Addis Ababa University

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Waste for Value: Designing Small-Scale Energy Recovery Centers for Apartment Dwellers in Addis Ababa.

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Addis Ababa, Ethiopia

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This Thesis is submitted to the school of graduate studies in partial fulfillment of the requirement for the degree of master of science in Infrastructure and Technology Management

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This is to certify that the thesis prepared by Yasmin Teleha: Waste for Value: Designing Small-Scale Energy Recovery Centers for Apartment Dwellers in Addis Ababa, submitted in partial fulfillment of the requirement for the degree of master of science in Infrastructure and Technology Management complies with the regulations of the university and meets the accepted standards for originality and quality.

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DECLARATION

I, Yasmin Teleha, registration number GSR 0585/16 do here by declare that this thesis is my original work and that it has not been submitted partially or in full by any other person for an award of a degree in other universities.

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This thesis has been submitted for examination with my approval as university supervisor.

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Note on AI Usage: I responsibly utilized artificial intelligence tools to assist my tasks such as grammar refinement and language enhancement ensuring that all content reflects my original ideas and adheres to academic integrity standards.

ABSTRACT

This research investigates the feasibility and transformative potential of small-scale waste-to-energy (WtE) systems in Addis Ababa's apartment complexes to address escalating solid waste management challenges and foster sustainable urban development. The study aimed to design community-driven WtE solutions that minimize landfill dependency and produce renewable energy. Employing a mixed-methods approach, the study integrated quantitative waste characterization, resident surveys, technical assessments, and qualitative stakeholder interviews across three apartment complexes of varying sizes in diverse neighborhoods. The research quantified waste generation patterns, revealing substantial organic waste suitable for WtE conversion, and evaluated technologies, identifying anaerobic digestion (AD) as the most viable due to its compatibility with high-moisture organic waste, low emissions and compact design suitable for urban constraints. Technical assessments confirmed AD's feasibility, particularly in medium complexes, where sufficient basement space and garbage chute availability facilitate integration, producing energy for communal lighting or cooking. Socially, strong resident willingness to sort waste, motivated by incentives like energy credits, supports adoption, though challenges such as social stigma around waste handling and irregular collection require targeted interventions like resident committees and awareness campaigns. Economically, AD systems are viable with initial costs offset by potential savings and subsidies, aligning with global models like Bangalore's residential AD success. The study proposes AD pilots in medium complexes to reduce landfill pressure, enhance energy reliability amidst frequent outages, and position Addis Ababa as a model for contributing to urban resilience and sustainable development goals.

Keywords: waste-to-energy, anaerobic digestion, solid waste management, apartment complexes

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List of Acronyms

AD	Anaerobic Digestion
BAT	Best Available Techniques
CO_2	Carbon Dioxide
EC	European Commission
ETB	Ethiopian Birr
IEA	International Energy Agency
MSW	Municipal Solid Waste
NGO	Non-Governmental Organization
PCDD	Polychlorinated Dibenzodioxins
PCDF	Polychlorinated Dibenzofurans
SD	Standard Deviation
SWM	Solid Waste Management
SWMS	Solid Waste Management Systems
TPB	Theory of Planned Behavior
UNEP	United Nations Environment Programme
WtE	Waste-to-Energy

Chapter 1: INTRODUCTION

1.1. Background of the study

Addis Ababa faces significant waste management challenges due to rapid urbanization and population growth, generating nearly 2,500 tons of solid waste daily, with only 65% collected through formal systems (Addis Ababa City Administration, 2021). To address waste generation and promote sustainable urban waste management, several mechanisms have been implemented source segregation initiatives to promote sustainable waste management and Community-based awareness campaigns educate households, which produce 76% of waste, on separating organic and inorganic waste to enhance composting and recycling, though only 21.3% frequently segregate due to limited facilities and stigma (Humanities and Social Sciences Communications, 2023). In high-density apartment complexes, these issues are exacerbated by insufficient space and inadequate infrastructure, leading to overflowing communal bins and unauthorized dumping (Tadesse et al., 2021). Apartment-specific waste management in Addis Ababa relies on door-to-door collection services, public containers, and limited on-site communal bins, but space constraints restrict storage and composting options, resulting in unhygienic conditions (Cheru, 2016) Based on my observation, apartments are increasingly incorporating garbage chutes as a practical waste management solution, especially in high-rise and mid-rise buildings. These systems enable residents to dispose of their trash conveniently by dropping it into a chute on their floor, which efficiently transports the waste to a centralized collection point. Only 40% of apartment residents sort their waste, hindered by limited recycling facilities and awareness campaigns, while inconsistent collection schedules contribute to bin overflows and improper disposal (Gebremariam & Assefa, 2022). Standard solutions designed for single-family homes with private backyards are inadequate for apartments, where residents lack space for waste segregation or composting, missing opportunities for sustainable practices (Hirpe & Yeom, 2021). Globally, apartment waste management systems offer valuable insights: for example, Singapore’s high-rise estates use pneumatic waste collection systems to transport waste via underground pipes to centralized facilities, reducing overflow and improving hygiene (Tan & Neo, 2019). Similarly, Sweden’s apartment complexes integrate automated sorting systems and on-site composting units, achieving recycling rates above 50% (Andersson & Nilsson, 2020). Organic waste is most likely the biggest opportunity and challenge, comprising 60-70% of Addis Ababa’s municipal waste stream, presents a key opportunity for sustainable solutions like anaerobic digestion or composting, yet 85% of collected waste is sent to the overburdened Koshe landfill, with the remainder processed at the Reppie waste-to-energy facility (Federal Democratic Republic of Ethiopia, 2019). The Koshe landfill, which suffered a deadly 2017 collapse, underscores the need for alternatives (Amnesty International, 2018). Small-scale waste-to-energy (WtE) technologies, such as anaerobic digesters or modular gasification units, could treat organic waste on-site in apartment complexes to produce biogas or electricity, but adoption is limited by low public awareness, spatial constraints, and insufficient policy support from the Ministry of Urban Development and Housing (MoUDH), Environment Protection Authority, and Ministry of Health (MoH) (GIZ, 2023).

This study specifically examines the feasibility of waste exchange and energy recovery centers integrated for apartment buildings. These centers integrate small-scale WtE systems to produce comprehensive solutions that facilitate resource conservation, reduce landfill waste, and produce renewable energy. The study develops functional models that bridge the technical, as well as the social aspect of sustainable waste management in dense environment.

1.2. Problem Statement

Due to high population growth and increasing numbers of apartment buildings in Addis Ababa have exacerbated solid waste management issues generating significant environmental, public health, and energy-related implications. Inefficiencies in collection systems, inadequate infrastructure, and low public awareness lead to severe waste accumulation in apartment complexes (Addis Ababa City Administration, 2021). Inconsistent waste collection, often limited to once or twice weekly, causes communal bins to overflow, particularly in apartment complexes where spatial constraints restrict storage capacity (Cheru, 2016). This prompts residents to resort to unauthorized dumping in open spaces, drainage systems, or rivers, resulting in leachate contamination that pollutes soil and groundwater, waste clogs drainage systems, leading to flooding during rainy seasons, threatening agricultural productivity and potable water sources (Mengistu et al., 2021). The high organic content (70%) of uncollected waste decomposes anaerobically, releasing methane, a greenhouse gas 25 times more potent than CO_2, exacerbating climate change and contradicting Ethiopia's commitments to the Paris Agreement (Hirpe & Yeom, 2021). Furthermore, open burning of uncollected waste, a common response to bin overflows, releases toxic pollutants like dioxins and particulate matter, deteriorating air quality in densely populated areas (GIZ, 2023). Without intervention, these environmental impacts will intensify, compromising ecosystem health and urban livability. Frequent power outages, occurring 3-5 times per week in apartment buildings, disrupt daily life, underscoring the need for reliable, localized energy solutions (International Energy Agency, 2022). The lack of innovative apartment-focused waste management strategies, such as waste-to-energy (WtE) systems, results in missed opportunities to reduce landfill dependency, generate renewable energy, and improve living conditions. For instance, unutilized organic waste, which could be converted into biogas via anaerobic digestion, represents a lost resource for addressing both waste and energy challenges. Globally, advanced systems like South Korea's automated waste sorting in high-rise apartments, which achieves over 60% recycling rates, and Germany's community-based composting initiatives in urban residences demonstrate effective models for managing waste in dense settings (Schmidt & Wagner, 2019). Without targeted interventions, the ongoing inefficiencies in waste management will continue to degrade public health, pollute the environment, and hinder sustainable urban development in Addis Ababa. This study proposes an implementation strategy that integrates WtE technologies with robust community engagement to address these multifaceted challenges, tailoring solutions to the unique spatial and social dynamics of apartment complexes while drawing on global best practices to foster sustainable waste management and energy reliability.

1.3. Research Objective

1.3.1. General Objective

The general objective of this study is to examines the environmental, technical and Spatial feasibility of small-scale waste-to-energy technologies in Addis Ababa apartment buildings as a sustainable option for Solid waste management system.

1.3.2. Specific Objective

- To evaluate the effectiveness of current Solid waste Management systems.
- To assess the viability of different waste-to-energy technologies for small-scale use in apartment building.
- To propose a prototype design that allocates space within apartment buildings for integrating small-scale waste-to-energy technology.

1.4. Research Question

1. What are the primary challenges and opportunities for the implementation of small-scale waste-to-energy systems in apartment buildings in Addis Ababa?
2. Which waste-to-energy technologies are most suitable for small-scale applications in apartment buildings, considering energy output, environmental impact, and community acceptance?
3. How should waste-to-energy systems be architecturally integrated into apartment building space design to maximize benefits with a minimum disruption?

1.5. Significance of the Study

City of Addis Ababa: This research provides a model for integrating waste-to-energy (WtE) and waste exchange systems into apartment buildings, addressing the city's solid waste management challenges. By demonstrating the feasibility of organic WtE technologies within spatial constraints, it offers a scalable solution to reduce landfill dependency, mitigate environmental pollution, and enhance energy reliability in high-density residential areas.

Policymakers: The findings advocate for policy reforms to incorporate WtE technologies into apartment building permit processes, potentially mandating their inclusion as a requirement for approval.

Scientific Community: The study supports the integration of sustainability-focused waste management education into curricula, addressing gaps in public awareness and fostering long-term environmental stewardship. Additionally, it serves as a foundation for further studies on energy output, environmental impact, and compatibility with urban infrastructure, encouraging interdisciplinary collaboration in sustainable waste management.

1.6. Scope of the Study

1.6.1. Thematic Scope

This study Thematically focuses on organic waste-to-energy (WtE) technologies for apartment buildings in Addis Ababa, excluding other waste treatment processes like plastic, electronic, and hazardous waste recycling due to their lower decomposability and energy content. It examines the feasibility of these technologies by analyzing waste collection intervals, household participation, and waste separation mechanisms, evaluating their energy output, environmental impact, and compatibility with urban infrastructure.

1.6.2. Spatial Scope

Spatially, the study is confined to the limited space of apartment buildings, exploring how these technologies can be implemented within such constraints.

1.6.3. Temporal Scope

Temporally, it targets currently available technologies deployable within five years in apartment settings.

1.7. Limitations

Although the concept of waste to energy has been implemented in Addis Ababa, it is still relatively new concept, so it was challenging to obtain comprehensive information about this practice in Addis Ababa as well as in Ethiopia. To mitigate this, the study analyzed global small-scale waste-to-energy models and assess their applicability to Addis Ababa. Additionally, since these projects are usually large-scale worldwide, many case studies of small-scale initiatives inside apartment complexes were not found. However, this was addressed via pilot projects that produce results that are comparable.

Chapter 2: LITERATURE REVIEW

2.1. Introduction

The significance of this topic is that it promises to redefine living in the city of Addis Ababa by balancing solid waste management and energy requirements. It discusses how small-scale WtE technologies can be part of apartment complex addressing both opportunity such as resource recovery and community empowerment and challenges such as technological feasibility and social acceptability. the major parameters of implementation of such systems, providing grounds for the design of sustainable energy recovery and waste exchange facilities appropriate for apartment dwellers. It is structured as a review of theoretical considerations that present waste-to-energy in the context of a sustainable urban approach, an analysis of real-world evidence, and conceptual model development for implementation. The theory section addresses ideas like Systems thinking and Behavioral theories principles that justify WtE as a sustainable urban approach. The empirical review includes synopses of evidence on existing practices, technologically viable WtE practices, and residential case studies globally. Finally, the conceptual section proposes models for integrating WtE into apartment development and successful community engagement. Separately and together, these viewpoints attempt to respond to the research questions.

2.2. Theoretical Review

The major concepts and theory of solid waste management and WtE systems are explained in this chapter, tailored to the conditions of Addis Ababa as well as opportunities and challenges of apartment building. The theories offer a context which can be utilized to conceptualize energy recovery, waste management, and community participation as a model for sustainable solutions.

2.2.1. Concepts of Solid Waste

Solid waste refers to any non-liquid, non-gaseous material discarded by households, commercial establishments, institutions, or industries, encompassing a wide range of materials such as food scraps, paper, plastics, metals, glass, textiles, and construction debris (UNEP, 2017). Solid waste is typically categorized based on its source (municipal, industrial, agricultural) and composition (organic, recyclable, hazardous), with municipal solid waste (MSW) being the primary focus in urban settings like apartment complexes (Hirpe & Yeom, 2021). In the context of Addis Ababa, solid waste is predominantly organic waste, constituting mainly food residue in apartment buildings, accounts for over 60% of MSW in Addis Ababa

(Federal Democratic Republic of Ethiopia, 2019). Practice is currently disposal-situated due to large-scale unofficial dumping resulting from a lack of infrastructure (Kennedy et al.,2011). In apartment settings, energy recovery through WtE is applied in accordance with the waste hierarchy to utilize organic waste to generate energy instead of disposal focused.

2.2.2. Solid Waste Management Systems

Solid waste management systems (SWMS) are comprehensive frameworks designed to manage the collection, transportation, treatment, and disposal of solid waste from residential, commercial, and industrial sources, with the goal of minimizing environmental impact, promoting recycling and resource recovery, and safeguarding public health and safety (Hoornweg & Bhada-Tata, 2012). These systems are critical in addressing the growing challenges posed by urbanization and population density, particularly in cities where waste generation rates are increasing rapidly. SWMS encompass a range of activities, including the segregation of waste at the source, efficient transportation networks to move waste to processing facilities, and advanced treatment methods such as composting, recycling, or controlled disposal to mitigate pollution and resource depletion (UNEP, 2017). For instance, in urban settings like Addis Ababa, SWMS play a pivotal role in transforming waste into valuable resources, such as compost or energy, while reducing the burden on overburdened landfills (Regassa et al., 2011).

The effectiveness of SWMS relies on integrated approaches that combine technological innovation with community participation. Modern systems often incorporate infrastructure like garbage chutes in apartment buildings to streamline collection, enhancing convenience and hygiene for residents (Tan & Neo, 2019). Additionally, SWMS must address logistical challenges, such as the need for regular waste pickup and the management of hazardous materials, to prevent environmental hazards like groundwater contamination or air pollution from open burning. The World Bank emphasizes that well-designed SWMS can significantly lower greenhouse gas emissions by diverting organic waste from landfills, where it would otherwise decompose and release methane, a potent greenhouse gas (Hoornweg & Bhada-Tata, 2012). Furthermore, successful implementations demonstrate how tailored SWMS can adapt to local contexts, fostering sustainability and reducing waste management costs over time (Andersson & Nilsson, 2020).

2.2.3. Theories Supporting Waste-to-Energy (WtE) Systems

Systems Thinking

Systems Thinking approaches urban issues with a focus on incorporating elements such as waste management, energy production, and architectural design (Meadows, 2008). In the context for small-scale WtE in apartment buildings this theory would see the system as an inputs (waste), processes (conversion technologies), and outputs (energy, minimized waste). Positive feedback loops may increase efficiency, for example, AD biogas may power waste processing equipment in a closed-loop system as self-sustaining cycle (Hoornweg & Bhada-Tata, 2012). Negative loops, nevertheless, complexity of the system poses challenges: WTE implementation in apartment buildings entails balancing technical viability (e.g., space for digesters) and social dynamics (e.g., residents' collaboration) (Capra, 2015). This approach enables adaptive management, where performance data on waste inputs, energy outputs, and user engagement can be continually used to optimize operations and ensure system resilience.

Feedback mechanisms of WtE systems, like biogas fueling waste shredders to decrease manual labor by 20%, are not commonly applied within Addis Ababa because of infrastructural deficiencies (Beyene et al., 2018). In Addis Ababa, where there is irregular garbage collection and poor electricity supply, Systems Thinking highlights the necessity for WtE to integrate perfectly with the current infrastructure (IEA, 2022). Systems thinking emphasizes interdependencies among technology, policy, and user behavior, this systems approach is key to capturing the maximum benefits of WtE and reducing disruptions.

Behavioral Theories

The viability of small-scale WtE systems depends on the participation of residents, and so Behavioral Theories become an essential theoretical foundation. The Theory of Planned Behavior (TPB) formulated by Ajzen (1991) argues that people's behavior such as waste sorting or embracing WtE is motivated by attitudes, subjective norms, and perceived behavioral control.

In Addis Ababa, the social culture of waste management is a major inhibitor of resident participation in small scale WtE operations. (Tadesse et al., 2021) reports that 40% of residents consider waste management work to be low-status, deterring community-based sorting and recovery operations, TPB suggests that awareness campaigns can alter attitudes, and community leaders can establish norms for waste exchange (Cheru, 2016). For instance, if apartment dwellers see energy conservation as a practical benefit, their participation intention can be strengthened (Kollmuss & Agyeman, 2020). In order to overcome these challenges, targeted behavioral interventions are required, such as education and awareness campaigns, incentive schemes, and demonstration projects that present waste as not a problem, but more so a community asset.

The above theories highlight the multidimensionality of waste-to-energy system design. Systems thinking and behavioral theories provide micro-level implementation strategies, the theories inform the significant research questions by placing in context the integration opportunities and challenges of WtE in Addis Ababa apartment buildings.

2.2.4. Community Engagement Models

The success of WtE systems hinges on resident engagement, which requires conceptual platforms that foster public acceptance. Drawing on participatory design and social innovation theories, two models emerge: waste exchange systems and co-management systems (Hegger et al., 2017). In Addis Ababa, where there is a lack of awareness on sustainable waste management, these models attempt to reconcile technical solutions with social dynamics (Cheru, 2016).

The model of waste exchange provides that citizens sort organic and recyclable waste, loading it into their respective chutes or bins against energy credits such as biogas for use in cooking or electricity to be used in public areas. A study conducted in Nairobi proved that incentives enhanced the sorting rate by 60%, with the residents exchanging 1 kg of waste against 0.5 kWh of electricity (Mwangi et al., 2022). Education programs rooted in the Theory of Planned Behavior would be supporting attitudes about sorting, whereas leaders in society may establish a system of participation (Ajzen, 1991).

The co-management approach envisions residents and building managers as collaborating to operate WtE systems. For example, there can be shared responsibility of waste input and maintenance by a tenant committee with shared benefits of cheaper utility bills. In Swedish ecovillages, it assisted in enhanced efficiency of the system by 30% due to shared responsibility (Andersson & Nilsson, 2020). At Addis Ababa, live heritage of shared living remains, and co-management may build on social harmony, although opposition from culture must be tackled wisely (Tadesse et al., 2021). Both models focus on participation as a driver for sustainability, in accordance with the "Waste for Value" philosophy.

2.3. Empirical Review

Empirical evidence for the use of small-scale waste-to-energy (WtE) plants in apartment buildings in Addis Ababa, technological operation evidence, and case study evidence worldwide. This section identifies appropriate WtE technology for small-scale application, and discusses real-world examples of WtE. By consolidating information on energy generation, environmental effect, and public acceptance, this review discusses the feasibility and issues of incorporating WtE in apartment complex in Addis Ababa context.

2.3.1. Waste-to-Energy Technologies (WtE)

Waste-to-Energy (WtE) technologies consist of any waste treatment process that creates energy in the form of electricity, heat and fuels from several types of waste: from the semi-solid (e.g, thickened sludge from effluent treatment plants) to liquid (e.g, domestic sewage) waste (Hoornweg & Bhada-Tata, 2012). There are two main recovery or conversion processes of WTE technologies (i.e., biochemical and thermochemical) depending on the waste composition and moisture content (GIZ, 2023). Different technologies require appropriate waste components with certain characteristics to serve as suitable feedstock for their optimal performance (Maisarah et al., 2018).

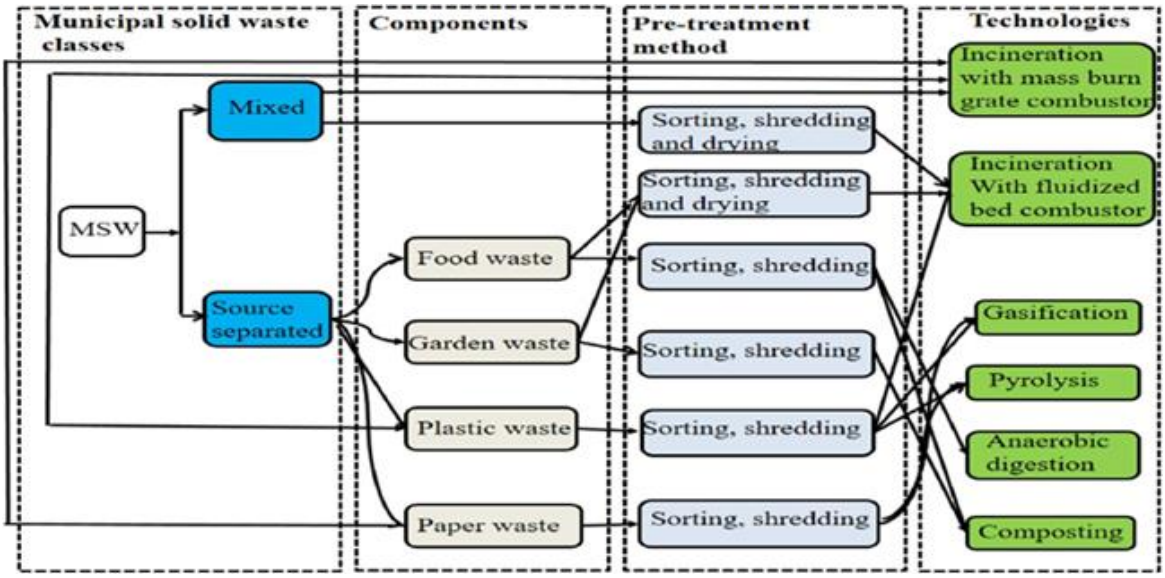

Figure 2.1 Mapping of feedstocks with suitable waste-to-energy technologies (Maisarah et al., 2018).

A. Thermochemical conversion process

Thermochemical process involves decomposition of carbonaceous organic matter under high temperature to produce heat energy, fuel oil or gas and other value-added product such as charcoal (Hoornweg & Bhada-Tata, 2012). The main technological options under this category include incineration, pyrolysis and gasification. Thermochemical process is useful for less dense wastes and low moisture content (Rajaeifar et al., 2017).

B. Biochemical conversion process

The biochemical conversion process involves decomposition of biodegradable organic components of the waste under the influence of bacterial. The microbial action can take place either in the presence or absence of oxidant (oxygen) leading to the production of different products (compost or biogas) (Hirpe, & Yeom, 2021). The biochemical conversion processes are preferred for wastes that have high percentage of bio-degradable organic matter and high level of moisture/water content, which aids microbial activity (UNEP, 2017). The main technological pathways for biochemical process are anaerobic digestion, composting and landfilling each leveraging natural biological process to transform waste into usable resources (Hoornweg & Bhada-Tata, 2012).

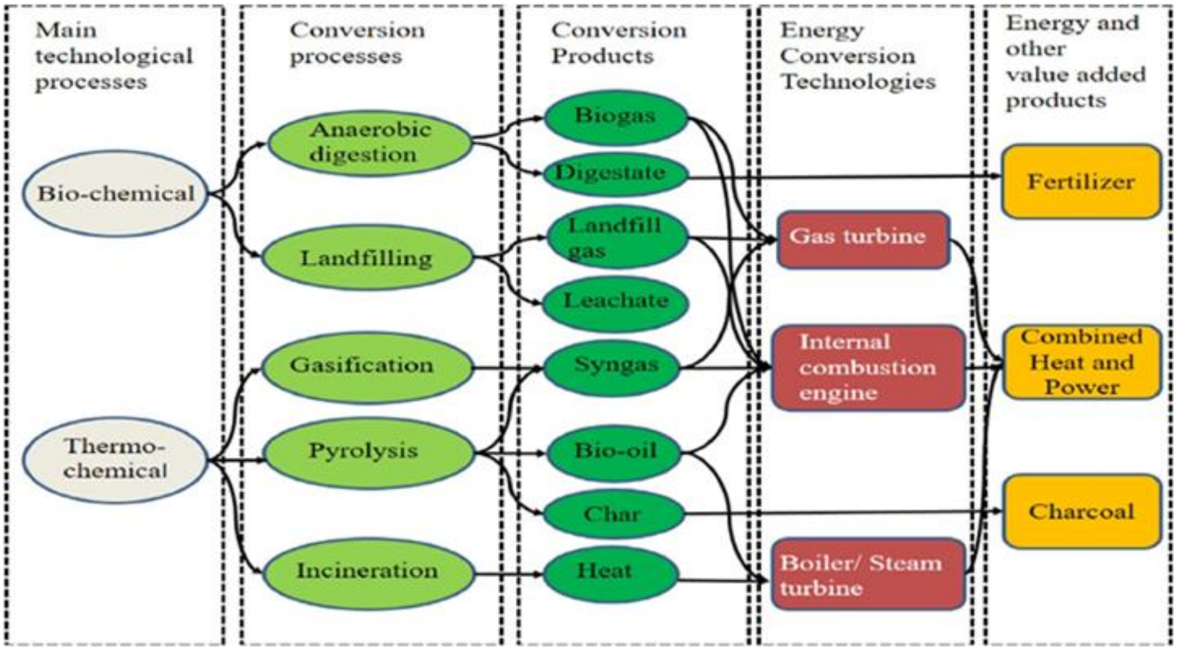

Figure 2.2. waste-to-energy conversion routes/technologies (Ogunjuyigbe et al., 2017).

2.3.2. Small-Scale Waste-to-Energy Technologies

Several WtE technologies have been tested globally for small-scale applications, offering insights into their suitability for apartment buildings in Addis Ababa. Three options stand out based on energy output, environmental impact, and feasibility in urban settings: anaerobic digestion (AD), small-scale incineration, and gasification.

A. Anaerobic Digestion (AD)

Anaerobic digestion breaks down organic wastes in oxygen-free conditions to yield biogas (methane-rich) and digestate (fertilizer by-product). AD is especially promising with Addis Ababa's waste stream, where the organic content is high. Experiments in urban India demonstrate that small-scale AD units (capacity 1-5 tons/day) can yield 50-100 kWh of electricity per ton of waste or biogas sufficient for cooking in 20-30 households (Kumar & Samadder, 2020). Environmentally, AD is low-emitting, but methane leaks must be managed (IPCC, 2021). Its compact footprint suits apartment building basements or rooftops, but disadvantages include high capital costs (around $5,000-$10,000 for small-scale units) and the requirement of ongoing organic input, which requires resident sorting (Beyene et al., 2018). AD's ability to function during power outages suits the city's unreliable electricity grid (IRENA, 2019).

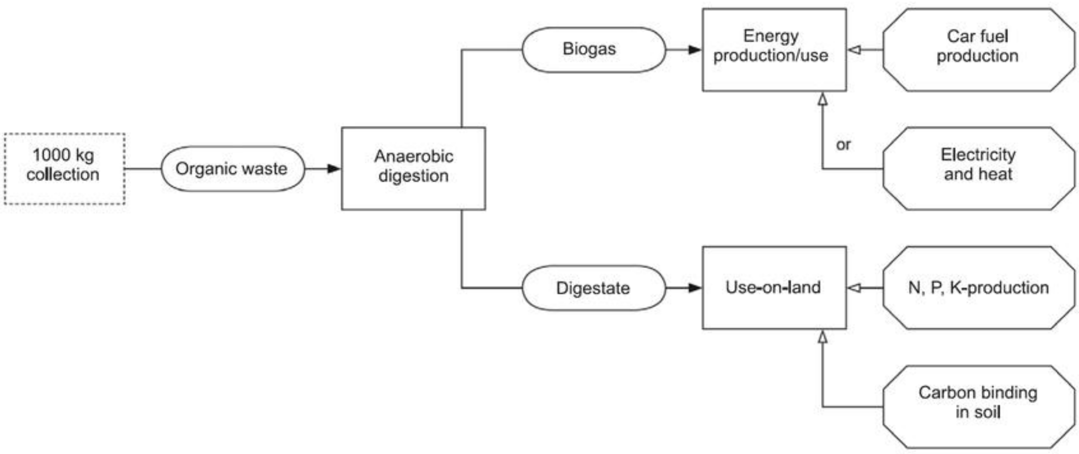

Figure 2.3. Conceptual overview of anaerobic digestion

B. Small-Scale Incineration

Incineration burns mixed waste to produce heat or electricity and is flexible for apartment buildings with diverse wastes. Research from urban contexts is promising since small-scale facilities processing 2-3 tons of waste per day can produce 200-300 kWh of electricity sufficient to power communal facilities like lights or elevators in apartments (Hoornweg & Bhada-Tata, 2012). But incineration has one environmental impact: without sophisticated filtration systems, it releases toxins like dioxins, with health and environmental implications (GIZ, 2019). Small-scale incinerators cost between $15,000 to $20,000, and the added cost of operating emission controls is factored into the cost burden, which, in resource-constrained environments, represents a heavy burden (Hoornweg & Bhada-Tata, 2012). In Addis Ababa, where maintenance technical expertise is scarce, operational issues can undermine effectiveness, though incineration’s ability to handle unsorted waste aligns with current resident habits (Regassa et al., 2011). Although it can be scaled for apartment utilization, its uptake is moderated by environmental effects and logistical considerations, as with the case of the Reppie plant's inability to deploy at large scale (UNEP, 2017).

C. Gasification

Gasification transforms waste into syngas a combination of hydrogen and carbon monoxide through high-heat processing with greater energy efficiency compared to incineration as it yields a flexible fuel gas (Hoornweg & Bhada-Tata, 2012). East African experience has determined that 1-2 tons per day small-scale gasifiers can produce 150-250 kWh per ton of waste, with less emission due to the fact that combustion conditions are managed to limit pollutants (GIZ, 2019). For example, a project in Dar es Salaam showcased a gasifier fueling water pumps for a block of residential flats, with 70% less waste, showing its potential as an application for residential estates in urban areas (UNEP, 2017). Gasification in Addis Ababa can be used to treat mixed waste efficiently, taking advantage of the city's heterogeneous waste stream, although its expense, $20,000 to $30,000 for small plants, and requirement for skilled operators are major challenges (Hoornweg & Bhada-Tata, 2012). Environmentally, gasification has fewer particulates produced compared to incineration, a benefit to air quality management, although its optimization for high-moisture organic waste widespread in Addis Ababa should be improved (Hirpe, & Yeom, 2021). There are also compact gasification principles for apartment buildings, yet space demands and expense constraints continue to be chief barriers to widespread uptake (GIZ, 2019).

Table 2.1. comparison between Small-Scale Waste-to-Energy Technologies (Hoornweg & Bhada-Tata, 2012)

Aspect	Anaerobic Digestion (AD)	Small-Scale Incineration	Gasification
Process	Breaks down organic waste without oxygen, creating biogas and fertilizer.	Burns mixed waste to produce heat or power.	Heats waste to form syngas (gas mixture) efficiently.
Energy Yield	50-100 kWh/ton, ideal for cooking or small lighting.	200-300 kWh/ton, powers shared building features.	150-250 kWh/ton, runs pumps or moderate loads.
Waste Reduction	Cuts waste by ~80%, effective for organics.	Reduces waste by ~85%, handles all types.	Shrinks waste by ~70%, versatile but less with wet.
Eco Impact	Low emissions, minor methane risk	High pollution (e.g., dioxins) without filters.	Cleaner than incineration, fewer particulates.
Cost (Initial)	$5,000-$10,000, budget-friendly startup.	$15,000-$20,000, pricier with extra control costs.	$20,000-$30,000, most expensive upfront.
Space Fit	Compact, fits basements or rooftops easily.	Bulkier, manageable in urban setups.	Small units possible, but space is tight.
Key Challenge	Relies on sorted organic waste from residents.	Tough to maintain with limited local know-how.	High cost and skill demand limit use.
Local Edge	Steady energy during blackouts.	Matches unsorted waste habits.	Efficient power with less pollution.
Scalability	Easy for small buildings, proven in pilots.	Hindered by cost and eco concerns.	Promising but held back by funding and tech needs.

Anaerobic digestion (AD) is the most suitable waste-to-energy technology for Addis Ababa’s apartment complexes, given the 60-70% organic waste stream (Federal Democratic Republic of Ethiopia, 2019). AD processes high-moisture organic waste into biogas and digestate, fitting compact apartment spaces and operating during power outages with low emissions (Kumar & Samadder, 2020). Incineration, generating 200–300 kWh/ton, risks dioxin emissions and high costs ($15,000–$20,000), while gasification, producing 150–250 kWh/ton, is less effective for organic waste and costlier ($20,000–$30,000) with technical demands (Hoornweg & Bhada-Tata, 2012). AD’s lower cost ($5,000–$10,000) and alignment with waste composition make it ideal for sustainable waste management and energy resilience.

2.3.3. Case Studies of Residential WTE Implementation

Global examples provide empirical lessons for Addis Ababa. In Bangalore, India, a 50-unit apartment complex installed a 1-ton/day AD system in 2019, reducing organic waste by 85% and generating 60 kWh daily for lighting and elevators (Sharma & Jain, 2021). Residents sorted waste after training, and a cooperative model shared maintenance cost. Environmental impact was minimal, with biogas replacing LPG for some households, cutting emissions by 20 tons of CO_2 annually (Kumar & Samadder, 2020).

A Nairobi, Kenya case integrated AD and waste exchange: tenants traded sorted organic waste for biogas credits, powering cooking stoves in 30 units (Mwangi et al., 2022). Waste volume dropped 75%, and resident buy-in increased with incentives, though initial funding came from NGOs, highlighting scalability issues (UN-Habitat, 2020). These cases suggest AD's fit for Addis Ababa's organic waste, while incineration and gasification require more investment and oversight.

Belleville saw great success with a first-of-its-kind pilot initiative that promoted food waste diversion in apartment buildings. Beginning in 2020, carried out in partnership with Thurlow Housing and Food Cycle Science has begun collaborating with local governments and installing Food Cyclers in single-family residences. A countertop kitchen appliance called the Food Cycler turns organic materials into soil (Food Cycle Science, 2024).

Belleville's Green Task Force Committee decided to pilot the Food Cycler program in one apartment building. The pilot ran from January to April 2024, with residents in 13 apartment units tracking their weekly usage of the Food Cycler (Quinte News, 2024). At the end of the 12-week pilot, residents completed an exit survey, providing usage data and feedback. Each apartment unit is estimated to divert 771.6 lbs. (350kg) per year (Food Cycle Science, 2024). Based on the data from this pilot program, if Food Cyclers were deployed in each of the 9,000 apartment units in the city, approximately 3.1 million kg (3,100 metric tons) of food waste would be diverted from the landfill annually. This is equal to 4,650 metric tons of CO_2 equivalents annually, the same impact as taking 1,100 gas-powered cars off the road every year (Food Cycle science,2024). The success of this pilot program demonstrates the viability of the Food Cycler Municipal Program in the multi-residential setting (Quinte News, 2024).

2.3.4. Environmental and Energy Outcomes

Empirical data Empirical data on waste-to-energy (WtE) outcomes differ depending on the technology employed. Anaerobic digestion (AD) typically produces 50–100 kWh per ton with minimal emissions (0.1–0.2 kg CO_2/kWh), making it well-suited to Addis Ababa's needs (IPCC, 2021). In contrast, incineration generates 200–300 kWh per ton but emits 0.5–1 kg CO_2/kWh without filters, posing risks to air quality (WHO, 2021). Gasification offers a balanced output of 150–250 kWh per ton with emissions of 0.3–0.5 kg CO_2/kWh; however, its efficiency decreases when processing wet waste (Ofori-Boateng et al., 2021). Across these technologies, waste reduction averages 70–90%, significantly alleviating pressure on landfills (Kumar & Samadder, 2020).

In December 2019, the European Commission (EC) released an updated Best Available Techniques (BAT) Reference Document for Waste Incineration (Frederik et al., 2019), establishing stricter environmental standards, particularly for emissions of toxic and persistent organic pollutants such as mercury, polychlorinated dibenzodioxins (PCDDs), and dibenzofurans (PCDFs) (European Commission, 2019). This development has led to a broad scientific consensus that modern WtE systems, when compliant with BAT, do not adversely affect human health (GIZ, 2019). Several systematic reviews have confirmed that contemporary WtE plants, adhering to these standards, show no significant negative health or environmental impacts (European Commission, 2019). This evidence underscores the potential for safe WtE operations in urban areas, offering a reliable waste management alternative without compromising public health, provided BAT compliance is maintained (GIZ, 2019). In Addis Ababa, where energy demand surpasses supply (IEA, 2022), even a modest output of 20–50 kWh per day from a small WtE plant could meet apartment energy needs, reducing reliance on the grid.

2.3.5. Synthesis and Implications

Empirical evidence confirms that small-scale WtE facilities can meet Addis Ababa's waste and energy demands. AD is best suited to local waste streams and spatial constraints, offering modest but reliable energy with minimal environmental impact. Incineration and gasification provide greater output but need greater investment and technical skill, less feasible without external support.

2.4. Conceptual Review

The conceptual framework for the implementation of small-scale waste-to-energy (WtE) systems in Addis Ababa apartment complexes integrates technical, spatial, and social dimensions to address waste management and energy needs. Three key areas are proposed throughout this chapter: architectural integration of WtE systems in building design, community engagement models to promote resident involvement, and viability assessment to examine feasibility and scalability. These concepts serve to maximize gains from WtE waste reduction and energy generation while minimizing disruption in high-density residential settings, offering a feasible framework for "Waste for Value" in Addis Ababa.

2.4.1. Framework for Architectural Integration

Integrating small-scale WtE systems into apartment complexes involves reimagining architectural design to fit technology into spatial limitations. In Addis Ababa, where apartment complexes tend to have limited excess land, WtE units need to be integrated into existing buildings, such as basements, rooftops, or service shafts enables discreet and effective deployment (IEA, 2022). Based on the principles of sustainable architecture, an integration model strikes a balance between residents' comfort, aesthetics, and functionality (McLennan, 2019).

Aesthetic integration is crucial as well. WtE facilities wrapped behind building facades or within utility rooms preserve building appeal, and signs and green design elements such as plant-covered walls can trigger sustainability (Gibberd, 2022). In Addis Ababa, where cost in building often ranks above innovation, prefabricated and scalable module WtE layouts offer a sensible solution (Beyene et al., 2018). This model visualizes apartments as self-sufficient ecosystems, in which waste easily flows into energy production without disrupting livability.

For example, basement spaces with direct waste chutes from upper floors could be equipped with mini anaerobic digestion plants appropriate for Addis Ababa's organic waste composition (Kumar & Samadder, 2020). The layouts could involve insulated digesters of capacity 1-2 m^3, treating 0.5-1 tons of waste per day and producing biogas to be piped to shared facilities or kitchen areas. Alternatively, gasification units but a larger size may be located on rooftops, and light generators may be syngas-fueled (Ofori-Boateng et al., 2021).

2.4.2. Viability Assessment

Assessing the viability of small-scale WtE in Addis Ababa apartment buildings involves analyzing costs, benefits, and scalability within local conditions. This conceptual framework uses a cost-benefit approach to the analysis of technologies like AD, incineration, and gasification according to energy generated, waste reduced, and economic feasibility (World Bank, 2021).

Anaerobic digestion is highly feasible for Addis Ababa. At an installation cost of $5,000-$10,000 for a 1-ton/day unit and a payback period of 3–5 years when there are partial subsidies, AD produces 50-100 kWh/ton of organic waste that is enough for cooking or lighting in a 20-unit building (Kumar & Samadder, 2020). Operating cost is low ($200-$300/year), and waste reduction is 80%, which alleviates landfill pressure (Mwangi et al., 2022). In a city where there is unreliable electricity (IEA, 2022), even 20-50 kWh/day would decrease energy expenses by 10-15%, and biogas replaces LPG consumption, with a household saving between $50-$100 yearly (Kumar & Samadder, 2020). Incineration, at $15,000-$20,000/unit, produces 200-300 kWh/ton and is appropriate for mixed waste in larger complexes (Li et al., 2020). High operating cost ($500-$1,000/year) and emission control, however, strains feasibility under Addis Ababa's resource-scarce situation (WHO, 2021). Gasification, at a cost of $20,000-$30,000, produces 150-250 kWh/ton with lower emissions but, given technical complexity as well as the need for preprocessing waste to be dry, has limited practicality (Ofori-Boateng et al., 2021). Scalability of WtE integration in apartment buildings depends on apartment size and waste volume, with a phased pilot approach for anaerobic digestion (AD) in one building followed by expansion based on collected data offering a practical way to assess feasibility (UN-Habitat, 2020). Community willingness, bolstered by engagement models, enhances this feasibility, though financial mechanisms such as public-private partnerships, microfinance for cooperatives, or government subsidies are essential for scalability (Cheru, 2016).

The conceptual model for WtE in Addis Ababa’s apartment buildings integrates three core components: infrastructure featuring modular, architecturally concealed AD units in basements, ventilated for comfort, treating organic waste from chutes linked to resident sorting stations designed for convenience with minimal disruption, producing 20–50 kWh/day to power common facilities and surplus biogas for kitchens; community participation through incentivized waste exchange programs supported by education and web-enabled portals managed by a tenant committee overseeing operations; and institutional support via policy alignment, funding models, and regulations to facilitate adoption.

2.4.3. Risk Identification and Mitigation

Successful execution requires forecasting and reducing potential risks. Technical risks include equipment failure, smell complaints, and inconsistency of feedstock. Uncertain profits and a lack of initial investment are associated with financial risks. Social risks cover resistance by residents and maintenance non-adherence.

Mitigation actions include yearly maintenance funds collected by way of service fees, in-house staff training, and regular system auditing. Testing runs of systems in chosen apartments with high community participation can generate pressure for changes and act as learning opportunities.

2.5. Research Gaps

Existing research on Addis Ababa's waste management focuses broadly on municipal systems, landfill issues and general recycling challenges (Hirpe & Yeom, 2021). However, there is minimal exploration of small-scale WtE technologies, such as anaerobic digestion or modular gasification, designed for the spatial and logistical constraints of apartment complexes, where 60-70% of waste is organic and suitable for energy recovery (Federal Democratic Republic of Ethiopia, 2019). Studies like (Gebremariam and Assefa, 2022) address waste sorting in high-density residences but do not investigate the integration of WtE systems at the apartment level, leaving a gap in understanding technical feasibility and operational models.

The WtE case study of the review is merely a general description since it is not apartment-oriented and does not contain detailed system data. Additionally, there are no studies especially carried out for solid waste-to-energy solutions within Addis Ababa's apartments, which deters customized solutions. Closing these gaps will enhance the practicality and impact of future pilot projects and research.

Chapter 3: RESEARCH METHODOLOGY

3.1. Study Area

The research targets three apartment complexes small (38 units), medium (78 units) and large (144 units) apartment complex chosen from diverse neighborhoods Lebu, Kazanchis and Mexico to reflect varying building sizes, resident demographics, and waste patterns. This selection ensures findings apply across the city's residential landscape.

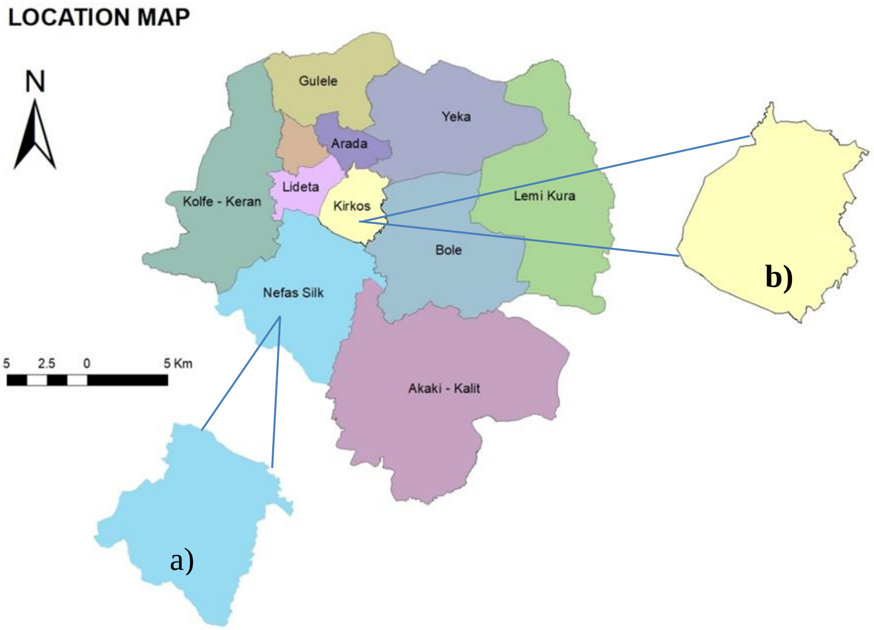

Figure 3.1. Study Area Location map: a) NifasSilk Lafto Subcity where the small (Lebu) Apartment complex is located; b) Kirkos Subcity where the medium (Kazanchis) and large (Mexico) Apartment complex is located

3.2. Research Design

The research employed the mixed methods approach. This is a combination of qualitative and quantitative and multi-phase analysis to achieve integrative insight into the challenges, opportunities, and potential solutions to small-scale waste-to-energy technologies among apartment buildings in Addis Ababa. The exploratory-applied design filled data loopholes in waste data, architectural feasibility, social acceptance, and economic scalability in developing viable WtE solutions.

3.3. Source of Data

The study utilized a combination of primary and secondary data sources to investigate the feasibility of small-scale waste-to-energy (WtE) systems in Addis Ababa's apartment buildings. Primary data were collected through surveys of 75 residents across three apartment complexes in Lebu, Kazanchis, and Mexico, capturing waste generation, sorting habits, and

WtE adoption willingness. A three-week waste characterization survey measured daily waste from 9 units. Semi-structured interviews with four stakeholders. Focus groups with 6 residents explored perceptions and preferences. Secondary data included academic journals and policy documents contextualizing local waste management practices and global WtE case studies. These sources ensured a comprehensive dataset to address research gaps in localized waste patterns, technical feasibility, and community acceptance.

3.4. Sampling Design

3.4.1. Sampling Population

The sample population comprised residents and stakeholders associated with apartment buildings in Addis Ababa, selected to represent diverse perspectives relevant to WtE implementation. Residents were drawn from three purposively chosen apartment complexes: a small complex (38 units) in Lebu, a medium complex (78 units) in Kazanchis, and a large complex (144 units) in Mexico, reflecting varied socio-economic profiles and waste management practices. Stakeholders included a municipal official with waste policy expertise, an NGO representative familiar with community-driven models and two architects knowledgeable in spatial design. Apartment units on one floor per complex (2–4 units) were selected for waste characterization to capture representative waste patterns. This population was targeted to provide data on waste behavior, community engagement, technical integration, and policy implications specific to high-density residential settings.

3.4.2. Sample Size

The sample size was carefully determined to balance data sufficiency with practical constraints, ensuring robust analysis of WtE feasibility. For resident surveys, a balanced sample of 75 residents (25 per complex) was selected to reflect diverse waste habits, sorting willingness, and attitudes toward waste-to-energy (WtE) adoption, enabling cross-tabulations by income and complex size. Focus groups included 6 residents drawn from survey respondents, providing qualitative depth. The waste characterization survey monitored 9 units (2 in the small complex, 3 in the medium, 4 in the large) categorizing it as Non-Recyclable organic, Non-Recyclable dry and Recyclable daily for three weeks, yielding 189 data points. Four stakeholder interviews (one municipal official, one NGO representative, and two architects) covered policy, technical, and operational perspectives. Technical assessments were conducted in all three complexes, modeling one 0.5-ton anaerobic digestion unit per site. These sizes were sufficient to address research gaps, achieved data saturation with consistent response types and waste weights and remain manageable for in-depth analysis.

3.4.3. Sampling Technique

Purposive sampling was employed to select participants and sites that best addressed the study's objectives and research gaps in localized waste data, architectural integration, community acceptance, and economic scalability. Three apartment complexes were chosen based on size diversity (small: 38 units, medium: 78 units, large: 144 units), resident engagement, neighborhood diversity (Lebu, Kazanchis, Mexico), accessibility, and infrastructure suitability for WtE integration, excluding complexes with poor maintenance, low cooperation, and restricted access. One floor per complex (2–4 units) was selected for waste characterization, prioritizing floors with diverse household types, collection accessibility, and typical layouts, while excluding those with low occupancy and atypical designs. Residents (75 for surveys, 6 for focus groups) were chosen for gender balance, varied income levels, engagement indicators, and long-term residency, excluding transient residents or those with extreme biases. 4 Stakeholders were selected for relevant expertise, excluding those with limited WtE knowledge and commercial agendas. This technique ensured targeted, information rich cases for the exploratory applied study.

3.5. Method of Data Collection

The data was obtained from both quantitative and qualitative data sources. It was mainly collected through surveys, measuring waste from one floor per complex over three weeks via a waste characterization log sheet, and four expert interviews conducted on integration of WtE.

A. Qualitative

Resident Surveys: Administered questionnaires (Appendix 2) to 75 residents, capturing demographics (gender, income, household size), waste generation (kg/day, types), sorting habits, satisfaction with collection, and WtE willingness. Open-ended questions explored motivators and barriers.

Focus Group Discussions: Conducted with 6 residents using discussion guides to explore perceptions, preferences, and concerns about WtE adoption, complementing survey data with qualitative depth.

Semi-Structured Interviews: Conducted with 4 stakeholders (Appendix 4), using tailored questions to explore WtE integration (space options, design constraints) and funding models.

Secondary Data: Reviewed policy documents and academic literature to contextualize findings and address research gaps.

B. Quantitative

Waste Characterization Survey: Daily waste from 9 units (2–4 per complex) was collected, weighed, and categorized (Non-Recyclable organic, Non-Recyclable dry and Recyclable) using scales, bins, and log sheets (Appendix 6) over three weeks, yielding 189 data points.

Technical Assessments: Measured available spaces (basements, rooftops) using tape measures and sketched layouts to assess spatial capacity. Simulated 0.5-ton AD unit placement using ArchiCAD and AutoCAD, estimating retrofitting needs (ventilation, insulation) and costs (Appendix 7).

3.6. Method of Data Analysis

This study employed a mixed-methods approach, data collected from 75 residents. Excel was used to analyze frequencies, cross-tabulation, averages and standard deviations of quantitative data's such as waste volume, and percentages, while qualitative responses such as open-ended questions and interviews were coded thematically using manual methods. Thematic presentation of results was made, with graphic visualizations and a waste log artifact.

3.6.1. Analysis Type

- **Qualitative Analysis:** Thematically coded for open-ended survey responses (e.g., motivators, barriers) and expert interview showed recurring themes such as benefits, simpler sorting, clean environment, and spatial limitations, in response to cultural and technical barriers.
- **Quantitative Analysis:** Descriptive statistics (percentages, means, standard deviations) and cross-tabulations in Excel summarized waste generation, sorting habits, satisfaction, and WtE willingness by demographics (gender, income, complex size). Chi-square tests evaluated associations (e.g., income vs. sorting willingness, gender vs. comfort) to identify major relationships, ensuring insights into waste patterns and community acceptance.

Descriptive statistics provided precise values for WtE planning, while cross-tabulations revealed complex specific and demographic determinants. Thematic coding captured nuanced resident and expert opinion, critical to breaking down stigma, distrust, and integration in the urban Addis Ababa context.

3.7. Method of Data Presentation

The presentation was structured to clearly convey findings through a combination of textual, visual, and narrative elements. Results were thematically organized in the Results and Discussion section, addressing key aspects. Visualizations enhanced clarity, with figures using bar charts, pie charts, and line graphs to illustrate the results and findings. Tables provided precise quantitative summaries and including a waste log summarizing daily waste data. A narrative synthesis integrated quantitative metrics, with qualitative insights to comprehensively answer research questions ensuring a robust and accessible presentation for both academic and practical audiences.

3.8. Validation

To ensure the validity and reliability of findings, validation strategies were implemented. Triangulation combined data from surveys, waste characterization, focus groups, interviews, and secondary sources, confirming consistency (e.g., 35% food scraps in surveys aligned with 68–72% organic waste in logs). Member checking involved sharing preliminary findings with 10 residents and stakeholders to verify accuracy. Statistical rigor included chi-square tests for significant associations and standard deviations to confirm waste data consistency. Pilot testing of survey tools and waste weighing protocols with 5 residents refined clarity and feasibility. Reflexivity was maintained through a research journal documenting assumptions. Findings were contextualized against global case studies and local data, ensuring relevance. These strategies validated the study's credibility and alignment with research questions on WtE feasibility and implications.

3.9. Ethical Consideration

The study adhered to ethical principles to protect participants and ensure integrity, complying with Addis Ababa University's guidelines. Informed consent was obtained from all participants, clearly explaining the research purpose, procedures, potential risks, and benefits. Confidentiality and Anonymity was ensured by securing data, anonymizing personal information, implementing confidentiality agreements, coding resident data (A1–A75) and reporting stakeholder inputs without names. Non-maleficence was prioritized by avoiding sensitive questions and conducting waste weighing non-intrusively. Beneficence aimed to benefit communities through sustainable WtE solutions. Academic integrity was upheld with proper APA citations, transparent AI tool usage for grammar refinement, and ethical approval from the university's committee, ensuring participant safety and study credibility.

Chapter 4: RESULTS AND DISCUSSION

4.1. Demographic Profile & Response rate of Respondents

The survey of 75 residents from three apartment complexes in Addis Ababa small (38 units, Lebu), medium (78 units, Kazanchis), and large (144 units, Mexico) provided a diverse demographic profile and achieved a 100% response rate, ensuring robust data for analyzing waste-to-energy (WtE) feasibility.

4.1.1. Demographic Profile

The demographic profile of the 75 survey respondents from three apartment complexes in Addis Ababa provides insight into the diverse socio-economic and household characteristics relevant to waste-to-energy (WtE) adoption. Gender distribution showed 57.3% female (43 respondents) and 42.7% male (32 respondents), reflecting a slight female majority, possibly due to higher female engagement in household waste management. Household sizes varied, indicating a mix of small and medium sized families typical of urban apartments. Income levels highlighted economic diversity, suggesting a predominantly middle to high income sample. Age ranges included with most households having 18–30 and 31–45 years old, reflecting working age adults likely influencing waste practices. The complexes were equally represented, with 33.3% (25 respondents) each from small, medium, and large complexes, capturing varied building sizes and waste generation patterns to ensure a balanced sample for comparison. This demographic diversity ensures the findings are applicable across different household types and socio-economic groups in Addis Ababa's apartment settings.

Table 4.1. Demographic Profile of Respondents

Demographic Characteristic	Category	Count	Percentage (%)
Gender	Female	43	57.3
	Male	32	42.7
Household Size	1–3 members	37	49.3
	4–7 members	33	44.0
	7–10 members	5	6.7
Age range of household members	Toddlers	28	37.3
	Under 18	35	46.7
	18-30	35	46.7
	31-45	36	48
	46-60	17	22.7
	Over 60	10	13.3

Income Level (ETB/month)	>30,000	41	54.7
	15,000–30,000	20	26.7
	5,000–15,000	11	14.7
	3,000–5,000	3	4.0
Apartment Complex	Small (38 units, Lebu)	25	33.3
	Medium (78 units, Kazanchis)	25	33.3
	Large (144 units, Mexico)	25	33.3

4.1.2. Response Rate

The survey achieved a 100% response rate, with all 75 targeted residents across the three apartment complexes completing the questionnaire, ensuring robust data for analyzing waste management practices and WtE feasibility. The sample was evenly distributed, with 25 respondents (33.3%) from each complex. This high response rate was facilitated by purposive sampling, targeting residents with long-term occupancy (>1 year) and willingness to participate. The questionnaire, administered in Amharic and English, was pilot-tested with 5 residents to ensure clarity and reduce ambiguity, contributing to full participation. No respondents withdrew, and all questions were answered, with open-ended responses providing additional qualitative depth. This complete response rate strengthens the study's reliability, as it eliminates non-response bias and ensures the data fully represent the sampled population's perspectives on waste habits, sorting willingness and WtE adoption.

Table 4.2. Response Rate of Respondents

Apartment Complex	Targeted Respondents	Completed Responses	Response Rate (%)
Small (38 units, Lebu)	25	25	100
Medium (78 units, Kazanchis)	25	25	100
Large (144 units, Mexico)	25	25	100
Total	75	75	100

4.2. The Effectiveness of Solid Waste Management Systems

The effectiveness of solid waste management systems was evaluated through resident participation, sorting practices, and satisfaction with collection methods. Collection methods included weekly pickup (52%, 39 respondents), self-disposal (24%, 18 respondents) and irregular pickup (23%, 17 respondents). Sorting habits and satisfaction were quantified (% always/never sorting, % satisfied). Satisfaction was moderate, with 60% (45 respondents) somewhat satisfied, 25% (19) not satisfied (citing irregular pickup, odor), and 15% (11) very satisfied. Irregular pickup correlated with higher dissatisfaction (47% not satisfied), particularly in small complexes (32% irregular), addressing waste management gaps highlighting the need for reliable collection to support WtE integration.

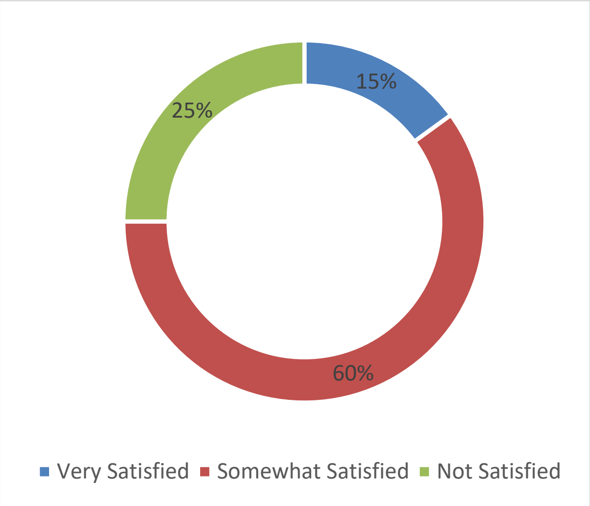

Figure 4.1 Resident Satisfaction with Waste Collection

The pie chart highlighted widespread dissatisfaction (25%), particularly in small complexes, driven by irregular pickup. This highlighted the urgency of reliable WTE systems to improve waste management and rebuild trust, especially in smaller complexes with weaker infrastructure.

Table 4.3. Resident Satisfaction with Waste Collection Methods in Apartment Complexes

Collection Method	Count	Percentage (%)	Not Satisfied (%)	Somewhat Satisfied (%)	Very Satisfied (%)
Weekly Pickup	39	52.0	23.1	69.2	7.7
Self-Disposal	18	24.0	11.1	44.4	44.4
Irregular Pickup	17	23.0	47.1	52.9	0.0
Daily Pickup	1	1.0	0.0	100.0	0.0
Total	75	100.0	25.0	60.0	15.0

4.2.1. House Holds Participation

Household participation in waste management was assessed through disposal practices and satisfaction with collection services. Of the 75 respondents, 60% (45) were somewhat satisfied, but 25% (19) were not satisfied, especially in small complexes with 32% irregular pickup (36% not satisfied). Weekly pickup, dominant in medium (56%) and large (60%) complexes, yielded 69.2% somewhat satisfied but only 7.7% very satisfied, indicating service inconsistency.

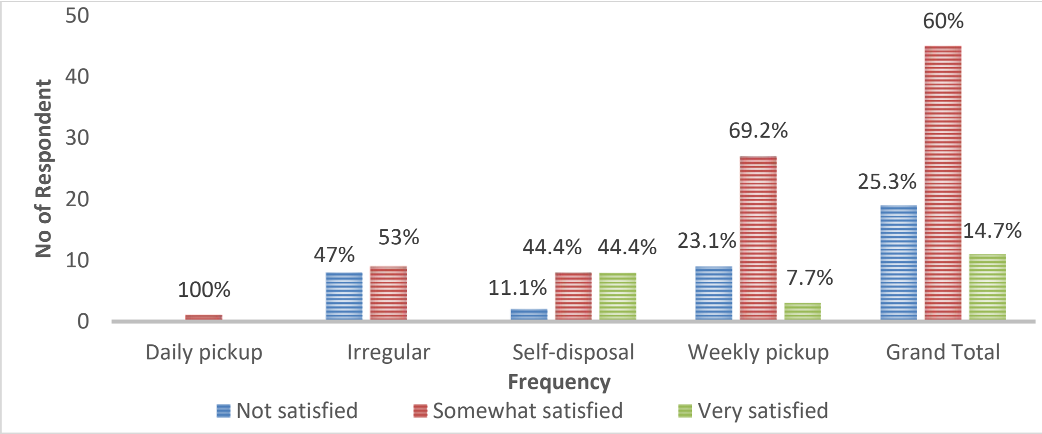

Figure 4.2. Resident Satisfaction by Waste Collection Frequency

Resident Satisfaction by Waste Collection Frequency" and "Resident Satisfaction by Garbage Chute Availability," showed that regular waste collection and garbage chute presence notably improved resident satisfaction, essential for the feasibility of WTE systems in Addis Ababa apartment complexes. Irregular collection (47% dissatisfied, n=8/17) and lack of chutes (40% dissatisfied, n=12/30) were major issues, most particularly in small complexes (32% irregular pickup, fewer chutes), reducing trust and sorting compliance (43% always sorted). Weekly collection (85% very/somewhat satisfied, n=33/39) and chutes (84% very/somewhat satisfied, n=38/45), prevalent in medium/large complexes.

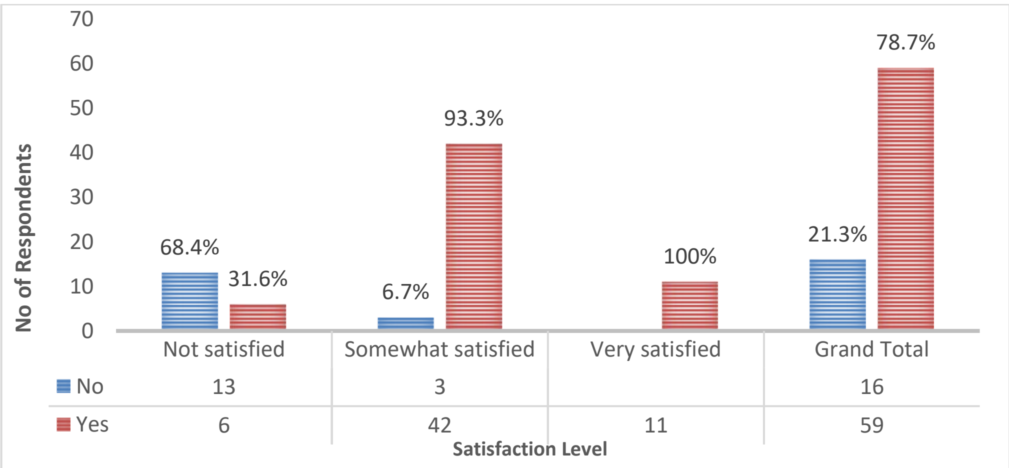

Figure 4.3 Resident Satisfaction by Garbage Chute Availability

Household size impacted waste generation: 1–3 member households (49%, 37 respondents) produced 0.5–1 kg/day (46%) or 1–2 kg/day (46%), while 4–7 member households (44%, 33) produced 1–2 kg/day (72%) or over 2 kg/day (11%). Larger households (7–10 members, 7%, 5 respondents) generated 40% over 2 kg/day.

Table 4.4. Waste Generation by Household Size

Household Size	Count	Percentage (%)	0.5–1 kg/day (%)	1–2 kg/day (%)	Over 2 kg/day (%)	Less than 0.5 kg/day (%)
1–3 Members	37	49.3	46.0	46.0	2.7	5.4
4–7 Members	33	44.0	18.2	72.7	11.0	0.0
7–10 Members	5	6.7	20.0	40.0	40.0	0.0
Total	75	100.0	33.3	56.0	9.3	2.7

4.2.2. Sorting Mechanisms

Sorting mechanisms were evaluated through residents' sorting habits and perceptions of waste handling. Only 43% (32 respondents) always sorted waste, 36% (27) sorted sometimes, and 21% (16) never sorted, with females sorting more frequently (60% always/sometimes vs. 37% males). Waste composition included food scraps (35%), plastic (35%), paper (16%), and other (14%), with 67 respondents reporting food scraps, supporting AD viability. Medium complexes showed higher sorting willingness (76% for WtE) than small (64%) or large (68%), likely due to better infrastructure (60% weekly pickup, 60% chutes). Limited sorting adoption, driven by stigma and logistical barriers, suggests WtE systems should simplify sorting and offer incentives to boost participation.

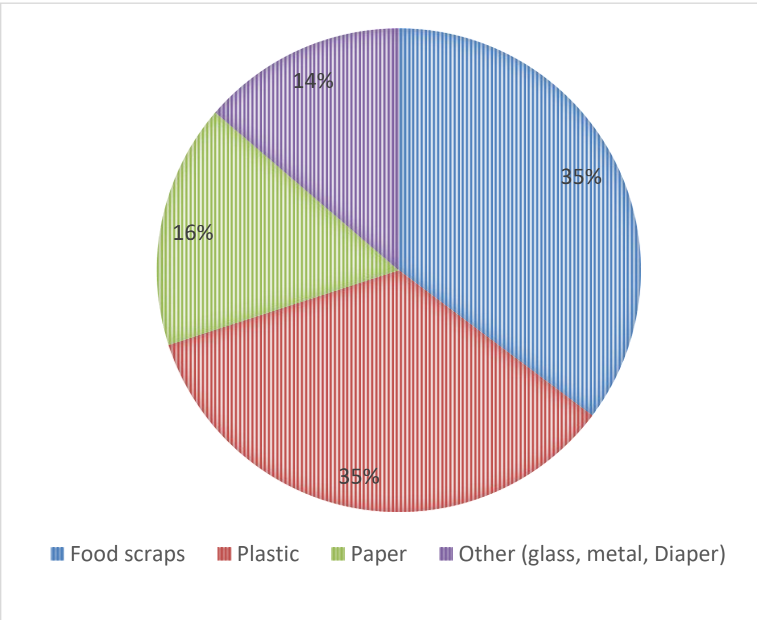

Figure 4.4 Percentage Distribution of Waste Types Reported by Residents

There is a significant organic content suitable for anaerobic digestion (AD) and a recyclable fraction with potential for waste exchange schemes. Paper accounted for 16% (n=31), suggesting a lower but potential recyclable component, with the "other" category (glass, metal; 14%, n=26) suggested AD-incompatible wastes materials that would have to be managed via other disposal routes.

The data indicates 35% food waste exceeding Addis Ababa's 19.3% from (Gelan, 2021), highlights methodological differences this research is apartment-focused data likely prioritizes food waste, while city-wide studies include diverse sources (e.g., 10% street sweepings)

Table 4.5. Waste Sorting Practices by Gender and Apartment Complex Size

Sorting Practice	Count	Percentage (%)	Female (%)	Male (%)	Medium Complex (%)	Small Complex (%)	Large Complex (%)
Always	32	42.7	60.5	18.8	48.0	36.0	44.0
Sometimes	27	36.0	25.6	50.0	36.0	44.0	28.0
Never	16	21.3	14.0	31.3	16.0	20.0	28.0
Total	75	100.0	100.0	100.0	100.0	100.0	100.0

4.3. Viability of Small-scale Waste to Energy Technology for Apartments

The viability of small-scale WtE technologies, particularly anaerobic digestion (AD), was assessed through resident willingness, waste composition and generation, technical compatibility and economic feasibility. Surveys showed 69% (52 respondents) were willing to sort waste for energy applications (lighting, cooking gas), motivated by benefits like reduced bills (63%, 47 respondents favored rewards). Waste composition (68–72% organic) and generation (22.8–158.4 kg/day per complex) supported AD, yielding 15–25 kWh/day for a 0.5-ton unit. Technical assessments confirmed 70–80% basement availability and 60% chute presence, though retrofitting costs (≥300,000 ETB) require subsidies. Economic feasibility was bolstered by 47% (35 respondents) willing to share costs, especially high-income residents (>30,000 ETB, 61%). AD's low emissions (0.1–0.2 kg CO_2/kWh) and compatibility with frequent power outages (3–5 weekly) enhance its viability, despite challenges like stigma (60%) and irregular collection (47% dissatisfaction).

Table 4.6. Resident Viability Indicators for Waste-to-Energy Implementation in Apartment Complexes.

Viability Indicator	Category	Count	Percentage (%)
Willing to Sort for Energy	Yes	52	69.3
	Maybe	14	18.7
	No	9	12.0
Willing to Share Costs	Yes	35	46.7
	No	40	53.3

4.3.1. Resident Willingness to Adopt WtE

Resident willingness to adopt WtE was strong, with 69% (52 respondents) agreeing to sort waste for energy, 19% (14) maybe willing, and 12% (9) unwilling. Medium complexes showed the highest willingness (76%, 19/25), followed by large (68%, 17/25) and small (64%, 16/25), likely due to better collection (60% weekly) and chute availability (60%). High-income residents (>30,000 ETB, 88%, 36/41) were more willing than medium (15,000–30,000 ETB, 60%, 12/20) or low-income (5,000–15,000 ETB, 36%, 4/11), driven by rewards (63%, 47 respondents). Open-ended responses highlighted motivators: bill reductions (40%), simpler sorting (25%), and cleaner environments (20%). Education and incentives could enhance adoption, particularly in medium complexes ideal for AD pilots.

Table 4.7. Willingness to Sort Waste for Energy by Apartment Complex Size

Complex Size	Willing to Sort: Yes (%)	Maybe (%)	No (%)	Count
Small (38 units)	64.0	28.0	8.0	25
Medium (78 units)	76.0	12.0	12.0	25
Large (144 units)	68.0	16.0	16.0	25
Total	69.3	18.7	12.0	75

The Willingness to Adopt WTE by Complex chart verified strong WTE support, particularly in medium complexes (76% sort), initiated by rewards (72%). Lower co-management willingness (56%) indicated a preference for passive participation (e.g., sorting), emphasizing the need for user-friendly systems and professional management to sustain engagement.

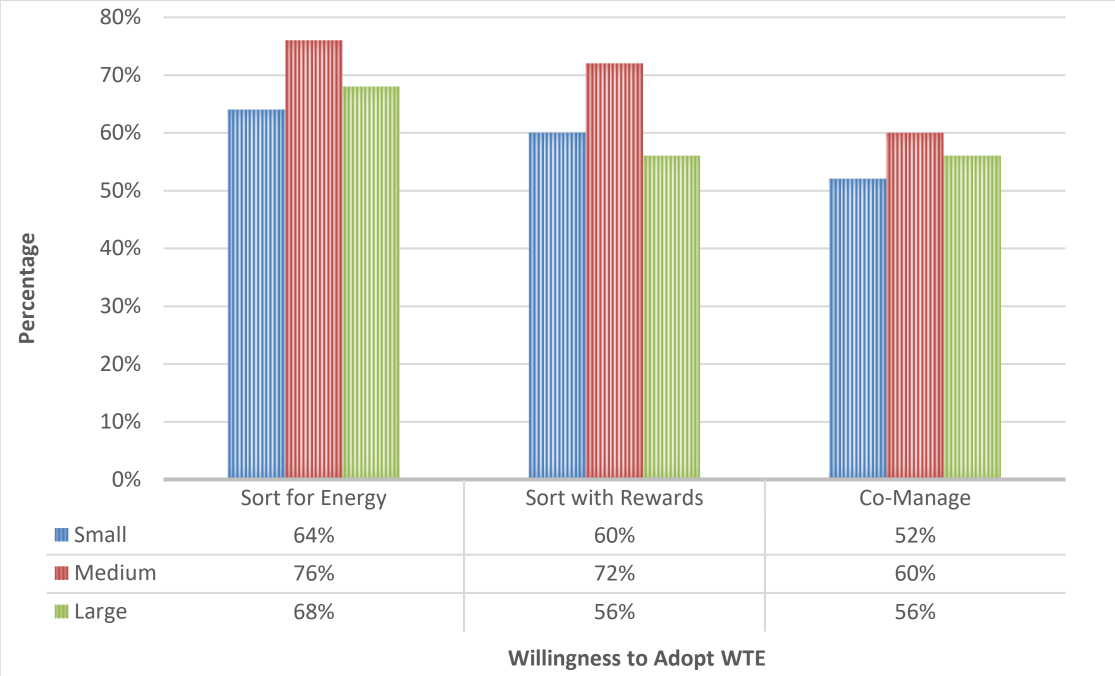

Figure 4.5. Willingness to Adopt WTE by Complex

4.3.2. Waste Composition and Generation

A waste log sheet was constructed for one floor per complex (small: 2 units, medium: 3 units, large: 4 units) over 3 weeks (21 days), the measured data was: 0.6 kg/unit/day (small), 0.85 kg/unit/day (medium), and 1.1 kg/unit/day (large) and it was categorized as organic, dry, recyclable with Excel calculating daily/weekly averages, proportions, and standard deviations to address the localized waste data gap. The waste log confirmed:

- **Small Complex:** 0.6 kg/unit/day (1.2 kg/floor, 2 units), 70% organic (0.84 kg), 25% recyclable (0.30 kg), 5% dry (0.06 kg), SD=0.04 kg/day.
- **Medium Complex:** 0.85 kg/unit/day (2.55 kg/floor, 3 units), 72% organic (1.84 kg), 23% recyclable (0.59 kg), 5% dry (0.13 kg), SD=0.06 kg/day.
- **Large Complex:** 1.1 kg/unit/day (4.4 kg/floor, 4 units), 68% organic (2.99 kg), 27% recyclable (1.19 kg), 5% dry (0.22 kg), SD=0.08 kg/day.

Weekly totals per floor were: small (8.4 kg), medium (17.85 kg), large (30.8 kg). Scaled to full complexes, daily waste was 22.8 kg (small, 38 units, 16 kg organic), 66.3 kg (medium, 78 units, 47.7 kg organic), and 158.4 kg (large, 144 units, 107.7 kg organic). A 0.5-ton/day anaerobic digester (AD) suited medium/large complexes, processing ~70% organic waste (~49-150 kg/day), yielding ~15-25 kWh/day (Vögeli et al., 2014).

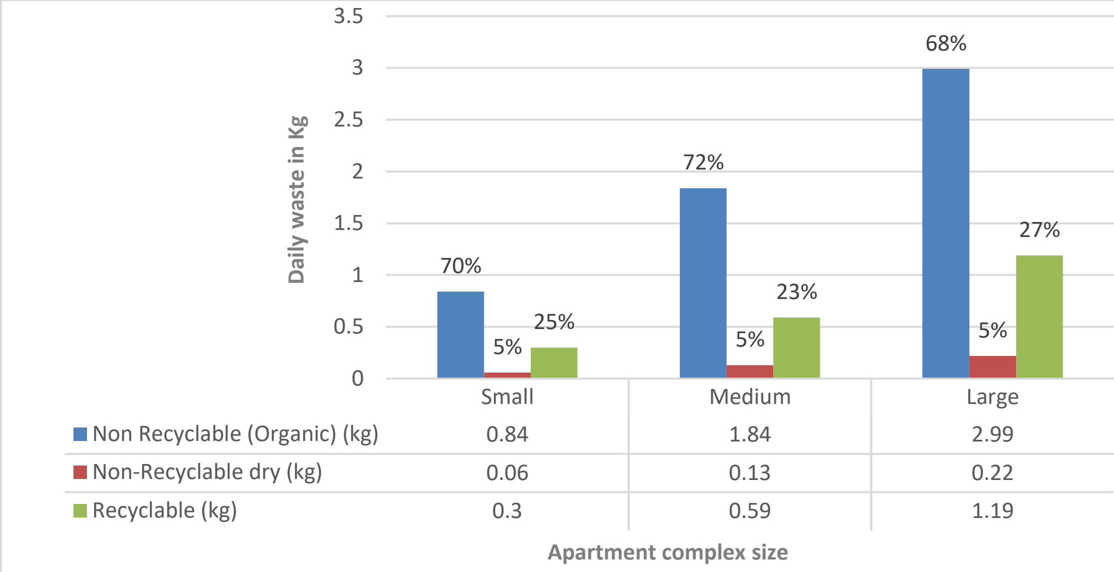

Figure 4.6 Daily Waste Composition by Complex n=9 units, 3 weeks.

The Daily Waste Composition by Complex chart showed that organic waste's dominance (68-72%), validating AD's suitability for medium/large complexes, which generated sufficient organic waste (1.84-2.99 kg/floor/day) for a 0.5-ton AD. Small complexes (0.84 kg/floor) suggested smaller or shared systems to optimize energy output.

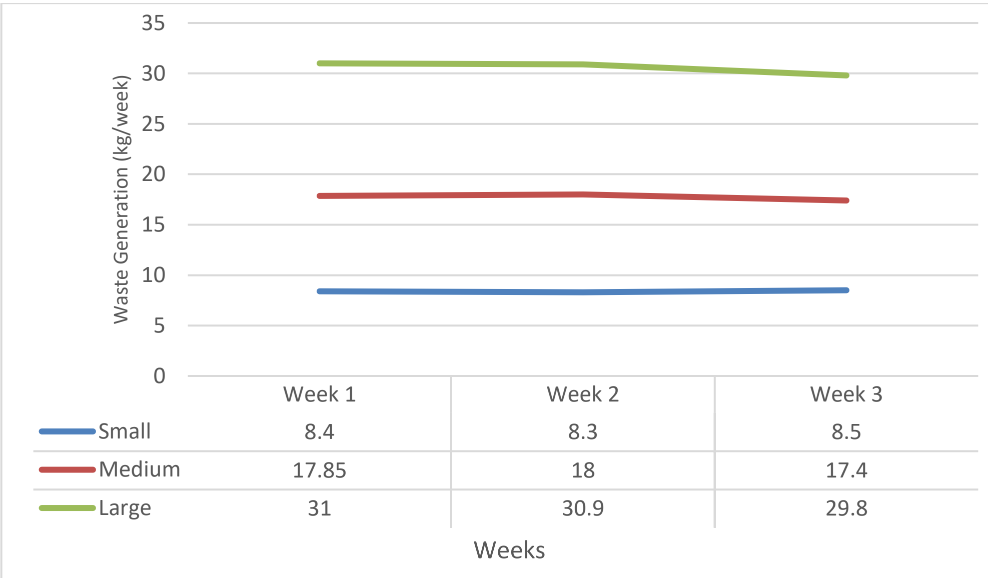

Figure 4.7 Weekly Waste Generation per Floor by Complex n=9 units, 3 weeks.

The line chart showed stable waste generation (SD=0.04-0.08 kg/day), ensuring reliable waste amount for WTE systems. Medium and large complexes consistent output (17.85 kg/week) and (30.8 kg/week) supported precise AD sizing.

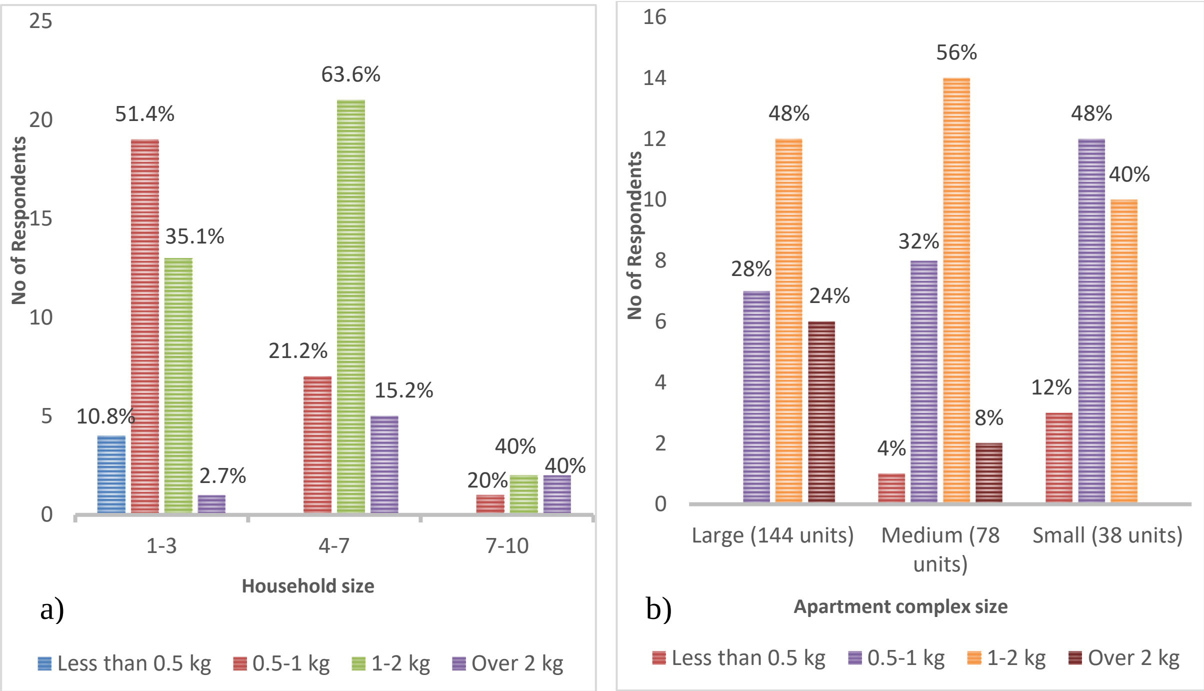

Figure 4.8: a) Daily Waste Production by Household Size; b) Daily Waste Production by Apartment Complex Size

Cross-tabulations between "Daily Waste Production by Household Size" and "Daily Waste Production by Apartment Complex Size," revealed that the larger households (4-7 people, 72% at ≥1 kg/day) and large complexes (144 units, 72% at ≥1 kg/day) produced more waste than small households (1-3 people, 46% at ≥1 kg/day) and small complexes (38 units, 44% at ≥1 kg/day), with high correlations (χ^2=9.8, p<0.05; χ^2=12.6, p<0.01). Aligned with the waste log (0.6-1.1 kg/unit/day), Small complexes (16 kg/day) required smaller or shared systems, and education is necessary to enhance sorting (43% always sorted) for all, enhancing WTE feasibility. large (158.4 kg/day, 107.7 kg organic) and medium complexes (66.3 kg/day, 47.7 kg organic) supported a 0.5-ton anaerobic digester (15-25 kWh/day), and medium complexes (76% sorting willingness) ideal for pilots.

4.3.3. Economic Feasibility

Responses on cost-sharing were quantified (% yes/no) and cross-tabulated with income. Expert interview insights on funding models (microloans, grants) were thematically coded, addressing economic scalability. Economic feasibility was supported by 47% (n=35) were willing to share WtE costs, 53% (n=40) not, with high-income residents (>30,000 ETB) most willing (61%, n=25/41, χ^2=18.9, p<0.01). Low-income residents (3,000-15,000 ETB) showed 0% willingness. Medium complexes showed balanced willingness (48%, n=12/25), followed by large (44%, n=11/25) and small (40%, n=10/25).

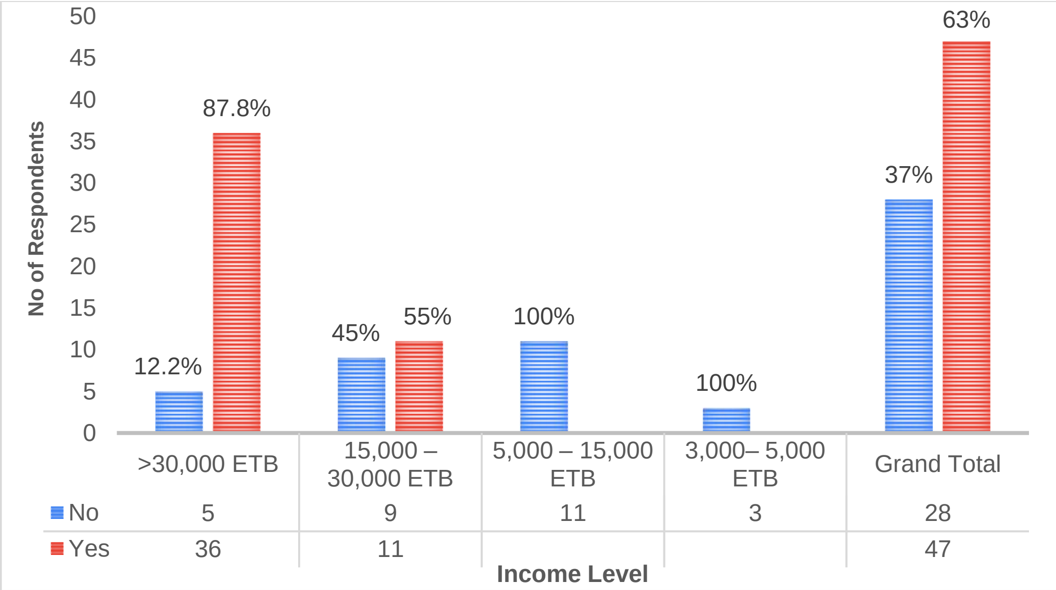

Figure 4.9 cost-sharing willingness by income level

The graph identified cost-sharing revenue inequalities, with residents with high incomes (61%) being significant contributors. The zero willingness of low-income groups (0%) indicated the need for external financing to enable equal access, particularly in small complexes with lower income levels.

A 0.5-ton AD costs ~ $6,500, with ~$450/year savings, resulting in a payback of 6-7 years for medium complexes. Stakeholders recommended microloans ~$2,500 and grants ~$3,000 to reduce waste fees in order to offset expenses ~$100/year, practical for medium/large complexes. Cost-Benefit Ratio with initial costs of $6,500 for a 0.5-ton AD unit and annual benefits of $324–$647 (energy + fertilizer), the ratio is estimated at 1.3–1.5 over 10 years with an 8% discount rate, enhanced by subsidies (Beyene et al., 2018).

4.4. Design Options to Integrate Small Scale Waste to Energy Technology for Apartments

Expert interviews on WTE integration were thematically coded for placement options, design constraints, retrofitting needs, and important tips. Design options for integrating small-scale WtE technologies, particularly AD, focused on spatial compatibility and community engagement. Technical assessments using ArchiCAD modeled 0.5-ton AD units (2m x 2m) in basements (70–80% availability) and rooftops, with basements preferred for odor control and chute connectivity (60% prevalence). Designs must incorporate modular AD units, chute-linked AD unit stations, and resident-led committees to ensure sustainability and minimize disruption in high-density apartments.

4.4.1. Technical Feasibility

Quantitative data from the technical feasibility assessment (space measurements, software integration) Cross-referenced with survey data (60% of residents had garbage chutes) to assess compatibility with resident practices, addressing the technical integration gap. Technical feasibility was confirmed by 70–80% basement availability in medium/large complexes and 60% chute presence, facilitating AD integration, Small complexes lacked enough basement spaces.

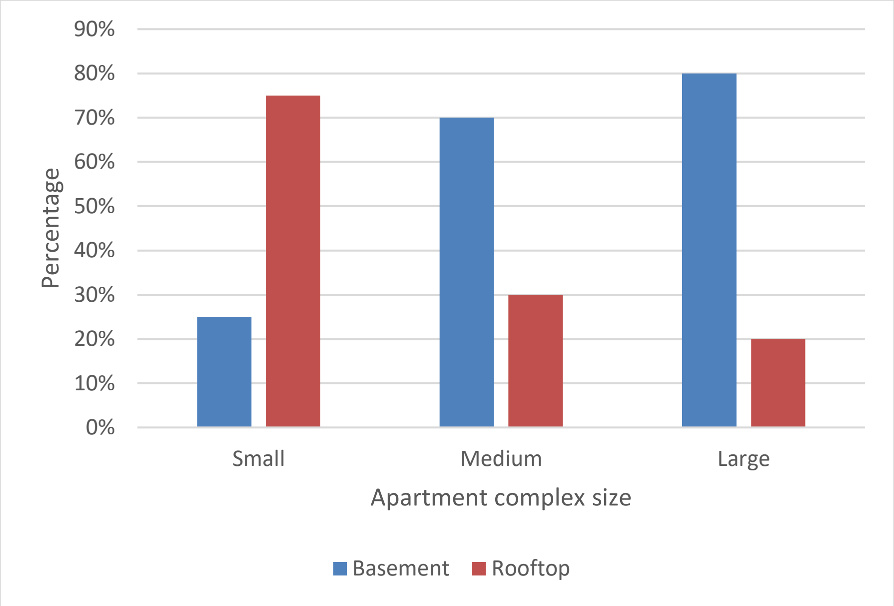

Figure 4.10 Available Space for WTE by Complex

The graph indicated medium/large complexes' high basement availability (70-80%), confirming their suitability for AD installation. Small complexes' reliance on rooftops (75%) represented higher costs and structural concerns, suggesting shared systems or subsidies to enhance feasibility.

Table 4.8. Availability of Basement and Rooftop Spaces for Waste-to-Energy Systems by Apartment Complex Size

Complex Size	Basement Availability (%)	Rooftop Availability (%)	Count
Small (38 units)	25	75	25
Medium (78 units)	80	20	25
Large (144 units)	70	30	25

4.4.2. Spatial Integration Options

Spatial integration prioritized basements, from Experts view basements (8-12 m^2) in medium/large complexes as ideal for 0.5-ton AD units (2m x 2m), based on accessibility, ventilation, and least disruption. Small complexes mostly lacked enough basement spaces and had to be installed on rooftops with structural support (≥150,000ETB). Retrofitting existing older buildings required ventilation system improvement and insulation (≥ 300,000ETB), whereas new buildings could have utility rooms initially designed in for 100,000ETB. Limitations were noise (controlled by soundproofing), odor (controlled by sealed units), and disruption during installation (4-8 weeks). Best practice suggestion was the inclusion of waste chutes linked directly to AD units in new constructions, reducing sorting effort and matching resident interest (25% cited easier sorting). Survey data showed 60% (n=45) of residents had chutes, facilitating WtE integration in medium/large complexes.

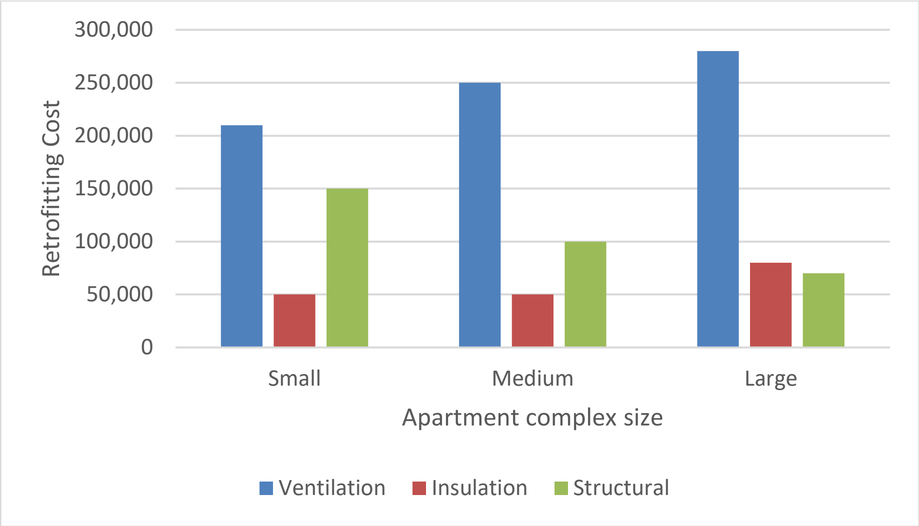

Figure 4.11 Retrofitting Costs for WTE by Complex

The graph showed higher retrofitting costs for small complexes (410,000ETB in total), spearheaded by structural needs for rooftops, compared to medium/large complexes (400,000-430,000ETB). Retrofitting costs (300,000 ETB) were lower for basements than rooftops (410,000 ETB for small complexes). This meant that medium/large complexes were to be prioritized for cost-reduction pilots, with subsidies for small complexes for inclusiveness.

4.4.3. Prototype Architectural Integration

Using data, a small-scale AD system (0.5-ton/day capacity) conceptually designed for a medium sized complex. It includes waste chutes, a basement digester, and biogas distribution for cooking.

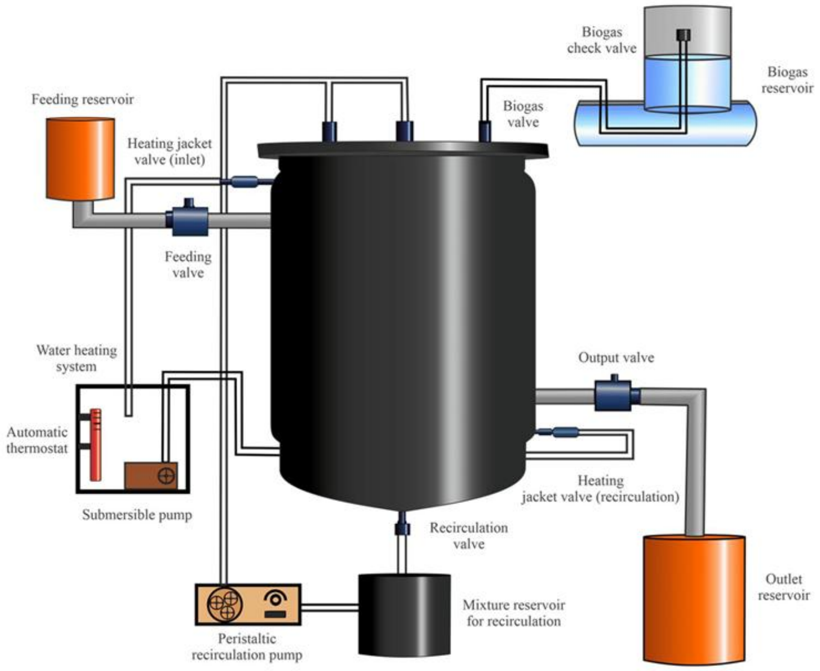

Figure 4.12. Schematic diagram of anaerobic digestion system

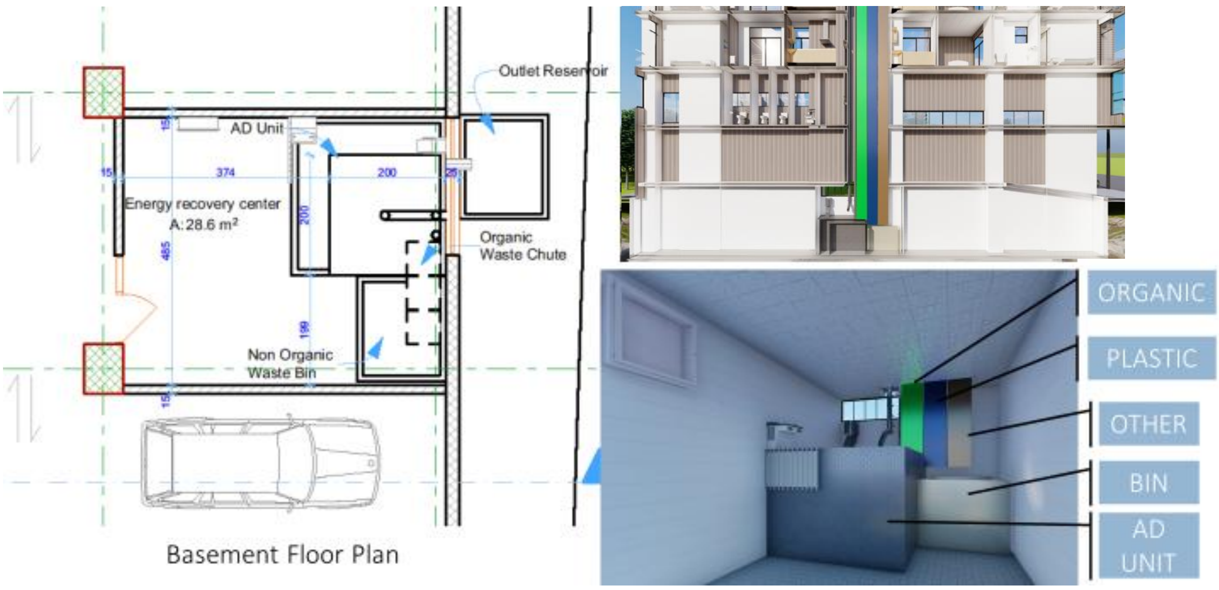

Figure 4.13. Schematic Layout of Anaerobic Digestion (AD) Integration in Basement

The architectural integration section outlines the seamless incorporation of anaerobic digestion (AD) units into apartment designs. Utilizing basements in medium and large complexes and chutes for waste transport, the system ensures minimal disruption. Three color-coded garbage chute lines dedicated to organic, plastic, and other waste types—connect directly to apartment floors. The organic chute feeds directly into the AD unit, while the others route to separate collection bins.

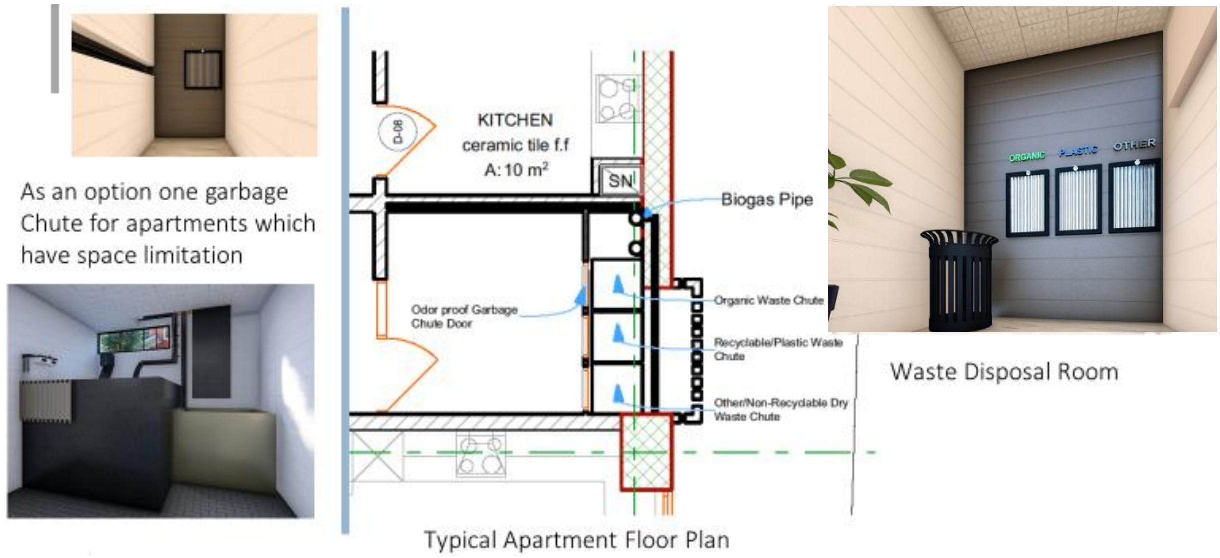

Figure 4.14. Typical Apartment Floor Plan with Garbage chute Integration and Waste Disposal Layout

Each household's kitchen pipe is equipped with an individual controller for safety and concealed within cabinets for aesthetic integration. The external portion of the waste chute is enclosed with louvers to ensure ventilation and features a green cover to enhance visual appeal. This schematic layout outlines the integration of anaerobic digestion (AD) systems into Addis Ababa's apartment buildings.

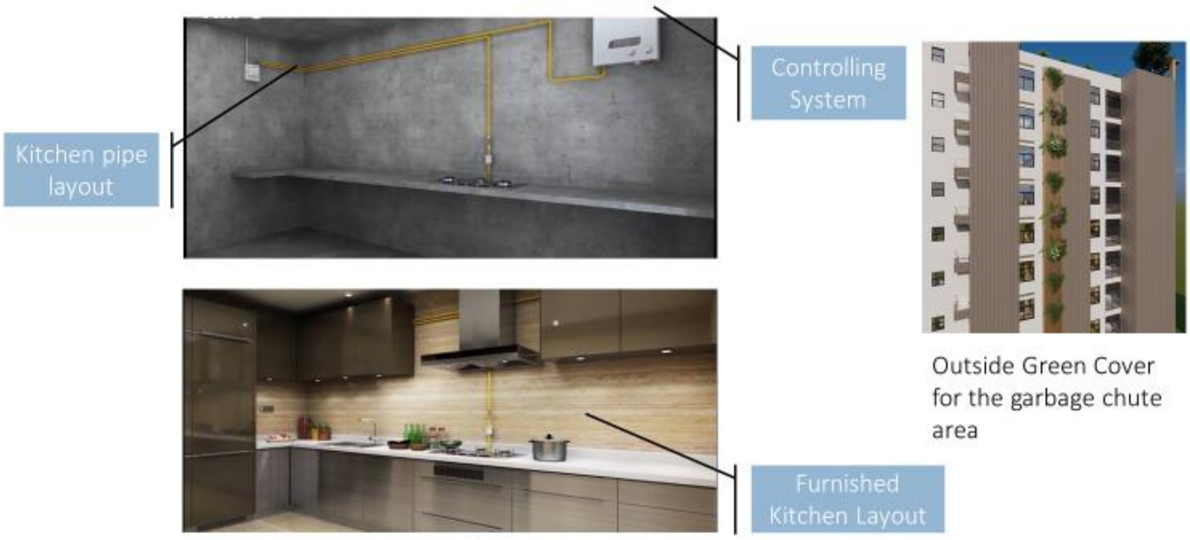

Figure 4.15. kitchen pipe layout with a controlling system

4.5. Major Findings

- The effectiveness of solid waste management systems in the studied complexes is limited by inconsistent collection and low resident engagement pose challenges, emphasizing the need for reliable collection and infrastructure upgrades to support WtE integration, despite a favorable waste composition for WtE.
- The viability of small-scale WtE technologies, particularly AD, is promising but constrained by economic barriers. Resident willingness is strong to sort for energy applications (lighting, cooking gas), especially in medium complexes. Technically, 70–80% basement availability and 60% chute presence facilitate AD integration, producing 15–25 kWh/day per 0.5-ton unit, with low emissions (0.1–0.2 kg CO_2/kWh).
- Design options for integrating AD emphasize spatial compatibility and scalability, with medium complexes showing the greatest potential. Basements are ideal for 0.5-ton AD units due to space, odor control, and chute connectivity. Scalability is viable in medium and large complexes, but small complexes face rooftop constraints suggesting medium-complex pilots to reduce Addis Ababa's uncollected waste before city-wide scaling.

Chapter 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This thesis validates the feasibility of small-scale anaerobic digestion (AD) systems for addressing Addis Ababa's apartment waste crisis. The introduction highlighted the city's waste management challenges, with significant uncollected waste burdening landfills (Addis Ababa City Administration, 2021). The literature review identified AD as optimal due to its compatibility with organic-rich waste, low emissions, and compact design can efficiently processes moisture content organic waste, prevalent in Addis Ababa, producing biogas and digestate with minimal emissions and requiring less technical expertise and investment (Hoornweg & Bhada-Tata, 2012), unlike incineration or gasification, which face higher costs and environmental risks (Kumar & Samadder, 2020; Vögeli et al., 2014).

The methodology employed a robust mixed-methods approach, combining surveys, waste characterization, expert interviews, and technical assessments across three apartment complexes of varying sizes. This design bridged research gaps in localized waste data, community acceptance, and architectural integration, providing a comprehensive understanding of WtE implementation. The results and discussion revealed that apartment complexes generate substantial organic waste, sufficient to sustain 0.5-ton AD units capable of producing energy for communal lighting or cooking. Technical assessments confirmed the availability of basement spaces and garbage chutes in medium and large complexes, facilitating seamless AD integration, while smaller complexes faced spatial constraints necessitating alternative solutions like shared systems. Community engagement emerged as a cornerstone of success, with residents expressing strong willingness to sort waste for energy benefits, motivated by potential cost savings and environmental gains, though challenges like stigma and irregular collection require targeted interventions. Economically, AD systems present a viable investment with manageable installation costs and potential savings through reduced waste fees and energy bills, though initial funding barriers necessitate innovative financing models like microloans and grants.

AD's alignment with Addis Ababa's waste and energy needs makes it ideal for medium-complex pilots, fostering sustainable urban living through integrated waste-to-energy solutions. This study lays a foundation for future research and practical implementation, offering a scalable outline for urban waste-to-energy solutions in Addis Ababa and beyond.

5.2. Recommendation

- **Pilot AD in Medium Complexes**: Implement 0.5-ton AD units in complexes of 50–100 units, leveraging high organic waste output and sorting willingness to produce energy for communal use, with performance monitoring to assess scalability.
- **Incentives and Education**: Offer energy credits or bill reductions and conduct bi-monthly awareness sessions, using champions to promote sorting and reduce stigma, enhancing community buy-in.
- **Funding Strategy**: Secure microloans and grants to offset AD installation costs, targeting affluent residents for cost-sharing and partnering with NGOs or municipal authorities for subsidies, especially for smaller complexes.
- **Simplify Sorting Processes**: Install color-coded, odor-proof chutes and bins in medium and large complexes to streamline sorting, replacing irregular collection with daily organic waste pickups to improve efficiency.
- **Community Engagement Campaigns**: Launch local media campaigns emphasizing environmental benefits and community pride, targeting youth via social media to normalize waste handling and sustain long-term adoption.
- **Technical Adaptability**: Design modular AD units (0.3–0.7 tons) with backup storage to handle waste variability, ensuring consistent biogas production during peak generation periods.
- **Monitoring and Feedback**: Establish resident committees to monitor AD performance, collect monthly feedback, and provide transparent reports on energy savings and waste reduction to maintain trust and engagement.

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APPENDIX 1: Publishable Manuscript

Viability Assessment of Small-Scale Waste-to-Energy Technologies for Apartment Buildings in Addis Ababa

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Abstract

Addis Ababa's rapid urbanization has increased solid waste management problems, primarily in high density apartment buildings, where organic waste (68–72% of total waste) dominates inefficient collection systems. The study assesses the viability of small-scale waste-to-energy (WTE) technologies anaerobic digestion (AD), incineration, and gasification for apartment buildings with focus areas as energy output, environmental sustainability, and integration ease with urban infrastructure. A mixed-methods analysis used, including waste characterization (0.6–1.1 kg/unit/day), technical assessments, and stakeholder interviews, three apartment complexes were evaluated (38, 78, 144 units). AD was the most viable, yielding 15–25 kWh/day from 0.5-ton units with reduced emissions (0.1–0.2 kg CO_2/kWh) and 70–80% basement acceptance. Incineration and gasification gave higher outputs (200–300 and 150–250 kWh/ton, respectively) but were met with challenges related to space requirement, emissions and cost ($15,000–$30,000). AD's compatibility with organic waste streams and municipal constraints reinforces its uptake, though its scalability depends on resident engagement and subsidy. The findings advocate for AD pilots in medium-sized complexes as a means to drive Addis Ababa's circular economy goals.

Keywords: Waste-to-energy, anaerobic digestion, incineration, gasification, apartment buildings

Introduction

Addis Addis Ababa faced with mounting solid waste management problems caused by population growth and urbanization and generates ~2,500 tons of municipal solid waste (MSW) per day, of which 65% are collected legally (Addis Ababa City Administration, 2021). Apartment residents produce 0.6–1.1 kg/unit/day composed of 68–72% organic waste, which fills containers and results in illegal dumping (Regassa et al., 2011). The 2017 collapse of the Koshe landfill, killing over 100 people emphasizes the need for sustainable answers (Amnesty International, 2018). Small-scale waste-to-energy (WTE) technologies can turn organic waste into a source of energy.

This study contrasts the viability of three WTE technologies anaerobic digestion (AD), small-scale incineration, and gasification on apartment blocks in Addis Ababa, relative to energy production, environmental performance, and urban infrastructure integration. The research bridges a gap in localized, small-scale WTE application, considering the technical and financial hurdles that large-scale projects like Reppie face (GIZ, 2023). Guided by a mixed-methods approach of waste characterization, technical assessment, resident surveys, and stakeholder interviews, it identifies the most suitable technology for apartment buildings in the context of Addis Ababa's sustainable city development.

Waste-to-Energy Technologies

Waste-to-Energy (WtE) technologies consist of any waste treatment process that creates energy in the form of electricity, heat and fuels from several types of waste (Hoornweg & Bhada-Tata, 2012). There are two main recovery or conversion processes of WTE technologies which is Biochemical (e.g., AD) and Thermochemical (e.g., incineration, gasification) depending on the waste composition and moisture content (GIZ, 2019). Biochemical conversion processes are preferred for wastes that have high amount of organic matter and high level of moisture contents and thermochemical process is useful for less dense wastes and low moisture contents (Rajaeifar et al., 2017).

Anaerobic Digestion (AD): AD breaks down organic wastes in oxygen-free conditions to yield biogas (methane-rich) and digestate (fertilizer by-product). Urban India's 1–5-ton/day AD facilities generate 50–100 kWh/ton, which is suitable for small-scale uses (Kumar & Samadder, 2020). Low emissions (0.1–0.2 kg CO_2/kWh) and low footprints (2m x 2m) make AD ideal for small spaces, despite high capital costs ($5,000–$10,000) and sorting by the residents (Beyene et al., 2023).

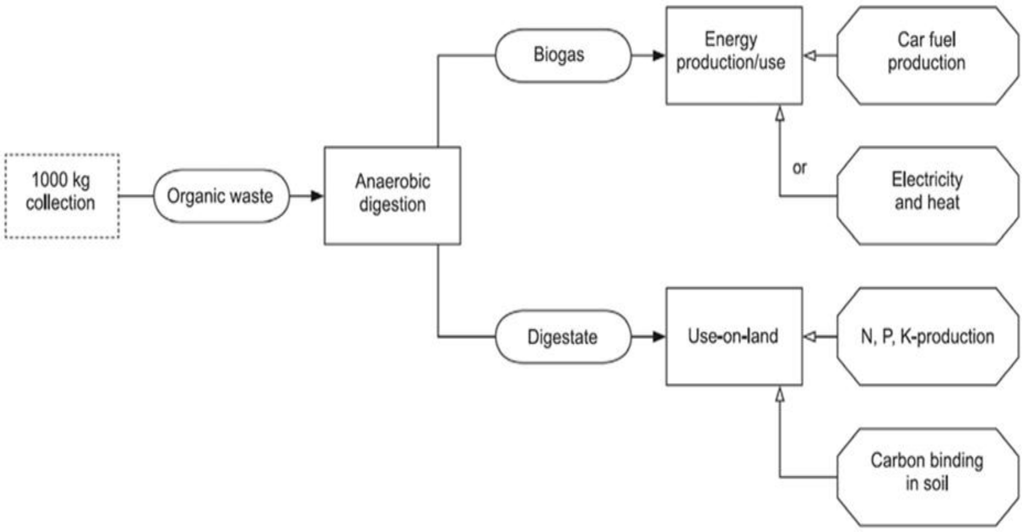


Figure 1.5.1 Conceptual overview of anaerobic digestion

Small-Scale Incineration: Mixed waste is burnt by incineration and produce 200–300 kWh/ton, but with 0.5–1 kg CO_2/kWh and dioxins without sophisticated filtration (WHO, 2021). It is not easily applicable in resource-scarce settings such as Addis Ababa due to high costs ($15,000–$20,000) and maintenance needs (Li et al., 2020).

Gasification: Gasification converts waste into syngas with 150–250 kWh/ton and reduced emissions (0.3–0.5 kg CO_2/kWh). It is less efficient when applied to wet trash, and its prices ($20,000–$30,000) require skilled operators (Ofori-Boateng et al., 2021), which is challenging in this city.

Addis Ababa Context

Addis Ababa's waste composition (60–70% organic) is suitable for AD technology, but sorting out waste is done by only 40% of the population due to a lack of awareness and infrastructure (Gebremariam & Assefa, 2022). The Reppie WTE plant, constructed for large scale incineration, is struggled by technical and financial problems, thus necessitating small-scale solutions (GIZ, 2023). Apartment complexes face irregular collection (47% dissatisfaction) and space constraints, necessitating compact, community-driven WTE systems (Tadesse et al., 2018).

Methods

Study Design

A mixed-methods, exploratory-applied design was used to assess WTE viability in three apartment complexes (small: 38 units, Lebu; medium: 78 units, Kazanchis; large: 144 units, Mexico), selected purposively for size diversity, resident demographics, and infrastructure suitability.

Data Collection

Resident Surveys (n=75, 25 per complex): Sorting willingness, attitudes toward WTE adoption, and cost-sharing were collected to evaluate the engagement of the community. Surveys also quantified waste generation (kg/unit/day) and composition (% food scraps, plastic, paper, other).

Stakeholder Interviews: Five experts (municipal official, NGO representative, two architects, Reppie project staff) gave information on WTE integration, costs, and Reppie's lessons.

Waste Characterization: Waste from one floor (2–4 units) per complex was measured daily for three weeks, classified as organic, recyclable and dry (non-recyclable).

Technical Assessments: Spaces (basements, rooftops) were measured and modeled using ArchiCAD to simulate 0.5-ton AD unit placement. Retrofitting needs (ventilation, insulation) and costs were estimated for existing vs. new buildings.

Data Analysis

- Quantitative data were analyzed in Excel for descriptive statistics (means, percentages, standard deviations) and chi-square tests for associations (e.g., complex size vs. waste output, income vs. sorting willingness).
- Qualitative interview responses were thematically coded for barriers (e.g., space, costs) and enablers (e.g., chute integration). Technologies were compared based on energy output (kWh/ton), emissions (kg CO_2/kWh), costs (ETB), and infrastructure compatibility (space availability, retrofitting needs).

Results

Waste Characterization

Daily waste production ranged from 0.6 kg/unit (small complex) to 1.1 kg/unit (large complex), with organic waste comprising 68–72% (Table 1). Large complex produced 158.4 kg/day (107.7 kg organic), medium complex produced 66.3 kg/day (47.7 kg organic), and small complex produced 22.8 kg/day (16 kg organic). Recyclables (23–27%) and dry waste (5%) were minor, supporting AD's focus on organic waste. Stable generation (SD=0.04–0.08 kg/day) ensured consistent feedstock for WTE systems.

large complexes (144 units, 72% at ≥1 kg/day) produced more waste than small complexes (38 units, 44% at ≥1 kg/day), with high correlations ($\chi^2=9.8$, $p<0.05$; $\chi^2=12.6$, $p<0.01$). Aligned with the waste log (0.6-1.1 kg/unit/day),

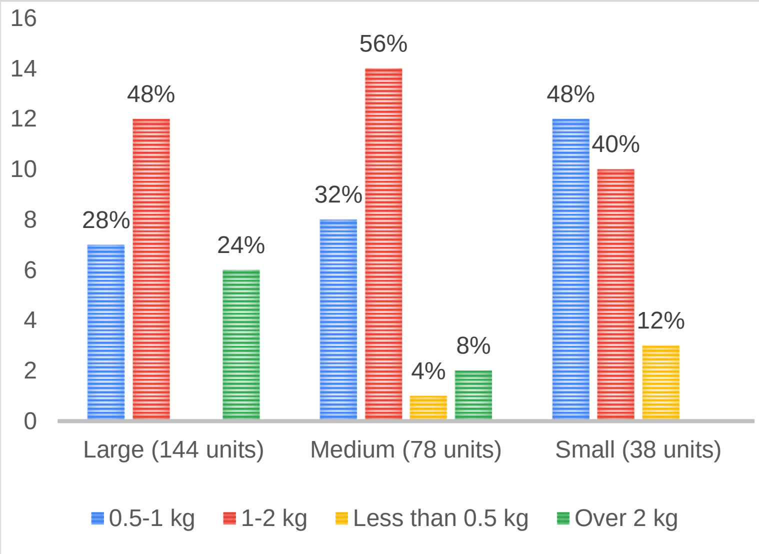


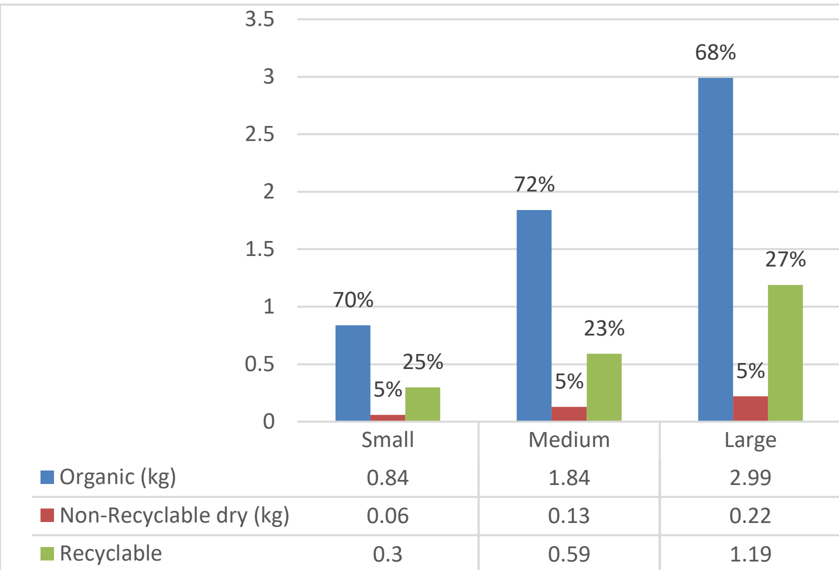
Figure 1.5.2. Daily Waste Production by Apartment Complex Size

Table 1.5.1. *Waste Generation and Composition by Apartment Complex*

Complex Size	Units	Daily Waste (kg/unit)	Organic (%)	Recyclable (%)	Dry (%)	Total Daily (kg)	Organic Daily (kg)
Small	38	0.6	70	25	5	22.8	16.0
Medium	78	0.85	72	23	5	66.3	47.7
Large	144	1.1	68	27	5	158.4	107.7

Note: Data from waste log (n=9 units, 3 weeks). SD=0.04–0.08 kg/day.

The high percentage of food waste (35%) was consistent with the waste log data's organic fraction (68-72%)



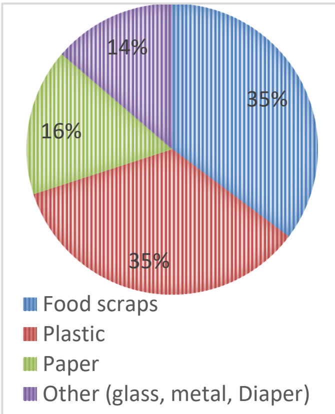


Figure 1.5.3 Daily Waste Composition by Complex

Figure 1.5.4. Percentage Distribution of Waste Types Reported by Residents

WTE Technology Assessment

Anaerobic Digestion (AD)

AD processes organic waste to produce biogas and digestate. A 0.5-ton AD unit, suitable for medium/large complexes, produced 15–25 kWh/day from 47.7–107.7 kg organic waste. Emissions were low (0.1–0.2 kg CO_2/kWh), and units take up 70–80% of basements (8–12 m²). Installation cost are ~$6,500 (≥877,500ETB), with ~$450 (≥60,750ETB)/year savings (20 kWh/day at $0.05/kWh, Vögeli et al., 2014), in a 6–7 years of payback. New designs required ventilation involved units at 100,000 ETB whereas Retrofitting needs improvements at 300,000 ETB. AD's high compatibility with high-moisture waste (72% organic) and frequent power outages (IEA, 2022) make it more likely feasible.

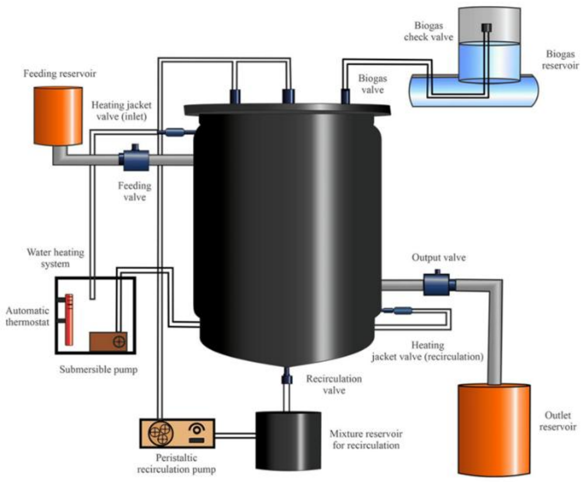


Figure 1.5.5. Schematic diagram of anaerobic digestion system

Small-Scale Incineration

Incineration burns mixed type of trashes, producing 200–300 kWh/ton appropriate for lighting or powering lifts. Emissions (0.5–1 kg CO_2/kWh) and risks of dioxins without filtration plants are environmental issues (WHO, 2021). Costs of installation ($15,000–$20,000) and additional operation cost complicate feasibility in Addis Ababa's limited resource context. The ability to manage unsorted wastes aligns with minimal sorting habits rate (43%), yet technical capacity is limited (Regassa et al., 2011).

Gasification

Gasification produces syngas, yielding 150–250 kWh/ton with emissions of 0.3–0.5 kg CO_2/kWh. It requires dry waste preprocessing, challenging for Addis Ababa's wet waste (72% organic). Costs ($20,000–$30,000)) and skilled operator needs limit adoption. Rooftop placement in small complexes adds extra structural costs, reducing compatibility (Ofori-Boateng et al., 2021)

Table 1.5.2. Comparison of Small-Scale WTE Technologies

Technology	Energy Output (kWh/ton)	Emissions (kg CO_2/kWh)	Cost	Space Requirement	Compatibility
AD	50–100	0.1–0.2	$5,000-$10,000	Basement (2m x 2m)	High
Incineration	200–300	0.5–1	$15,000–$20,000	Basement/Rooftop	Moderate
Gasification	150–250	0.3–0.5	$20,000–$30,000	Rooftop	Low

Note: Costs include installation; compatibility based on waste type and infrastructure

Infrastructure Compatibility

Medium and large complexes had 70–80% basement space, which was enough for AD units, and garbage chutes were accessible by 60% of residents, which made delivery of waste convenient. Small complexes had to utilize rooftops, which contributed to retrofitting costs (410,000 ETB vs. 400,000–430,000 ETB for medium/large). Architects gave priority to chute-linked AD units in new designs to minimize disruption and to fulfill resident preferences for simpler sorting (25%). Noise (mitigated by soundproofing) and odor (sealed units) were manageable.

Table 1.5.3. Infrastructure Compatibility by Complex Size

Complex Size	Basement Availability (%)	Chute Prevalence (%)	Retrofitting Cost (ETB)	Preferred WTE Placement
Small	20	40	410,000	Rooftop
Medium	70	60	400,000	Basement
Large	80	65	430,000	Basement

Note: Data from technical assessments and survey.

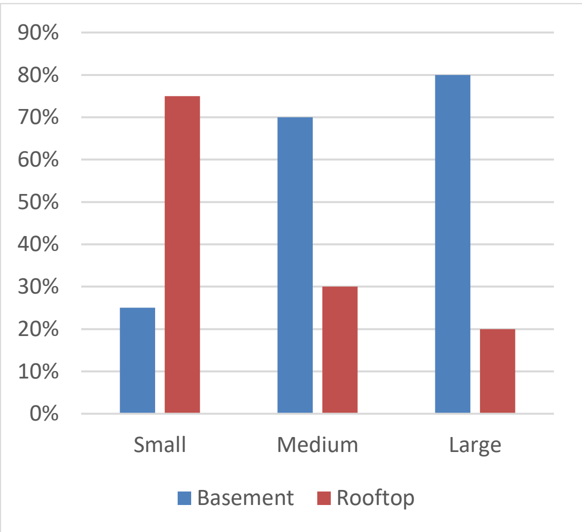


Figure 1.5.6 Available Space for WTE by Complex

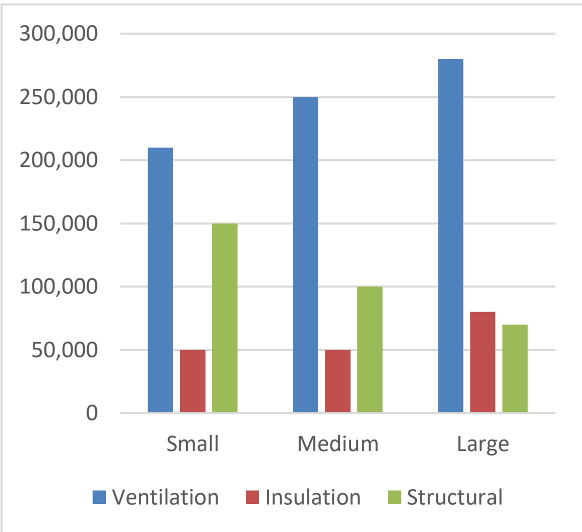


Figure 1.5.7 Retrofitting Costs for WTE by Complex

Community and Economic Considerations

Surveys showed 69% resident willingness to sort waste for WTE, 76% in medium complexes, with rewards as motivation (63% favored energy credits). High-income residents (>30,000 ETB) were more willing to contribute to costs (61%), while low-income residents (3,000–15,000 ETB) were 0% willing, and subsidies would be necessary. Microloans (≥337,500 ETB) and grants (≥405,000 ETB) were proposed by stakeholders to fund AD costs. Stigma (60% believed waste handling as low-status work) must be dispelled with education to increase acceptance.

Table 1.5.4. Resident Willingness and Economic Feasibility

Parameter	Small Complex	Medium Complex	Large Complex	Overall
Sorting Willingness (%)	64	76	68	69
Cost-Sharing Willingness (%)	40	48	44	47
Annual Savings (ETB)	45,000	65,000	80,000	-
Payback Period (Years)	8–10	6–7	5–6	-

Note: Savings based on 20 kWh/day at $0.05/kWh; payback for 877,500 ETB AD unit

Discussion

Energy Output and Environmental Impact

AD's comparatively low output (15–25 kWh/day) is ideal for medium/large complexes, powering lighting or cooking and reducing grid reliance amidst 3–5 weekly outages (IEA, 2022). Its low emissions (0.1–0.2 kg CO_2/kWh) aligns with WHO air quality guidelines, which are main issues in the polluted urban air of Addis Ababa (WHO, 2021). Incineration high yield is balanced by dioxin risk and cost, and gasification efficiency decreases with wet waste, limiting its feasibility (Ofori-Boateng et al., 2021). Landfill pressure is reduced by 70–90% with AD, which decreases Koshe's high amount waste disposal (Regassa et al., 2011).

Infrastructure Compatibility

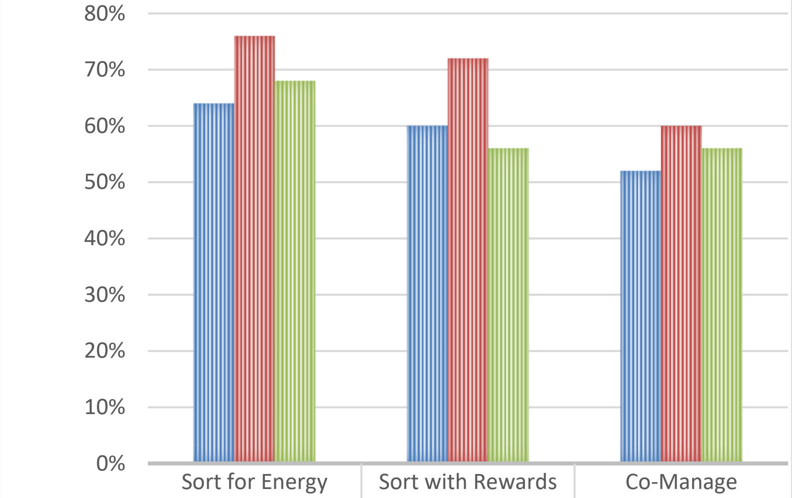
Basement space availability (70–80%) and chute availability (60%) in medium/large complexes facilitate AD integration. Rooftop reliance of small complexes increases cost, which suggests shared facilities or subsidy. Garbage Chute integrated designs has positive impact with residents' desire (25% preferred easier sorting) and decrease irregular collection (47% dissatisfaction), helps to increase the operational efficiency (Mwangi et al., 2022).

Comparative Analysis with Global Cases

Bangalore's AD system (60 kWh/day, 85% waste reduction) and Nairobi's waste exchange (75% waste reduction) highlight AD's potential, though Addis Ababa's lower sorting rates (43%) and stigma (60%) necessitate stronger education efforts. Belleville's Food Cycler pilot (3,100 tons/year diversion) suggests scalable waste reduction, but its countertop design is less suited to Addis Ababa's communal needs (Quinte News, 2024). AD's adaptability to organic waste and low-tech maintenance makes it preferable over incineration and gasification.

Community and Economic Viability

High sorting willingness (69%) and reward-driven participation (63%) indicate community buy-in, but stigma (60%) and low-income resistance (0% cost-sharing) require targeted interventions. Nairobi's biogas credit system offers a model for incentives (Mwangi et al., 2022). AD's 6–7-year payback is feasible with subsidies, aligning with circular economy goals (Ellen MacArthur Foundation, 2019). Policy reforms, like those suggested by stakeholders (microloans, grants), are critical for scalability.



	Sort for Energy	Sort with Rewards	Co-Manage
Small	64%	60%	52%
Medium	76%	72%	60%
Large	68%	56%	56%

This verified strong WTE support, particularly in medium complexes (76% sort), initiated by rewards (72%). Lower co-management willingness (56%) indicated a preference for passive participation (e.g., sorting), emphasizing the need for user-friendly systems and professional management to sustain engagement

Figure 1.5.8 Willingness to Adopt WTE by Complex

Limitations

Limited apartment-level WTE case studies in Addis Ababa constrained direct comparisons. Variability of waste data (SD=0.04–0.08 kg/day) suggests seasonal studies are necessary for AD sizing optimization. Limited data from Reppie constrained technical failure lessons. Stigma by residents (60%) and irregular collection (47%) require further behavioral research for long-term uptake.

Conclusion

Anaerobic digestion is the most viable small-scale WTE technology for Addis Ababa apartment complexes, processing organic waste (68–72%) to produce 15–25 kWh/day with negligible emissions (0.1–0.2 kg CO2/kWh). Medium complexes (78 units, 66.3 kg/day) are best suited for pilots due to high waste generation, basement availability (70%), and sorting willingness (76%). Incineration and gasification are less favorable due to cost ($15,000–$30,000), emissions, and technicality. Subsidies, chute integration, and stigma education are central to scalability, and thus AD is a keystone to Addis Ababa's circular economy and energy resilience.

Recommendations

- **Pilot AD in Medium Complexes:** utilize 0.5-ton AD units in 50–100-unit complexes, processing 66.3 kg/day organic waste for 15–25 kWh/day, with performance monitoring.
- **Incentives and Education:** Offer energy credits (63% resident support) and campaigns targeting women (65% willing to sort) to reduce stigma (60%).
- **Policy Support:** Secure microloans (377,500 ETB) and grants (405,000 ETB) to finance 877,500 ETB AD costs, prioritizing low-income residents.
- **Simplify Sorting Processes**: Install color-coded, odor-proof chutes and bins in medium and large complexes to streamline sorting, replacing irregular collection with daily organic waste pickups to improve efficiency.
- **Community Engagement Campaigns**: Launch local media campaigns emphasizing environmental benefits and community pride.
- **Monitoring and Feedback**: Establish resident committees to monitor AD performance, and provide transparent reports on energy savings and waste reduction.

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APPENDIX 2: Resident Survey Questionnaire

Instructions: Please answer honestly. Your responses are confidential and will help improve waste management in your building. (Takes 5-10 min)

1. Demographics
   - Gender: [ ] Male, [ ] Female
   - Household Size: [ ] 1-3, [ ] 4-7, [ ] 7-10, [ ] 10+
   - Age range of household members: [ ] Toddlers, [ ] Under 18, [ ] 18-30, [ ] 31-45, [ ] 46-60, [ ] Over 60
   - Apartment Complex: [ ] Small (38units), [ ] Medium (78 units), [ ] Large (144 units)
   - Income levels: [ ] Low Income (3,000– 5,000 ETB), [ ] Mid- Medium Income (5,000 – 15,000 ETB), [ ] Medium Income (15,000 – 30,000 ETB), [ ] High (>30,000 ETB)
2. Waste Generation Habits
   - How much waste does your household produce on a daily basis? Approximately (1 kg = small trash bag) [ ] Less than 0.5 kg [ ] 0.5-1 kg [ ] 1-2 kg [ ] Over 2 kg
   - What is the main type of waste that you throw away? [ ] Food scraps [ ] Plastic [ ] Paper [ ] Other (specify e.g. glass, metal: ______)
3. Current Waste Practices
   - Do you sort waste (e.g., organic vs. recyclable) before disposing of it? [ ] Always, [ ] Sometimes [ ] Never (If never why? ______)
   - How is waste collected in your building? [ ] Daily pickup [ ] Weekly pickup [ ] Irregular [ ] Self-disposal
   - Does your building have a garbage chute? [ ] Yes, [ ] No
   - Are you satisfied with waste collection here? [ ] Very satisfied [ ] Somewhat satisfied [ ] Not satisfied (why: ______)
4. Willingness to Adopt WTE
   - Would you sort waste if it is utilized as energy (e.g., lighting, cooking gas)? [ ] Yes [ ] Maybe (depends on: ______) [ ] No
   - Would rewards like energy credits or lower bills encourage you to join a waste exchange program? [ ] Yes [ ] Maybe [ ] No
   - Would you be willing to share the cost of implementing waste-to-energy technologies in your building? [ ] Yes, [ ] No
   - Could you help manage a WTE system (e.g., feeding waste, basic upkeep) with others? [ ] Yes [ ] Maybe (depends on: ______) [ ] No
5. Open-Ended
   - What would make you more likely to support a WTE system in your building? (e.g., training, benefits, simpler sorting)

APPENDIX 3: Sample Resident Survey Response

Instructions: Please answer honestly. Your responses are confidential and will help improve waste management in your building. (Takes 5-10 min)

1. Demographics
    - Gender: [ ] Male, [✓] Female
    - Household Size: [ ] 1-3, [✓] 4-7, [ ] 7-10, [ ] 10+
    - Age range of household members: [✓] Toddlers, [✓] Under 18, [ ] 18-30, [✓] 31-45, [ ] 46-60, [ ] Over 60
    - Apartment Complex: [ ] Small (38units), [ ] Medium (78 units), [✓] Large (144 units)
    - Income levels: [ ] Low Income (3,000– 5,000 ETB), [ ] Mid- Medium Income (5,000 – 15,000 ETB), [ ] Medium Income (15,000 – 30,000 ETB), [✓] High (>30,000 ETB)
2. Waste Generation Habits
    - How much waste does your household produce on a daily basis? Approximately (1 kg = small trash bag) [ ] Less than 0.5 kg [ ] 0.5-1 kg [ ] 1-2 kg [✓] Over 2 kg
    - What is the main type of waste that you throw away? [✓] Food scraps [✓] Plastic [✓] Paper [ ] Other (specify e.g. glass, metal: ______)
3. Current Waste Practices
    - Do you sort waste (e.g., organic vs. recyclable) before disposing of it? [✓] Always, [ ] Sometimes [ ] Never (If never why? ______)
    - How is waste collected in your building? [ ] Daily pickup [ ] Weekly pickup [ ] Irregular [✓] Self-disposal
    - Does your building have a garbage chute? [✓] Yes , [ ] No
    - Are you satisfied with waste collection here? [ ] Very satisfied [✓] Somewhat satisfied [ ] Not satisfied (why: ______)
4. Willingness to Adopt WTE
    - Would you sort waste if it is utilized as energy (e.g., lighting, cooking gas)? [✓] Yes [ ] Maybe (depends on: ______) [ ] No
    - Would rewards like energy credits or lower bills encourage you to join a waste exchange program? [✓] Yes [ ] Maybe [ ] No
    - Would you be willing to share the cost of implementing waste-to-energy technologies in your building? [✓] Yes, [ ] No
    - Could you help manage a WTE system (e.g., feeding waste, basic upkeep) with others? [ ] Yes [ ] Maybe (depends on: ______) [✓] No
5. Open-Ended
    - What would make you more likely to support a WTE system in your building?

      ANS: Benefits and Simpler sorting

APPENDIX 4: Semi-Structured Interview

Expert Interview on Integration of WTE into Apartment Buildings

Purpose: To investigate how small-scale WTE systems can be integrated into Addis Ababa's apartment blocks feasibly, considering available space, structural, and costs.

1. Where might a small waste-to-energy plant for an ordinary Addis Ababa apartment complex, maybe 20-30 units fit, like basements or rooftops or other options?
   - Follow-up: What are the challenges of each spot space, access, load or other challenges?
2. What design features limit WTE integration?
3. Could new apartments be planned with WTE in mind, or is retrofitting old ones more realistic?
   - Follow-up: What changes would each need structural or utility changes are needed?
4. What's one design tip to make WTE fit Addis Ababa's apartments something simple but game-changing?"
   - Follow-up: Why would that matter most here?

Stakeholder Interview on WTE Technologies and Reppie Project Insights

1. Any past projects successful or not that show how funding could work or fail for this?
2. If a system saves money like cutting waste fees or powering lights how could that convince funders or residents to invest?
3. What other benefits might sway investors?
4. From your perspective, what was Reppie supposed to achieve like how much tons of waste processed or energy made?
5. What's stopping Reppie from running as planned now technical, financial or policy issues?
6. What lessons from Reppie could help design a small-scale WTE setup for apartments?

APPENDIX 5: Waste Characterization Survey: Log Sheet

Title: Daily Waste Collection Record

Purpose: To track waste amounts and types from apartment complexes over three weeks.

Instructions: Fill out each day after weighing waste from bins. Use one sheet per complex per week. Record in kilograms (kg). Note any unusual observations.

- Apartment Complex: [ ] Small (38 units), [ ] Medium (78 units), [ ] Large (144 units)
- Location: _______________
- Number of Participating Households: _______________
- Week Number: _______________

Date	Non-Recyclable Wet (Organic, e.g. food scraps)	Non-Recyclable dry (e.g. textiles)	Recyclable (e.g. plastic, paper)	Total Waste (Recyclable + Non-Recyclable)	Notes (e.g. peak day, unusual items)
Day 1 (e.g. 01/04/2025)					
Day 2					
Day 3					
Day 4					
Day 5					
Day 6					
Day 7					
Weekly Total					

Recorder Name: _______________

Signature: _______________

Date Submitted: _______________

APPENDIX 6: Filled Waste Characterization Log Sheet

Title: Daily Waste Collection Record

Purpose: To track waste amounts and types from apartment complexes over three weeks.

Instructions: Fill out each day after weighing waste from bins. Use one sheet per complex per week. Record in kilograms (kg). Note any unusual observations.

- Apartment Complex: [ ] Small (38 units), [✓] Medium (78 units), [ ] Large (144 units)
- Location: Kazanchis
- Number of Participating Households: 3 Households (one floor)
- Week Number: 1

Date	Non-Recyclable Wet (Organic, e.g. food scraps)	Non-Recyclable dry (e.g. textiles)	Recyclable (plastic)	Total Waste (Recyclable + Non-Recyclable)	Notes (e.g. peak day, unusual items)
Day 1 (07/04/2025)	1.84	0.13	0.58	2.55	
Day 2 (08/04/2025)	1.8	0.13	0.57	2.5	
Day 3 (09/04/2025)	1.88	0.12	0.6	2.6	
Day 4 (10/04/2025)	1.82	0.14	0.58	2.54	
Day 5 (11/04/2025)	1.85	0.13	0.59	2.57	
Day 6 (12/04/2025)	1.9	0.13	0.61	2.64	Weekend, slight increase
Day 7 (13/04/2025)	1.81	0.12	0.58	2.51	
Weekly Total	12.9	0.9	4.11	17.91	Average: 2.56 kg/day

Recorder Name: Mohammed Nur

Signature: _______________

Date Submitted: 14/04/2025

APPENDIX 7: Technical Feasibility Assessment

- Measure available spaces (e.g., basements, rooftops) using tape measures length, width, height (m).
- Obtain or sketch building layouts to identify utility areas, access points and structural limits.
- Assess retrofitting needs (e.g., ventilation, insulation) for existing buildings vs. ideal placement in new designs.
- Simulate a 0.5-ton/day AD unit installation using ArchiCAD software, estimating biogas piping to kitchens or lighting.
- Record constraints (e.g., space, noise, installation cost or resident disruption) and solutions.