

Sustainable Municipal Solid Waste Management in the City of Baku: Contemporary Challenges and Innovative Solutions

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Abstract

Because of population growth, rapid urbanization, expanding consumption habits, and intensive economic activity, there has been a steady increase in the generation of municipal solid waste, making its effective management one of the key challenges for the sustainable development of modern cities. Against the backdrop of increasing anthropogenic impact, traditional approaches to waste management are no longer capable of ensuring a stable level of environmental protection, resource efficiency, or adherence to the principles of the circular economy. In Baku, this issue has become relevant due to the city's rapid social and economic development, population growth, and the need to upgrade the existing waste management system in line with current international environmental standards. The aim of this study is to conduct an all-round assessment of the current state of the municipal solid waste management system in Baku, identify the principal environmental, organizational, and technological challenges, and develop innovative solutions aimed at increasing the overall effectiveness of the system. This research includes an analysis of the waste management infrastructure, the regulatory and legal framework, the best international practices, and advanced technological approaches, with particular emphasis on the principles of the circular economy, resource conservation, and the digitalization of waste management processes. The results of the study are expected to identify priority directions for advancing the municipal solid waste management system in Baku, substantiate the feasibility of implementing innovative organizational and technological solutions, and provide scientifically grounded recommendations directed at decreasing the environmental impacts of waste, growing resource efficiency, and facilitating the transition toward a sustainable waste management model consistent with the United Nations Sustainable Development Goals.

Keywords: Baku city, solid waste, recycling, innovative technologies, waste management system.

1. Introduction

Over the last 10 years, rapid population growth, accelerated urbanization, industrialization, and increasing levels of consumption have become the principal factors of the continuous growth in municipal solid waste (MSW) generation worldwide (Kaza et al., 2018; UNEP, 2019). According to current projections, global municipal solid waste generation is expected to increase from 2,1 billion tons in 2020 to 3,8 billion tons by 2050, representing an increase of nearly 56%. Although recycling and waste treatment technologies have improved, only about 62% of the produced waste is recycled, used to generate energy, or placed in properly managed landfills. The last 38% is still disposed of in ways that can harm the environment (ISWA, 2024; Hoornweg & Bhada, 2012; Chen, 2020). This trend significantly hinders the

achievement of sustainable development aims and requires the transition to more effective waste management models based on the principles of the circular economy, resource efficiency, and environmental sustainability.

Improper trash utilization can cause a lot of problems for the environment, people's lives, and their money. When we throw out trash in landfills or dump it wherever, it releases more greenhouse gases and pollutes the air, soil, and groundwater. It also makes things less clean and can spread diseases. Experts think that the amount of greenhouse gases from trash could increase a lot by 2050, from about 1300 million tons in 2015 to almost 2400 million tons. This shows that we really need to get better at managing our waste. If we do better, we can reduce pollution, use our resources more effectively, and help cities grow in a way that lasts.

This problem is very important for quickly developing countries because the number of people is growing, which means more consumption and a lot more trash. Azerbaijan is a good example. In 2023, it was recorded that the country produced 4086.1 thousand tons of waste, which is more than 3985.1 thousand tons in 2022. This is the highest amount for this year. Since 1995, when only 247 thousand tons were generated, waste has increased more than sixteen times. This shows that the current waste management system is under pressure and needs to be modified. Most of Azerbaijan's trash comes from Baku, the main city for government, business, and the economy. In Baku, there are a lot of people, buildings, businesses, and services. Because so many people live there, the city is growing, and people's needs are becoming more, so the amount of trash keeps going up. This makes it harder to collect, move, sort, recycle, and get rid of all the waste efficiently. Despite improvements lately, like building better waste management facilities and starting to separate trash at the source, there are still environmental, organizational, and technical problems. These problems are preventing Azerbaijan from managing waste sustainably and moving towards a system where resources are reused.

High population density, intensive urban development, territorial expansion, and increasing consumption patterns have resulted in a continuous increase in municipal waste generation, placing greater demands on the efficiency of waste collection, transportation, sorting, recycling, and final disposal. Although considerable progress has been achieved in recent years through the development of modern waste management infrastructure and the introduction of selected elements of source-separated waste collection, several environmental, organizational, and technological challenges remain, limiting the implementation of sustainable waste management principles and the transition toward a circular economy (EC, 2020; Zhang et al., 2024; 10, Tamiz Shahar JSC, 2023).

Contemporary scientific literature places considerable emphasis on improving municipal solid waste management systems through the adoption of innovative recycling technologies, the digitalization of waste management processes, the application of Life Cycle Assessment (LCA), and the implementation of circular economy principles. However, comprehensive studies evaluating the sustainability of the municipal solid waste management system in the city of Baku, while considering contemporary international approaches and the potential for implementing innovative solutions, remain limited (Chen et al., 2020; Kirchherr et al., 2017; Geissdoerfer et al., 2017; Pires et al., 2011; Wilson et al., 2015).

2. Research Aim and Objectives

The aim of this study is to evaluate the current municipal solid waste management system in Baku, identify its main ecological, organizational, and technological problems, and propose practical solutions to improve its efficiency. The study also considers ways to make waste control more sustainable and support the principles of the circular economy. These research objectives will be achieved through the following:

1. Analyze the current condition of solid waste management in Baku and the major trends in its evolution;
2. Investigate the existing methods of collecting, transferring, grading, recycling, and ultimately disposing of municipal solid waste and the factors affecting its effectiveness;

3. Explore how municipal solid waste management can be organized in an environmentally friendly and economical way and what the challenges of this management are from an organizational perspective as well as from an economic perspective.
4. To analyze current international methodologies for effectively managing municipal solid waste and to explore how modern technologies can support the sustainable management of municipal solid waste and become applicable for solid waste management in Baku.
5. To develop the system of managing municipal solid waste on the example of "Baku" through the development of a wide range of recommendations, which will be based on scientific principles and will consist of innovative methods of managing municipal solid waste, following the principles of the circular economy and resource efficiency, as well as the principles of sustainable development.

The aim of this study is to examine the current waste management system in Baku, identify its main environmental, organizational, and technological problems, and suggest practical solutions to improve its efficiency. The study also focuses on ways to make waste management more sustainable and support the principles of the circular economy.

3. Materials and Methods

This study performs a comprehensive assessment of the municipal solid waste management system in Azerbaijan's capital, Baku, covering not only environmental and organizational factors but also technological and legal/regulatory factors. Besides being aligned with the latest international principles for evaluating the sustainability of municipal solid waste management systems, this research methodology also adheres to the methodologies for assessing waste management systems according to the circular economy.

The study information base used official statistical data published by the State Statistical Committee of the Republic of Azerbaijan, the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, the Organization for Economic Cooperation and Development, the World Bank, the International Solid Waste Association, as well as legislative and regulatory documents governing municipal solid waste management in Azerbaijan (OECD, 2025; Gosudarstvennyi komitet statistiki Azerbaidzhanskoi Respubliki, 2024; The World Bank, 2020; Gosudarstvennyi komitet statistiki Azerbaidzhanskoi Respubliki, Helms & Nixon, 2010). In addition, scientific publications indexed in the Scopus and Web of Science databases were analyzed, with an emphasis on sustainable waste management, resource efficiency, the circular economy, and the implementation of innovative waste treatment technologies (Kirchherr et al., 2017; Geissdoerfer et al., 2017; Pires et al., 2011; Zaman, 2015; Ferronato & Torretta, 2019; EUA, 2023).

To reach the research goal, a mix of complementary methods was used. First, an in-depth review of scientific literature helped capture current approaches to municipal solid waste management, highlighting key trends shaping the sector, and detecting gaps in existing studies. Then, a comparative analysis assessed Baku's waste management system by looking at how it stacks up against practices in European Union countries and other nations that have successfully embraced sustainable waste strategies. Statistical methods allowed the exploration of patterns of waste generation, tracked vital performance indicators, and identified major developments within the system. By using official data, the research was able to measure the volume of waste produced and uncover factors that affect how well the current management system functions. A SWOT analysis was employed to evaluate the internal and external factors that affect the development of the municipal solid waste management system in the city of Baku. This approach facilitated the identification of the system's strengths and weaknesses, as well as the opportunities for its improvement and the potential risks associated with its future development.

To develop practical recommendations, we applied a systems approach, clearly examining how waste is generated, collected, transported, sorted, recycled, and ultimately disposed of. The results were analyzed through the lenses of sustainable development, the circular economy, resource efficiency, and environmental sustainability (Kirchherr et al., 2017; Geissdoerfer et al., 2017; MacArthur, 2013; Ferronato & Torretta, 2019; Khan et al., 2019; Zhang et al., 2015). By combining these research methods, we get a

clear, overall picture of the Baku municipal solid waste management system. This type of approach helped detect main operational challenges and formed a solid scientific foundation for creating evidence-based recommendations. These recommendations focus on modernizing the system by introducing innovative solutions.

4. Results

4.1. Current Status of Waste Generation in Azerbaijan

An important measure of how well a waste management system works is how much waste is produced and how effectively it is recovered or utilized. According to official statistics, Azerbaijan has seen a steady rise in industrial and municipal waste over the last fifteen years. This growth is driven by factors like population growth, fast industrial development, widening cities, more construction, and shifts in how people consume goods (Kaza et al., 2018; ISWA, 2024; OECD; Gürel & Tat, 2017).

Table 1. Waste Generation, Recovery, and Treatment in Azerbaijan, 2009-2024.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Industrial and Municipal Waste Generated, thousand tonnes	2287,6	2281,5	2789,6	3096,7	2575,6	2386,0	2350,4	3019,7	2754,5	2896,1	3256,0	3452,3	3778,2	3985,1	4086,1	4365,0
Per Capita, kg	256	252	304	333	274	250	247	309	283	295	329	346	377	395	402,4	427,8
Industrial and Municipal Waste Recovered and Treated, thousand tonnes	503,1	476,1	572,3	665,0	537,2	497,3	771,7	796,6	767,3	848,3	713,4	792,1	1563,1	801,9	1139,2	1148,4
Per Capita, kg	56	53	62	72	57	52	81	82	79	85	72	79	156	79	112,2	112,6

As shown in Table 1, the total volume of industrial and municipal waste generated increased from 2287,6 thousand tonnes in 2009 to 436 thousand tonnes in 2024, indicating an almost twofold increase over the study period. The most pronounced growth occurred after 2018, when waste generation increased annually and reached its highest recorded level in 2024. The analysis of per capita indicators reveals a similar trend. While each resident accounted for 256 kg of generated waste in 2009, this figure increased to 427,8 kg by 2024, reflecting the growing anthropogenic pressure on the environment and increasing consumption levels (OECD, Ferronato & Torretta, 2019; Kaza et al., 2018).

A positive trend can also be observed in the recovery and treatment of waste. During the study period, the volume of recovered and treated industrial and municipal waste more than doubled, increasing from 503.1 thousand tonnes to 1,148.4 thousand tonnes. Despite this progress, the rate of increase in waste generation continues to exceed the rate of waste recovery and treatment, indicating the need for further improvement of the national waste management system.

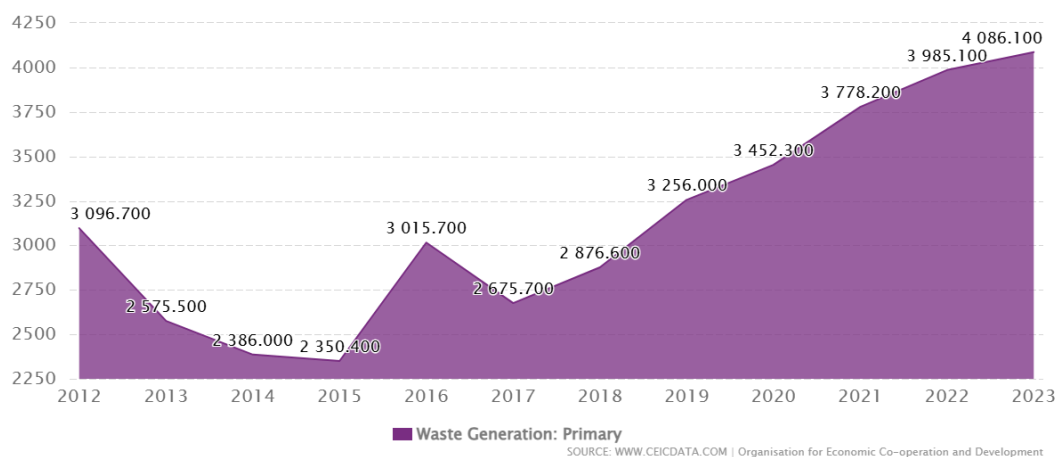


Figure 1. Waste generation figures for Azerbaijan for 2012–2023.

An analysis of the trends shown in Figure 1 [43] reveals a steady increase in waste generation volumes throughout virtually the entire period under review. The most pronounced growth was observed after 2020, which is linked to the recovery of economic activity following the COVID-19 pandemic, an increase in construction volumes, the expansion of industrial production, and rising consumption. In 2023, the volume of waste generation reached 4,086.1 thousand tonnes, which is the highest figure for the period under review.

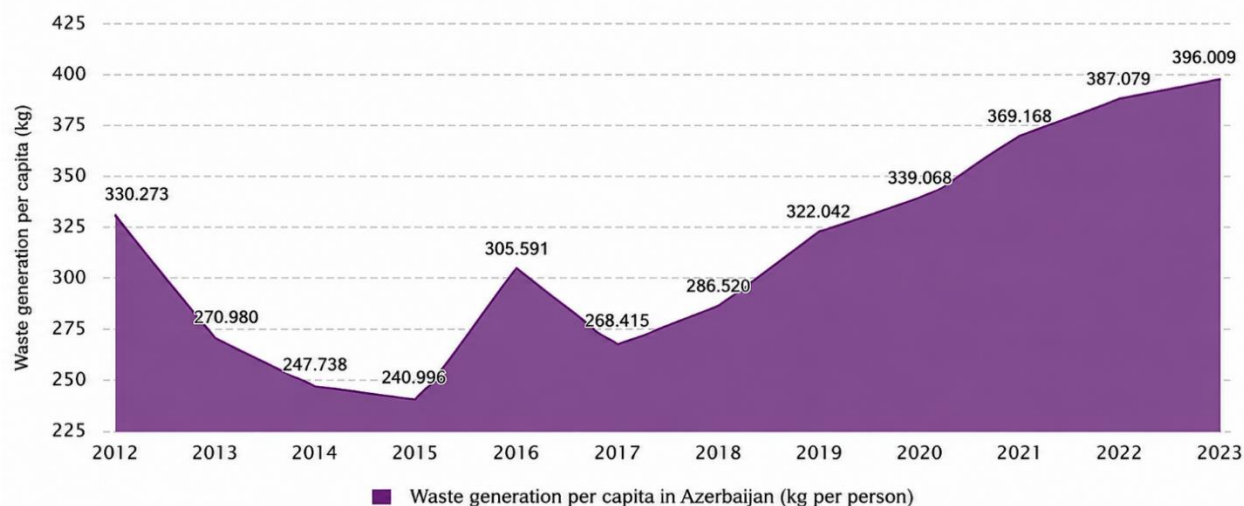


Figure 2. Per capita waste generation figures in Azerbaijan for 2012–2023.

One of the most informative indicators of the efficiency of natural resource use is the volume of waste generation per capita. The data in Figure 2, show a gradual increase in the amount of waste generated per capita. According to information from the Organization for Economic Co-operation and Development (OECD), this figure stood at 396,0 kg per person in 2023, compared with 387,1 kg in 2022. This increase is attributable to rising levels of household consumption, the expansion of urban agglomerations, and changes in the composition of municipal waste generated. Despite positive developments in the field of waste recycling, the rise in per capita waste generation highlights the need to introduce waste prevention measures, raise public environmental awareness, and develop a separate collection system. An important indicator of the environmental efficiency of the economy is the volume of waste generated per unit of gross domestic product.

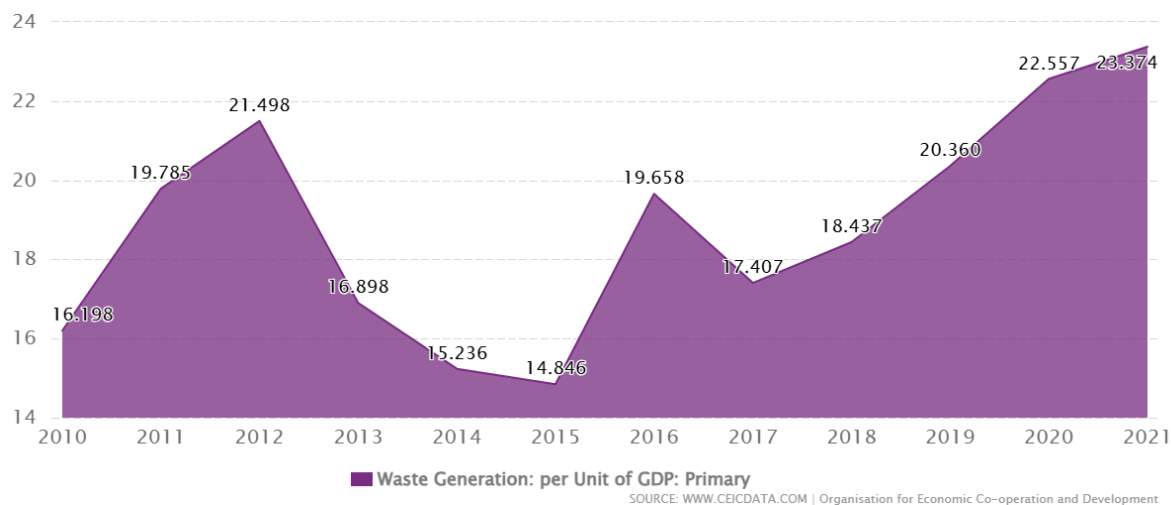


Figure 3. Waste generation rates per unit of GDP in Azerbaijan for 2010–2021.

The data show that waste generation per unit of GDP is changing at a slower rate than the absolute volume of waste. This indicates a gradual improvement in resource efficiency and an increase in economic productivity. At the same time, the persistently high level of waste generation points to the need for further implementation of low-waste technologies, resource-efficient production processes, and the principles of the circular economy [44]. The household sector has a significant impact on the total volume of municipal solid waste generated.

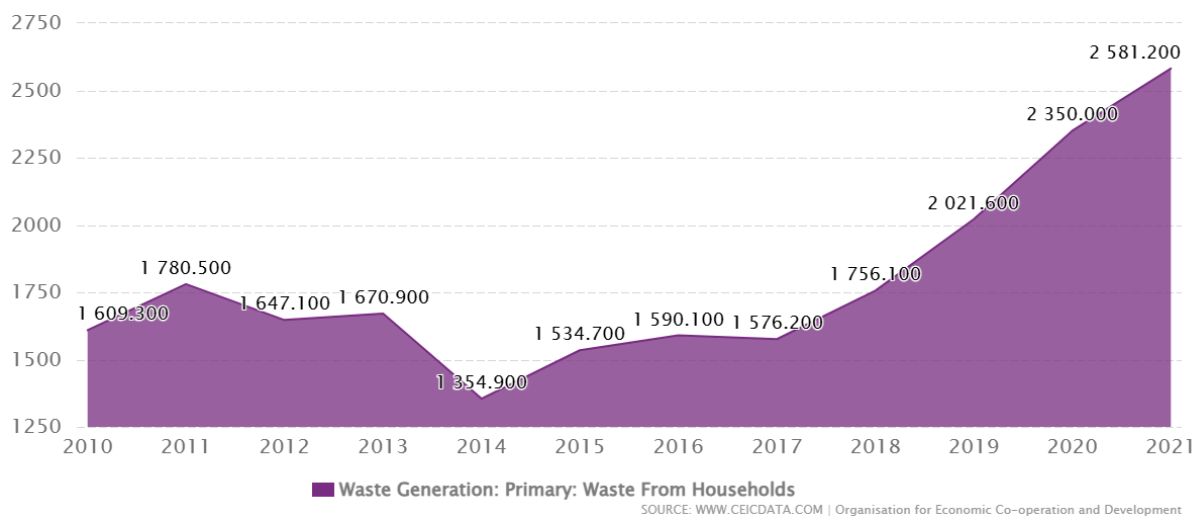


Figure 4. Household waste generation figures in Azerbaijan for 2010–2021.

Analysis of the data shows a steady increase in the volume of waste generated by households. Whilst this figure stood at around 1,3 million tons in 2010, by 2021 it had reached 2,58 million tons. This trend is driven by population growth, rising living standards and the expansion of the consumer market [40, 41, 45, 46]. The findings confirm that the domestic sector remains one of the main sources of municipal solid waste, which necessitates further improvements to the system for its separate collection and recycling.

The Current State of the Municipal Solid Waste Management System in Baku

As more than a quarter of Azerbaijan's population is concentrated in Baku, it is the capital that generates the largest volume of municipal solid waste in the country. In recent years, a range of measures has been implemented in the city aimed at modernizing the waste management system and improving the efficiency of waste collection, transport, sorting, and subsequent recycling.

The most important project is the creation of a new container system for collecting municipal solid waste that gradually covers all 9 administrative districts (Narimanov, Nizami, Nasimi, Yasamal, Khatai, Pirallahi, Surakhani, Binagadi and Sabail) of the city. Systematic observation of the amounts of sorted garbage shows positive dynamics. A good illustration is the case of Binagadi district: after the launch of the project, the amount of sorted waste grew from 6-8 tons/day at start-up to 21-23 tons/day now. This trend demonstrates the high effectiveness of the measures being taken to raise public environmental awareness, improve the logistics system, and enhance the quality of municipal services. To ensure the operation of a modern waste management system, 164 units of specialized municipal vehicles were purchased, enabling a significant modernization of the material and technical infrastructure (UNEP, 2024; ISWA, 2024; Kirchherr et al., 2017; OECD, 2024).

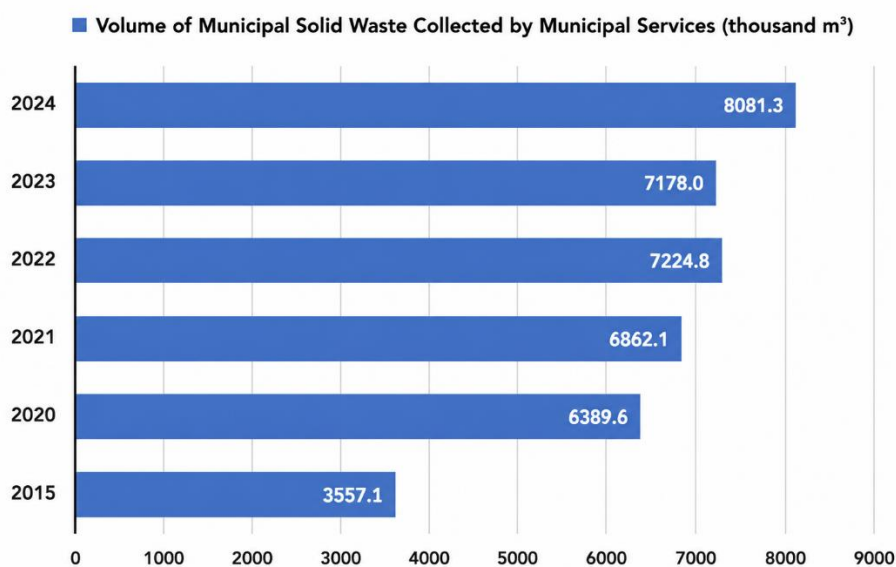


Figure 5. Changes in the volume of household waste in Baku by year (estimate, thousands of tons).

An analysis of trends in household waste generation in the city of Baku reveals a steady upward trend, driven by population growth, the development of urban infrastructure, and rising consumption levels. At the same time, the implementation of measures to improve the waste management system is contributing to a gradual increase in the proportion of waste sent for recycling and energy recovery (Tamiz Shahar ASC, 2024; World Bank, 2020).

According to official statistics, 4.086 million tons of waste were generated in Azerbaijan in 2023, of which 66.6 per cent was solid household waste. Of the total volume of municipal waste, 79.4 per cent was sent to landfill sites, 19.5 per cent was used for energy production, and 1.1 per cent was sold domestically as secondary raw materials. Using trash to generate energy produced 223 million kWh of electricity, an increase of 8.6 percent compared to last year. This shows that we're slowly moving away from just throwing waste away and moving toward a more sustainable way of utilizing it, focusing on saving resources and getting energy back (Kaza et al., 2018; Wilson et al., 2006; EEA, 2023; UNEP, 2024).

Table 2. Generation of specific types of industrial and household waste in Azerbaijan, 2005-2024.

Type of waste	2005	2010	2015	2017	2018	2019	2020	2021	2022	2023	2024
Waste generated during the preparation and processing of meat, fish and other products of animal origin	3,3	3,6	8,7	7,0	5,9	6,3	6,0	6,4	7,8	10,9	12,5
Waste generated during the preparation and processing of fruit, vegetables, cereals, vegetable oils, tea and tobacco	105,0	59,0	37,9	54,1	51,6	49,4	61,5	69,6	113,5	51,5	62,7
Waste from sugar production	x	28,1	-	11,2	13,7	38,5	30,1	8,7	20,1	36,2	25,1
Waste from the processing of dairy products	-	-	0,1	1,0	1,1	1,2	0,5	0,6	0,4	0,8	0,8
Waste from the cotton ginning industry	30,3	4,1	2,9	34,4	64,9	96,4	89,7	87,3	83,5	58,6	53,0
Paper and cardboard waste	0,6	0,6	2,2	5,7	8,9	38,4	38,9	43,8	46,8	55,9	56,1
Recycled textiles	0,4	0,3	0,1	0,1	0,1	0,1	0,0	0,0	0,0	0,0	0,05
Glass containers and cullet	0,3	0,4	0,1	0,1	1,9	2,5	9,6	0,8	1,9	7,2	4,6
Plastics and polymers	0,6	0,3	0,4	2,5	3,2	2,6	2,4	2,3	1,9	1,6	1,6
Waste from mineral extraction, the mining industry, quarries, and the physical and chemical processing of minerals	13,4	3,2	1,3	29,7	4,2	4,7	5,0	4,8	3,5	3,4	7,4
Ferrous metal waste	514,6	303,4	346,3	495,7	468,8	426,4	376,2	367,3	449,0	453,3	506,8
Non-ferrous metal waste	0,4	1,2	0,1	0,5	0,4	0,4	0,8	0,9	0,6	0,7	0,9
Bottom ash	x	x	103,5	98,0	46,7	119,6	69,0	146,6	95,4	107,9	111,7
Wood waste, thousand m ³	4,3	2,4	0,6	22,4	15,5	16,7	12,0	4,7	4,6	4,8	7,4
Household waste, million m ³	7,3	6,7	6,4	6,6	7,3	8,4	9,8	10,8	11,1	11,3	12,6

Table 2 shows the trends in the generation of different types of industrial and household waste in Azerbaijan over the period 2005-2024. The results show significant changes in the composition of waste, driven by the development of industrial production, rising consumption, the better of the waste management system, and shifts in the sectoral structure of the economy.

Among the categories, ferrous metal waste accounted for the highest volume throughout the entire period under review, ranging from 303,4 thousand tons in 2010 to 506,8 thousand tons in 2024. It shows a high concentration of metallurgical and industrial production, as well as significant potential for the further integration of metal waste into the secondary economic cycle (Habitat, 2021; UN, 2015).

The big changes are also observed in the category of paper and cardboard waste. If in 2005 the volume amounted to just 0,6 thousand tons, then by 2024 this figure had increased almost a hundredfold, reaching 56,1 thousand tons. This trend reflects the increase in the consumption of packaging materials, the development of trade and logistics, and the constant improvement of the system for recording and separately collecting waste paper.

A positive trend is also evident for organic waste from the food industry. For instance, the volume of waste generated during the processing of meat, fish and other products of animal origin increased from 3,3 thousand tons in 2005 to 12,5 thousand tons in 2024. Similar trends are observed in waste from the processing of fruit, vegetables, cereals, vegetable oils, tea and tobacco, which is linked to the development of the country's agro-industrial complex and food industry.

Attention should be paid to the growth of household waste. Its volume increased from 7,3 million m³ in 2005 to 12,6 million m³ in 2024. This increase can be linked to population growth, urbanization, changes in consumption habits, and improvements in living standards. The growing amount of municipal waste puts more pressure on the existing systems for waste collection, transportation, treatment, and disposal. Therefore, further development of waste management infrastructure is needed.

The analysis also shows that the waste situation in Azerbaijan is changing not only in terms of the total amount of waste generated, but also in its composition. The growing share of materials such as paper, cardboard, glass, and metals shows that there is good potential for developing separate waste collection and recycling. At the same time, the increase in the size of household and organic waste highlights the need to introduce more sustainable waste management. These methods should include better resource use, circular principles, and modern technologies for waste collection, treatment, and recycling. These types of measures are especially important for large cities and urban agglomerations, including Baku.

5. Conclusion

This research assessed the current municipal solid waste management system in Baku and examined the main ecological challenges related to its development. The results show that population growth, urbanization, economic development, and changing consumption models have increased the amount of waste generated. These changes show the need to improve the existing waste management system and move towards a more effective approach based on better use of resources.

An analysis of statistical data has detected a steady trend of an increase in the total volume of waste in Azerbaijan. In 2023, the volume of waste generation reached 4.086 million tons, with solid household waste accounting for more than two-thirds of this total. At the same time, there was an increase in per-capita waste generation and a rise in the volume of municipal waste, confirming the need to introduce the newest waste prevention mechanisms, enlarge the separate collection system, and increase the recycling rate.

In the research, we can see that, in Baku, in recent years, several significant measures have been implemented to modernize the municipal solid waste management system. The introduction of separate waste collection in nine administrative districts of the city, the update of the fleet of specialized municipal vehicles, the modernization of the Balakhaniy landfill site, and the implementation of the “Integrated Solid Waste Management” project with the support of the World Bank have been important milestones in the development of a new management infrastructure. The positive trend in the growth in the volume of sorted waste indicates a gradual improvement in the system’s operation and a rise in the population’s environmental responsibility.

At the same time, the research findings indicate that the existing waste management model remains heavily reliant on landfill disposal. Despite the increase in energy recovery and recycling, the majority of municipal solid waste continues to be sent to junk yards, which limits the potential for the rational use of secondary material resources and increases the load on the environment.

An analysis of the waste composition has verified that there is significant potential for expanding the recycling of paper, cardboard, glass, metals, plastics, and organic waste. This opens the way for the wider implementation of recycling principles, which aim to maximize the saving of material resources within recycling, reduce the volume of waste sent to the landfill, and improve the efficiency of natural resource use.

The practical significance of the research is based on the development of a set of scientifically grounded recommendations aimed at modifying the municipal solid waste management system in Baku. Priority areas include enlarging the infrastructure for separate waste collection, introducing digital technologies for monitoring waste streams, growing the efficiency of sorting facilities, developing enterprises for the processing of recyclable materials, refining public-private partnership mechanisms, and raising public environmental awareness through educational and information programs.

The main scientific value of this study is that it considers the municipal solid waste management system from several different sides. The study combines statistical data, an assessment of existing waste management infrastructure, international experience, and the principles of sustainable growth and recycling. The recommendations presented in the study can be useful for government agencies, local authorities, and other organizations working in this field. They can be used to improve waste management in Baku and other major cities of Azerbaijan.

Future research can focus on design models to predict the level of municipal waste using artificial intelligence and GIS technologies. It would also be useful to study the environmental and economic consequences of different waste management technologies till the end of their life cycle. Another important area is the assessment of digital waste management systems and their role in the progress of smart and sustainable cities.

Overall, we see that the results that Azerbaijan needs to move towards a new and integrated waste management system. This type of system should focus on recycling, effective use of resources, and new technologies. This approach can help decrease environmental impacts, improve the urban environment, and support the achievement of the Sustainable Development Goals in Azerbaijan.

Author's contribution

The sole author is responsible for conceptualizing, collecting, and analyzing data, and writing and editing the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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