARTICLE INFO

Article History:
Received: 02 April 2026
Revised: 20 May 2026
Accepted: 14 June 2026

Keywords:
Zero Waste
Circular Economy
Source Segregation
Recycling
Anaerobic Digestion
Material Flow Analysis

Article Citation:
Agyenim, F. B., Armoo, E. A., Antwi , B. Y., Mohammed , L., Nsiah-Gyambibi, R., Mohammed , M., … Oteng-Yeboah , K. K. (2026). Zero Waste Disposal (ZeWAD): A Case Study with Economic Assessment. Green Technology & Innovation, 2(1), 297–313. https://doi.org/10.65582/gti.2026.015

1. INTRODUCTION

The United Nations has declared 2020 to 2030 as a decade of action in achieving the Sustainable Development Goals (SDGs) with climate change and waste management remaining major challenges linking to SDGs 3, 6 and 12–15 (UN 2024). Municipal Solid Waste (MSW) generation currently exceeds 2 billion tonnes annually, yet only 16% is recycled while 46% is disposed of unsustainably (Maalouf & Agamuthu 2023; Nandy et al. 2022). Additionally, faecal waste management remains a major concern in developing countries because both human and animal waste are important methane sources and pose significant health

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risks. MSW generation is expected to increase to 3.40 billion tonnes by 2050 due to rapid population growth and urbanization (Godfrey et al. 2020).

In emerging economies such as Ghana, waste management is particularly challenging: 33.4% of MSW is collected, 37.5% is dumped indiscriminately and 29% is uncollected (mostly openly burnt). Ghana's population was estimated at 34 million in 2023 and is projected to rise by 50% by 2050 (GSS 2022). With this, daily waste generation is estimated at more than 12,000 tons (Miezah et al. 2015). Conventional waste management in Ghana largely follows a linear chain from generation to open burning or dumping. Beyond a few major cities with engineered landfills, most towns rely on open fields, drains and uncontrolled disposal (Mohammed et al. 2022). Organic waste, which makes up 60–70% of domestic waste is a major GHG source (Adedara 2023). Ghana's waste sector is prioritized in the Nationally Determined Contributions and Climate Change Adaptation Strategy due to increased emissions from 1.31 $MtCO_2eq$ in 1990 to 4.5 $MtCO_2eq$ in 2012, accounting for nearly 24% of Ghana's total GHG emissions excluding AFOLU (EPA 2022; UNFCC 2024). On the other hand, 13,000 GWh of energy can potentially be generated from waste by 2030 (Darmey et al. 2023). Sustainable, locally applicable and economically viable waste management models are therefore urgently required.

Circular economy (CE) offers a alternative pathway to the conventional linear waste model by promoting waste reduction, material recovery, resource recirculation (European Parliament 2018; Sillanpaa 2019). CE depends on two principal cycles: biological and material (Heshmati 2017). These processes recirculate outputs such as energy, compost, chemicals and recycled materials thereby reducing virgin material extraction and lowering emissions (El Bari & Trois 2023; Agyenim et al. 2020). However, implementation in developing countries is constrained by weak infrastructure (Nketiah et al. 2022).

1.1. ZERO WASTE DISPOSAL CONCEPT WITHIN THE GLOBAL PERSPECTIVE

1.1.1. ZERO WASTE CONCEPT AND ITS IMPLEMENTATION CHALLENGES

The zero-waste concept emerged in the 1970s in response to the rising global population and associated consumption patterns with the early efforts of Paul Palmer who begun the zero-waste movement in the chemical industry. Since then, initiatives, such as the Urban Ore, No Waste by 2010, Zero Waste USA and the Zero Waste Conference have gradually refined the concept (Mohajan 2025). The Zero Waste International Alliance has defined zero waste as: the conservation of all resources by means of responsible production, consumption, reuse, and recovery of all products, packaging, and materials without burning them and with no discharges to land, water, and air that threaten the environment and human health (ZWIA 2018). Zaman and Ahsan (2019) also describe the aim of zero waste as eliminating waste generation by ensuring that all materials are fully utilized, leaving nothing to be landfilled or incinerated.

However, these definitions present a practice-based limitation. Recent studies interpret the concept as a performance-based objective/ target rather than a literal elimination of all waste. The definition of the Welsh Assembly Government captures this clearly: "An aspirational end point where all waste that is produced is reused or recycled as a resource without the need for any landfill or energy recovery" (Cole et al. 2014). Although 100% source recovery is emphasised, real-world systems operate under material and economic constraints that necessitate residual management. Consequently, terms such as "zero waste to landfill", "net zero emissions" and "zero waste city" are now commonly used to describe systems achieving high diversion rates and near-zero landfill dependence, rather than absolute zero outputs (Bakkaloglu et al. 2022; Permana et al. 2023; Usapein & Chavalparit 2013).

Practical municipal-scale examples support this interpretation. San Francisco (USA) reports diversion rates of around 80%, through mandatory recycling and composting although residual waste treatment remains necessary (Kaza et al. 2018). Similarly, Kamikatsu (Japan) increased recycling rates from 59% in 2008 to 81% (2020) through intensive source separation yet still incinerates residual fractions including high health risk items such as cigarette butts and sanitary products (19%) (Shenyoputro & Jones, 2023). Likewise, Ljubljana (Slovenian) reports diversion rates of 78% mainly through recycling and composting but also relying on residual treatment through incineration and landfilling (Brglez et al. 2025). Studies for the city to Tshwane in South Africa focused on technological configuration to achieve zero waste to landfill in the long term (Snyman & Vorster, 2011). These cases demonstrate that even advanced municipal systems achieve near-zero landfill rather than absolute zero waste.

1.1.2. ZERO WASTE DISPOSAL (ZEWAD) CONCEPT IN THIS STUDY

In this study, the term “zero waste” is applied in an operational rather than literal sense through a proposed Zero Waste Disposal (ZeWaD) system. It appropriately describes a zero waste-to-landfill framework which has a primary objective to minimize waste disposal to landfills and uncontrolled environments such as open spaces and drainage channels which is particularly common in Ghana (GSS 2022). Although diversion of waste from incinerators is important in some countries, this is not the case in Ghana. There are only 244 small scale incinerators mainly for onsite medical waste treatment which is not a key component of municipal waste management (Ofori Boateng et al. 2013; Zaman 2015). Consequently, the ZeWaD system in this study considers diversion from landfill a top priority while seeking to only direct residual end of life materials to the incinerator.

Institutional waste management can provide an effective pathway towards broader zero waste implementation within communities and cities due to their relatively closed operational boundaries. Studies on higher education institutions shows that zero waste measures can be implemented with comparatively lower logistical and financial complexity such as lower collection and transportation costs (Rodríguez-Guerreiro et al. 2024). For example, the Utrecht University, has developed an operational management sustainability plan with a goal to achieve zero waste to incineration or landfill by 2030 by optimizing separation and circularity (Utrecht University 2025). Similarly, University of Malaya also introduced a Zero Waste Campaign in 2011 which operates onsite reuse, composting and anaerobic digestion and external recycling. Diversion rates of 620 tonnes from the landfill have been achieved over six years with the aim of 60% diversion rate by 2040 and to provide research outputs within the field (Yusoff 2018). Ebrahimi & North 2017 highlights best practices from some United States universities including prioritizing investment into a robust source separation model (bins) and education/ publicity campaigns, publication of long term zero-waste campus targets with specific timelines, sustainable procurement policies, extensive stakeholder engagement and comprehensive monitoring and audits.

1.2. THE ZERO WASTE DISPOSAL (ZEWAD) PILOT SYSTEM IN GHANA

1.2.1. BACKGROUND TO PILOT ZEWAD SYSTEM

The Council for Scientific and Industrial Research (CSIR-IIR) CSIR-IIR is located at East Legon in Accra, Ghana’s capital city. Prior to the implementation of ZeWaD, both solid and liquid wastes were managed through municipal disposal systems. Unsorted solid waste was collected and transported directly to landfill sites, while blackwater was stored in septic holding tanks and periodically desludged by municipal collectors. Between 2010 and 2024, several studies into sustainable waste management technologies were undertaken, leading to onsite development and installation of multiple systems (Table 1). The ZeWaD pilot system presents an integrated operation of these technologies as a single waste management system comprising source segregation, three onsite treatment pathways (anaerobic digestion (AD), plastics recycling, and incineration) and supported by external treatment (recycling).

Table 1. Studies forming the background of the ZeWaD pilot system.

Technology	Main objective	Reference
Source segregation	Preliminary data on waste composition from source sorting	Antwi et al. 2019
	Survey on acceptance of source segregation at CSIR-IIR	Antwi et al. 2021
	Factors influencing effective solid waste collection at CSIR-IIR	Antwi et al. 2020
AD	Performance of the ABBR (AD) for the treatment of blackwater at a high school	Quashie et al. 2019
	Effect of temperature and pH variation on anaerobic digestion for biogas production	Zainudeen et al. 2021
Recycling	Recycle source segregated Polystyrene plastics using the hot melt method for artefacts and souvenirs	Antwi et al. 2022
	Incorporation of plastic waste as a binder in asphaltic mix	Tagbor et al. 2022
	Performance evaluation of LDPE plastics in asphaltic mix	Mohammed et al. 2024
	Wood sawdust and plastic waste composite materials	Koranteng et al. 2015
	The qualities of Waste Polystyrene and sawdust composite with sawdust fiber filler and oyster shell powder (OSP) as additives	Antwi et al. 2024

Technology	Main objective	Reference
Incinerator	The construction and assessment of De-Montfort type intermittent medical incinerator for a medical facility by the CSIR-IIR	Akuffo-Kumi et al. 2014
	Analyses of the bottom ash from DeMont biomedical waste incinerator	Debrah & Dinins 2023
	Thermal efficiency of the modified De-Montfort incineration using calorific value	Oduro et al. 2016

1.2.2 THE BROADD TECHNICAL CONFIGURATION OF ZEWAD

The system boundary of ZeWaD involves waste generation, onsite treatment, production of new products and linkages to external value chains. Figure 1 shows how these individual systems operate in one integrated system to achieve a zero-waste outcome. Interaction between the inner system and external value chains involve importation of medical waste and exportation of recyclables. This is intended to improve the financial sustainability of the system through additional revenues and reduce disposal of waste to landfills.

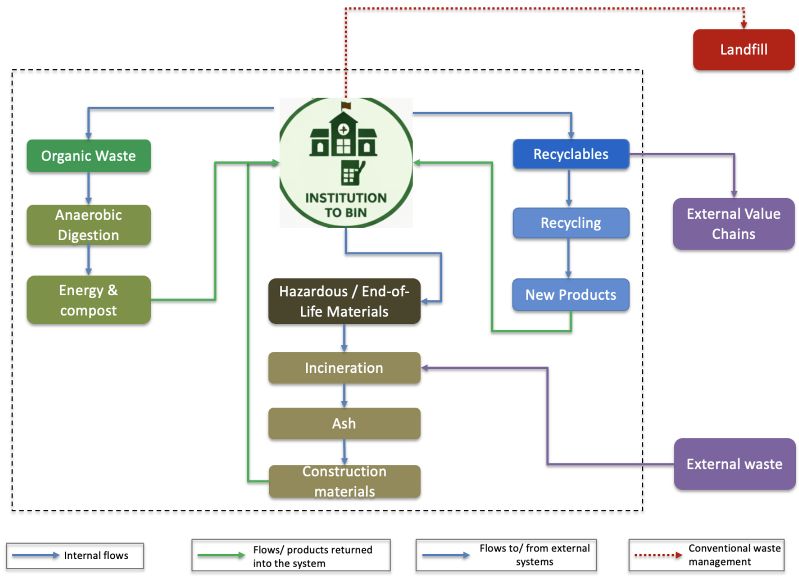

Figure 1. System boundaries and scope of the piloted ZeWaD system showing how materials and energy are cycled.

1.2.3. COMPONENTS OF THE ZEWAD SYSTEM

Source segregation is the first stage. Preliminary waste characterization was conducted which led to the design of a four chambered bin (Figure 2). The bin is locally welded with scrap metal, metal mesh and aluminium foil with local materials and expertise. Different coloured plastic bags are used to make segregation easier for users. Also, aluminium foil is required at the edge of the input area to reduce rust and avoid injuries due to rusting metal edges. An extensive education and feedback system was put in place to enhance user compliance with source segregation and reduce post collection segregation.

Figure 2. The four-chambered locally designed bin and the segregated residuals, food waste, paper and plastics.

The anaerobic digester (AD) is constructed onsite using an anaerobic baffled reactor design with the same design as shown in Quashie et al. (2019) (Figure 3). The organic fraction of source segregated waste and the blackwater from water closet toilets are co-digested to produce digestate and biogas. The liquid digestate is pumped into an overhead tank for irrigation of an onsite garden whiles the solid digestate is disinfected and used as manure. The biogas is used for energy in the laboratory.

Figure 3. Manual feeding of the biodigester with food waste and gas collected in a balloon.

Onsite plastic recycling is done with the use of the hot melt process. Specifically, the hot melt process has been applied to water sachet bags (Mohammed et al. 2024; Tagbor et al. 2022) and polystyrene food packaging (Antwi et al. 2022; Antwi et al. 2024). The preliminary study for this process successfully produced name plates, floor tiles, and educational learning materials from a combination of waste polystyrene and 20% v/w of lauric fatty acid (Figure 4). The final material showed good tensile strength, moderate heat resistance and a smooth surface (Antwi et al. 2022).

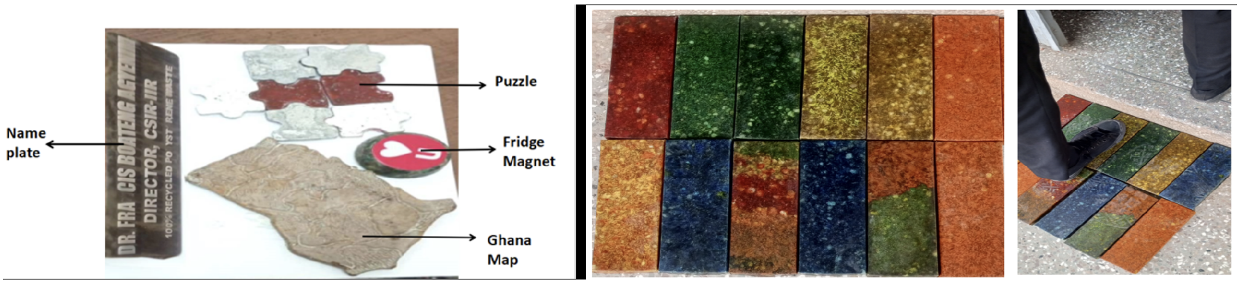

Figure 4. Recycling of Polystyrene (PS) waste into floor tiles and other artefacts.

The onsite incinerator treats residual waste which mainly contains end-of life plastics and paper and medical waste from nearby health facilities. The De-Montfort type incinerator was constructed with local materials and expertise. The design integrates a front-loading mechanism and a 5 m high refractory brick chimney: leaving only the metal grate exposed to high temperatures between 500-800 °C (Akufo-Kumi et al. 2014; Oduro et al. 2016) (Figure 5). Periodic maintenance ensures combustion and emission control is functioning effectively. The bottom ash is used as a construction material in sand plastic composite material, however with caution (Zhang et al. 2020). Bottom ash from incinerated medical waste in Ghana may contain high heavy metal concentrations above WHO permissible levels for soil (Debrah & Dinis 2023). Ongoing studies aim to optimize the incineration process through heat recovery and alternative safe uses of the bottom ash (Adazabra et al. 2023). With increased optimization, incineration may contribute to resource recovery rather than a disposal pathway.

Figure 5. The modified De-Montfort type incinerator [50].

1.3. GOAL AND OBJECTIVES OF THE STUDY

A high waste (material) diversion rate from landfill has been used by decision makers as an important performance indicator and a success benchmark of waste management systems. Zaman & Lehmann (2013) for instance proposes a broader performance indicator, the Zero Waste Index (ZWI), which assesses materials, energy, water and emissions. One limitation of the ZWI is the overreliance on quantification and environmental assessment of flows and stocks within the system, leaving out other key indicators such as economic sustainability and social acceptability (Vlachokostas et al. 2020). Developing countries are especially lagging in research on economic assessment of waste management systems based on a review of 568 articles in the Web of science database (Medina-Mijangos and Segui-Amortegui 2020). This is especially critical in Ghana, a developing country where government financing into waste management is insufficient and heavily relies on external financing from development partners and the private sector (Agyapong & Tweneboah 2023). In addition, although zero waste is generally well represented in waste management studies, there is also an identified gap in independent research regarding institutional zero waste initiatives. Notably, most available data is self-published on websites rather than objective research publications (Rodríguez-Guerreiro et al. 2024).

The goal of this study is therefore to investigate the material flows and economic viability of the pilot zero-waste disposal to landfill (ZeWaD) system in Ghana. Although previous studies by the authors analysed individual components, this study extends the earlier works into an integrated system. The main target is to attain economic sustainability whiles achieving material recovery rates of at least 78% and 100% diversion from landfill based on global examples from San Francisco, Kamikatsu and Ljubljana. Typically, such systems have long term targets of achieving near zero or absolute zero waste disposal. With continuous optimization, ZeWaD can potential near zero waste levels. The following objectives are outlined:

1. To conduct a material flows analysis of pilot ZeWaD system based on the technological configuration of the case study system;
2. To conduct a comparative economic analysis of the pre-ZeWaD (baseline) and ZeWaD systems;
3. To recommend a general framework for future research and subsequent replication hypothesis or research question.

2. METHODOLOGY

The methodology was designed following similar economic studies on waste management systems with configurations similar to ZeWaD (Esfilar et al. 2020 and Mabalane et al. 2021). Firstly, a technical assessment of the system is conducted to compute the material flows. The economic assessment follows with an assessment of costs and benefits. The study follows two major steps: (1) material flow analysis (MFA) and (2) Economic assessment. Each of these steps are discussed in detail in the following sections.

2.1. MONITOTING AND DATA COLLECTION

The flows shown in Figure 1 forms the basis for the MFA. The monitoring and data collection for this study covered a 12-month period from November 2023 to October 2024. Based on the system boundary, the flows, stocks of waste materials entering and existing the system are quantified. Mass measurements were done manually using weighing scales. For fluids (biogas, liquid waste and digestate) flow meters are used. A direct onsite manual data logging is used for record keeping. Organic waste and residuals were input daily (on working days) using calibrated weighing scales and logs were taken immediately after each loading. The anerobic digestion process on the other hand is slow. Digestate volumes were measured once every month during lifting into overhead tanks. Biogas yield, digestor temperature and pH were continuously monitored twice each day for process stability. Incineration temperature was measured once a week. Bottom ash samples from each incineration batch were analysed in the laboratory for heavy metals.

2.2. MATERIAL FLOW ANALYSIS (MFA)

MFA involves a comparison of inputs, stocks and outputs/sinks of processes within a system following the guide provided in Brunner & Rechberger (2016). Within the context of ZeWaD, the target for material outputs from the system to recycling is 78% whereas direct transfer of untreated waste to landfill is zero. The STAN software version 8 is used to compute the flows ensuring a balance within the system (Cencic & Rechberger 2008). This was then transferred to the SankeyMATIC online software which provides visualization of MFA and automatically balances flows to ensure calculation errors are detected.

Several sources of uncertainty were considered, including variability in waste composition, manual measurement error, seasonal variations and equipment measurements. The annual monitoring duration captures both high and low occupancy levels and consequent fluctuations in waste generation and composition. Seasonal variations such as rainy days did not significantly affect any of the processes. Calibration was done periodically at CSIR-IIR ISO certified metrology lab.

2.3. ECONOMIC ANALYSIS

The most common methodologies for carrying out economic assessments within the waste management field are Life cycle costing and Cost Benefit Analysis (CBA) (Medina-Mijangos and Segui-Amortegui 2020). This study uses the CBA method following Ayeleru et al. (2021), Murphy et al. (2004) and Reza et al. (2013). A comparative economic assessment was conducted based on the 2024 values. The currency used was the USD ($) at an exchange rate of GHC14.18 to USD1.00 which is the annual average exchange rate for 2024 from the Bank of Ghana (B.O.G, 2024). The details of the key parameters, the cost components and supporting references are shown in Table 2. The costs were obtained from the financial records of the institute whiles and revenues were logged over the 12 months monitoring period.

Table 2. Details of parameters used in the economic analysis.

Parameter	Breakdown	Cost components	References
Capital cost	Segregation + AD + Recycling + Incinerator + plumbing works	Direct investment cost. Includes design, labour, materials, construction and operationalization	Mohammed et al. 2017
Operational & Maintenance cost (O&M)	Labour + replaced parts	Labour, Scheduled and unscheduled maintenance, replacement of worn-out parts. No taxes, direct insurance, fuel costs, disposal costs	Hadidi & Omer 2017
Direct income/ revenue streams (ZeWaD)	Selling price recyclables	On site storage for collection	Kessman 2019
	External waste incineration	Waste from external firms for incineration	
Direct Income (Pre-ZeWaD)	None	No income	
Savings (ZeWaD - Pre-ZeWaD)	Waste collection	Replaces payment of municipal collection fees	Ayodele et al. 2018 and Mohammed et al. 2017
	Waste water dislodging	Replaces payment of black water dislodging	
	Biogas	Replaces cost of LPG previously used energy in the laboratories	
	Recyclables for research	Replaces cost of purchase of raw materials for research	

A financial model was developed within the MS EXCEL software using the discounted cash-flow approach over a 20-year project lifespan. All costs and benefits were evaluated in nominal terms. The initial capital investment (CAPEX) was assumed to occur in year 0, while annual benefits and operating and maintenance (O&M) costs were assumed to occur from year 1 onward (Mabalane et al. 2021). Both benefits and O&M costs were escalated at 15.12% which represents the long-term historical average annual inflation rate (2004 - 2023) to reflect expected price evolution over the project lifetime (Armoo et al. 2024b). A nominal discount rate of 10% was applied to all future cash flows (Ayodele et al. 2018).

The total benefits are the sum of the direct revenues and savings from avoided costs compared to the pre-ZeWaD case. Annual net cash flow (NCF) in year t was calculated as the difference between Benefits and O&M costs. Net present value (NPV), IRR, ROI and PBP are calculated as (Mohammed et al. 2017):

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t} \tag{1}$$

where r is the nominal discount rate and n is the project lifetime in years.

The internal rate of return (IRR) was determined as the discount rate that satisfies:

$$0 = \sum_{t=0}^{n} \frac{NCF_t}{(1+IRR)^t} \tag{2}$$

where IRR represents the discount rate at which the net present value of the project equals zero.

The Return on investment (ROI) was calculated using discounted cash flows as:

$$ROI = \frac{\sum_{t=1}^{n} NCF_t}{CAPEX} \times 100 \tag{3}$$

The payback period (PBP) was estimated as the first year in which cumulative net cash flow becomes non-negative:

$$\sum_{k=0}^{t} NCF_k \geq 0 \tag{4}$$

where k represents each year from project initiation to year t.

To evaluate robustness under uncertainty, a sensitivity analysis was conducted by independently varying capital cost, annual benefits, operating and maintenance costs, and the inflation rate, while holding all other parameters constant. The sensitivity ranges were selected based observed variability and a comparison of the input parameters to other studies (Ayeleru et al. 2021; Hadidi & Omer 2016). For each sensitivity case, NPV, IRR, ROI, and payback period were recalculated using the same cash-flow structure as the base case.

3. RESULTS AND DISCUSSION

3.1. Material flow analysis (MFA)

Waste characterization showed a predominance of plastics (49.7%), organic (39.3%), paper (9.3%), and 0.62% other materials. However, recoverable fractions decreased substantially after disposal, particularly paper and plastics reduced to 31.8% and 5.3%, respectively, due to contamination from food residues and poor source segregation practices. Source segregation remains difficult in Ghana because of weak policy direction and limited local enforcement (Alhassan et al. 2020). Continuous user education and the introduction of additional bins for stained and unstained fractions could improve recovery quality. Overall, 37.72% of the segregated waste qualified as recyclables, although only 26.3% of plastics were recycled onsite, mainly for research purposes. Polystyrenes (PS) and polyethylenes (LDPE/HDPE) were processed internally, while PET and other recyclables were transferred for external recycling. Meanwhile, 100% of organics and liquid waste were directed to anaerobic digestion, generating 309 kg of biogas and 3.9 tons of digestate annually, both of which were reused onsite. The material flows are shown in Figure 6.

The resulting waste characteristics differs from national household averages of 61% organics, 14% plastics and 5% paper (Miezah et al. 2015). The lower organic fraction reflects the institutional setting, where domestic cooking is absent, while the higher plastic fraction is dominated by food packaging and the paper fraction reflects administrative activity. The 37.7% recovery rate significantly exceeds Ghana's national plastic recycling rate of 5%, highlighting the benefits of source segregation and quality-controlled recovery (Okai

2020). Continued education is expected to reduce the 21.93% rejected fraction further. Integration into external value chains is particularly important because informal waste actors remain central to urban waste management, collecting about 47% (720 tonnes/day) in Accra (Oduro-Appiah et al. 2019).

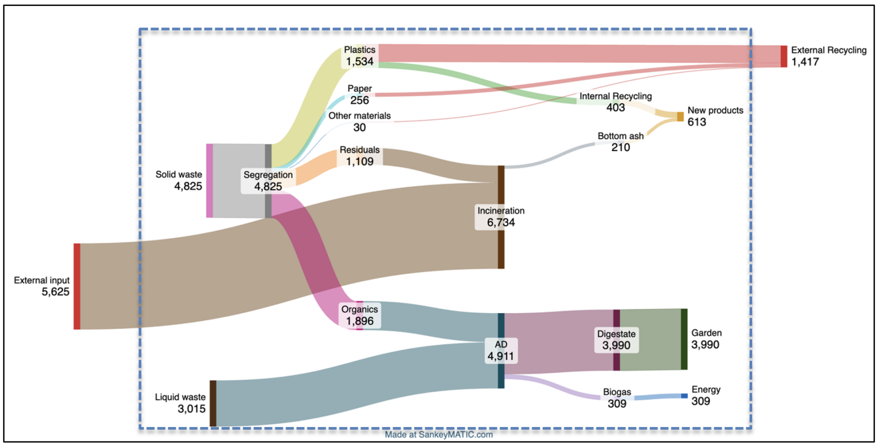

Figure 6. The material flows within the ZeWaD pilot system.

Following the generally accepted waste diversion from landfill benchmark, the ZeWaD system diverted 100% of waste from the landfill and 77.02% from both landfill and incineration (Zaman & Lehmann 2017). The diversion rates fall slightly short of the target but higher than institutional zero-waste examples from some U.S universities which achieved between 21-57% between 2012 and 2014 with higher long-term goals (Rodríguez-Guerreiro et al. 2024). Also, Canada recorded a national diversion rate of 48% between 2002 and 2018.

3.2. Economic Assessment of ZeWaD at the Case Study Site

3.2.1. Cost Benefit Analysis

The total recorded capital cost was $13,584, which is relatively low for the annual waste throughput because internal expertise was used; thereby significantly cutting the labour costs. The AD and incinerator systems constitute the highest technological investment (Figure 7b). Labour, materials, and parts replacement formed the major cost components of O&M. Total benefits on the other hand amounted to $4,100.5 over the 12 months monitoring period, comprising $2,778.5 in revenues and $1,322 in avoided costs. Compared to the baseline, the system is projected to save $82,010 over 20 years, excluding revenue escalation. Figure 7 presents the detailed comparative analysis.

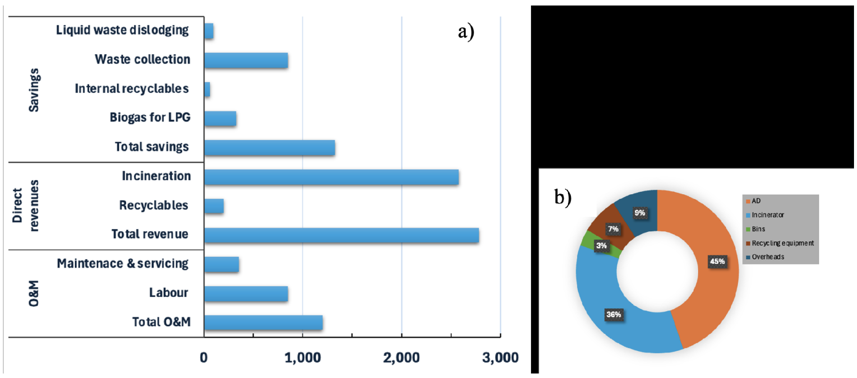

Figure 7. **(a)** The comparison of cost and benefit ($) and **(b)** relative contribution of sub-systems to capital cost.

Among the three technologies, incineration provided the highest economic return, whereas AD accounted for the highest share of capital cost. However, AD remains environmentally significant because landfill methane impacts from raw organics can be reduced by more than 50% (Bakkaloglu et al. 2022). Future improvements in heat recovery could further improve incineration economics. For example, waste incineration in Ghana has been projected to generate 400 MW from 14,000 tonnes/day, although tariff structures currently reduce profitability, as with AD and plastic pyrolysis systems (Armoo et al. 2024a; Yakah, 2024). Additional valorization of bottom ash in agriculture, ceramics, and wastewater treatment presents further opportunities (Bansal et al. 2024). The locally designed biodigester offers a flexible and cost-effective solution for institutions and households, consistent with successful co-digestion systems in Ghana (Agyenim et al. 2020). By reducing the volume requiring transport, the system supports local businesses and small-scale aggregators while creating jobs in external value chains (Lane et al. 2023). Revenues remain essential for long-term financial sustainability (Zaman 2022).

3.2.2. Feasibility Assessment

The financial assessment was conducted using the MFA and the financial parameters indicated in the methodology section. Table 3 shows the values for all parameters analysed. As compared to the capital cost, the NPV is positive, the IRR is far above the discount rate of 10% and the PBP is 5 years as compared to a project lifespan of 20 years. This shows a strong feasibility for replication. It must be noted that both revenues and costs were escalated at the 20-year historical average inflation rate of 15.12% which is higher than reported values from other countries. However, NPV results are positive with a short PBP.

Table 3. The financial indicators of feasibility of the installed ZeWaD system.

Metrics	**Indicators**
NPV	$6,9459.10
IRR	35.7%
ROI	2168.7%
PBP	4.68 years

The financial feasibility of the ZeWaD concept compares favorably with similar decentralized and hybrid systems reported in both African and global contexts. The internal rate of return (IRR) of 35.7% and discounted payback period of 4.68 years obtained in this study are stronger than the 16% IRR and 15.2-year payback period reported for a large-scale waste-to-energy plant at the Oti landfill in Kumasi, Ghana (Asante et al. 2023). The shorter payback in the present work is likely due to the modular integration of multiple resource recovery pathways—including composting, recycling, and ash valorization—which distribute revenue risks across several product streams rather than relying solely on electricity sales. Similarly, the strong feasibility aligns with the findings of Amponsem et al. (2023), who demonstrated that decentralized biogas-to-electricity recovery from municipal organic waste in Ghana is technically and economically viable. Compared with large thermochemical systems such as the hybrid anaerobic digestion–gasification configuration reported in South Africa by Mabalane et al. (2021), ZeWaD benefits from lower capital intensity and phased deployment, making it particularly suitable for institutional and district-scale applications. These comparisons suggest that ZeWaD's hybrid circular design improves financial resilience by combining material recovery, biological treatment, and future energy recovery potential within a single modular system.

Beyond the positive financial indicators, the feasibility of ZeWaD should also be interpreted within the global circular economy transition, where decentralized waste valorization systems are increasingly recognized as financially resilient alternatives to centralized disposal systems. The strong IRR of 35.7% and short payback period of 4.68 years compare favorably with similar zero-waste and circular resource recovery systems reported in higher education institutions and industrial pilots globally (Monte et al. 2009; Trushna et al. 2024 and Vea et al. 2018). This suggests that the ZeWaD model does not only perform well within the Ghanaian institutional context, but also aligns with international evidence that modular circular systems can achieve economic returns when supported by effective segregation and downstream value chains.

3.2.3. Sensitivity Analysis

A sensitivity assessment is carried out to compare the impact of NPV, IRR and PBP on four parameters: capital cost, O&M costs, Total benefits and Escalation rates (Figures 8 & 9). The increase in the Capital and

O&M costs has a negative effect on the NPV, IRR and PBP whiles the Total benefits and escalation rate have a positive effect. Figure 8 shows relatively limited sensitivity to capital and O&M cost escalation. This may be due to the simple modular configuration which was developed over a four-year period and the extensive use of internal expertise. Compared to the financing models for commercial systems, items such as taxes, debt interest rates, high labour costs are not included in the capital and O&M costs. This explains the wide sensitivity ranges which assumes a comparatively high capital and O&M when installed under different scenarios requiring the excluded parameter. It may also give an indication of the low and high investment scenarios (Hadidi et al. 2017). This confirms the deduction by Rodríguez-Guerreiro et al, 2024 that zero waste systems can be implemented at lower cost at higher education institutions (HEI). Although CSIR-IIR is not a HEI, its research activities and operations are similar to it.

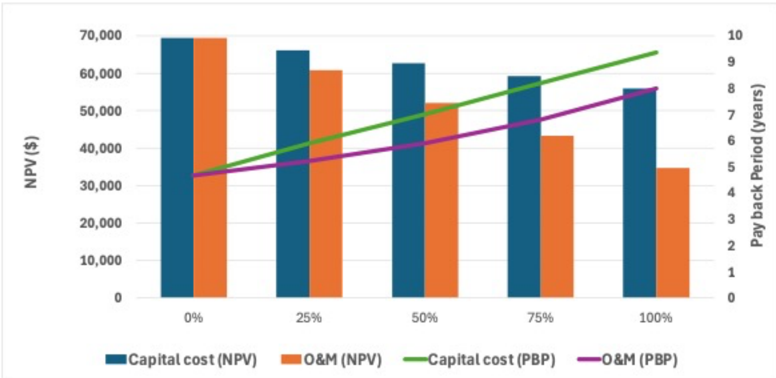

Figure 8. Sensitivity analysis for Capital cost and O&M considering the NPV and PBP.

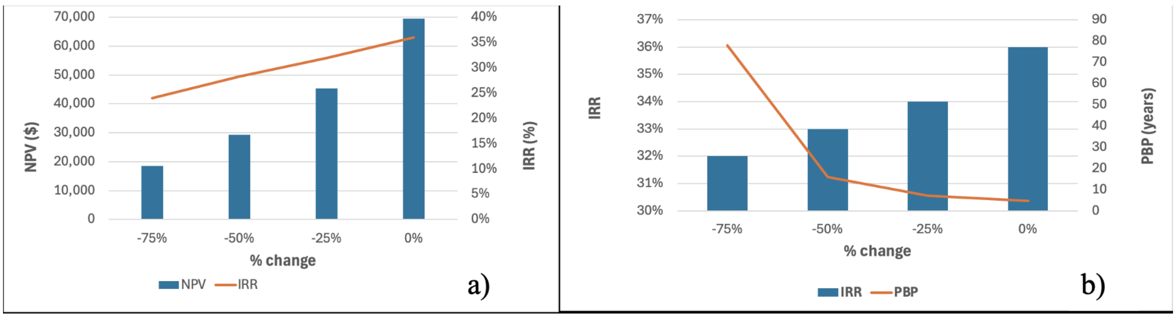

Figure 9. The sensitivity assessment for total benefits using **(a)** Escalation rate **(b)** NPV, IRR and PBP.

The sensitivity of the total benefits and its escalation rate in Figure 9 shows that total benefits exert the strongest positive influence on financial performance. Increases in revenues and avoided disposal costs substantially improve NPV and IRR while shortening the payback period. This indicates that the long-term economic sustainability of ZeWaD depends strongly on stable and diversified value chains for recyclables, and possible waste treatment services for external institutions. In global circular economy systems, economic viability is highly dependent on stable demand for compost, recyclable materials, and residual treatment (Makan et al. 2025). The strong sensitivity to benefits highlights the policy direction in to improve economic feasibility for institutional waste management systems— particularly focusing on the recycling industry, construction material users, and compost market.

3.3. Replication Concept and Scale-Up

Building on the ZeWaD concept in the introduction, ZeWaD describes a modular zero-waste to landfill system that combines source segregation, onsite treatment, material and energy recovery, and external circular value chains to support a broader circular economy (Figure 10). The configuration can also be adapted to include other technologies including biological (e.g composting), thermochemical (e.g gasification, pyrolysis), or chemical, depending on locally feasible end-products. The generally proposed technological configuration involves:

- Source segregation
- Biological treatment for organic waste,
- Recycling of metals, paper, glass or any other feasible materials,
- Incineration of end- of life materials.

This design reflects emerging CE strategies built on local treatment efficiency and industrial symbiosis, particularly relevant in African cities where SMEs and informal aggregators drive material circulation (Kessman 2019). From a global zero-waste city perspective, ZeWaD can function as modular urban metabolism nodes (Lucertini & Musco 2020). In developing countries where large city or municipal scale waste management is a challenge, decentralized systems can support the attainment of large goals. However, effective policy and regulatory oversight are essential to manage risks associated with contaminants such as heavy metals and emerging contaminants. Preliminary studies and case studies are important to highlight the context specific issues and to validate the concept (Al-Ansary et al. 2025).

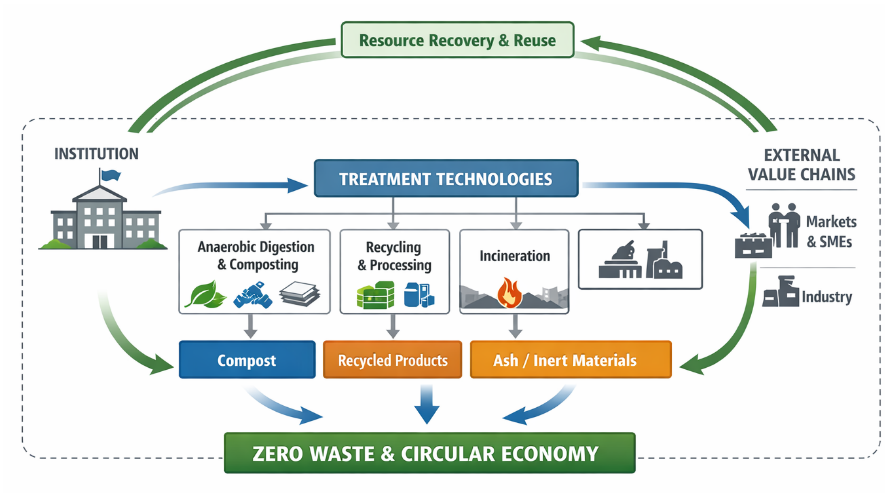

Figure 10. Conceptual ZeWaD framework illustrating how source segregation, modular treatment technologies, and integration of external value chains create cycles that achieve zero waste and circular economy outcomes.

For future implementation, a recommended process is presented in Figure 11. The process should begin with waste characterization, followed by source segregation design with strong education, technology selection and local construction, continuous piloting and optimization, and finally linkage of excess materials to external value chains.

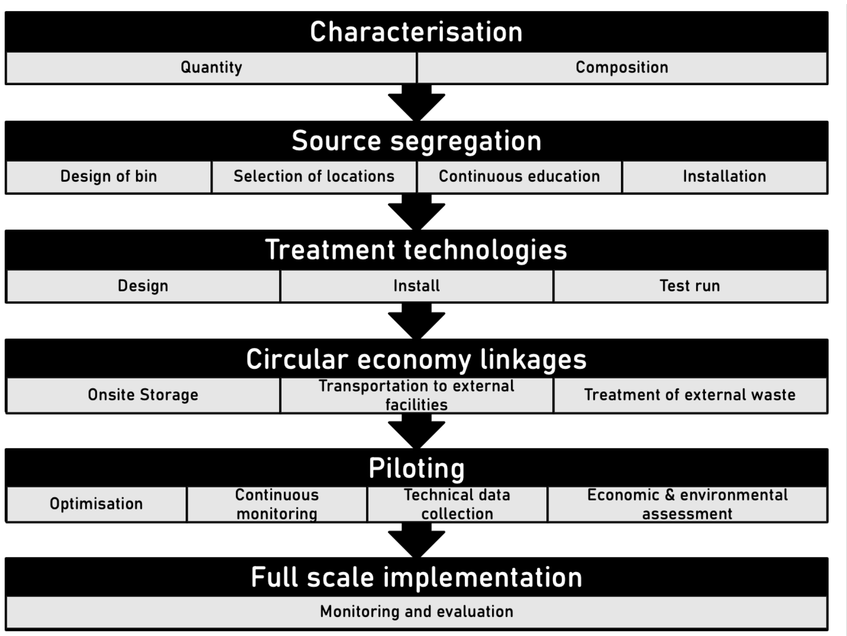

Figure 11. Process flow for the development of the ZeWaD case study system.

4. Conclusion and Recommendations

Despite its benefits, investment for large scale waste management systems remain a major barrier. Similar large-scale systems in Accra have highlighted the capital intensity of improved recovery systems (Armoo 2024c). Likewise, the incineration system requires improvements in terms of emission control and energy recovery which could increase investment costs (Yakah, 2024). However, ZeWaD's modularity offers a strategic advantage because technologies can be introduced progressively, beginning with the most economically attractive fractions.

Beyond landfill diversion, ZeWaD has the potential for reduce emissions from landfills and virgin material extraction. CE assessments indicate such systems may reduce projected waste emissions growth by 30–39% by 2050 (Ijimdiya 2026). These environmental and social dimensions must be incorporated before full scale implementation (Siddhika et al. 2025). Multicriteria decision-making studies are recommended to integrate technical efficiency with economic viability and environmental sustainability. Behavioural change across larger and more diverse populations remains another challenge. Continuous education, stakeholder engagement, adequate storage for recyclables, and policy reforms are required. Nevertheless, these challenges can be addressed through phased implementation, proper planning, and continuous optimization during piloting. Beyond this, strong policy and regulatory frameworks are needed for widespread implementation of such decentralized systems due to potential environmental pollution from poor onsite management of AD and incineration systems.

Acknowledgement

The authors would like to thank the Management of CSIR - Institute of Industrial Research (CSIR-IIR) particularly the Director for initiating the ZeWAD concept. The authors would also like to thank the government of Ghana for financially supporting this work.

AUTHOR CONTRIBUTIONS

Francis Boateng Agyenim: Conceptualisation: Developed the overarching themes and objectives of the study Methodology, Designed the methodological framework and criteria for literature selection. Writing: Wrote the initial manuscript outline, required data and key sections. Quality control: ensured analysis and results were consistent. Supervision – Supervised the study. **Ekua Afrakoma Armoo:** Methodology: Designed broad framework. Analysis and curation of data: Conducted MFA and economic assessment. Writing: review and editing for coherence and consistency. **Latifatu Mohammed:** Literature Review: Conducted a comprehensive search and analysis of relevant literature. Writing – Review & Editing: Contributed to the revision of the manuscript, focusing on clarity and coherence. **Boniface Yeboah Antwi:** (Lead: Segregation and Recycling studies): Coordinated the design, construction, operation and data collection. Writing: Prepared first draft and conducted a review and editing. **Mutala Mohammed:** Data Curation: Organized and synthesised data from selected studies for inclusion in the review. **William Oduro:** (Incineration system): Coordinated the design, construction, operation and data collection and analysis: Writing – Review & Editing: Assisted in editing and refining the final manuscript, ensuring accuracy and completeness. **Elizabeth Von-Kiti:** (Incineration system): Coordinated the design, construction, operation and data collection and analysis: Writing – Review & Editing: Assisted in editing and refining the final manuscript, ensuring accuracy and completeness. **Kofi Ampomah Benefo:** (Lead: Anaerobic digestion system.): Coordinated the design, construction, operation and data collection. Writing – Review & Editing: contributed to the write up, ensuring accurate information. **Raphael Nsiah -Gyambibi:** Writing – Review & Editing: Assisted in editing and refining the final manuscript, ensuring accuracy and completeness. **Japhet Otchere Gyamfi:** Images and data visualisation. **Kevin Oteng-Yeboah:** Analysis and curation of data to ensure consistency in the representation and discussion of results. All authors have read and approved the final version of the manuscript.

COMPETING INTERESTS

Authors declare no competing interests

AVAILABILITY OF DATA

The data for the study were collected directly from institutional operation of the system over the study period. Further analysis was conducted based directly on the collected data which is available from the institute.

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