Sustainable Management of Organic Waste in Municipalities: Pathways to Bio-Energy, Bio-Fertilizer Production, and Climate Action

Mbugua J. K[1], & Waswa A. G[2]

[1]Limuru Municipality, Kiambu County P.O. BOX 2344-00900, Kiambu, Kenya

[2]Department of Physical Science, South Eastern Kenya University, P.O. Box 170-90200 Kitui, Kenya

Abstract

Kenya's municipalities are experiencing rapid urbanization, which has led to a significant increase in the generation of organic waste, particularly from slaughterhouses, open-air markets, and wastewater systems. Poor management of this waste contributes heavily to environmental pollution, public health hazards, and greenhouse gas (GHG) emissions. This study investigates sustainable pathways for managing municipal organic waste, with a focus on waste-to-bioenergy and waste-to-biofertilizer solutions as integral components of climate action. This research emphasizes the untapped potential of anaerobic digestion and composting technologies to convert slaughter and market wastes into valuable energy and agricultural inputs. It also examines the role of decentralized treatment systems in mitigating methane emissions and enhancing urban sanitation. Grounded in Kenya's policy context and supported by recent literature; the study outlines the technical, institutional, and financial barriers to adopting circular waste strategies. It proposes a multi-stakeholder approach involving local governments, private sector actors, and development partners to implement scalable, low-carbon solutions. The paper concludes with targeted recommendations aimed at improving source segregation, promoting decentralized biogas and composting systems, enforcing wastewater treatment regulations, and unlocking climate finance opportunities. These strategies, if well-executed, could transform Kenya's urban waste landscape into a driver of green growth, public health, and environmental sustainability.

Keywords

Bio-enegy, Bio-fertilizer, Climate Action, Municipalities, Sustainability

1. Introduction

The exponential growth of urban populations across Kenya's municipalities has led to an unprecedented surge in organic waste generation, particularly from slaughterhouses, open-air markets, and urban wastewater systems [1]. According to the National Environment Management Authority (NEMA), over 60% of solid waste generated in urban Kenya is organic, yet only a fraction of that is safely managed or valorized [2]. Slaughterhouses produce significant amounts of organic waste-including blood, intestinal contents, fats, and bones-while markets contribute large volumes of biodegradable vegetable and fruit residues. Compounding the issue, untreated wastewater from these facilities and surrounding urban areas often flows directly into rivers and drainage systems, contributing to environmental degradation, disease outbreaks, and the emission of greenhouse gases (GHGs) such as methane and nitrous oxide [3-5].

The mismanagement of organic waste has far-reaching socio-economic and environmental consequences. Municipal landfills are overwhelmed, informal dumpsites proliferated, and valuable resources are lost rather than recovered. At the same time, Kenya is grappling with pressing challenges related to climate change, energy insecurity, soil degradation, and urban food insecurity. Ironically, the organic waste burden-if well-managed-offers a pathway to multiple sustainable development objectives. Technologies for converting waste to bioenergy and biofertilizer are now technically and economically viable, offering municipalities an opportunity to transition from linear waste disposal systems to circular economy models [6,7].

Globally, many cities have adopted sustainable waste-to-resource models, using anaerobic digestion for bioenergy generation and composting for organic fertilizer production. In Kenya, however, these innovations remain underutilized or implemented at only a small scale, often by private entrepreneurs or community groups. For instance, Nairobi's Dagoretti slaughterhouse has piloted biogas production, but lacks the investment to scale up to a city-wide system [8,9]. Similarly, market waste in cities like Kisumu and Mombasa is often dumped or burned rather than converted into compost or digestate. The lack of regulatory incentives, limited awareness, and weak enforcement of waste segregation laws have stalled progress, even as climate change intensifies and the demand for clean energy and soil fertility grows [10].

This study, therefore, investigates the sustainable management of organic waste in Kenya's municipalities, with a specific focus on slaughterhouse waste, market waste, and wastewater. It explores integrated approaches that can transform these waste streams into bioenergy and biofertilizer while contributing to climate change mitigation. Through

this lens, the research aligns with Kenya's Vision 2030, its Nationally Determined Contributions (NDCs) under the Paris Agreement, and the Sustainable Development Goals (SDGs)-particularly SDG 11 (Sustainable Cities and Communities), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

The objectives of this study are threefold: first, to assess the nature and scale of organic waste from slaughterhouses, markets, and wastewater systems in urban Kenya; second, to evaluate the current waste management practices and identify opportunities for bioenergy and fertilizer recovery; and third, to analyze the climate impacts of organic waste and the potential mitigation strategies available. By focusing on practical, scalable solutions grounded in Kenya's context, the study contributes to policy making, investment planning, and community awareness around sustainable waste management.

In summary, Kenya stands at a crossroads where urban waste challenges could either spiral into ecological crises or be harnessed as a lever for environmental sustainability, clean energy, and rural-urban development. The transformation of organic waste into energy and fertilizers presents a viable and urgent path forward-one that this research seeks to illuminate in both theoretical and applied terms.

2. Literature Review

2.1 Overview of Organic Waste in Urban Kenya

Kenya's urban centers are experiencing rapid population growth, which has consequently led to a rise in waste generation, especially organic waste. According to the Kenya National Bureau of Statistics [11], municipal solid waste generation exceeds 8 million tonnes annually, with over 65% categorized as organic. Marketplaces and slaughterhouses are identified as the largest single-point sources of biodegradable waste in urban Kenya. Market waste includes vegetable residues, fruits, peels, and food remains, while slaughterhouse waste comprises blood, bones, ruminal contents, and fats [12]. Wastewater from these sources is often untreated, discharged directly into drainage systems or open environments [13]. Despite this massive waste potential, resource recovery remains negligible.

2.2 Slaughterhouse and Market Waste Characteristics

Organic waste from slaughterhouses and markets is rich in nutrients and biochemical energy, making it highly suitable for recovery processes such as anaerobic digestion and composting [5]. Recent studies have shown that slaughterhouse waste has high biochemical methane potential (BMP), with total solids ranging between 10 - 20 % and volatile solids between 60 - 80 % [14,15]. Market waste, although seasonally variable, contains high levels of carbohydrates and moisture content, which supports rapid microbial decomposition [16]. These characteristics are crucial for determining the viability of bioenergy and biofertilizer production [5].

However, the current disposal methods for these wastes are inefficient and environmentally harmful. Common practices include dumping in open spaces, incineration, and discharge into waterways-all of which contribute to public health risks and GHG emissions [17]. Municipal authorities lack adequate infrastructure for segregating, collecting, and processing this waste sustainably.

2.3 Organic Waste to Bio-Energy

Bioenergy production, particularly biogas generation through anaerobic digestion (AD), has emerged as a promising solution for urban organic waste. Anaerobic digestion involves the breakdown of organic matter by microorganisms in the absence of oxygen, producing methane-rich biogas and nutrient-rich digestate. According to Mbugua and Gikonyo et al., [4,18], pilot biogas plants in Nairobi and Kisumu have demonstrated technical feasibility, yet remain underutilized due to inconsistent feedstock supply and inadequate public-private partnerships.

The potential for bioenergy in Kenya is significant. A study by the Kenya Association of Manufacturers [19] estimated that Nairobi's daily slaughterhouse and market waste could produce over 35,000 m^3 of biogas per day-enough to power small industries and provide cooking gas to over 50,000 households. Integrating biogas systems with wastewater treatment plants, as proposed in Kisumu County's Integrated Urban Waste Management Plan (2022), can further optimize energy recovery while addressing water pollution

Still, barriers such as financing constraints, lack of trained personnel, and policy fragmentation continue to hinder widespread adoption of bioenergy systems. The Energy and Petroleum Regulatory Authority highlights the need for targeted subsidies, carbon credit frameworks, and training programs to scale up the use of organic waste for energy in urban areas [20].

2.4 Organic Waste to Bio-Fertilizer

Beyond energy recovery, the transformation of organic waste into bio-fertilizer offers an equally vital path for sustainable waste management. Composting and the use of anaerobic digestate as fertilizer enriches soils, improves crop yields, and reduces dependence on chemical fertilizers. Urban and peri-urban farmers can particularly benefit from locally produced compost and digestate, which are cost-effective and environmentally friendly [4,21].

Studies from Nakuru and Eldoret municipalities indicate that market and slaughterhouse compost can meet over 40% of the organic fertilizer demand for urban farming [22]. However, concerns about pathogen content, heavy metals, and odor have limited public acceptance and regulation. Compost quality certification and education campaigns are necessary to promote wider use. Additionally, circular business models, such as farmer co-operatives managing composting units, have shown promise in building local value chains [23].

The government has incorporated composting into the National Sustainable Waste Management Policy (2022) [24], encouraging counties to develop material recovery facilities (MRFs) and compost hubs. Despite this progress, implementation remains patchy, and support mechanisms for community-based initiatives are limited [25].

2.5 Wastewater Reuse and Integration

Wastewater from slaughterhouses and marketplaces is a significant but overlooked resource in Kenya's urban waste management landscape. If properly treated, this wastewater can be reused in irrigation or aquaculture. More importantly, coupling anaerobic digesters with high-strength wastewater from abattoirs can enhance biogas yields by up to 30%, as demonstrated in recent pilot studies in Kiambu and Kisii [26].

Constructed wetlands, upflow anaerobic sludge blanket reactors (UASBs), and decentralized wastewater treatment systems (DEWATS) have been identified as cost-effective and scalable solutions for Kenyan towns. However, their adoption remains minimal due to high capital costs and inadequate technical knowledge. Public health risks related to untreated wastewater are substantial, with studies showing high incidences of gastrointestinal diseases in communities living near open discharge points [27-29].

2.6 Climate Change and GHG Emissions from Organic Waste

Organic waste, when improperly managed, contributes significantly to greenhouse gas emissions, mainly methane (CH_4) from anaerobic decay in landfills and nitrous oxide (N_2O) from untreated effluents. These gases are up to 28 and 265 times more potent than CO_2, respectively, in terms of global warming potential. According to Kenya's Third National Communication to the UNFCCC [30], municipal waste contributes approximately 5.8% of total national GHG emissions.

Waste-to-energy and composting offer powerful mitigation pathways. The capture of methane from anaerobic digesters prevents its release into the atmosphere, while composting reduces the formation of leachate and CH_4 in landfills. Furthermore, substituting chemical fertilizers with organic digestate reduces N_2O emissions from agriculture. These climate co-benefits are critical as Kenya seeks to fulfill its Nationally Determined Contributions (NDCs), which include a 32% reduction in GHG emissions by 2030 [31].

2.7 Policy and Institutional Framework

The legal framework governing waste management in Kenya has evolved significantly in recent years. The Sustainable Waste Management Act (2022) mandates counties to adopt circular waste solutions, including recovery, recycling, and energy generation. NEMA has also developed guidelines for biowaste segregation and safe composting. Nonetheless, there remains a gap in harmonizing environmental, health, and energy policies to support integrated organic waste solutions.

Capacity building, enforcement of source segregation, and investment in infrastructure are still insufficient. International partnerships and green financing-such as through the Green Climate Fund (GCF) or Africa Adaptation Acceleration Program (AAAP)-could catalyze adoption of bioenergy and fertilizer technologies in Kenya's urban centers [1].

3. Methodology

3.1 Research Design

This study adopts a qualitative-descriptive research design, supplemented by secondary data analysis, to explore sustainable organic waste management in Kenyan municipalities, particularly focusing on slaughterhouse waste, market waste and wastewater. The design facilitates a comprehensive analysis of current practices, technological options, policy environments, and climate implications relevant to the Kenyan urban context.

3.2 Study Area and Scope

The research primarily focuses on urban areas/municipalities in Kenya, with case references from Nairobi, Kisumu, Nakuru, and Mombasa, where waste generation is high, and pilot resource recovery systems exist. The types of waste included are:

- Slaughterhouse waste (bones, blood, fats, ruminal content)
- Market waste (fruits, vegetables, peels)
- Wastewater (from abattoirs and markets)

The scope includes assessing their potential for bio-energy and bio-fertilizer production, and implications for climate mitigation strategies.

3.3 Data Collection

This study relies primarily on secondary data sources, including:

- Government reports e.g. Ministry of Environment and Forestry, Ministry of Water and Sanitation.
- County Integrated Waste Management Plans (CIWMPs)
- Peer-reviewed journals published between 2019 and 2025
- Reports from regulatory bodies like NEMA, EPRA, and UNEP
- Pilot project documentation from NGOs and academic institutions

The data collected includes statistics on waste generation volumes, composition, treatment methods, GHG emissions, biogas potential, and compost output.

3.4 Data Analysis

A thematic content analysis approach was used to synthesize findings from the collected literature. The main themes guiding the analysis included:

- Current state and challenges in municipal organic waste management
- Technological options for waste recovery
- Environmental and climate impacts of organic waste
- Policy and regulatory frameworks
- Case studies and best practices in Kenya

The data was organized and analyzed using Microsoft Excel and NVivo software to identify trends, patterns, and policy gaps relevant to waste valorization in Kenya.

3.5 Ethical Considerations

Since the study is based on secondary data, no human participants were involved. However, all data sources were cited appropriately, and only publicly accessible or institutionally authorized materials were used. The study complies with the academic integrity and ethical standards set by the institution.

4. Results and Discussion

4.1 Overview of Organic Waste Generation in Kenyan Municipalities

Urban areas/municipalities in Kenya are experiencing significant growth in waste generation, driven by population increase, urbanization, and economic activities. According to the National Environment Management Authority [2], Kenya produces approximately 8 million tonnes of waste annually, with over 60% being organic. Major sources include slaughterhouses, urban markets, and institutional kitchens, alongside domestic and wastewater sources [32].

In cities such as Nairobi, Mombasa, Kisumu, and Nakuru, slaughterhouse waste is considerably high. For instance, Dagoretti and Kariokor abattoirs in Nairobi process more than 1,500 animals per day, generating significant volumes of blood, rumen contents, manure, and fats [11,33]. Similarly, Gikomba and Wakulima markets produce tonnes of vegetable and fruit waste daily, much of which ends up in landfills or is dumped into water drains. Additionally, wastewater from abattoirs and markets, often untreated, contributes to organic pollution and methane emissions [5,6].

Despite the predominance of organic waste, municipal waste systems remain largely linear, with limited segregation, recovery, or recycling, undermining resource recovery and increasing environmental and public health risks [4].

4.2 Bio-Energy Recovery from Slaughter and Market Wastes

Bio-energy presents a promising pathway for managing municipal organic waste in Kenya. Anaerobic digestion (AD) is particularly effective for processing high-organic-content waste such as slaughterhouse effluents and market residues. Through microbial activity in oxygen-free environments, anaerobic digestion produces biogas (mainly methane) and digestate [5,14].

Studies show that slaughterhouse waste, due to its high lipid and protein content, has a biogas potential of 0.65 - 0.85 m^3/kg of volatile solids, making it more efficient than purely vegetable-based waste [13,34,35]. When combined with market waste in co-digestion systems, the balance of carbon-to-nitrogen ratio improves, enhancing methane production and stabilizing digestate quality [14,16,34].

Successful initiatives include:

- Kisumu Integrated Slaughterhouse Pilot: Produced biogas used for heating and waste sanitation, significantly reducing methane emissions and operating costs.

- Mukuru Biocentres in Nairobi: Utilize organic market and fecal waste to generate biogas for communal kitchens, improving sanitation and reducing reliance on firewood.

However, barriers remain. Most Kenyan municipalities lack:

- Infrastructure for large-scale biodigesters, technical expertise in biogas system design and operation, Financial incentives to attract private investment, And public awareness of the benefits of bio-energy recovery.

Furthermore, waste segregation at the source is almost non-existent, complicating feedstock quality control.

4.3 Bio-Fertilizer Production from Organic Waste

Following anaerobic digestion, the digestate can be refined into bio-fertilizers, rich in nitrogen, phosphorus, and potassium. This offers a sustainable alternative to synthetic fertilizers, whose use in Kenya has declined due to high costs [36,37].

Experiments by Egerton University (2022) demonstrated that composted vegetable and slaughterhouse waste produced high-quality organic fertilizer, improving maize and tomato yields by up to 20% in peri-urban farms. Additionally, wastewater sludge, when treated and stabilized, can be used as soil conditioner, improving water retention and fertility [38].

In urban areas, organizations like the Dandora Green Composting Project are composting market waste to supply peri-urban farms. Despite these efforts, scaling up is challenged by:

- Lack of clear compost quality standards,
- Weak distribution channels for bio-fertilizers,
- Negative public perception of using waste-based fertilizers,
- And limited funding for decentralized composting systems.
- Integrating slaughter and market waste into structured composting programs, with adequate pretreatment and pathogen management, can unlock large-scale fertilizer production, reduce landfill volumes, and promote circular agriculture.

4.4 GHG Emissions from Organic Waste Stream.

Kenya's municipal organic waste is a major contributor to greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O). These emissions arise from:

- Anaerobic decomposition in open dumpsites e.g.Dandora,
- Untreated wastewater, especially from abattoirs,
- Burning of organic market waste, a common practice in informal settlements.

The Ministry of Environment and Forestry [10] estimates that methane emissions from waste contribute about 7.2% of Kenya's total GHG emissions. Open dumping of food waste can release 20-30 times more methane than controlled anaerobic digestion.

Wastewater from slaughterhouses is especially problematic. A study by WASREB (2023) found that less than 30% of slaughterhouses in urban Kenya treat their wastewater. When this high-BOD wastewater enters open drains, it decays anaerobically, releasing methane and polluting surface water [39].

Mitigating these emissions is essential for meeting Kenya's Nationally Determined Contributions (NDCs) under the Paris Agreement. Integrating AD and composting into municipal waste strategies not only reduces emissions but generates renewable energy and improves soil health [40,41].

4.5 Mitigation Strategies and Opportunities

Several strategic interventions can be implemented to mitigate the climate and environmental impacts of organic waste in Kenya:

4.5.1 Strengthening Regulatory Frameworks

Kenya has made progress with the Sustainable Waste Management Act (2022) [42-44] and the Climate Change Act (Amendment, 2023) [45]. These laws mandate waste segregation at source, encourage public-private partnerships, and promote circular economy principles. However, enforcement remains weak. County governments must:

- Implement source-segregation mandates,
- Incentivize organic waste collection systems,
- And develop localized waste-to-resource action plans.

4.5.2 Decentralized Waste-to-Resource Technologies

Instead of relying on large centralized plants, cities can adopt modular biogas and composting units near major waste generation points-markets, slaughterhouses, and informal settlements.

For example:

- The Biogas International Ltd. Project in Nakuru uses modular digesters to serve slaughter facilities.
- Jua Kali cooperatives can be engaged to run community composting sites, creating jobs and reducing transport costs.

4.5.3 Financing Mechanisms and Incentives

Access to green financing, carbon credits, and climate bonds can drive investment into organic waste recovery. Programs like Kenya Climate Innovation Center (KCIC) and AGNES support start-ups in this field. More county-specific financing frameworks are needed to attract local entrepreneurs.

4.5.4 Public Awareness and Capacity Building

Without public support and awareness, source segregation and community-level recovery remain difficult. Public campaigns, school programs, and training for market traders and slaughterhouse staff can transform waste behavior.

4.6 Case Study: Nairobi City County

Nairobi generates over 2,500 tonnes of waste daily, 65% of which is organic. Yet, collection services only cover 40-45% of the city, and the rest is dumped illegally or burnt (Nairobi City County, 2022) [20].

Despite challenges, initiatives are emerging:

- Mukuru Biocentres provide clean energy from organic waste to slum households.
- Private firms like TakaTaka Solutions collect and compost market waste, selling the compost to peri-urban farmers.
- Pilot slaughterhouse digesters in Dagoretti show promise but remain small in scale.

Scaling these initiatives citywide requires stronger institutional coordination, technical support, and integration with Nairobi's County Climate Action Plan (CCAP, 2023) [46].

5. Conclusion and Recommendations

5.1 Conclusion

The sustainable management of organic waste in Kenyan municipalities-especially from slaughterhouses, open-air markets, and wastewater-presents a critical opportunity for both environmental protection and resource recovery. As demonstrated throughout this study, the current waste management systems are largely linear, dominated by unsorted dumping, open burning, and minimal recovery efforts. This status quo contributes significantly to greenhouse gas (GHG) emissions, especially methane and nitrous oxide, thereby exacerbating Kenya's vulnerability to climate change.

Organic waste constitutes over 60% of Kenya's municipal solid waste. Slaughter and market waste, alongside high-strength wastewater, form a considerable portion of this biodegradable waste stream. Yet, these waste types possess immense potential as feedstocks for circular economy pathways, especially anaerobic digestion for bio-energy production and composting for bio-fertilizer generation.

Innovative solutions such as decentralized anaerobic digesters, composting hubs, and sludge treatment systems can help convert municipal organic waste into clean energy, agricultural inputs, and economic opportunities. These solutions also provide co-benefits including improved sanitation, climate mitigation, job creation, and soil health restoration.

Despite the promise, the actual uptake of these technologies remains limited due to weak policy enforcement, inadequate technical capacity, insufficient investment incentives, and lack of public awareness. Furthermore, most counties lack the infrastructure for waste segregation, organized organic waste collection, and professional waste valorization systems.

Meeting Kenya's Nationally Determined Contributions (NDCs) and Vision 2030 targets will depend significantly on how effectively the country integrates organic waste management into its climate action and sustainable urban planning frameworks.

5.2 Recommendations

5.2.1. Develop and Enforce Source Segregation Policies

Mandatory source segregation of organic waste at markets, slaughterhouses, and food establishments should be implemented by county governments. This can be supported through:

- Training programs for market vendors and butchers.
- Provision of color-coded bins and signage.
- Fines and incentives to promote compliance.

5.2.2. Invest in Decentralized Waste-to-Energy Systems

Municipalities should prioritize small to medium-scale biogas plants at key waste generation points such as:

- Slaughterhouses (e.g., Dagoretti, Kisumu, Eldoret),
- Central markets (e.g., Gikomba, Kongowea),
- Informal settlements where sanitation and fuel access are limited.
- Partnerships with companies like Biogas International Ltd. and NGOs such as Practical Action can help design, fund, and manage these systems.

5.2.3. Scale up Composting and Bio-Fertilizer Programs

County departments of agriculture should partner with waste management firms to:

- Collect and compost market and household food waste.
- Set up regional composting centers with certified quality standards.
- Promote bio-fertilizer use among smallholder farmers via extension services.

Policy support should also be given for the formal recognition and certification of organic compost products.

5.2.4. Regulate and Treat Slaughterhouse Wastewater

Enforce existing environmental laws requiring effluent treatment before discharge. Counties should:

- Mandate installation of wastewater pre-treatment units at all licensed slaughterhouses.
- Promote co-treatment of slaughterhouse wastewater with fecal sludge in municipal systems.
- Offer tax incentives or low-interest loans for facilities investing in wastewater treatment technologies.

5.2.5. Leverage Green Financing and Climate Fund

Counties and private sector actors should actively pursue climate finance mechanisms, including:

- Carbon credits for avoided methane emissions,
- Green bonds for infrastructure development,
- Grants and technical support from organizations such as KCIC, UNEP, FAO, and GEF.
- Strengthen Public Awareness and Institutional Capacity

National and county governments must invest in long-term awareness campaigns to:

- Change public attitudes towards waste handling.
- Encourage community ownership of composting and biogas projects.
- Build capacity of local artisans, technicians, and youth in waste-to-resource technologies.

Capacity-building programs for county staff, environmental inspectors, and waste entrepreneurs will be essential for implementation and oversight.

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- Capacity-building programs for county staff, environmental inspectors, and waste entrepreneurs will be essential for implementation and oversight.

5.3 Final Remarks

As Kenya’s urban population grows and the impacts of climate change intensify, the need to rethink waste management becomes more urgent. Focusing on organic waste-particularly from slaughterhouses, markets, and wastewater-can lead to transformational change in urban sustainability, food security, and emissions reduction. The technologies exist. The policies are emerging. What remains is bold implementation, effective partnerships, and community engagement to transition Kenya from waste crisis to circular opportunity.

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