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Sustainable Management of Organic Fraction of Municipal Solid Waste in Nairobi: Anaerobic Digestion for Biogas Production in Kenya

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Summary

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List of Acronyms:

NEMA	National Environment Management Authority
MSW	Municipal solid Waste
OFMSW	Organic Fraction of Municipal solid waste
AD	Anaerobic digestion
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambiente
RRU	Rapporto Rifiuti Urbani
CHP	Combined heat power
EU	European Union
VFAs	Volatile Fatty Acids
CH4	Methane
CO2	Carbon Dioxide
N2	Nitrogen
O2	Oxigen
H2	Hydrogen
H2S	Hydrogen sulfide
NH4	Ammonia
LCV	Lower Calorific Value
STP	Standard Temperature Pressure
BCM	Billion Cubic Meter
VS	Volatile Solid
TS	Total Solid
HRT	Hydraulic Retention Time
OLR	Organic Loading Rate

Abstract

The present study examines the sustainable management of the organic fraction of municipal solid waste (OFMSW) in urban areas of Nairobi, Kenya, and Italy through a comparative analysis of waste generation patterns, current treatment technologies, regulatory frameworks, and institutional practices. The research highlights the significant yet underutilized potential of anaerobic digestion (AD) in Kenya, particularly in Nairobi, where organic waste from households, food markets, livestock, agricultural activities, municipal waste, and wastewater streams offers promising opportunities for resource recovery and renewable energy production.

The study is grounded in the observation that Kenya generates approximately 22,000 tons of municipal solid waste per day, with a substantial share originating from urban areas, while Italy generates more than 82,000 tons daily. In Kenya, more than 75% of municipal solid waste is mismanaged, contributing to environmental degradation and public health risks. At the same time, organic waste is estimated to represent between 60% and 80% of the total waste stream in Kenya, compared with about 35% in Italy. However, waste collection remains fragmented in Kenya, with only a limited share of waste formally collected and recycled, resulting in the loss of significant recovery opportunities. By contrast, Italy presents a more consolidated system supported by an effective regulatory framework and relatively high collection efficiency.

Based on this comparative analysis, the study focuses on Nairobi, Kenya's largest urban center and home to the Dandora dumpsite, with the aim of proposing a sustainable pilot model for OFMSW management at neighborhood scale. The proposed model integrates source separation, stakeholder participation, and anaerobic digestion as a pathway for biogas production and energy recovery. A pilot neighborhood of approximately 1,000 inhabitants was performed to assess the biogas production potential of anaerobic digestion. When this scenario was extrapolated to the current population of Nairobi, the city was found to have the potential to generate approximately 0.28 million Nm^3 of biogas per day. This corresponds to an average electrical energy output of approximately 601 MWh_e/day and a thermal energy output of approximately 773 MWh_{th}/day.

The findings suggest that the proposed approach could be transferable to other sub-Saharan African cities facing similar waste management challenges. By valorizing source-

separated organic waste through anaerobic digestion, the model may reduce environmental pressure, lower dependence on firewood and charcoal for cooking, support cleaner energy access, and contribute to circular economy and sustainable urban development.

Chapter 1: Introduction

1.1 Background and problem statement

In 2015, more than 50% of the world's population lived in urban areas, and this figure is projected to rise to about 70% by 2050. This population growth will happen most in the developing countries. The Africa's urban population is projected to reach 1.5 billion in 2050 making the continent the highest urban population [1]. Past study reported that in 2025 some African cities accounted up to 85% of the population in Africa. Kenya's population is estimated to reach approximately 60 million by 2030, and this population growth will lead to municipal solid waste generation increase as well. It is important to keep in mind that inappropriate waste management has serious health and environmental consequences. In fact, municipal solid waste management remains among the main issue faced by developing country which include Kenya. In 2020 the country's waste sector pollution contributed 3-4% of the GHG emission. If current trends continue, waste-related emissions are expected to double in 2030 [2].

However, municipal solid waste (MSW) should not be viewed solely as a problem to be eliminated. Behind it lies significant, untapped potential: the capacity to create employment opportunities for young people and to drive the transition from a linear to a circular economy. In Kenya, the organic fraction of municipal solid waste (OFMSW) constitutes approximately 80% of the total MSW stream, representing another major opportunity. This high organic content makes anaerobic digestion (AD) a particularly suitable technology for converting waste into energy.

AD is widely recognized as one of the most effective treatments for OFMSW, as it helps reduce waste volumes while contributing to climate change mitigation. The process yields two valuable outputs: biogas, which can be used for energy generation, and digestate, which can be utilized as nutrient-rich fertilizer. Together, these products can support Kenya's efforts to achieve the sustainable development goals outlined in Vision 2030 by promoting renewable energy use, improving agricultural productivity, and advancing resource efficiency.

1.2 Research Objectives

This research aims to provide a comprehensive analysis of Kenya's waste management system and regulatory framework, conducting a detailed comparative assessment with Italy's established reference model. The study begins with a thorough examination of MSW generation at both the national level and across macro-areas in Kenya and Italy, establishing a foundational understanding of waste volumes and patterns in each country.

Furthermore, this research places particular emphasis on the current state of MSW management in both nations, with a specific focus on the OFMSW. By analyzing how each country handles organic waste, the study identifies critical gaps in Kenya's system and best practices implemented in Italy that could serve as valuable benchmarks for improvement.

The study also seeks to identify the key features and success factors that characterize the Italian waste management system. Building on this analysis, the research proposes concrete strategies for transferring the most sustainable and effective elements from Italy to Kenya. This transfer process carefully considers the diverse stakeholder landscape, including government agencies, private sector operators, waste collectors, communities, and policymakers, while acknowledging the unique contextual realities, socio-economic conditions, and infrastructural challenges that define Kenya's waste management environment.

A critical goal of this study is to estimate the untapped potential for anaerobic digestion of OFMSW in Kenya. This assessment quantifies the significant energy, environmental, and social benefits that could be realized through implementation of proper waste management practices. Specifically, the research evaluates the potential for renewable energy production through biogas generation, the reduction of greenhouse gas emissions from uncontrolled waste disposal, the mitigation of environmental pollution, and the creation of social benefits such as improved public health, job creation, and enhanced community well-being.

Finally, the study proposes a practical pilot model designed for implementation in Nairobi neighborhoods. This model integrates all the findings and recommendations from the comparative analysis, considering the main implications and requirements for all stakeholders involved. The pilot framework addresses operational, regulatory, and social dimensions, providing a scalable and adaptable solution that can serve as a foundation for broader waste management improvements across Kenya. Through this comprehensive approach, the research contributes valuable insights for policy-makers, practitioners, and researchers working to develop more sustainable and effective waste management systems in Kenya.

1.3 Thesis Structure

This thesis is organized into five interrelated chapters. Chapter 1 introduces the study by presenting the background, research problem, and overall scope of the investigation. Chapter 2 examines Italy’s municipal solid waste management system, with particular emphasis on the organic fraction, in order to identify its technical characteristics, institutional arrangements, and regulatory drivers, and to assess the extent to which these features may be transferable to the Nairobi context while accounting for local socio-economic conditions, stakeholder roles, and community characteristics. Chapter 3 provides an overview of anaerobic digestion technology, including its operating principles and the feedstocks suitable for biogas production, and then evaluates the biogas and biomethane production potential in Italy and Kenya, with particular reference to OFMSW. Chapter 4 presents a pilot project for a Nairobi neighborhood aimed at developing a sustainable and socially inclusive organic waste management system, incorporating relevant stakeholders and estimating biogas production from OFMSW through anaerobic digestion. Chapter 5 summarizes the main findings, draws the final conclusions, and offers recommendations for future research and practical implementation.

- **Chapter 1**: Introduction

This chapter presents the background of the study, the research problem, and the overall rationale and scope of the thesis.

- **Chapter 2**: State of the Art: Municipal Solid Waste Management in Italy and Kenya.

This chapter reviews existing literature on municipal solid waste management in both countries, with emphasis on OFMSW generation, collection, and management at the national level.

- **Chapter 3**: Anaerobic Digestion Technology and Biogases Production Potential in Italy/Kenya

This chapter explains the principles of anaerobic digestion, identifies suitable feedstocks for biogas production, and assesses the potential for biogas and biomethane generation from OFMSW in Italy and Kenya.

- **Chapter 4**: Pilot Case for a Sustainable and Socially Inclusive OFMSW Management System in a Nairobi Neighborhood.

This chapter develops a pilot project for a Nairobi neighborhood, focusing on sustainable organic waste management, stakeholder participation, and the estimation of biogas production through anaerobic digestion.

- **Chapter 5**: Conclusion

This chapter summarizes the main findings, draws final conclusions, and presents recommendations for future research and practical implementation.

Chapter 2: State of art of Municipal Solid Waste Management Italy and Kenya

First, this chapter examines Italy's municipal solid waste system. It starts by outlining how much municipal solid waste the country generates, with a focus on major urban areas and their waste production. We will also pay close attention to organic waste, which is a significant component of municipal waste and plays a central role in Italy's waste management system. Additionally, the chapter will analyze current organic waste management practices across the country, along with the regulatory and policy framework guiding its collection, treatment, and recovery.

Subsequently, we will apply the same analysis structure to Kenya. The chapter will review Kenya's municipal waste generation, highlight the situation in its major urban centers, and examine the makeup and management of its organic fraction. It will also discuss the existing regulatory and policy frameworks. The aim is to compare both countries, understand their situations, and identify lessons that could help improve organic waste management and circular economy strategies.

2.1. Current Italian's Waste Generation and Composition

Italy counts roughly 58.9 million inhabitants with northern as the largest region with about 27.5 million people. According to the Municipal Waste 2025 report published by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambiente), the Italian public institution responsible for environmental protection and monitoring, the total current Italian's municipal waste generation is approximately 29.9 million tons, this represents a 2.3% increase (approximately 664 thousand tons) compared to 2023 [3].

Table 1 Italy's waste generated and collected Data from [3]

Area Geografica	Popolazione	Raccolta Differenziata (t)	Rifiuti Urbani (t)	RD (%)
NORD	27.521.524	10.898.169,838	14.684.227,399	74,22 %
CENTRO	11.704.312	3.978.531,587	6.299.584,993	63,16 %
SUD	19.708.341	5.383.779,889	8.948.919,489	60,16 %
ITALIA	58.934.177	20.260.481,314	29.932.731,881	67,69 %

Table 1 shows that waste generation varies significantly by region, with Italy producing approximately 30 million tons of MSW per year, of which 67.67% is collected.

The Nord region generates the highest amount of waste, nearly double that of the national average, and achieves the highest collection rate as well.

The organic fraction accounted for 34.8% of total MSW generation, corresponding to approximately 10 million tons, making it the largest component of Italy's municipal waste stream [3].

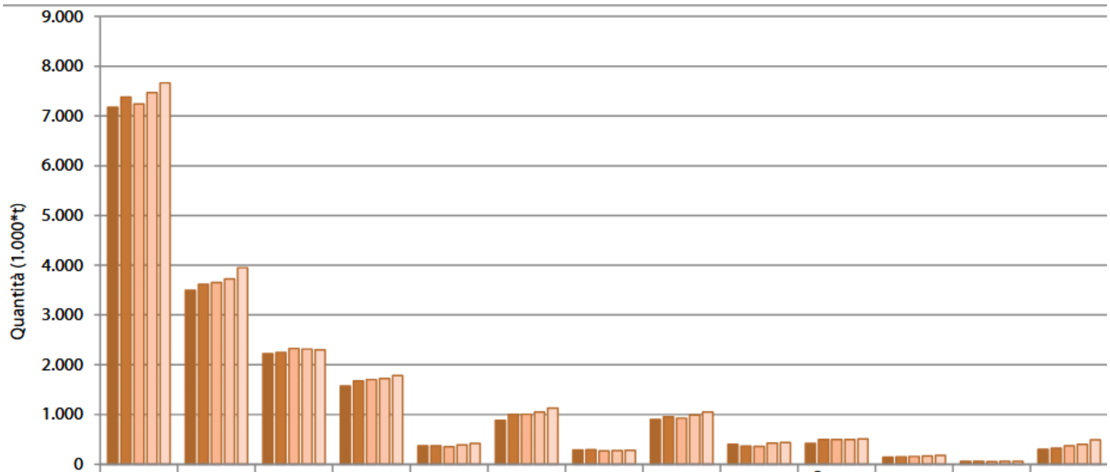
Table 2: Municipal Solid Waste generation per region. Data from [3].

Regione	2020	2021	2022	2023	2024
			(t)		
Piemonte	2.075.790	2.134.953	2.107.724	2.141.320	2.222.063
Valle d'Aosta	75.887	74.242	75.746	76.318	79.733
Lombardia	4.680.306	4.782.257	4.619.138	4.725.212	4.865.729
Trentino-Alto Adige	512.341	542.792	522.980	528.844	541.459
Veneto	2.320.680	2.368.470	2.309.796	2.414.756	2.546.970
Friuli-Venezia Giulia	597.621	599.862	589.473	626.637	640.329
Liguria	791.481	822.293	813.782	804.496	828.678
Emilia-Romagna	2.844.728	2.839.418	2.803.812	2.847.725	2.959.267
Nord	**13.898.833**	**14.164.287**	**13.842.450**	**14.165.307**	**14.684.227**
Toscana	2.153.388	2.199.464	2.153.005	2.146.320	2.159.850
Umbria	438.903	445.321	442.039	445.877	458.784
Marche	753.387	785.640	764.224	767.633	764.869
Lazio	2.815.268	2.883.043	2.859.769	2.864.949	2.916.082
Centro	**6.160.946**	**6.313.469**	**6.219.037**	**6.224.780**	**6.299.585**
Abruzzo	585.046	587.165	577.428	579.099	583.423
Molise	109.137	112.195	108.581	109.956	111.542
Campania	2.560.489	2.652.820	2.613.566	2.587.009	2.616.802
Puglia	1.851.161	1.864.835	1.829.588	1.813.928	1.810.121
Basilicata	188.717	193.214	191.815	190.370	188.801
Calabria	723.560	758.474	739.462	731.010	741.559
Sicilia	2.151.927	2.224.867	2.200.814	2.153.696	2.168.221
Sardegna	711.634	746.912	728.425	713.877	728.450
Sud	**8.881.672**	**9.140.482**	**8.989.681**	**8.878.944**	**8.948.919**
Italia	**28.941.451**	**29.618.238**	**29.051.168**	**29.269.031**	**29.932.732**

Errore. L'origine riferimento non è stata trovata. highlights the overall municipal solid waste generation in Italy in every region. In the northern part of the country, Piedmont and Lombard are the regions with the highest municipal waste generation. This could be attributed to their large populations, high levels of industrialization, and strong economic activity, as they are among the most important and densely populated regions in the country. In 2020 the municipal solid waste amount is lower compared to the other years, due to the pandemic reason. However, within this substantial volume of waste, the organic fraction is of particular interest as it represents the most significant component of Italy's municipal waste stream.

2.1.2 Organic waste generated in Italy

The organic stream is mainly composed of biodegradable waste from kitchen and canteen that represent the humid fraction, the waste from garden and park so called green fraction, waste from market. It should be noted that the biodegradable waste destined for domestic composting is excluded from the collection system.[3]



	Frazione organica	Carta	Vetro	Plastica	Metallo	Legno	RAEE	Ingomb. misti	Rifiuti da C&D	Spazz. Stradale a rec. (1)	Tessili	Selettiva	Altro (2)
2020	7.174,6	3.497,1	2.223,7	1.574,8	368,1	881,5	284,4	900,7	402,9	421,6	143,3	55,9	305,4
2021	7.379,3	3.615,2	2.252,0	1.677,4	371,7	1.005,8	290,3	957,9	364,3	499,1	154,2	57,3	328,2
2022	7.241,7	3.652,8	2.329,7	1.703,1	356,0	1.003,5	272,0	930,5	359,3	499,3	160,3	54,2	368,1
2023	7.470,5	3.727,0	2.317,5	1.722,8	394,3	1.048,0	274,2	988,1	428,7	499,7	171,5	56,6	406,5
2024	7.666,8	3.950,9	2.298,7	1.787,3	421,6	1.127,7	280,7	1.052,3	436,9	507,6	180,3	59,0	490,7

Figure 1: Italy's waste Separate collection by product fraction, 2020s to 2024, Data from [3].

Figure 1 shows how important organic waste is in Italy's system for handling city waste. From 2020 to 2024, organic waste was still the biggest type collected separately, growing from 7.17 million to 7.67 million tons. Paper, glass, and plastic also showed a slight increase, indicating that the separate collecting system is stable and continues to expand. Smaller waste streams, such as waste electrical and electronic equipment, textiles, and other separately collected fractions, accounted for a lower share of the total waste generated. Nevertheless, these fractions also showed a gradual increase over time. Overall, the figure confirms that recovering organic waste is a key part of Italy's circular waste system. Also, most of this organic waste is kitchen and canteen scraps (68.1%), with garden waste making up 27%, as the chart below shows.

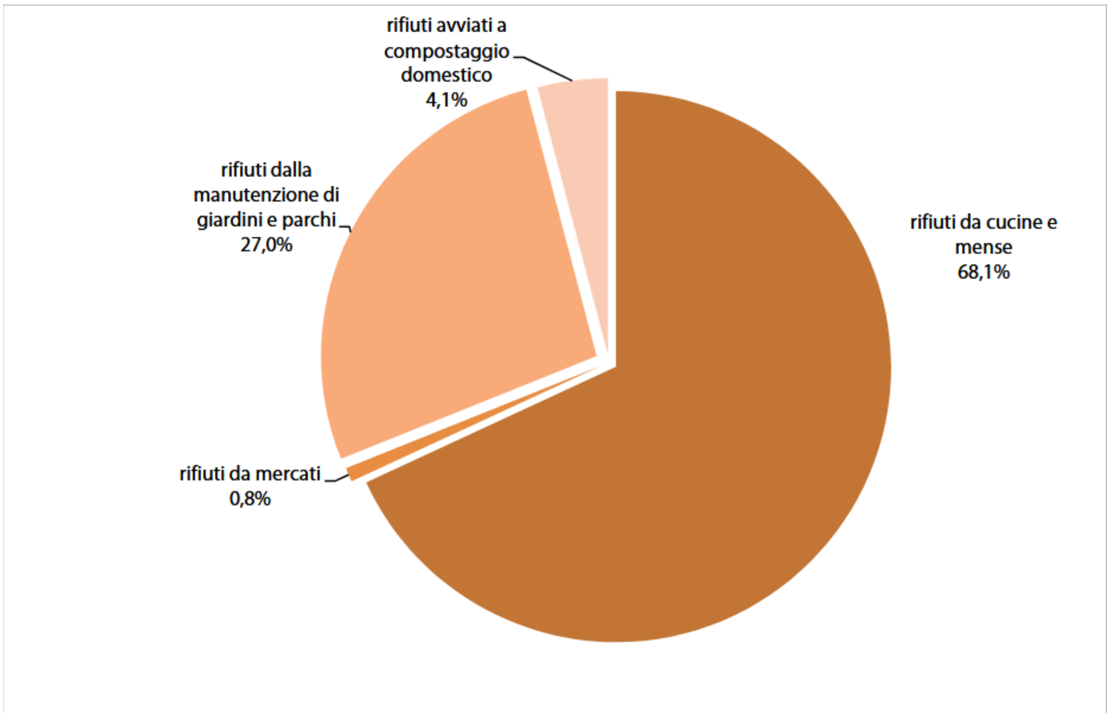


Figure 2: The breakdown of national waste separated into organic fractions in the year 2024, Data from [3]

2.1.3 Per capita Municipal solid Waste generation in Italy

The per-capita waste generation varies across regions. Indeed, in 2024 the Northern, Southern and Center part had generated respectively 533.6 kg/y, 538.2 kg/y and 454.1 kg/y per capita. The average Italy's per capita waste generated slightly increased from 486 kg/year over the 2010-2022 to approximately 508 kg/year in 2024.

Table 3: per capita Municipal Solid Waste Generation in Italy's County, Data from [3]

Regione	Popolazione 2024	2020	2021	2022	2023	2024
		(kg/abitante* anno)				
Piemonte	4.255.702	485,8	502,1	497,0	503,5	522,1
Valle d'Aosta	122.714	612,5	601,9	616,0	620,4	649,7
Lombardia	10.035.481	469,6	479,9	464,2	471,6	484,9
Trentino-Alto Adige	1.086.095	475,1	503,5	486,3	488,7	498,5
Veneto	4.851.851	478,2	487,9	477,4	497,7	524,9
Friuli-Venezia Giulia	1.194.095	498,5	501,0	494,4	524,0	536,2
Liguria	1.509.908	524,2	545,5	541,6	533,2	548,8
Emilia-Romagna	4.465.678	639,9	640,7	633,4	639,2	662,7
Nord	**27.521.524**	**506,3**	**516,8**	**506,1**	**515,3**	**533,6**
Toscana	3.660.834	587,0	598,3	589,7	585,7	590,0
Umbria	851.954	507,4	518,1	517,5	521,9	538,5
Marche	1.481.252	501,8	527,4	516,1	517,1	516,4
Lazio	5.710.272	492,1	504,5	501,1	500,8	510,7
Centro	**11.704.312**	**524,1**	**537,7**	**531,8**	**530,9**	**538,2**
Abruzzo	1.268.430	455,2	461,0	454,7	456,0	460,0
Molise	287.966	368,0	385,9	374,6	379,9	387,3
Campania	5.575.025	450,8	474,5	467,4	462,8	469,4
Puglia	3.874.166	471,4	476,7	469,0	466,3	467,2
Basilicata	529.897	344,6	357,8	357,4	356,7	356,3
Calabria	1.832.147	385,3	411,2	401,6	397,7	404,7
Sicilia	4.779.371	444,5	463,4	458,3	449,2	453,7
Sardegna	1.561.339	445,3	473,0	462,5	454,7	466,6
Sud	**19.708.341**	**442,9**	**460,9**	**453,8**	**449,0**	**454,1**
Italia	**58.934.177**	**488,4**	**502,1**	**493,6**	**496,2**	**507,9**

From Table 3 clearly shows the amount of municipal waste generated per person in the different Italian regions- Per-capita waste generation is highest in northern Italy, followed by the central regions, whereas the southern regions consistently remain below the national average. Overall, on a national basis, the amount of waste generated per person annually increased from 488.4 kg in 2020 to 507.9 kg in 2024. This difference represents a North-South dichotomy in waste production that is likely driven by varying levels of economic activities, urbanization, and consumption practices.

2.1.4 National and Per-Capita Organic Waste Generation

In Italy, about 7.67 million tons of organic waste were collected separately in 2024. This represents an increase of 2.6%, compared with the previous year, corresponding to an additional 196,000 tons of organic waste collected. This type of waste represents the largest part of Italy's municipal waste. It accounts for 34.8% of all municipal waste produced, which is over 10 million tones, including both what is sorted and what is not. Most municipalities in Italy carry out separate collection of organic waste, with participation reaching 97% across the country. On average, each person in Italy collects 130 kg of organic waste annually. Examining the composition of the organic waste fraction, kitchen and canteen waste is the largest part, at 68.1% (5.2 million tons). Green waste from gardens and parks makes up 27.0%, while home composting accounts for 4.1%. A small portion, 0.8%, comes from market waste. From 2013 to 2024, the amount of organic waste collected has grown consistently by an average of 3.6% each year.

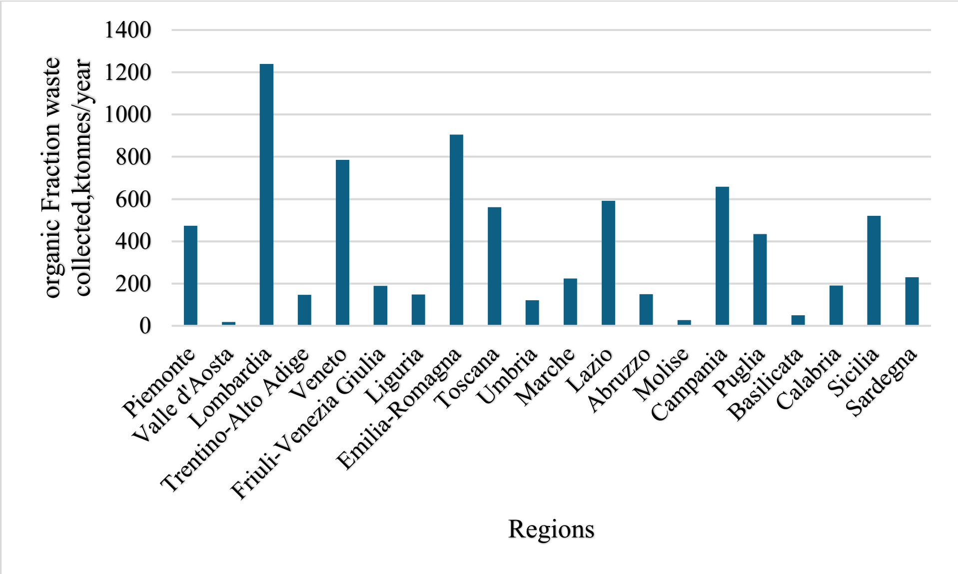


Figure 3: Organic waste on regional basis, year 20224, Data from [3]

The graph above shows that most of Italy's organic municipal waste comes from specific areas. The North produces the largest amount, led by Lombardy, Emilia-Romagna, Veneto, and Piemonte. The Central and Southern regions collect less waste overall, though places like Lazio, Campania, Sicilia, and Puglia still contribute a lot. This pattern is due to differences in population density, how urbanized areas are, and economic activity. It also confirms how important regional planning is for collecting and treating organic waste. Furthermore, it is useful to observe at per-capita organic waste at national level. Thereby, the Figure 4 represents that Italy's average per capita organic waste production at the national level is approximately 130.09 kg per person each year. At the regional level, Emilia-Romagna produces more than any other regions with 202.76 kg of organic waste per person per year; it is followed closely by Veneto (161.75 $kg/person/year$) and Friuli-Venezia Giulia (158.96 $kg/person/year$). The two regions with the least amount of organic waste production are Molise (92.03 kg/person/year) and Basilicata (94.57 $kg/person/year$). In general, the per capita organic waste production is fairly evenly distributed throughout the various regions, however there are some regions located in northern and central Italy that produce a greater quantity of waste due to variations in consumer behavior, population density, and waste management practices.

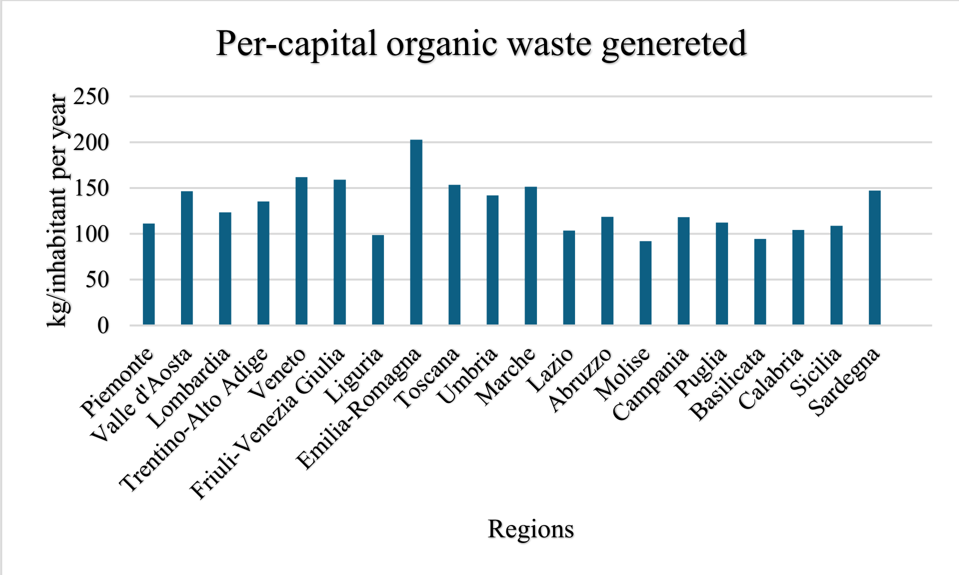


Figure 4: National distribution of per-capita organic waste generated, year 2024, Data from [3]

2.1.5 Current waste management in Italy

Waste management in Italy has a clear structure that may differ from one area to another. In general, the waste management of urban areas is decentralized in Italy in that while the central government provides the legal framework for managing waste, the regions plan the whole process while the municipalities manage the collection of waste and the provision of local services. The operators who perform the duties daily are either public or private. Usually, it is the local municipal authorities acting via public entities that implement waste management in Italy. Urban waste in Italy falls into various categories depending on the EWC code, namely 191212 (Other waste including mixed wastes from mechanical treatment of waste), 191210 (Combustible waste/CSS), 190501 (non-composted fraction of municipal and similar waste), 190503 (Off-specification compost), and 190599 (Waste resulting from aerobic treatment process not elsewhere specified).

Table 4 Number of municipal waste management facilities, by type and by geographical macro-area, year 2024, Data from [3]

Tipologia		Numero impianti			
		Nord	Centro	Sud	Totale
Trattamento biologico	Compostaggio	147	36	67	**250**
	Trattamento integrato	39	12	15	**66**
	Digestione anaerobica	24	2	2	**28**
Trattamento meccanico o meccanico biologico	TMB	29	27	51	**107**
	TM	8	13	4	**25**
Coincenerimento		8	1	3	**12**
Incenerimento		25	4	6	**35**
Discariche		45	23	34	**102**
Totale		**325**	**118**	**182**	**625**

above provides details regarding the facilities that treat and recycle waste produced within the macro-areas of Italy. Altogether, the number of plants for the treatment of organic fractions of MSW consists of 344 units. They comprise 250 plants for composting, 66 plants for integrated aerobic and anaerobic treatment, and 28 plants for anaerobic digestion. In addition, the facilities include 132 plants for the mechanical and/or mechanical-biological treatment of MSW, 102 landfills, 35 incinerators, and 12 industrial units with the co-incineration of MSW.

Italy's north has the largest number of such facilities (325 or 52% of the total number). Central and Southern Italy have 118 and 182 treatment plants, correspondingly. Thus, the above-mentioned distribution clearly indicates the existence of an evident territorial inequality concerning waste management infrastructure facilities in the country. Particularly, there is a tendency toward concentration of the facilities in the northern regions of Italy.

In addition, the fact that in Italy a considerable amount of municipal waste goes into the process of recycling and reuse should be regarded as an important distinction compared to the Kenyan situation.

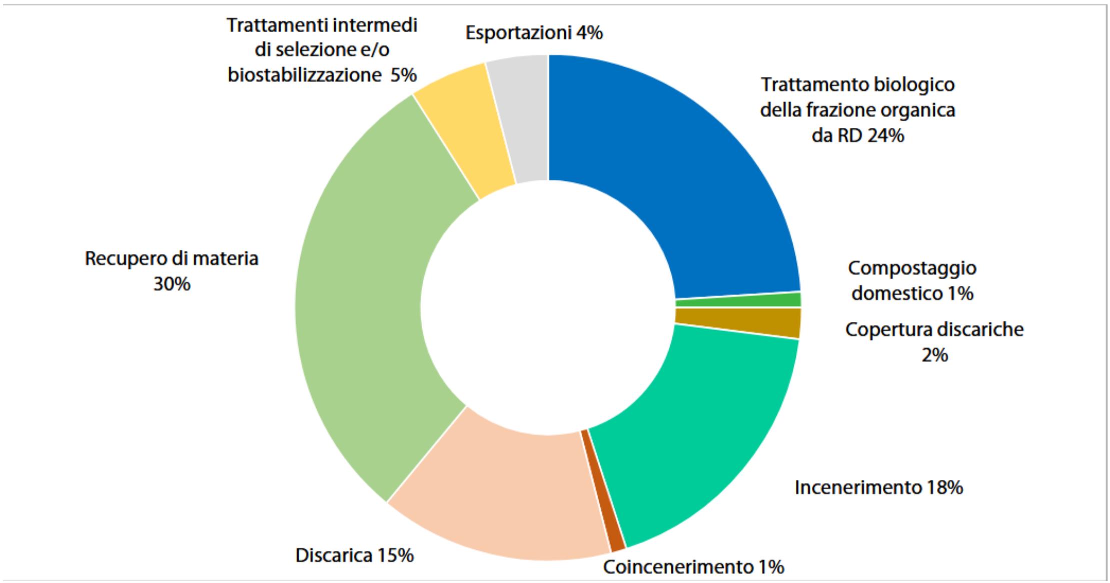


Figure 5: Percentage breakdown of municipal waste management, year 2024, Data from[3]

Figure 5 illustrates the end-of-life pathways of municipal waste. The most notable aspect is that 54% of municipal waste is directed toward recycling or reuse. Of this share, 24% is treated in plants that recover the organic fraction of municipal waste (wet and green waste), while the remaining 30% is processed in facilities that recover other material fractions from separate collection. Another relevant point is that only 15% of municipal waste is disposed of in landfills. Overall, these figures suggest a waste management system that is increasingly oriented toward material recovery and landfill diversion, reflecting a shift toward more sustainable and circular waste management practices.

2.1.6 Regulatory and Institutional Framework

Municipal waste management system in Italy consists of a multilevel hierarchical structure regulated by national laws and European Union directives. In particular, the EU creates the legal basis for managing waste throughout all the EU member states; there can be differences between regions and local communities due to specific local conditions and actions. The basic law regarding the matter is Legislative Decree 152/2006, setting the legislative base for waste management. Moreover, the law aims at minimizing waste, its reusing and recycling, as well as providing for the creation and functioning of safe and controlled waste disposal facilities. In particular, the "polluter pays" principle, according to which people producing waste take responsibility for them, is one of the key points in the legislation. At the same time, the new Circular Economy Action Plan approved by the EU on 20 March 2020 obliged all member states to adopt a circular economic and social model till 2050, reducing waste as much as possible and utilizing it as a secondary resource when it is possible. One of the other important directives is 2008/98/EC, according to which 50% of municipal waste is to be reused and recycled till 2020. This goal has been achieved; in particular, 54% of municipal waste has been reused and recycled in 2020.

Another key institutional framework is Italy's PNIEC 2024 (National Integrated Energy and Climate Plan), which serves as the country's roadmap for deep decarbonization and identifies the waste sector as a critical component for achieving emission reduction targets under the EU Effort Sharing Regulation. For municipal solid waste, the plan establishes ambitious goals to reduce the amount of waste sent to landfills to below 10% by 2035. A primary technological lever for achieving these objectives is anaerobic digestion, which processes the organic fraction of municipal waste (FORSU-Frazione Organica del Rifiuto Solido Urbano) to produce biogas that can then be upgraded to biomethane. The plan projects that total domestic production of biogas (for thermal and electrical uses) and biomethane will reach approximately 4.6 Mtoe (Millions of Tons of Petroleum Equivalents) by 2030. By implementing anaerobic digestion, Italy intends to not only generate renewable energy for industry and transport but also to significantly limit methane emissions compared to traditional landfill disposal while producing quality fertilizers (compost) within a circular economy framework.[4]

2.2 Kenya's Municipal Waste Generation

In 2025, Kenya's population is projected to reach 57.5 million inhabitants according to the Worldometer. This rapid demographic growth, coupled with increasing rates of production and consumption, is driving a marked rise in waste generation. In 2024, the total volume of municipal solid waste generated in Kenya was estimated at 22,000 tons per day, with projections indicating that this figure will triple by 2030.[5] Furthermore, 75% is mismanaged consequently only 25% is collected which 15% is recycled or reuse. Kenya's capital is the home of one of the world's 50 largest landfills, Dandora. MSW generation in Kenya varies significantly across different geographic areas, as illustrated in the table and graphs below. The four cities with the highest waste generation are Nairobi, Mombasa, Kisumu, and Nakuru. Nairobi produces the largest amount of MSW and also collects the most waste among all Kenyan cities.

Table 5 Amount of municipal solid waste generated, 'thousand tons per year, Data from[6]

County		2018	2019	2020	2021	2022	2023*
Nairobi+	Generated	730.0	839.5	876.0	1,095.0	1,095.0	1,191.5
	Collected	345.6	668.8	657.4	1,415.6	813.5	1,025.2
Mombasa+	Generated	804.0	879.0	914.0	920.0	1,000.0	1,200.0
	Collected	450.0	405.0	420.0	520.0	650.0	700.0
Kisumu	Generated	215.8	220.4	216.5	220.3	224.1	227.9
	Collected	64.7	66.1	65.0	66.1	67.2	68.4
Nakuru	Generated	-	-	-	-	383.3	400.0
	Collected	-	-	-	-	230.0	240.0

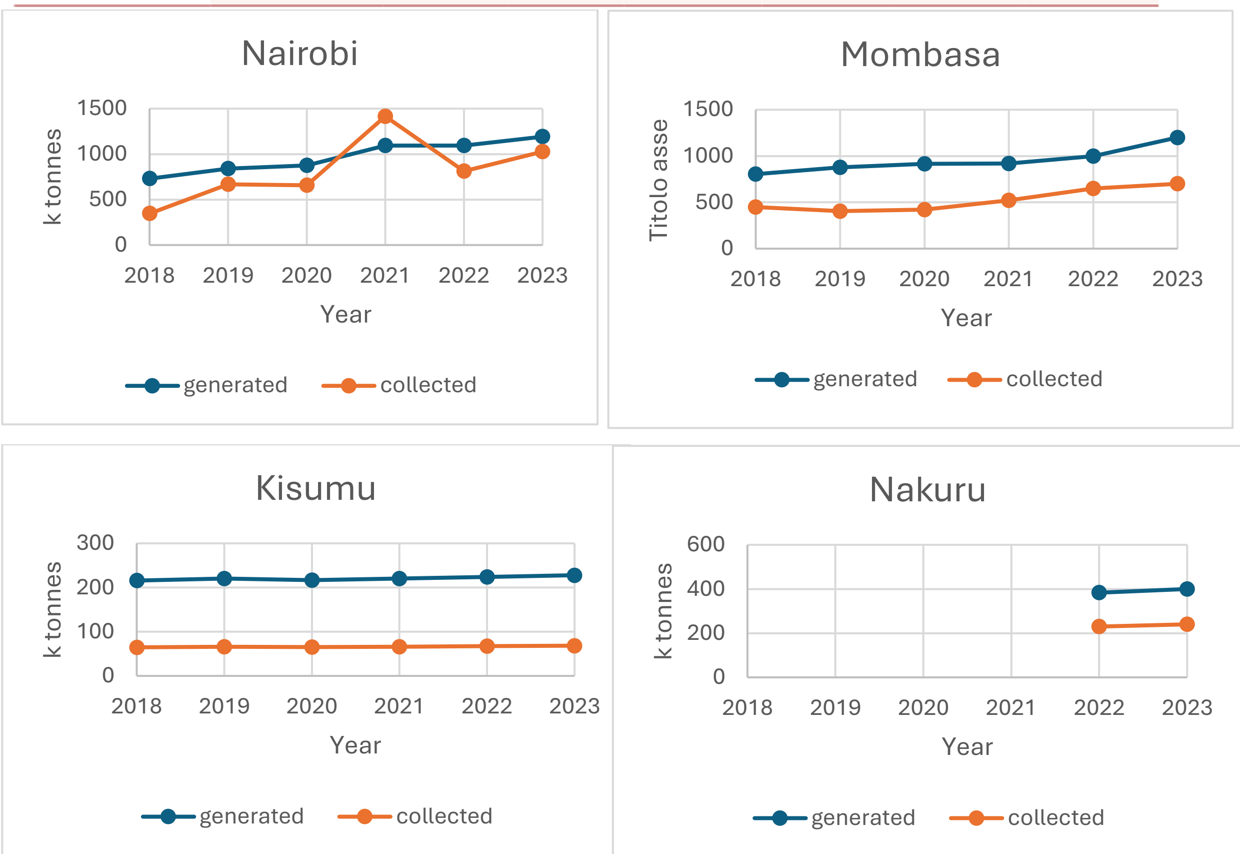


Figure 6: Waste generated and collected in macro areas of Kenya , Data from [6]

For the Nairobi case, the reported quantity of waste collected in 2021 is higher than the estimated amount of waste generated, suggesting a possible inconsistency in the data or a misinterpretation of the two indicators.

Of the total waste generated, approximately 70% consists of organic matter, a proportion that is double that observed in Italy.

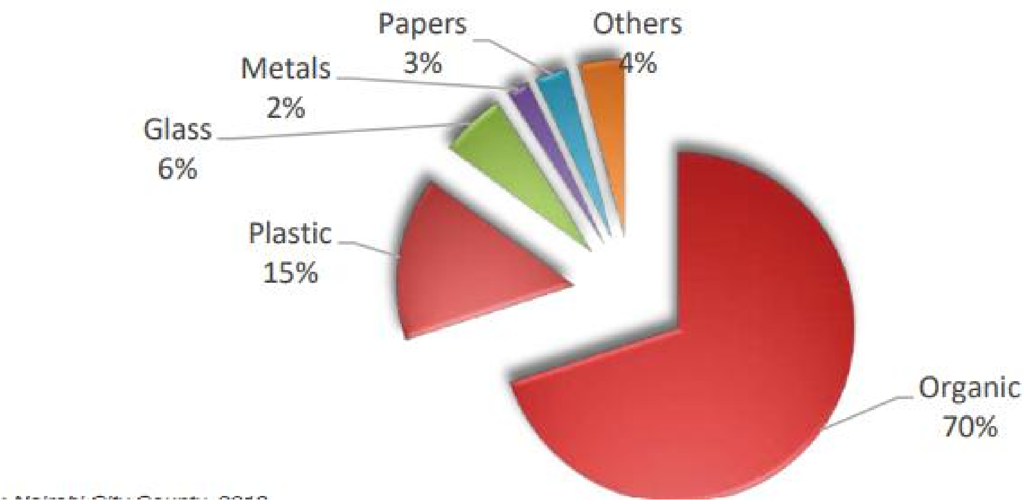


Figure 7: Composition of Kenya's waste generation , Data from [6]

Figure 7 illustrates the high proportion of OFMSW in Kenya's municipal solid waste stream, highlighting a substantial, untapped potential for bioenergy production. This organic fraction can be exploited through anaerobic digestion (AD) to generate biogas and digestate, with the biogas subsequently upgraded to biomethane. Furthermore, utilizing organic waste for bioenergy contributes to greenhouse gas emission reduction as is well established, organic matter deposited in open landfills undergoes anaerobic decomposition, releasing methane, a potent greenhouse gas, along with other hazardous substances into the environment. While Kenya's overall municipal solid waste situation presents significant challenges, the issue is particularly acute in its capital city, Nairobi.

Nairobi is recognized as one of the three largest and fastest-growing metropolitan areas in East Africa. In 2025, its population was estimated at approximately 5.7 to 6.1 million inhabitants, according to global statistical data. Owing to its strategic location, Nairobi functions as a major business hub and serves as a key transport center for the broader region. The city generates approximately 3,068 tons of municipal solid waste (MSW) per day, which 62.4% is organic stream[7]. The capital is the best county in collected waste with 72%. Waste composition analysis reveals:

Table 6 Municipal Waste composition in Nairobi, Data from [7]

Waste component	Percentage (%)
Organic waste (food)	62.4
Plastics	10.9
Papers	14
Metals	0.7
Glass	1.5
Others	10.5

It is also important to notice that the waste generation depends on the geography Area. In fact, waste generation in Nairobi is not uniform across the city but varies significantly by urban area. This variation is influenced by differences in population density, socioeconomic conditions, land use patterns, and the availability of waste collection services. For example, studies have shown that wealthier or more serviced areas such as Westland generate and manage waste differently from informal settlements such as Mathare, where collection rates are much lower and waste often accumulates in illegal dumping sites.

2.2.1 Institutional Framework and Regulatory Environment

2.2.1.1 National and County Government Roles

Kenya is composed of 47 counties, the National Environmental management Authority (NEMA) has been established under the Environmental management and coordination Act (EMCA),1999, as the principal government that's responsible for coordinate and manage all matters relating to environment. NEMA is charged to ensure clean and healthy environment for all citizens, in the other hand the latter have the duty to safeguard and enhance it.[5]

With the foundation waste's law established in 2010 named constitution of Kenya, 2010, the responsibility of waste management shift from national level to county government and leading county government the charge to organize waste management system and sanitation in other to respect the Kenya citizens' constitutional right.[8] Therefore, the counties authority must make sure that policies and legislation related to waste management and environment are observed by everyone. Thus, it's mandatory to acquire the licensing for who would like to operate in the waste management sector, this licensing is provided by the government authority of each county, and they can all hire private compagnies.[9]

Since all these directives listed above were not applicated by in many sectors across the country, the government established the wastes management regulations 2024 to enhance the existing waste management policies. Indeed, regulations seek to emphasize the reverse impact of poor solid waste management by setting clear measures for waste handling. it encourage the clean and sustainable practices for waste generation, among these, the segregation at the source, the adoption of recycling and reuse practices.[5]

However, despite the existence of these regulations and policies, Kenya continues to face serious challenges in municipal waste management due to a critical lack of disposal facilities for waste collection and source segregation. During my time in Kenya, I visited several markets, including Juja Market, where many lacked proper waste disposal infrastructures for either collection or segregation. Consequently, waste accumulates on streets and at crossroads. **Errore. L'origine riferimento non è stata trovata.** and **Errore. L'origine riferimento non è stata trovata.** clearly illustrate this issue: Figure 8 shows the visible organic fraction among the accumulated waste, while Figure 9 demonstrates the presence of organic waste through cows grazing and feeding on the waste, confirming that organic matter is a significant component of the unmanaged waste stream.

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Figure 8: Disposal waste,Juja market, 2025

Figure 9:Open dumpsite on Nairobi's street

2.2.1.2 Current Municipal Waste Management

Most European countries have centralized municipal waste management entities, in contrast Kenya's waste sector involves different actors such as public sector, private sector and informal sector.

Public sector*:* local authorities' government have the responsibility to provide bins and infrastructure to collect and segregate the trash. However, during the last two decades, this service has been on decline, forcing the city county to recruit private companies.

Private stakeholders*:* due to the failure of public sector whose lead to increase of solid waste across the country , local authorities proceeded to hire private companies to handle trash across all the 47 county of the city. Particularly in Nairobi there are more than 60 privates registered companies responsible to the collection, sorting and transportation of waste generate across the city.[10] however, the effective existing of these latter are not notable especially in the rural area where tracks can't reach and the separation at the source is almost inexistent.

Table 7 some private companies operating in waste management sector in Nairobi

Companies	What do they do?
Taka Taka solutions	Collect waste door-to-door from households, and markets
City fresh	Collaborate with municipalities, cooperate, and agriculture pack houses
Metro bins services	collect industrial waste disposal, commercial waste disposal, domestic/residential waste and biodegradable waste
Nairobi Green Limited	Coordinate garbage collection service in all municipalities in the city
Ephraim Solutions Ltd	Manage all kinds of waste

Most of these companies dump the waste collected to the Dandora dumpsite that's the official landfills in Nairobi, as can be observed it's an open and uncontrolled dumpsite; it's also considered as between the largest dumpsite in East Africa.

Figure 10: Dandora Dumpsite (Nairobi)

Figure 11: waste pickers at Dandora dumpsite (Nairobi)

The photographs in Figure 10 and Figure 11 were taken at Dandora dumpsite. As can be observed, individuals are waiting for trucks to arrive and subsequently sort through the waste to extract recyclable materials. Based on interviews conducted with some of these waste pickers, it was revealed that many collect plastic, metal, and organic waste, which they then sell to wholesalers at very low prices. For instance, the organic waste stream is sold to animal breeders at 20 KES (Kenyan shillings) per kilogram, which is equivalent to less than €0.50.

Informal waste Pickers: they are group of people usually young people and women who collect waste without license. They can be organized in association or organization, for instance NGOs (non-government organizations), BCOs (based community organizations). There are also those who collect pieces of metal, plastic, organic waste and sell to the resellers, some people sell organic waste to the farmers. Informal waste workers play a crucial role in waste management across the country, especially in the low-income area where assessment of waste disposal is almost inexistant.

2.2.2 Per capita Waste generation in Kenya

Kenya's urbanization rate is projected to increase by 10% by 2030, with waste generation estimated to reach 5.5 million tons per year. Consequently, the country's per capita waste generation is approximately 0.5 kg/day. This figure varies depending on income levels (low, middle, and high-income areas).[5]

It is estimated that approximately 34.8% (around 10 million people) of Kenya's population resides in urban areas. The five largest cities Nairobi, Mombasa, Kisumu, Nakuru, and Eldoret account for one-third of the urban population. These cities generate, respectively, 2,400, 2,000, 1,000, and 500 tons of solid waste daily.[11]

Available data indicate that waste generation is directly proportional to population size. presents the per capita solid waste generation rates for major cities in Kenya.

Table 8 Per capita Waste generation per city, Data from[11]

County	Per capita generation (kg/day)
Nairobi	0.75
Mombasa	0.38
Kisumu	0.31
Nakuru	0.41

2.3 Comparison between the two waste management systems: Italy vs Kenya

This comparison examines municipal solid waste (MSW) management systems in Italy and Kenya, with particular attention to organic fraction of municipal solid waste (OFMSW) and anaerobic digestion (AD). A key issue in interpreting the two cases is the unequal reliability of available data. In Italy, waste statistics are generally more robust because they are collected annually by national and European institutions and are regularly updated. In Kenya, by contrast, much of the available information is derived from estimates, pilot projects, or experimental studies, and detailed national-level datasets are often incomplete or unavailable.

Although Italy and Kenya differ substantially in terms of governance, socioeconomic conditions, settlement patterns, and waste infrastructure, both face the universal challenge of MSW generation. Italy has a population of approximately 58.9 million inhabitants, with the northern part of the country being the most populated, accounting for about 27.5 million people. Kenya's population is approximately 57.5 million, with Nairobi serving as the largest urban center, with an estimated population between 5.7 and 6.1 million. In 2025, Italy generated roughly 30 million tons of MSW annually, of which about 67.9% was collected. Kenya, in contrast, generated approximately 8 million MSW tons annually, with only about 25% collected. However, these figures for Kenya should be interpreted cautiously because of the limited reliability and completeness of the underlying data.

Per capita waste generation also differs between the two countries. In Italy, MSW generation is estimated at about 1.4 kg per person per day, whereas in Kenya it is around 0.61 kg per person per day. In Nairobi, the per capita MSW generation is higher than the national average, at approximately 0.75 kg per person per day. The organic fraction of MSW also varies considerably. In Italy, OFMSW represents about 34.8% of total MSW, while in Kenya it is estimated to be roughly 70%. Nairobi appears to follow a similar trend, with a particularly high proportion of organic waste in the waste stream.

From a governance perspective, Italy has a multi-level and relatively structured waste management system. It is governed by a clear regulatory framework at the European, national, regional, and municipal levels. Legislative Decree 152/2006 provides the main legal basis for waste management, emphasizing waste prevention, reuse, recycling, and the development of safe and controlled disposal facilities. In addition, the EU Landfill Directive (1999/31/EC), as amended by Directive (EU) 2018/850, requires Member States to progressively reduce the landfilling of biodegradable municipal waste in order to reduce methane emissions and promote recovery. Directive (EU) 2018/851 further requires separate collection of bio-waste by 31 December 2023. These regulations have strongly encouraged the development of dedicated treatment infrastructure for municipal waste, including biological treatment plants for source-separated organic waste, incineration facilities, mechanical and mechanical-biological treatment plants, and controlled landfills.

Kenya presents a very different institutional and operational context. Since the 2010 Constitution and the devolution of public functions, waste management responsibility has been transferred largely to county governments, which are expected to organize sanitation services and maintain clean urban environments. In practice, counties often rely on private contractors for waste collection and disposal. At the same time, the informal sector plays a major role in waste recovery and recycling. Informal waste pickers, including individuals, community-based organizations, and NGOs, recover materials such as metals, plastics, and organic waste, usually under unsafe working conditions and without formal licensing. This informal system is a significant component of waste management in Kenya, but it remains only partially integrated into official planning and governance.

Italy has developed specialized facilities for different stages of MSW treatment, including plants dedicated to biological treatment of separately collected organic waste, waste-to-energy incineration, mechanical treatment, and sanitary landfilling. As a result, the country has a well-established anaerobic digestion sector. Italy has 28 AD plants, of which 24 are located in the north, 2 in central Italy, and 2 in the south. These plants operate at industrial scale and are primarily used for biogas production, electricity generation, or upgrading to biomethane.

In Kenya, however, there are currently no formally documented large-scale AD facilities or material recovery facilities dedicated to processing the organic fraction of MSW in either Kenya as a whole or Nairobi specifically. Existing biogas systems are concentrated mainly in the agricultural and industrial sectors rather than in municipal waste treatment. The few formally recorded electricity-generating biogas plants include Biojoule Kenya Limited (2.0 MW) and James Finlay (Kenya) Limited (0.18 MW). Meanwhile, a large share of Nairobi's organic waste, estimated at between 62.4% and 80%, is still disposed of at the Dandora open dump site. Despite this infrastructure gap, studies suggest substantial untapped potential. For example, Nairobi's municipal market waste could produce approximately 144.774 m^3 of biogas per day, equivalent to replacing around 89,000 liters of petrol. The 2017 Reuters report on the Gorge Farm plant in Naivasha is often cited as an early biogas milestone in Kenya, but that facility uses crop residue rather than municipal solid waste. Overall, Kenya's AD landscape remains largely limited to pilot-scale or small-scale projects.

The table below summarizes the principal structural and operational differences between the Italian and Kenyan MSW systems.

Table 9 Main comparison table

Aspect	Italy	Kenya
Data reliability	High, because data are regularly collected and updated by national and European institutions.	Lower, because much of the information is based on estimates, pilots, and fragmented studies.
Population.	About 58.9 million inhabitants.	About 57.5 million inhabitants.
Main urban concentration.	Northern Italy is the most populated area, with about 27.5 million inhabitants.	Nairobi is the largest city, with about 5.7–6.1 million inhabitants.
MSW generation.	About 30 million tons per year in 2025.	About 8 million tons per year.
MSW collection rate.	About 67.9%.	About 25%.
Per capita MSW generation.	About 1.4 kg/person/day.	About 0.5 kg/person/day nationally; about 0.75 kg/person/day in Nairobi.
OFMSW share.	About 34.8% of MSW.	About 70% of MSW; Nairobi is similar.

Governance structure.	Multi-level system: EU, national, regional, and municipal regulation.	Decentralized system, with county governments responsible for waste management.
Legal framework.	Strong and detailed, including Legislative Decree 152/2006 and EU waste directives.	National legal framework exists, but implementation varies widely across counties.
Waste infrastructure	Well-developed, with separate biological treatment, incineration, mechanical treatment, and sanitary landfills.	Infrastructure remains limited; waste often ends up in open dumps such as Dandora.
AD development	28 industrial-scale AD plants, mainly in the north.	No formally documented large-scale MSW-based AD facilities; mainly pilot or small-scale projects.
Role of informal sector	Limited compared with Kenya.	Very important, but often informal, unregulated, and unsafe.
Main AD output	Biogas, electricity, and biomethane.	Mostly experimental biogas production; limited formal energy recovery from MSW.

Chapter 3: Anaerobic Digestion Technology and Biogases (biogas and biomethane) Production Potential in Kenya

3.1 Anaerobic Digestion: Process Overview

Anaerobic digestion (AD) is a fermentation technique that takes place in an anaerobic digester in the absence of oxygen, where organic materials including manure, food waste, sewage sludge, and organic waste from industries are converted into biogas and digestate. Anaerobic digestion (AD) is generally regarded as an environmentally friendly and efficient method of treating the organic fraction of municipal solid waste (MSW). The reason is because of its ability to handle various types of organic materials, hence making it suitable for OFMSW that consists of both liquid and solid organic wastes

Furthermore, as countries increasingly embrace their role in the prevention of climate change, anaerobic digestion becomes a promising means of dealing with the environmental problems caused by municipal solid waste. Incorrect handling of biodegradable waste, especially in areas without regulations, leads to the emission of harmful gases and causes pollution. In turn, anaerobic digestion reduces the number of emissions and allows the extraction of energy from waste.

Anaerobic digestion is defined by four basic steps:

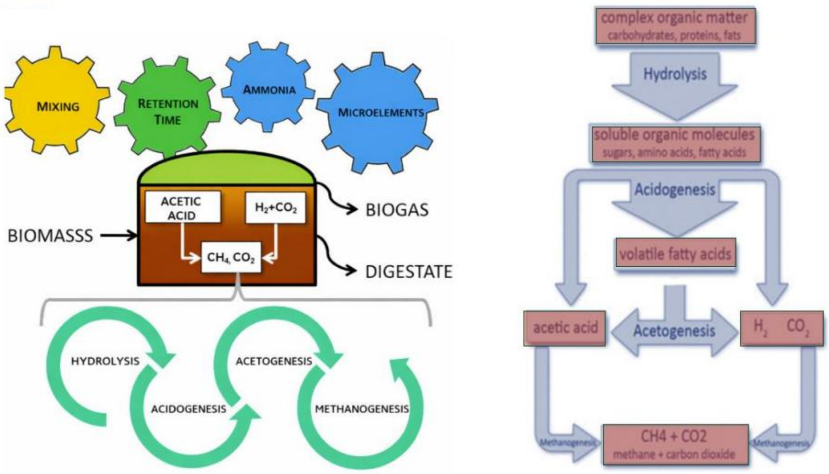


Figure 12 : The four steps of Anaerobic Digestion, Data from[11].

1. **Hydrolysis**

During this stage, hydrolytic bacteria degrade large molecules into simple monomers and oligomers. It is important to note that at this stage, polymers such as carbohydrates, proteins, and lipids are degraded to become soluble substances like sugars, amino acids, and fatty acids due to the effects of different hydrolyzing enzymes.

Dissolution begins when the first cellulosome is created. Cellulosomes are multi-enzymes formed by hydrolyzing bacteria in order to make the degradation process easier. The bacteria release different enzymes that help break down complex substances, such as glucanases, hemicellulases, chitinases, and ligninase.

The speed of the degradation process depends on the nature of the organic substance, its structure, and the degree of complexity. Carbohydrates can be easily broken down in a couple of hours, while proteins and lipids can take several days to complete the process.[11]

2. **Acidogenesis**

Once the monomers have been produced through hydrolysis, which consists of sugars, amino acids, and fatty acids with long chains, they become the substrate for acidogenic bacteria. Acidogenesis involves the metabolism of these components to short chain organic acids that are commonly referred to as volatile fatty acids (VFAs). The end products of this process include acetic acid, propionic acid, and butyric acid, among other byproducts like alcohols (methanol and ethanol), hydrogen, and carbon dioxide.
The composition of the fermentation products is greatly dependent on the hydrogen partial pressure. As the hydrogen partial pressure increases, more of the reduced products, including propionate and butyrate, are produced while less hydrogen leads to the production of acetate.

Various factors influence the performance of the acidogenic bacteria, and these include temperature and cell retention time, among others.

Acetogenesis

In the third step known as acetogenesis, the intermediates like volatile fatty acids (propionic acid, butyric acid, pentanoic acid) and alcohols get further metabolized to acetate. This is important as acetate acts as the main substrate in the methane production process. There are two major ways of forming acetate through different types of acetogenic microorganisms. First, the homoacetogens synthesize acetate through reductive processes using carbon dioxide and hydrogen. The second type, called syntrophic acetogenic bacteria, use intermediates that are not usable by methanogenic bacteria, thus changing them to methanogen usable substrates like acetate, hydrogen, and carbon dioxide.

This process involves cooperation among the involved acetogenic and methanogenic microorganisms, especially through control of hydrogen partial pressure.

Methanogenesis

The process of methanogenesis is the last stage in anaerobic digestion, whereby the intermediates are converted to methane and carbon dioxide through the action of the archaea called methanogens under anaerobic conditions. The main substrates used in this process include acetate, hydrogen, and carbon dioxide, which are produced at previous steps. The process of methanogenesis is considered to be one of the most important stages in the whole chain, due to the slow rate of chemical reactions involved. This process can greatly depend on external factors such as temperature, pH, and toxic materials in the reaction mixture.

The following section discusses the composition and energy content of biogas and biomethane, building on the previously described anaerobic digestion processes.

3.2 Biogases Composition and Energy Content

The composition and energy content of biogas and biomethane are primarily determined by the concentration of methane (CH_4) which serves as the energy-carrying component of the gas mixture. Raw biogas is produced through the anaerobic digestion of organic matter and typically exhibits a methane content in the range of $50-70\%$, with the specific percentage varying according to the substrate: for example, fats yield approximately 70% methane, whereas carbohydrates yield roughly 50%. Carbon dioxide (CO_2) constitutes $30-50\%$ of the biogas, while trace components include minor amounts of nitrogen (N_2) oxygen (O_2), hydrogen (H_2), hydrogen sulfide (H_2S), ammonia (NH_3) and water vapor. The heating value of raw Methane is approximately $9.94\, kWh/m^3$ (measured at 0 °C and $101{,}325\, Pa$), which corresponds to a lower heating value of $16-28\ MJ/m^3$. Due to the significant proportion of non-combustible CO_2, the energy density of biogas is considerably lower than that of pure methane [12].

Biomethane, on the other hand, is upgraded biogas in which impurities, primarily CO_2, are removed to increase the methane concentration. The methane content in biomethane is typically greater than 90% and often reaches $95-99\%$, depending on the upgrading technology employed (such as water scrubbing, pressure swing adsorption, or membrane separation). Carbon dioxide is usually reduced to less than 2%, and impurities such as H_2S, NH_3, H_2O, and siloxanes are largely removed. Once upgraded to approximately 98% methane, biomethane exhibits the same physicochemical properties as natural gas and can be injected into the natural gas grid or used as vehicle fuel. The energy content of biomethane is defined by the lower calorific value (LCV) of methane, which is measured as $50.4\ MJ/kg$ or $36\ MJ/m^3$ at standard temperature and pressure (STP) [12]. In Italy, the quality requirements for biomethane injected into the natural gas grid are defined by the Italian Ministerial Decree of 18 May 2018 and the technical standards UNI EN 16723-1 and UNI/TS 11537. In fact, the Decree updates the technical rules regarding the chemical and physical characteristics of combustible gas that can be transported in the Italian grid. The purpose is to establishes the baseline quality specifications and allowable components for common gases, ensuring pipeline compatibility, network safety, and continuity of service [13].

3.3 Different feedstocks for biogases production

Biogases can be produced from vary type of feedstock depending on the location and the collection suitability. According to the IEA report it classified three broad categories as potential sources of biogases production:

Agricultural residues and waste: they are grouped into two macro categories, crops residues (e.g. straw, husks or other organic matter from harvesting) and animal manure (that come from pig, cattle, sheep, poultry). Residues are subdivided by types of crops harvested, cereals and grain, oil and protein, sugar crops, roots and tubers.

Biowaste is composed of organic fractions of MSW (e.g. Food, and green), sewage sludge, industrial waste, wastewater that includes processing residues (dairy, drinks and distilleries, paper and pulp.

Woody biomass includes wood processing waste and log residue that are suitable for the biogases production through the thermal gasification process.

Biogases can be produced by others feedstock source such as sequential crops that are growing between two harvested crops. This allows farmers to struggle with erosion, preserve fertility of soil and maximize the agricultural output and the biogases production. Italy is known for employing sequential cropping as part of its biogas production [14].

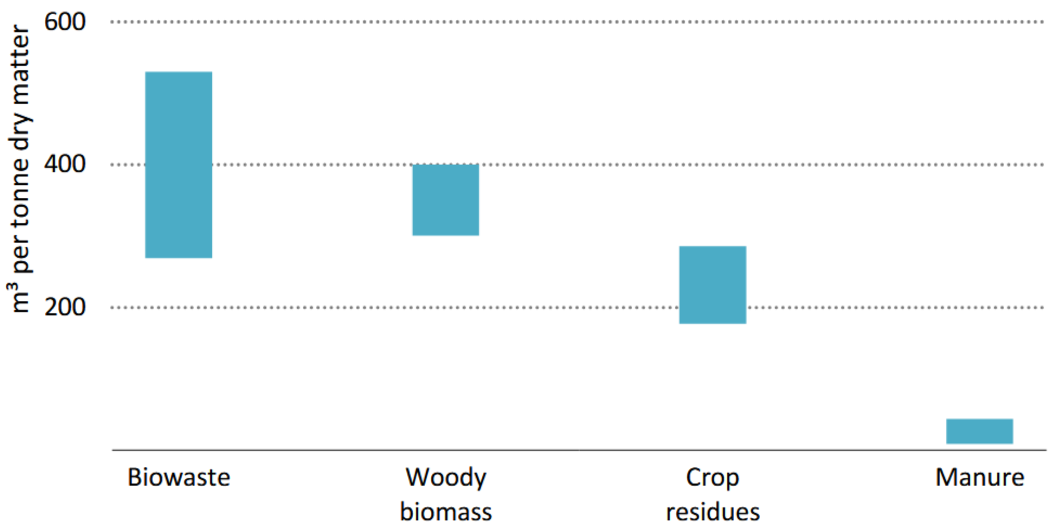


Figure 13 Range of methane yields for selected biogas feedstocks, Data from [15].

Figure 13 demonstrates that biowaste delivers high biomethane yields relative to other biogas feedstocks, revealing a considerable hidden potential for renewable energy recovery, per unit of dry matter.

3.4 Biogas/biomethane production comparison between Italy/Europe and Kenya

Biogas production is strongly influenced by feedstock type and availability across the world, including in Italy and Kenya. However, production patterns differ substantially between the two countries because of differences in technology maturity, incentive schemes, and policy frameworks. In 2023, global combined biogas and biomethane production reached approximately 50 bcm, equivalent to about 1,800 PJ, with Europe accounting for nearly 50% of global production, followed by China and the United States [15].

To examine the Italian context without focusing on a specific feedstock, the PNIEC (Piano Nazionale Integrato per l'Energia e il Clima), Italy's strategic national energy and climate plan, provides an important reference point. The plan sets a strategic target of approximately 4.6 Mtoe for total national biogas and biomethane production by 2030, while academic studies cited in the report estimate the sustainable biomethane potential at 5.7–6.5 bcm per year. According to the RRU 2025, total biogas production in Italy from OFMSW is approximately 0.535 bcm obtained by summing production from integrated anaerobic/aerobic plants (0.43 bcm) and dedicated anaerobic digestion plants (0.105 bcm). Focusing specifically on anaerobic digestion, production increased by 38.6% in 2024 compared with 2023. At the regional level, Lombardy records the highest production of both biogas and biomethane in Italy, with approximately 0.0435 bcm/year and 0.01286 bcm/$year$, respectively.

Table 10 Biogas energy production and recovery in anaerobic digestion plants, by region, year 2024, Data from [3]

Regione	Biogas (Nm³/a)	Biometano (Nm³/a)	Energia elettrica (MWh/a)	Energia termica (MWh/a)
Piemonte	3.438.804	0	5.210	454
Valle d'Aosta	0	0	0	0
Lombardia	43.583.805	12.864.557	41.202	14.737
Trentino-Alto Adige	4.441.312	0	11.801	380
Veneto	14.374.570	4.163.677	26.180	786
Friuli-Venezia Giulia	0	0	0	0
Liguria	0	0	0	0
Emilia-Romagna	20.845.502	12.508.291	7.633	0
Nord	**86.683.993**	**29.536.525**	**92.026**	**16.357**
Toscana	0	0	0	0
Umbria	0	0	0	0
Marche	0	0	0	0
Lazio	9.262.113	4.359.606	0	0
Centro	**9.262.113**	**4.359.606**	**0**	**0**
Abruzzo	0	0	0	0
Molise	9.940.054	3.451.402	6.066	0
Campania	0	0	0	0
Puglia	0	0	0	0
Basilicata	0	0	0	0
Calabria	0	0	0	0
Sicilia	0	0	0	0
Sardegna	0	0	0	0
Sud	**9.940.054**	**3.451.402**	**6.066**	**0**
ITALIA	**105.886.160**	**37.347.533**	**98.092**	**16.357**

The situation in Kenya is markedly different, as the biogas potential varies substantially according to feedstock type, source, and seasonal availability. A recent study evaluating biomethane production potential in Kenya analyzed a wide range of substrates, including organic waste from markets and households, invasive aquatic plants from Lake Kisumu, slaughterhouse waste from Isiolo, market waste from Embu, market and restaurant waste from Nakuru, and cattle farm waste from Nairobi. These substrates included fruit and vegetable residues, fish waste, food waste, household waste, water hyacinth, cattle manure, and slaughterhouse residues. The results showed methane yields ranging from 230 to 441 mL CH_4/g VS, indicating high biodegradability and significant energy recovery potential. Co-digestion and appropriate substrate blending were found to further enhance methane production.[2]

Another study on the anaerobic digestion of organic wastes in Kenya emphasized that the main feedstock sources are urban markets, households, livestock farms, and slaughterhouses. The authors noted that methane production is strongly affected by substrate properties such as the C/N ratio, moisture content, and feedstock origin. In particular, food waste and market waste are typically wetter and more readily degradable, whereas manure and fish wastes are richer in protein and nitrogen, which can improve methane potential but may also increase the risk of process inhibition under unsuitable operating conditions. This highlights that anaerobic digestion performance depends not only on feedstock availability but also on maintaining a balanced substrate composition.

Additional studies reported methane yields from mixed fruit and vegetable waste ranging from 288 to 516 mL CH_4/g VS, with values varying across seasons due to changes in waste composition. This seasonal and compositional variability underscores the limited availability of empirical data on actual methane yields in Kenya, especially for mixed municipal waste streams. Earlier Kenyan studies focused on single fractions such as manure or crop residues and did not fully capture the performance of mixed organic waste mixtures. Nevertheless, national assessments estimate that approximately 1,313 million m^3 of methane could be produced annually from agricultural residues and other biowastes.[2]

On the continental scale, Africa's biogas potential is strongly influenced by the distribution of feedstocks and their sustainable recovery. As shown in Figure 14, Nigeria has the largest estimated potential, dominated by crop residues at nearly 16 bmc natural gas equivalent, followed by animal manure and biowaste. Kenya's estimated biogas potential is at roughly 5 bcm equivalent, with crop residues and animal manure representing the dominant feedstocks, representing a level nearly twice that of Italy. By contrast, Italy's biogas production in 2024 remained stable at around 80 PJ per year, corresponding to approximately 2.23 bcm [16]. This comparison highlights that, although Kenya possesses substantial untapped biogas potential, Italy currently exhibits a more developed and established biogas sector.

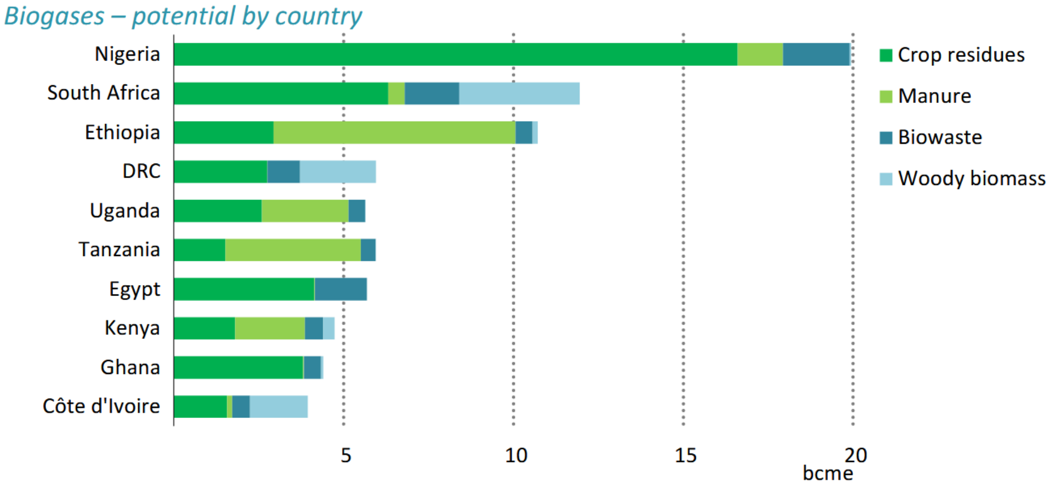


Figure 14: Biogases potential in some Africa countries, Data from [15]

Chapter 4: Pilot Case for a Sustainable and Socially Inclusive OFMSW Management System in a Nairobi Neighborhood

4.1 Introduction

This chapter examines a pilot case for a sustainable and socially inclusive municipal solid waste management system in a Nairobi neighborhood, with particular emphasis on the organic fraction of municipal solid waste (OFMSW). The pilot is conceived as a demonstrative model through which an integrated neighborhood-scale system can be designed and tested by taking into account population density, residents' participation, and the existing roles of private operators and informal waste collectors. In addition to the technical and organizational dimensions of waste management, the chapter emphasizes the role of government not only as a licensing and enforcement authority, but also as an active facilitator capable of coordinating actors, creating incentives, and rewarding effective segregation and collection practices in order to improve service performance and social inclusion.

The analysis draws on positive experiences from the Italian waste management system that may be transferable to the Nairobi context, especially in relation to the separate collection and biological treatment of OFMSW. Such transfer should not be understood as a direct replication of the Italian model. Indeed, Italy and Kenya significantly differ in terms of institutional capacity, economic structure, urban development patterns, cultural practices, and waste service coverage. Italy benefits from relatively mature data systems, stable regulatory enforcement, and a well-developed waste collection and treatment infrastructure, while Nairobi's waste management system is still characterized by incomplete collection coverage, uneven implementation of formal rules, and a strong dependence on informal and semi-formal recovery networks.[17] Nevertheless, several features of the Italian approach remain highly relevant, including the strategic prioritization of organic waste, the central coordinating role of local authorities, the use of behavioral and economic incentives, and the integration of waste collection with downstream recovery systems such as composting and anaerobic digestion.

4.2 Study area and neighborhood characteristics

The proposed pilot case is based on a representative Nairobi neighborhood with an assumed population of 1,000 inhabitants. This scale is suitable for a demonstrative intervention because it is large enough to generate a measurable quantity of organic waste, while still remaining manageable in terms of source separation, collection logistics, stakeholder coordination, and performance monitoring. The neighborhood is assumed to have a mixed urban structure, including households, small food shops, restaurants, and a local market cluster, which reflects the typical coexistence of residential and commercial food-related activities in Nairobi. Nairobi is characterized by rapid urbanization, uneven service coverage, and substantial variability in population density across formal and informal settlements. Recent sources indicate that the city generates approximately 3000 to 4000 tons of municipal waste per day, while organic waste constitutes the dominant fraction which approximately 80% of the total stream.[18] This makes neighborhood-scale OFMSW management particularly relevant, since dense urban areas can provide both high feedstock availability and efficient collection potential if segregation is effectively organized.

4.3 Estimated waste generation and OFMSW composition

For the pilot, household municipal solid waste generation is estimated at 0.61 kg per person per day, which is consistent with Nairobi residential data reported in the African Clean Cities platform.[19] For a population of 1,000 inhabitants, this corresponds to a total household waste generation of about 610 kg/day. Assuming an OFMSW share of 80%, in line with recent Nairobi studies reporting organic fractions, the neighborhood would generate approximately 488 kg/day of household organic waste before separation losses. In practice, not all of this material can be recovered because source segregation is rarely perfect. Assuming a realistic initial capture efficiency of 60%, the quantity of segregated household OFMSW available for treatment would be about 292.8 kg/day . To reflect the mixed-use nature of the neighborhood, it is further assumed that small restaurants and market activities contribute an additional 120 kg/day of separately collected organics. Under these assumptions and considering that household organic waste contains high moisture content from food scraps, fruit and vegetable peelings, leftovers, and other kitchen waste, the total feedstock available for anaerobic digestion would be approximately 412.8 kg/day OFMSW wet weight. These assumptions are consistent with broader evidence from Nairobi, where market waste has been shown to be especially suitable for recovery because of its high organic content and relatively low contamination. Studies on Nairobi markets report that about 95% of market waste by weight and volume is organic, while recent market characterization research found a 67% organic share in sampled market waste streams.[20]

4.4 Stakeholder roles: households, private firms, and informal collectors

The success of the pilot depends on the coordinated participation of households, private service providers, and informal collectors. Households are the primary actors in source separation because the quality of the OFMSW stream depends directly on segregation behavior at the point of generation. Residents must therefore be considered co-producers of the waste service rather than passive users. Their role includes separating organic waste, using designated collection containers correctly, and complying with collection schedules. Private firms are expected to provide transport, route organization, and, where available, treatment services. In the Nairobi context, however, formal waste management alone is insufficient to guarantee effective collection coverage. Informal collectors and community-based organizations already play a major role in waste recovery and service delivery, especially in areas where municipal systems are weak or fragmented. The pilot should therefore integrate these actors into the formal service chain through accreditation, training, safety support, and performance-based contracts. This arrangement would create a hybrid model in which households perform source separation, informal actors support local collection and community engagement, and private firms ensure transport reliability and technical operations. Such a model is socially more inclusive and institutionally more realistic than a purely top-down formalization approach.[21]

4.5 Source-separation and collection design

The core of the pilot should be a two-stream system composed of organic and non-organic waste. This model is realistic for the Nairobi neighborhood because it simplifies participation requirements while still enabling the capture of the most recoverable and problematic waste fraction. It also reflects the Kenyan legal requirement that non-hazardous waste be segregated into organic and non-organic fractions and placed in labelled receptacles.[8]

Households, restaurants, and market traders within the pilot area should receive clearly marked containers and simple instructions on acceptable materials. Organic waste should be collected more frequently than non-organic waste because of its rapid decomposition and potential to generate odor, leachate, and nuisance if left uncollected. Collection routes should be planned around local spatial conditions, taking into account road access, market peak times, and building density.

A major lesson from Italy is that high-quality biowaste collection depends on system regularity and user clarity. Milan's experience shows that dense neighborhoods can achieve relatively low contamination in collected organics when rules are simple and service is reliable. For Nairobi, this implies that the collection system should avoid excessive complexity. In the early phase, the objective should not be full material separation across many fractions, but rather the establishment of a stable and trusted OFMSW stream that can support recovery.[22]

4.6 Biogas potential, digestate production estimation, and biogas plant sizing

The pilot case is assumed to operate under mesophilic conditions (around 35°C), as this temperature range is widely used in pilot-scale OFMSW digestion studies and has been shown to support stable biogas production. The system is also designed as a continuous or semi-continuous process, consistent with pilot-scale anaerobic digestion applications reported in the literature [23]. The total daily OFMSW (on wet basis) available for digestion is 412.8 kg/day, including separately collected household organic waste and additional organics from restaurants and market activities. The Biogas Yield Factor is a value of 0.5 CH4 Nm^3/kg VS is often used for modelling [24]. The neighborhood-scale system would produce approximately $37.152\ Nm^3$ of biogas per day. This estimation remains cautious relative to laboratory methane potential studies from Kenya, which report methane yields ranging from 0.23 to 0.441 Nm^3CH_4/kg VS for representative organic waste streams and even higher yields for some market and co-digested feedstocks. The choice of a conservative planning value is appropriate because actual pilot performance will depend on contamination, moisture content, retention time, inoculum quality, and operating stability. [18]

To dimension the anaerobic digester, a diluted slurry feeding regime and a hydraulic retention time (HRT) of about 30 days was assumed according to pilot past case study [25]. Digester volume is calculated as follows:

$$V = Q * HRT$$

Q = Feeding flow rate $\frac{m^3}{day}$

Assuming a slurry density of approximately $1{,}000\ kg/m^3$, the influent volume is:

$$Q = \frac{825.6}{1000} = 0.8256\ m^3/day$$

So: $V = 0.8256 * 30 \cong 24.84\ m^3$

Under these conditions, the indicative digester volume is approximately 24.8 m^3. This value is obtained from both the organic loading rate and the HRT method. Assuming an organic fraction of 90% volatile solids (VS) and 20% TS according to the study carried out on kitchen waste and organic municipal solid waste.[26] therefore, the daily TS load is:

$$412.8 \times 0.20 = 82.56 \text{ kg TS/day}$$

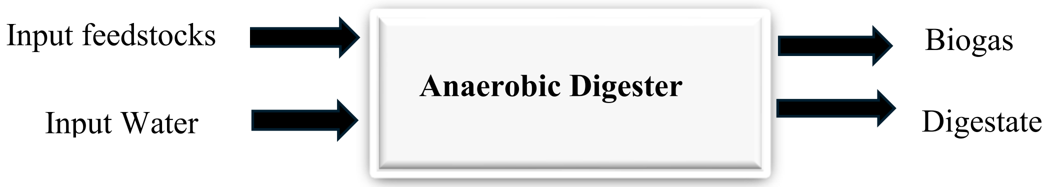
And the VS load is:

$$82.56 \times 0.90 = 74.304 \text{ kg VS/day}$$

In order to have an input feedstock equal to 10% of TS to allow the wet anaerobic digestion process, let calculate the make-up water to add. $Input_{water} = \frac{TS}{0{,}1} - Input_{feed} = \frac{82.56}{0.1} - 412.8 = 412.8\ kg/day$

The total digester input is: $Input_{water} + Input_{feed} = 825.6\ kgbiomass/day$

The diagram below illustrates the process with different input stream and output.



The organic loading rate (OLR) is calculated by using the follow formular:

$$OLR = \frac{mass.VS}{V} = \frac{74.304}{24.76} = 3\ kg\ VS/m^3 \cdot day$$

In energy terms, the estimated biogas output corresponds to about 222.912 kWh/day of gross energy, assuming an average energy content of approximately 6 $kWh\ /Nm^3$ of biogas, corresponding to a methane content of about 60%.

Given the relatively small scale of the plant and the neighborhood context, the most appropriate end use of the gas would be direct thermal applications, especially cooking in nearby institutions, community kitchens, or food businesses. This pathway is more practical than electricity generation or grid injection because it requires less conversion equipment and can deliver immediate local benefits. However, using an electrical efficiency of CHP for biogas of 35% and thermal efficiency of 45%, electrical energy generated is 78 Kwh_e/day and thermal energy of 100.3 Kwh_t/day [27].

For the digestate, using the biogas density of 1.15 kg/m^3. This means the digestate is calculated by following:

$$825.6 - 37.152 * 1.15 = 782.87 \text{ kg /day}$$

Assuming the digestate density of approximately 1,000 kg/ m^3, this corresponds to:

$$782.87 \div 1000 = 0.782 \text{ m}^3/\text{day}$$

or roughly 783 kg/day. The digestate can be de-watered and used as compost, soil amendment, or bio-slurry for urban and peri-urban agriculture, provided that quality and safety standards are met.

Here below is a table summarizing the input and output data:

Table 11 quantitative parameters of the pilot model

Parameter	Value	Unit	Sources
Population	1,000	People	Assumed
per-capital MSW	0.61	kg/day	[19]
Slurry density	1,000	kg/m^3	Assumed
biogas density	1.15	kg/m^3	[26]
Biogas energy content	6	kWh/Nm^3	Assumed
organic fraction	80%	-	[18]
Household MSW generated	610	kg/day	Calculated
Moisture content	80%		[24]
Biogas Yield	0.5	Nm^3/kg VS	[18]
efficiency collection	60%	-	Assumed
Household OFMSW captured	292.8	$kgbiomass/day$	Calculated
Commercial OFMSW	120	$kgbiomass/day$	Assumed
Mass_commercial_housseOFMSW	412.8	$kgbiomass/day$	Calculated
Volatile solid	90%	-	[26]
Mass Volatile solid	74.304	$kgVS/day$	Calculated
Make up Water	412,8	kg/day	Calculated
Total solid	20%	-	[26]
Total OFMSW fed to digester +Water	825.6	$kgbiomass/day$	Calculated
TS OFMSW	82.56	$kgTS/day$	Calculated
Biogas produced	37.152	$Nm^3\ /day$	Calculated
Digestate mass production	782.8752	kg/day	Calculated
Digestate volume production	0.7828752	m^3/day	Calculated
Gross Energy content	222.912	kWh/day	Calculated
Organic loading rate (OLR)	3	kg VS/ m^3/day	Calculated
Hydraulic retention time (HRT)	30	days	[25]
Recommended digester volume	24.768	m^3	Calculated
Q feeding flow rate	0.8256	m^3/day	Calculated
Electrical Energy	78.0192	kWh_e/day	Calculated
Thermal Energy	100.3104	kWh_t/day	Calculated

4.7 Governance, incentives, and monitoring indicators

A key premise of this chapter is that county government must play a broader role than licensing and enforcement alone. The Sustainable Waste Management Act and related policy instruments already assign public authorities' responsibilities for infrastructure provision, source-separation support, incentives, and data management. In the pilot context, this means that the county government should act as the system coordinator responsible for bringing actors together, setting performance conditions, and ensuring that segregated organic waste reaches licensed treatment facilities.

Government facilitation should take several practical forms. First, the county should define the pilot boundaries, set service rules, and register all participating actors, including community organizations and informal collectors. Second, it should support implementation by subsidizing or co-financing starter bins, liners, and local awareness campaigns where possible. Third, it should introduce incentive mechanisms, such as reduced service fees for compliant generators, bonus payments for collectors delivering low-contamination organic waste, or recognition programs for high-performing neighborhood blocks, schools, and markets.

Monitoring is equally important. The pilot should collect data on participation rates, quantities of OFMSW collected, contamination levels, collection frequency, treatment outputs, and the number of formalized jobs created or supported. Such indicators would allow the pilot to function as an evidence-generating platform as well as an operational service. In the Kenyan context, where waste data are often incomplete or fragmented, this monitoring function would have value beyond the pilot area itself.

4.8 Expected environmental and social benefits

The pilot is expected to produce both environmental and social benefits. From an environmental perspective, improved source separation of OFMSW would reduce the quantity of biodegradable waste sent to uncontrolled disposal sites and increase the availability of clean feedstock for composting or anaerobic digestion. This would support diversion from disposal, reduce sanitation pressures, and contribute to a more circular use of urban organic materials.

From a social perspective, the pilot would demonstrate whether more inclusive modernization is possible in Nairobi's waste sector. By integrating informal collectors into recognized service roles and linking payment to performance and safety standards, the system could support livelihoods while improving working conditions and institutional legitimacy. This is particularly important because exclusionary modernization strategies may undermine both social equity and operational effectiveness in contexts where informal recovery systems remain central to waste management.

In addition, the pilot could help strengthen public trust in local waste governance. Visible improvements in cleanliness, service regularity, and community participation may create positive feedback effects that improve compliance and willingness to separate waste. If successful, the pilot could therefore serve as a practical reference for scaling up neighborhood-based OFMSW management in Nairobi and, eventually, in other Kenyan cities.

4.9 Scale-up to Nairobi city

Based on an estimated population of 5.6 million inhabitants in Nairobi in 2026, and assuming a municipal solid waste generation rate of 0.61 $kg/capita/day$, the city is projected to produce approximately 3,416 tons of waste per day. If 80% of this stream is considered organic, household organic waste would amount to about 2,734 tons/day. Assuming that 60% of this fraction can be recovered through source separation, the recoverable household OFMSW would be approximately 1,640 $tons/day$. When commercial organic waste from markets, hotels, slaughterhouses, and related facilities is added, estimated at 1,540 $tons/day$, the total OFMSW available for treatment would reach approximately 3,180 tons/day.

Using a conservative biogas yield of $0.5Nm3/kgVS$, Nairobi could theoretically produce about 0.28 million Nm^3 of biogas per day. Assuming an average biogas energy content of 6 kWh/Nm^3, the corresponding gross energy production would be approximately 1,717 MWh/day. Under a combined heat and power (CHP) configuration with an electrical efficiency of 35% and a thermal efficiency of 45%, the system could generate approximately 601 MWh_e/day of electrical energy and 773 MWh_{th}/day of useful thermal energy. A total digester capacity of approximately 0.191 million m^3 would be required that was calculated based on the small case. A single centralized plant would be impractical. A more realistic configuration would consist of several decentralized or semi-centralized hubs, each equipped with multiple digesters. For example, the total required volume of approximately 0.191 million m^3could be distributed across 20 treatment hubs, each with about 9,540 m^3 of digester capacity, corresponding to roughly 10 digesters of 950–1,000 m^3 per hub. The proposed number of digesters is intended only as an illustrative design scenario. The actual configuration would need to be optimized according to waste availability, collection logistics, available land, and techno-economic considerations.

At the city scale, these results indicate that Nairobi should not depend on a single centralized anaerobic digestion facility. A more suitable approach would be a networked system composed of neighborhood- or district-scale source separation and multiple decentralized or semi-centralized treatment hubs. In particular, markets, institutional kitchens, hotels, slaughterhouses, and dense residential areas should be prioritized as feedstock sources because they produce more concentrated organic waste streams and are therefore better suited to low-contamination collection and treatment.

Conclusion

The present study set out to investigate municipal solid waste management in Kenya and Italy, with a particular focus on the OFMSW. It adopted a comparative approach to examine the waste management systems of the two countries and to propose a sustainable pilot model for organic waste management in Kenya, drawing inspiration from the Italian system while adapting it to the Kenyan context and its specific constraints.

The findings show that municipal solid waste remains a major challenge in Kenya, where the collection system is still largely insufficient. In 2024, the country was estimated to generate approximately 22,000 tons of waste per day, of which only about 25% was properly collected. This indicates the substantial effort still required to improve waste management performance. Nairobi, the largest waste-generating city in the country, produces around 3,084 tons of waste per day and is also home to Dandora, one of the world's largest dumpsites, where waste is disposed of without prior sorting.

The study also highlighted the limited reliability of waste-related data in Kenya, as available information is often fragmented and, in many cases, derived from experimental studies rather than from consolidated institutional monitoring systems. By contrast, Italy presents a well-structured waste management system, characterized by high levels of public participation and collection coverage, reaching nearly 97%. In 2025, Italy generated approximately 30 million tons of municipal solid waste, of which 67.5% was collected separately. These figures clearly indicate that the Italian waste collection system is considerably more mature and advanced than that of Kenya.

Although Kenya has established a regulatory and policy framework for waste management, including the 2010 Constitution, which assigns county governments responsibility for organizing waste management and sanitation in order to protect citizens' constitutional rights, municipal solid waste management remains a serious national problem. In practice, waste management in Kenya is largely carried out by private companies, informal waste pickers, and non-governmental organizations. This system differs significantly from the Italian model, in which waste management is primarily the responsibility of public authorities operating within a structured governance framework.

In Kenya, the most common waste disposal practices include incineration and uncontrolled dumping on streets, in rivers, and in illegal dumpsites, all of which contribute to environmental pollution. In fact, in 2020, the waste sector accounted for approximately 3–4% of greenhouse gas emissions in the country. With regard to organic waste, the most common treatment methods are composting and biogas production, although these are still mainly implemented through pilot initiatives. Biogas production in Kenya is more frequently associated with animal manure and agricultural residues than with the organic fraction of municipal waste.

By contrast, Italy has a well-developed OFMSW management system. The country has approximately 625 waste treatment and recycling facilities, of which 344 are dedicated to OFMSW treatment. These include 250 composting plants, 66 integrated aerobic and anaerobic treatment plants, and 28 anaerobic digestion facilities. These figures demonstrate the advanced and structured nature of the Italian waste management system, which is supported by strong policy measures. Legislative Decree 152/2006 provides the legal basis for waste management in Italy, with the objectives of minimizing waste generation, promoting reuse and recycling, and ensuring the development and proper functioning of safe and controlled disposal facilities. In addition, the European Union's Circular Economy Action Plan, approved on 20 March 2020, requires Member States to move toward a circular economic and social model by 2050.

Furthermore, Italy's PNIEC 2024, the national roadmap for deep decarbonization, identifies the waste sector as a critical area for achieving emissions reduction targets. The plan aims to reduce the amount of waste sent to landfills to below 10% by 2035. Overall, the comparison between the two countries shows a substantial disparity in institutional capacity, infrastructure, and policy implementation, while also highlighting the potential for adapting elements of the Italian model to support the development of more sustainable organic waste management practices in Kenya.

This study has demonstrated that anaerobic digestion of the organic fraction of municipal solid waste represents a technically viable and environmentally relevant strategy for improving waste management and resource recovery in Kenya. At the neighborhood scale, the pilot case for a population of 1,000 people showed the potential to generate 37.15 Nm^3 of biogas per day, together with approximately 78 kWh_e/day of electricity, 100.3 kWh_{th}/day of thermal energy, and 782.8 kg/day of digestate suitable for agricultural reuse. These results confirm the value of OFMSW as a local renewable resource with both energy and material recovery potential.

When extrapolated to the scale of Nairobi, the model suggests a daily biogas potential of approximately 0.28 million Nm^3, equivalent to about 1,717 MWh/day of gross energy. Under a CHP configuration, and assuming 35% electrical efficiency and 45% thermal efficiency, this would correspond to approximately 601 MWh_e/day of electricity and 773 MWh_{th}/day of useful thermal energy. The estimated digester volume required for Nairobi is approximately 0.191 million m^3, indicating that a single centralized plant would be impractical. A more realistic configuration would involve multiple decentralized or semi-centralized treatment hubs, each equipped with several digesters; for example, the total volume could be distributed across 20 hubs, with each hub providing about 9,540 m^3 of digester capacity, or roughly 10 digesters of 950–1,000 m^3 per hub. Overall, these results highlight the substantial untapped potential of OFMSW and the strategic role that anaerobic digestion could play in urban energy supply, waste diversion, and environmental protection.

The research also shows that, despite the existence of multiple policies addressing municipal solid waste in Kenya, implementation remains insufficient, thereby limiting the effectiveness of the current regulatory framework. Accordingly, future progress will require stronger and better adapted regulations, as well as the formal recognition and integration of informal waste pickers, whose role is essential to the functioning of the waste management system.

More broadly, the pilot model developed in this study may offer a relevant point of reference for other African cities that face similar structural, institutional, and socio-economic conditions. Its wider adoption could contribute to improved energy security, reduced environmental burdens, and better public health outcomes associated with unmanaged organic waste. Nevertheless, further research is needed to assess the economic sustainability of the model and to strengthen the reliability of laboratory-scale data in support of future implementation.

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