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Preface

The accelerating pace of global urbanization and the increasing complexity of modern consumption patterns have placed the issue of waste at the very center of economic, social, and environmental debates. In recent years, the concept of the waste economy has attracted growing attention from scholars and policymakers seeking to understand the multidimensional impacts of waste generation, management, and recycling on sustainable development.

At the same time, the digital transformation of economies and societies has created both new opportunities and challenges in addressing waste-related issues. The integration of digital tools—such as artificial intelligence, big data, blockchain, and the Internet of Things (IoT)—holds the potential to fundamentally reshape waste management systems, enhance efficiency, and reduce environmental costs. The intersection between waste economics and digitalization thus provides a fertile ground for academic inquiry, particularly in contexts characterized by rapid urbanization and persistent structural challenges.

Turkey, as a country experiencing dynamic economic growth while simultaneously confronting enduring urbanization problems, constitutes a compelling case for examining the intersection between the waste economy and digital innovation. By analyzing the Turkish experience within a global framework, this book aims to contribute to the academic literature and to offer policy-oriented insights not only for Turkey but also for other developing and emerging economies.

The primary objective of this book is to examine the waste economy from a digital perspective in a comprehensive and systematic manner. By integrating theoretical foundations, empirical evidence, and policy discussions, it seeks to provide a holistic understanding of the subject. The intended audience includes scholars, postgraduate students, policymakers, and practitioners interested in sustainable development, waste management, and the digital economy.

It is my sincere hope that this work will serve as a valuable resource for academic research and policy discussions on waste-related issues, while also inspiring new studies that explore the role of digital transformation in shaping sustainable futures.

Dr. Suad Muvakit

September 2025

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Introduction

The accelerating pace of global population growth, intensified migration flows, and shifting consumption patterns have positioned waste management at the very center of contemporary economic and environmental debates. While the process of urbanization has brought with it greater economic opportunities and improved living standards, it has also generated serious structural challenges such as housing shortages, environmental degradation, overexploitation of natural resources, and the growing volume of waste generation. Since the onset of industrialization and the rise of consumer culture, the phenomenon of the waste economy has come to represent not only a crucial component of environmental policy but also an indispensable element of economic sustainability.

In Turkey, environmental issues became increasingly visible in the post–World War II period as rapid population growth and unplanned urbanization began to reshape the social and economic landscape. The emergence of environmental health concerns in the 1970s, followed by intense migration waves toward major cities in the 1980s, introduced new challenges for both environmental management and waste policy. Today, the combined effects of accelerating urbanization and growing waste production have positioned waste management as a critical field in Turkey's pursuit of sustainable development goals.

Meanwhile, the rapid advance of digital transformation has introduced new opportunities and technological tools that are fundamentally reshaping waste management practices. Digital innovations such as artificial intelligence, big data analytics, blockchain technologies, and the Internet of Things (IoT) have opened the door to novel approaches for tracking waste, optimizing recycling processes, and reducing environmental costs. The intersection of waste economics and digitalization therefore represents a strategically significant field for both academic inquiry and policy development, offering new frameworks for addressing sustainability challenges in the twenty-first century.

This book examines the dynamics of the waste economy within the Turkish context, while also situating the discussion within a broader global and digital perspective. It begins by establishing the theoretical foundations of the economy–environment relationship through the lens of sustainable development, thereby laying the conceptual groundwork for the analyses that follow. Subsequent chapters explore the concept and types of waste, the mechanisms of recycling, and the global trends shaping contemporary waste management. The book then turns to the issue of urbanization and its implications for the Turkish waste sector, highlighting the economic, structural, and social dimensions of the problem. The discussion proceeds to examine the technological aspect of the waste economy, focusing on how digitalization creates opportunities for innovation and efficiency. Finally, the concluding chapter integrates the main findings, theoretical discussions, and policy implications, presenting a comprehensive synthesis of the research and offering guidance for future studies and policymaking.

By adopting this comprehensive approach, the book seeks to make a meaningful contribution to the academic literature and to serve as a guiding reference for scholars, practitioners, and policymakers engaged in the fields of sustainable development, waste management, and digital transformation.

CHAPTER 1

Sustainable Development and the Economics of Waste

The concept of sustainable development has become a central paradigm in contemporary economic and environmental discourse. This approach seeks to establish a balance between economic growth and the preservation of natural resources and ecological systems. Within this framework, the waste economy assumes a critical role, as waste generation and management are directly linked to production–consumption patterns and resource efficiency. Accordingly, understanding the relationship between sustainability and the waste economy is of vital importance for formulating effective policies that address both environmental protection and economic development in an integrated manner.

1.1. Sustainable Development: Economy and Environment

Sustainable development is no longer confined to environmental concerns alone; rather, it has evolved into a multidimensional framework encompassing economic growth, ecological preservation, and social equity. The Sustainable Development Goals (SDGs) adopted by the United Nations in 2015 have translated this approach into a set of concrete and measurable objectives. The growing challenges of climate change, biodiversity loss, and the depletion of natural resources have placed sustainable development at the core of both national and international policy agendas (United Nations, 2023, p. 4).

Table 1 : Global Trends in Selected Sustainable Development Indicators, 2020–2023

Indicator	2020	2021	2022	2023
Global CO_2 emissions (billion tons)	33,4	34,8	36,6	36,8
Renewable energy share in electricity (%)	28,4	29,2	30,5	31,5
Recycling rate of municipal waste (%)	19,5	20,3	21	21,7
Global poverty rate (% below $2.15/day)	9,3	9,4	9	8,6

Source: World Bank (2024); United Nations (2023)

Table 1, summarizes the main global trends in sustainable development indicators. During the period 2020–2023, global CO_2 emissions continued to increase, whereas the share of renewable energy in total electricity generation rose gradually. The modest improvement in the recycling rate of municipal waste indicates that circular economy policies have not yet produced the desired global impact. Meanwhile, the decline in the global poverty rate reflects partial progress in the social dimension of sustainable development.

The relationship between economic growth and environmental sustainability has long been the subject of academic debate. The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation tends to increase during the early stages of economic growth but may decline after a certain income threshold is reached. However, recent empirical studies have shown that this hypothesis does not hold universally. In many developing and emerging economies, economic growth often continues to coincide with rising environmental pressures. For countries such as Turkey, the key challenge lies in decoupling growth from emissions and resource consumption while maintaining competitiveness (OECD, 2022, p. 17).

Table 2: Comparative Dynamics of GDP Growth, CO_2 Emissions, and Renewable Energy in Selected Economies (2020–2023)

Country	Avg. GDP Growth (%)	CO_2 Change (%)	Renewable Energy Share (%)
Turkey	5,5	7,2	18,3
EU-27	2,1	-4,6	39,8
China	4,8	5,9	27,2
USA	2,3	-2,1	22,5

Source: OECD Green Growth Indicators (2023)

Table 2, illustrates that the relationship between economic growth and environmental pressures varies significantly across countries. In Turkey and China, high rates of economic growth have coincided with increases in CO_2 emissions. In contrast, both the EU-27 and the United States have achieved reductions in emissions despite their more moderate growth performance. The relatively high share of renewable energy in EU countries highlights the importance of institutional and regulatory policies for ensuring environmental sustainability.

In today's global economy, digital technologies are increasingly regarded as key enablers of sustainable development. Tools such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain play a crucial role in optimizing resource use, reducing waste generation, and enhancing environmental monitoring capacity. A recent study on European countries confirms that the digital economy exerts positive effects on both sustainable growth and environmental performance (Cigu, 2025, p. 3).

The following figure 1 illustrates how digitalization integrates with the Environmental, Social, and Governance (ESG)dimensions and outlines the technological stages that emerge within this process. It emphasizes the contribution of technologies such as Big Data, AI, IoT, and Blockchain to various phases of ESG performance. This framework demonstrates that digital transformation influences not only economic mechanisms but also the environmental and social pillars of sustainability. Particularly in developing economies such as Turkey, the integration of these technologies into the waste economy represents a strategic opportunity to reduce environmental costs and improve resource efficiency (Jiang, Guo & Wang, 2023, p. 15).

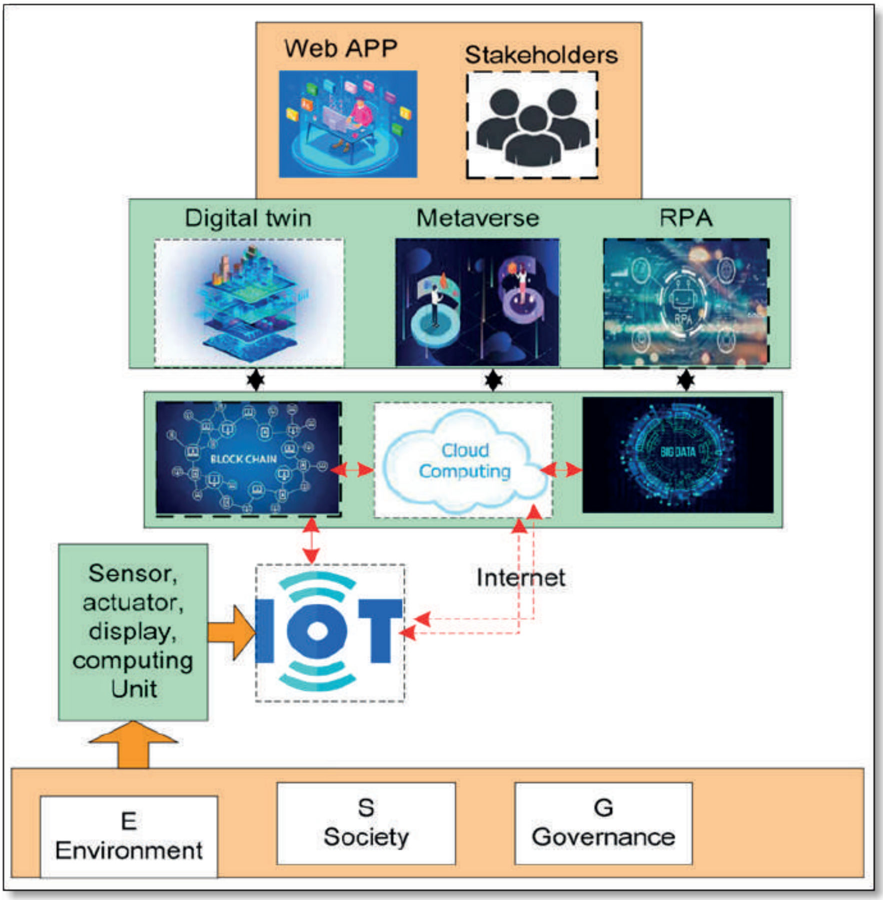

Figure 1: Integration of Emerging Digital Technologies within the ESG Framework

Source: Jiang, Guo, & Wang,(2023)

Sustainable development is closely linked not only to economic and technological processes but also to robust institutional frameworks and effective governance structures. Countries characterized by strong environmental policies, transparent regulatory systems, and substantial investments in green technologies tend to achieve faster progress toward the Sustainable Development Goals (SDGs). Although Turkey has made notable advances in renewable energy and recycling initiatives, significant challenges remain in the areas of urban waste management and the enforcement of environmental standards (World Bank, 2023, p. 12).

Table 3: Turkey's Selected Sustainable Development Indicators (2019–2023)

Indicator	2019	2020	2021	2022	2023
GDP per capita (USD)	9208	8600	9601	10659	13243
Urban population (%)	75,6	76,1	76,8	77,2	77,5
Recycling rate of municipal waste (%)	13,5	14,8	15,2	16,9	18
Renewable energy in total supply (%)	15,6	16,1	17,4	18,2	18,6

Source: TÜİK (2023); World Bank (2023).

Table 3 , presents the five-year trends in Turkey's sustainable development indicators. While GDP per capita has continued to rise, the urban population ratio has also increased steadily. The observed improvements in municipal waste recycling rates and the use of renewable energy indicate progress in sustainability efforts. However, the fact that these indicators still lag behind the OECD averages suggests that Turkey needs to design and implement more comprehensive and integrated policy measures.

Although noteworthy progress has been achieved, significant challenges remain in harmonizing economic developmentwith environmental sustainability. In particular, the so-called "rebound effect," in which gains in efficiency stimulate higher levels of consumption, may undermine long-term sustainability goals. Furthermore, the uneven distribution of sustainability achievements across countries raises concerns regarding global equity. Recent studies emphasize that in the digital era, sustainable development depends not only on technological advancement but also on inclusive institutionsand transformative social behavior (Piscicelli, 2023, p. 2).

Table 4: Opportunities and Challenges in Achieving Sustainable Development

Opportunities	Challenges
AI, IoT, and Big Data for waste reduction	Rebound effects from efficiency gains
Expansion of renewable energy	High upfront investment costs
Circular economy adoption	Limited institutional capacity in developing countries
Global SDG frameworks	Unequal progress across regions

Source: Piscicelli (2023); Cigu (2025)

Table 4, provides a comparative overview of the structural challenges to sustainable development alongside the opportunities offered by digitalization and circular economy practices. Technologies such as artificial intelligence (AI), the Internet of Things (IoT), and big data analytics create significant opportunities for waste reduction and energy efficiency. However, factors such as high investment costs, institutional capacity gaps, and uneven progress across countries continue to hinder the achievement of global sustainability objectives.

1.2. Sustainable Development in the Environmental Literature

In the academic literature, sustainable development is addressed as a holistic approach encompassing its environmental, economic, and social dimensions. The Sustainable Development Goals (SDGs), announced by the United Nations in 2015, have further reinforced the significance of this concept in both policy agendas and scholarly discourse. The environmental dimension of the SDGs primarily focuses on clean energy, climate action, and responsible production and consumption. Within this framework, sustainable development has become one of the most frequently adopted paradigms in environmental studies for explaining the dynamics of sustainability (United Nations, 2023, p. 7).

The following figure 2 schematically illustrates the sequential steps involved in setting national targets for the sustainable management of natural resources. According to Dickens et al. (2019), this approach can be effectively utilized to identify national priorities aligned with the SDGs and to define quantitative indicators along with their corresponding threshold values.

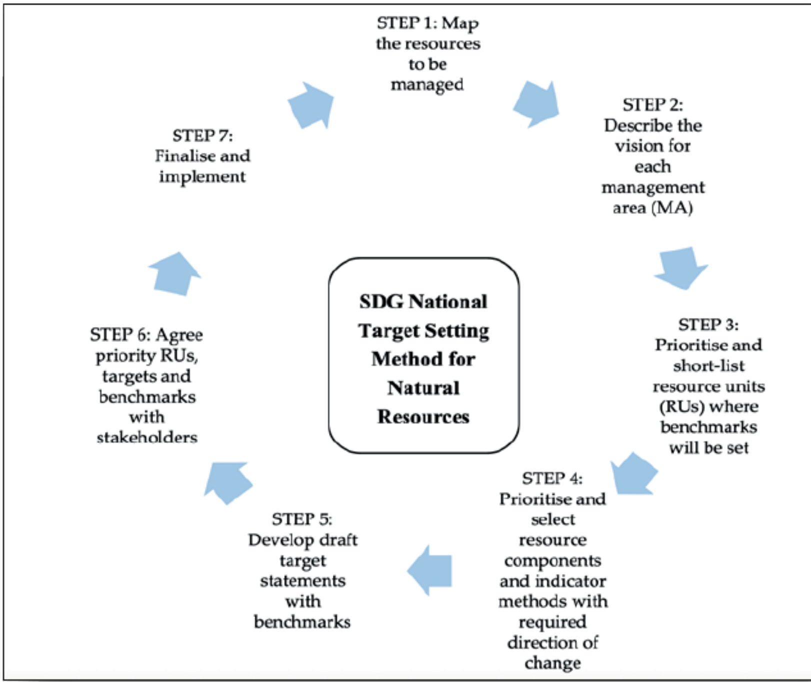

Figure 2: National SDG Target Setting Method for Natural Resources

Source: Dickens et al., 2019.

In environmental economics literature, the relationship between economic growth and the environment is frequently analyzed through the lens of the Environmental Kuznets Curve (EKC) hypothesis. However, recent empirical research suggests that the validity of this hypothesis remains limited in the context of developing economies. In countries such as Turkey, China, and India, economic growth has continued to progress in parallel with rising CO_2 emissions. This pattern underscores that achieving sustainable development depends not only on economic expansion but also on the capacity for effective environmental governance and management (Balsalobre-Lorente et al., 2022, p. 5).

Table 5: Comparative Trends in GDP Growth and CO_2 Emissions in Selected Economies (2020–2023)

Country	**Average GDP Growth (%)**	**CO_2 Emission Change (%)**
Turkey	5,5	7,2
EU-27	2,1	-4,6
China	4,8	5,9
USA	2,3	-2,1

Source: OECD, 2022; World Bank, 2023

Table 5 demonstrates that in Turkey and China, higher average GDP growth rates have been accompanied by a marked increase in CO_2 emissions. In contrast, the EU-27 and the United States have managed to reduce their emissions despite their more moderate levels of economic growth, illustrating that the link between economic performance and environmental degradation can indeed be weakened. These trends highlight the decisive role of policy frameworks and technological innovation in shaping the relationship between the economy and the environment.

Within the environmental literature, the circular economy has emerged as a key strategy for promoting sustainable development. By encouraging resource reuse, waste reduction, and recycling practices, circular economy approaches help minimize environmental impacts. In particular, the European Union's circular economy policies have led to significant improvements in waste recycling rates. This framework demonstrates that sustainability-oriented policies can generate positive outcomes both economically and environmentally (Geissdoerfer et al., 2020, p. 759).

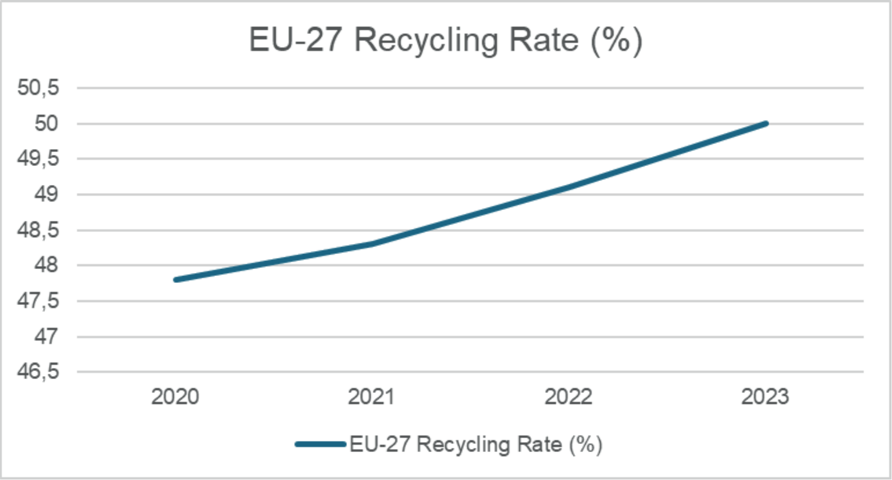

Figure 3: Municipal Waste Recycling Rates in the European Union (EU-27), 2020–2023

Source: Eurostat, 2023

Figure 3,presents the recycling rates of municipal waste in the European Union (EU-27) during the period 2020–2023. The data reveal a steady year-on-year increase in recycling rates, demonstrating the tangible outcomes of the EU's circular economy policies. This upward trend indicates that these policies have played an effective role in enhancing resource efficiency and environmental sustainability across member states.

In recent literature, the contribution of digitalization to sustainable development has become a major area of academic inquiry. Technologies such as artificial intelligence (AI), the Internet of Things (IoT), and big data analytics have improved efficiency in both waste management and energy optimization processes. Empirical findings confirm that the digital economy strengthens sustainable economic growth while enhancing environmental performance. This evidence positions digital transformation as a strategic component of sustainability within contemporary environmental studies (Cigu, 2025, p. 3).

Figure 4: Applications of AI and IoT for Environmental Sustainability

Source: DeltalogiX, 2021

The figure 4 above illustrates the applications of artificial intelligence (AI) and the Internet of Things (IoT) in the field of environmental sustainability. These technologies contribute to a wide range of areas, from agricultural sustainabilityand air quality monitoring to the use of renewable energy sources (DeltalogiX, 2021).

However, the literature on sustainable development also highlights several persistent challenges. High investment costs, limited institutional capacity, and phenomena such as the "rebound effect" constrain the effectiveness of policy implementation. Moreover, significant disparities remain between developed and developing countries in terms of sustainability performance. In this context, recent studies emphasize that the joint implementation of digitalization and circular economy strategies will play a critical role in achieving sustainable development in the future (Piscicelli, 2023, p. 2).

Table 6: Comparative Environmental Indicators in Developed and Developing Countries (2023)

Indicator	Developed Countries	Developing Countries
Recycling rate (%)	50,5	22,4
Renewable energy (%)	39,2	18,6
Municipal waste generation (kg per capita)	520	310
CO_2 emissions (tons per capita)	6,1	3,9

Source: World Bank, 2024

Table 6, reveals that while developed countries exhibit higher levels of recycling rates and renewable energy shares, these indicators remain relatively low in developing countries. Conversely, the higher per capita municipal waste generation observed in developed economies is noteworthy. These findings indicate that structural inequalities persist in global sustainability performance, reflecting the uneven progress between advanced and emerging economies.

Academic studies focusing on Turkey suggest that the discourse on sustainable development has largely concentrated on the dimensions of urbanization, waste management, and energy policy. According to data from TurkStat (TÜİK), although recycling rates have increased in recent years, Turkey still remains below the OECD average. Contemporary literature emphasizes that the integration of digitalization processes into Turkey's sustainable development strategiesis crucial for enhancing both economic growth and environmental performance (World Bank, 2023, p. 15).

Table 7: Selected Indicators of Sustainable Development in Turkey (2020–2023)

Indicator	2020	2021	2022	2023
Municipal waste recycling rate (%)	14,8	15,2	16,9	18
Renewable energy share (%)	16,1	17,4	18,2	18,6
CO_2 emissions (million tons)	409	421	430	438
Urban population (%)	76,1	76,8	77,2	77,5

Source: TÜİK, 2023; World Bank, 2023

Table 7, shows that both the recycling rate of municipal waste and the share of renewable energy have increased over the years. However, the simultaneous rise in CO_2 emissions during the same period highlights a critical area of concern for environmental sustainability. The continuing growth of the urban population further underscores the importance of effective waste management and comprehensive environmental policy frameworks.

1.3. The Waste Economy within the Framework of Sustainable Development

In the sustainable development literature, the waste economy has increasingly been recognized as a field of growing importance, encompassing both environmental and economic dimensions. This approach emphasizes that waste should not merely be regarded as a disposal problem, but rather as a valuable resource that can be transformed into economic value through processes of recycling and reuse. Accordingly, the waste economy is directly linked to the Sustainable Development Goals (SDGs)—in particular, SDG 12: Responsible Consumption and Production (United Nations, 2023, p. 11).

The figure 5 below presents the "Butterfly Diagram" developed by the Ellen MacArthur Foundation. This conceptual model illustrates how waste can be reintegrated into biological and technical cycles, thereby enhancing resource efficiency and generating economic value. The framework is explicitly aligned with SDG 12 – Responsible Consumption and Production, reflecting the central role of circularity in achieving sustainability objectives (Ellen MacArthur Foundation, 2021).

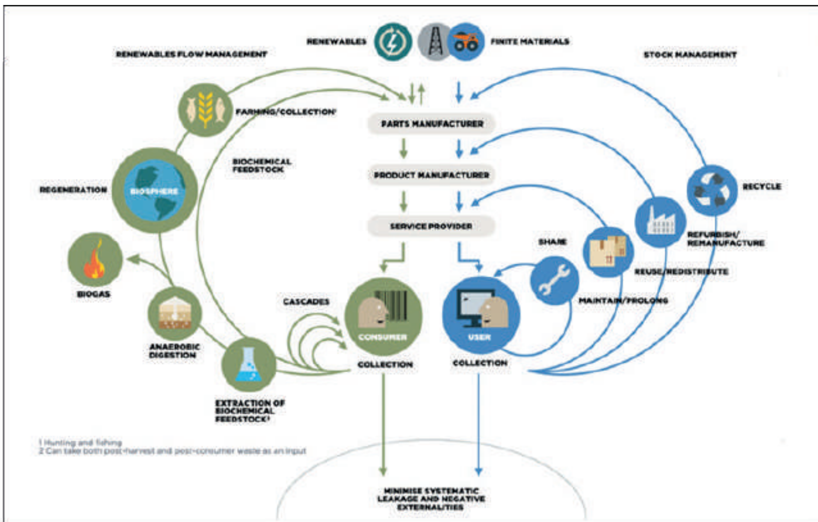

Figure 5: The Role of the Waste Economy in Sustainable Development: The Circular Economy Model (Butterfly Diagram)

Source: Ellen MacArthur Foundation, 2021.

The waste economy lies at the very core of the circular economy approach. Within this framework, the transformation of waste into secondary raw materials reduces the use of natural resources and alleviates environmental pressures. Recent research demonstrates that increases in recycling rates generate positive effects not only in terms of employment creation but also by improving energy efficiency. These findings reveal that the waste economy is critical not only for environmental sustainability but also for socio-economic sustainability, underscoring its multidimensional importance within the sustainable development agenda (Geissdoerfer et al., 2020, p. 760).

Table 8: The Contribution of the Circular Economy to Waste Management

Indicator	Impact Area	Example
Recycling rate	Resource efficiency	EU-27 rising to 50%
Reuse	Energy savings	Packaging sector
Waste reduction	Environmental benefit	Decrease in CO_2 emissions

Source: Geissdoerfer et al., 2020

Table 8, demonstrates that rising recycling rates, which have reached around 50% in EU countries, have significantly strengthened resource efficiency. Reuse practices, particularly in the packaging sector, contribute to energy savings, while waste reduction efforts help lower CO_2 emissions, thereby enhancing overall environmental benefits. Collectively, these indicators illustrate that the circular economy is directly aligned with the objectives of sustainable development.

Digital technologies are creating new opportunities for developing the waste economy in line with sustainable development goals (SDGs). Systems based on artificial intelligence (AI), blockchain, and the Internet of Things (IoT)enable more efficient and transparent management of waste collection and recycling processes. Recent literature highlights empirical evidence showing that digitalization reduces waste management costs while improving the overall performance of the circular economy (Cigu, 2025, p. 4).

The figure 6 below illustrates an IoT-based smart waste management system, which integrates smart bins, waste collection vehicles, and a centralized cloud infrastructure. Supported by AI algorithms, this system enhances efficiency and reduces operational costs in both waste collection and recycling processes (Addas, Khan & Naseer, 2024).

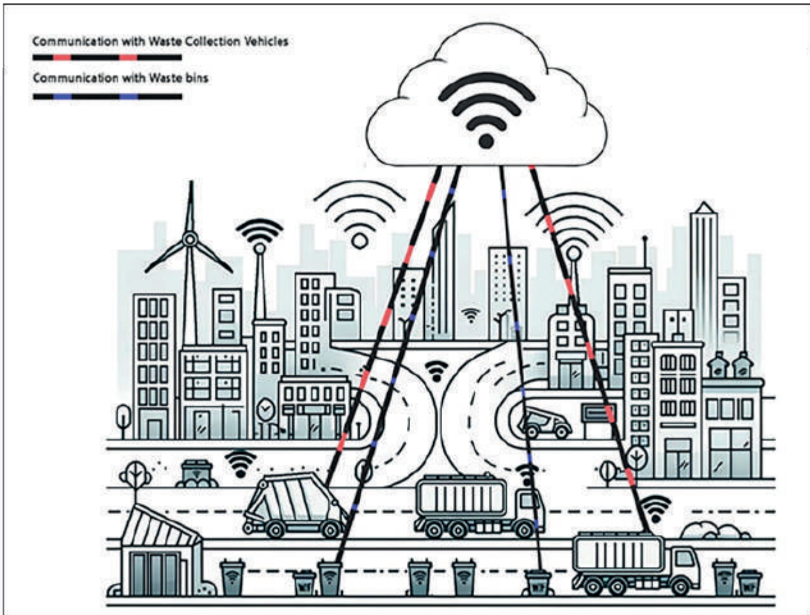

Figure 6: IoT-enabled waste bins, vehicles, and essential smart city infrastructures

Source: Addas, A., Khan, M. N., & Naseer, F. 2024.

Global trends in the waste economy reveal significant differences among countries. According to OECD data, approximately 50% of waste is recycled in developed economies, whereas this rate falls below 25% in developing countries. Although the recycling rate in Turkey has shown an upward trend in recent years—an encouraging development—it still remains below the EU average. This situation indicates that Turkey needs to consider the waste economy as a more strategic component within its sustainable development policies (World Bank, 2023, p. 18).

Table 9: Comparative Indicators of the Waste Economy Across Selected Countries (2023)

Country	Municipal Waste Recycling Rate (%)	Renewable Energy Share (%)
Turkey	18	18,6
EU-27	50	39,2
China	23,5	27,2
USA	34,1	22,5

Source: World Bank, 2023; Eurostat, 2023

Table 9, compares the waste economy indicators of Turkey, the EU-27, China, and the United States. While the EUdemonstrates higher levels of recycling rates and renewable energy shares, the corresponding indicators for Turkey and China remain relatively lower. This comparison highlights that differences in national policies and implementation practices play a decisive role in shaping the development of the waste economy across countries.

1.4. The Circular Economy and Waste Management

In recent years, the circular economy has become an increasingly prominent topic within the literature on sustainable development. It represents a holistic approach that seeks to promote the efficient use of resources and the transformation of waste into economic value. This model replaces the "take–make–dispose" logic of the linear economy with strategies centered on reuse, recycling, and remanufacturing throughout the entire product life cycle. In doing so, it helps to reduce environmental pressures while simultaneously supporting economic growth (Kirchherr, Piscicelli & Bour, 2022).

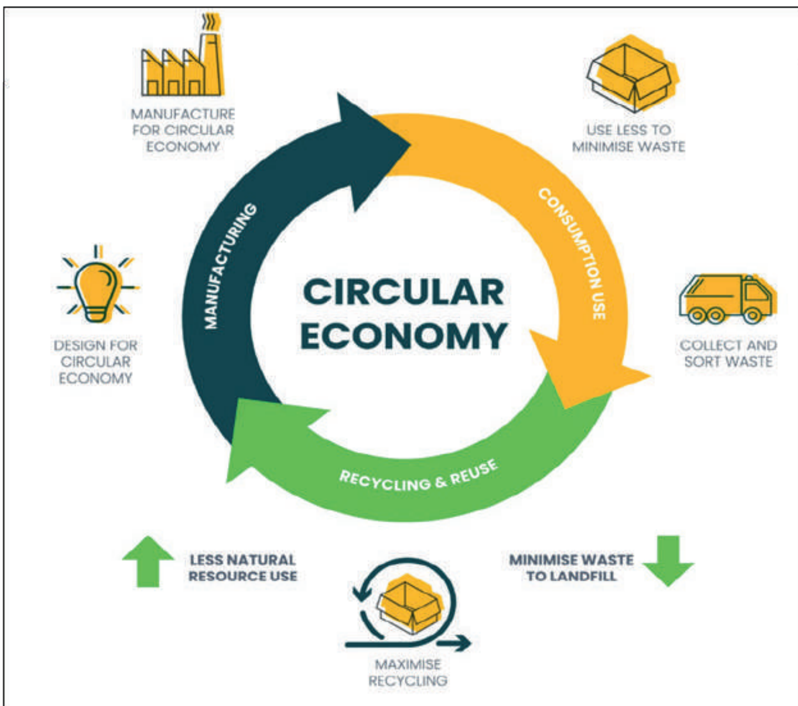

Figure 7: The Circular Economy Process: From Production to Consumption and Recycling

Source: City of Adelaide, 2025

Figure 7, illustrates the core stages of the circular economy. Extending from design and production to consumption, and further to waste collection, sorting, recycling, and reuse, this cycle aims to reduce natural resource consumption, minimize waste generation, and promote sustainable economic growth. This approach replaces the "take–make–dispose" logic of the linear economy with a model that prioritizes resource efficiency and environmental sustainability(City of Adelaide, 2025).

Rather than focusing solely on the disposal dimension of waste management, the circular economy encourages the treatment of waste as secondary raw materials. In this context, practices such as recycling, reuse, and remanufacturingenable waste to be managed in ways that generate economic value. In the European Union, the implementation of targeted policy instruments has led to a consistent increase in recycling rates, reflecting the effectiveness of circular economy strategies in fostering sustainable development (European Environment Agency, 2023).

Table 10: Trends in Municipal Waste Recycling Rates in the European Union (2019–2023)

Year	EU-27 Recycling Rate (%)
2019	47,3
2020	47,8
2021	48,3
2022	49,1
2023	50

Source: European Environment Agency. 2023.

Table 10, shows that during the observed period, recycling rates in the European Union increased from 47.3% to 50%. This upward trend demonstrates that the EU's circular economy policies have yielded effective results in waste management, contributing to progress that is well aligned with the Sustainable Development Goals (SDGs) (European Environment Agency, 2023).

However, the circular economy encompasses far more than recycling alone; it also includes innovative practices such as reuse, remanufacturing, and the sharing economy. These approaches help reduce the demand for primary raw materials, enhance energy efficiency, and thereby lower the carbon footprint. The literature emphasizes that such practices make a substantial contribution to climate change mitigation and to the broader transition toward sustainable production and consumption systems (Schroeder, Anggraeni & Weber, 2022).

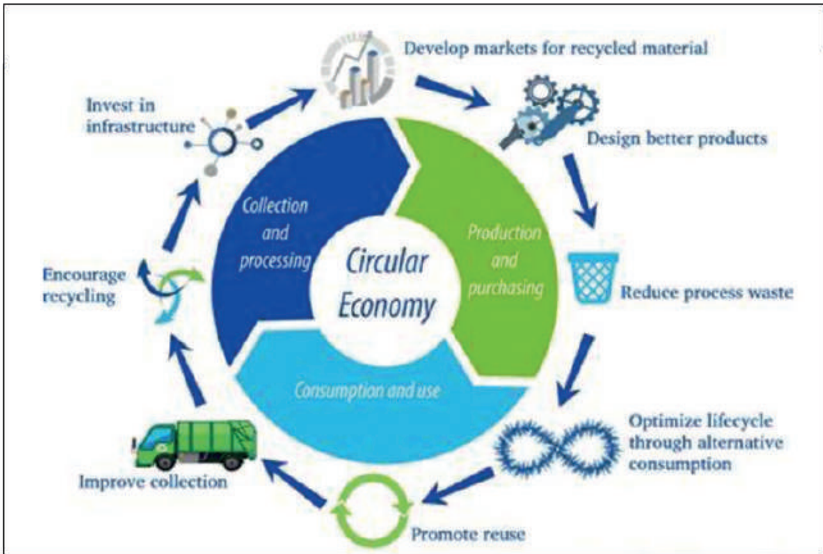

Figure 8: Innovative Application Areas in the Circular Economy

Source: Recycling Council of Ontario, 2023

The figure 8 above illustrates innovative practices within the framework of the circular economy, including reuse, remanufacturing, improved product design, and optimization of product life cycles. These processes help to reduce the demand for raw materials, enhance energy efficiency, and lower the carbon footprint. The literature emphasizes that such practices play a critical role in combating climate change (Recycling Council of Ontario, 2023).

The circular economy generates not only environmental but also significant socio-economic benefits. For example, the expansion of the recycling industry creates new employment opportunities, while reuse and sharing practices help to reduce consumer costs. Moreover, these initiatives are frequently cited in the literature for their contribution to strengthening local economies and promoting regional development (OECD, 2021).

In Turkey, circular economy initiatives have gained notable momentum in recent years, particularly through the “Zero Waste Project.” Key areas of focus include the segregation of municipal waste, the increase in recycling rates, and the implementation of energy efficiency strategies. However, the overall recycling rate in Turkey still remains below the EU average. This indicates the need for more effective and comprehensive implementation of environmental sustainability policies (World Bank, 2023).

Table 11: Trends in Circular Economy Indicators in Turkey (2020–2023)

Indicator	2020	2021	2022	2023
Municipal waste recycling rate (%)	14,8	15,2	16,9	18
Renewable energy share (%)	16,1	17,4	18,2	18,6
Urban population (%)	76,1	76,8	77,2	77,5

Source: TÜİK. 2023.

Table 11,reflects the key trends in circular economy indicators in Turkey. The municipal waste recycling rateincreased from 14.8% in 2020 to 18% in 2023, accompanied by a rise in the share of renewable energy. However, the simultaneous growth in the urban population ratio during this period indicates the need for a more comprehensive implementation of sustainability policies. These data suggest that although Turkey has made measurable progress in advancing the circular economy, it still remains below the EU average in most key indicators.

CHAPTER 2

The Waste Phenomenon – Concepts, Types, and Management

The phenomenon of waste has emerged as one of the most significant environmental and socio-economic challengesfaced by modern economies. Population growth, rapid industrialization, and urbanization processes have continuously increased the volume of waste while making its management increasingly complex. In this context, waste is not merely a problem to be disposed of, but rather a resource that can be reused and converted into economic valuewhen managed through appropriate methods.

This chapter discusses the concept and classification of waste, elaborates on recycling processes, presents global statistics, examines the economic costs associated with waste, and provides a comprehensive overview of the waste problem from both environmental and economic perspectives.

2.1. The Concept of Waste

Waste emerges as an inevitable by-product of production and consumption processes, referring to materials that have lost their functional value but can be reused or recycled when properly managed. In the literature, waste is not merely perceived as a burden to be disposed of, but rather as a resource that can be reintegrated into the value chain within the framework of the circular economy (UNEP, 2022).

When left uncontrolled, waste exerts adverse impacts on soil, water, and air quality. The irregular disposal of solid waste contaminates water resources, while the non-degradability of plastic waste poses a serious threat to ecosystems. Consequently, waste management plays a critical role in ensuring environmental health and the preservation of biodiversity (UNEP, 2022).

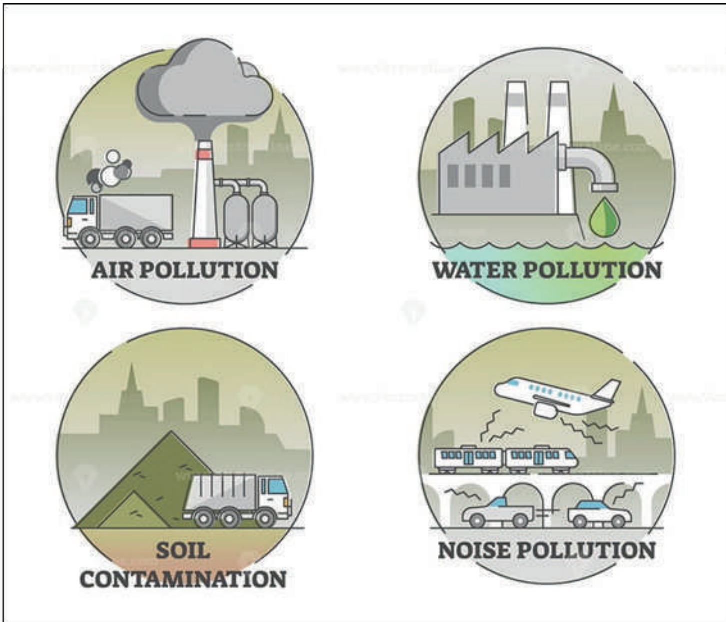

Figure 9 : Environmental Impact Areas of Waste: Air, Water, and Soil Pollution

Source: RyanMW794Manual. 2025.

The figure 9, above symbolically and clearly illustrates the three primary forms of pollution caused by waste — air, water, and soil pollution. This classification highlights the multidimensional nature of the waste problem and underscores the importance of addressing each environmental medium within comprehensive environmental management strategies.

In contemporary contexts, waste has also gained significant economic importance. According to World Bank data, the waste management sector not only provides disposal services but also contributes to employment generation and value creation through the reintegration of recycled materials into the economy. For instance, the recycling of materials such as metal, plastic, and glass reduces the need for raw material imports, thereby generating tangible economic benefits(World Bank, 2023).

Table 12 : Potential Economic, Environmental, and Social Contributions of the Waste Economy

Dimension	Contribution Area	Example
Economic	Job creation	Recycling sector
Environmental	CO_2 emission reduction	Waste reduction
Social	Cost reduction	Reuse

Source: UNEP 2022; OECD 2021; European Commission 2020.

Table 12, highlights the multidimensional contributions of the waste economy to sustainable development. Economically, the recycling sector generates new employment opportunities, thereby fostering inclusive growth. Environmentally, waste reduction initiatives help to lower CO_2 emissions and mitigate climate change. Socially, reuse practices contribute to reducing consumer costs while promoting responsible consumption patterns. Collectively, these dimensions demonstrate that waste is not merely a disposal challenge but also a driver of environmental and socio-economic value creation.

The process of digital transformation has significantly broadened the scope of the waste concept. Electronic waste (e-waste) refers to discarded digital and electronic devices that contain not only valuable metals but also environmentally hazardous substances. The global volume of e-waste has been rising rapidly, reaching 53.6 million tons in 2020. This trend reveals that technology-based waste encompasses both opportunities and risks, underscoring the need for effective management strategies to ensure sustainable digitalization (Forti et al., 2020).

2.2. Types of Waste

In the waste management literature, the accurate classification of waste types is of critical importance for the development of effective environmental and economic policies. Different categories of waste are classified according to their origin, composition, and environmental impact, each presenting its own risks and opportunities. In this context, the main categories—household, medical, hazardous, industrial, construction, and technological (e-waste)—constitute the foundation of sustainable waste management practices (UNEP, 2022; World Bank, 2023).

2.2.1. Household Waste

Household waste consists of organic and inorganic materials generated through domestic consumption processes. The most common components include food residues, plastic packaging, glass bottles, paper, and textile products. These wastes exert significant environmental pressures in densely urbanized areas, where population growth and consumption intensity are high (World Bank, 2023).

The irregular disposal of household waste contributes to the release of methane gas, thereby accelerating climate change. Moreover, the non-biodegradability of plastics leads to the formation of microplastic pollution in oceans, posing long-term risks to both ecosystems and human health. Consequently, proper management of household waste is essential for mitigating environmental degradation and achieving sustainable urban development (UNEP, 2022).

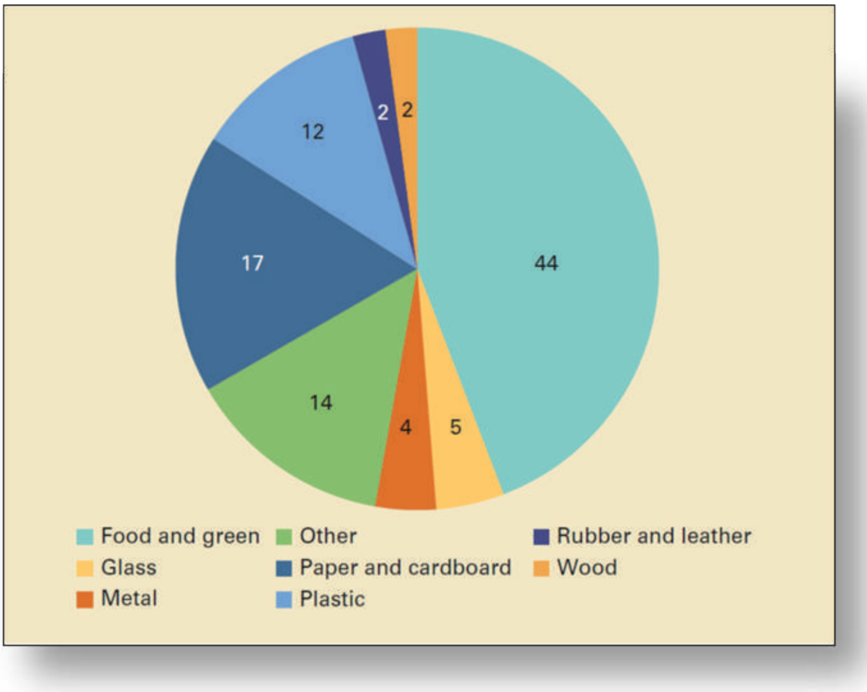

Figure 10 : Main Components of Household Waste

Source: Krel. 2021.

According to the data presented in Figure 10, food and green waste constitute the largest share at 44%, followed by paper and cardboard (17%), plastics (12%), glass (5%), and metals (4%). Wood, rubber, and leather waste are represented at comparatively lower proportions. This distribution highlights which components should be prioritized in household waste management strategies at the global level, underscoring the dominance of organic waste in municipal solid waste streams.

2.2.2. Medical Waste

Medical waste includes infectious, pathological, chemical, and pharmaceutical materials generated by hospitals, clinics, and laboratories. Such waste poses a direct threat to human health, requiring careful handling, segregation, and disposal in accordance with public health and environmental regulations (WHO, 2022).

During the COVID-19 pandemic, the widespread use of single-use masks, gloves, and personal protective equipment (PPE) led to a dramatic increase in the volume of medical waste. WHO reports indicate that between 2020 and 2021, the generation of medical waste in healthcare facilities increased by more than 30%, reflecting the intensified pressure on waste management systems worldwide (WHO, 2022).

Table 13 : Types of Medical Waste and Associated Risk Areas

Type	Example	Risk Area
Infectious	Blood-stained bandage, syringe	Risk of infectious disease
Pharmaceutical	Expired medicine	Chemical pollution
Pathological	Tissue, organ samples	Biological contamination

Source: WHO, 2022

Table 13, shows that infectious waste consists of materials such as blood-soaked bandages and used syringes, which can contribute to the spread of infectious diseases. Pharmaceutical waste includes expired medications and, when improperly managed, can lead to chemical pollution. Pathological waste, composed of tissue and organ samples, carries a significant risk of biological contamination. This classification underscores the critical importance of proper medical waste management for ensuring both public health and environmental safety.

2.2.3. Hazardous Waste

Hazardous waste exhibits toxic, corrosive, explosive, or radioactive properties and therefore poses the greatest potential risk to both the environment and human health (UNEP, 2022). For instance, batteries and pesticidescontaining heavy metals such as lead and mercury can leach into soil and water, causing long-term damage to ecosystems. As a result, international conventions—most notably the Basel Convention—strictly regulate the transboundary movement and management of hazardous waste to minimize these risks (OECD, 2021).

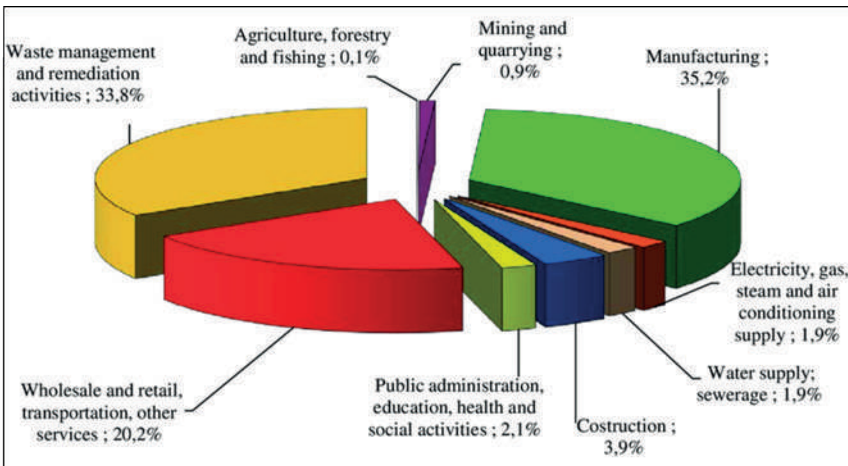

Figure 11 : Percentage Distribution of Hazardous Waste Generation by Economic Activity Sector (2020)

Source: ISPRA (Italian National Institute for Environmental Protection and Research). 2022.

The figure 11, above illustrates the sectoral distribution of hazardous waste generation worldwide as of 2020. According to the data, the manufacturing sector (35.2%) and waste management activities (33.8%) together account for nearly two-thirds of total hazardous waste production. Meanwhile, service sectors such as transportation, wholesale, and retail trade represent 20.2% of the total share. This distribution indicates that hazardous waste is predominantly industry-driven, underscoring the critical role of effective management policies in industrial sectors to mitigate environmental and health risks.

2.2.4. Industrial Waste

Industrial waste encompasses solid, liquid, and gaseous residues generated from production and manufacturing activities. The textile, energy, and mining sectors are among the principal contributors to this type of waste (OECD, 2021). The recycling of industrial waste plays a vital role in supporting the objectives of the circular economy by reducing the demand for raw materials and minimizing environmental pressure. For instance, metal waste generated by the mining industry can be reprocessed and reintegrated into the economy, thereby promoting both resource efficiency and sustainable production (European Commission, 2020).

Figure 12 : Distribution of Industrial Waste by Type in the Global Waste Management Market (2022)

Source: KBV Research. 2023

The figure 12, illustrates that within the global industrial waste management market, construction and demolition wasteaccounts for the largest share, followed by manufacturing, mining, and chemical waste. This distribution reveals the dominant role of resource-intensive sectors in global waste generation and emphasizes the necessity of developing sector-specific strategies to improve recycling efficiency and mitigate environmental impacts.

2.2.5. Construction and Demolition Waste

Construction and demolition (C&D) activities constitute the primary source of high-volume waste materials, including concrete, wood, metal, glass, and plastics. Globally, this category accounts for approximately one-third of total waste volume (World Bank, 2023). Such a significant proportion clearly underscores the importance of implementing effective waste management policies within the construction sector.

The recycling of construction and demolition waste contributes to both economic efficiency and environmental sustainability by reducing the demand for raw materials. For instance, recycled concrete can be processed into new infrastructure materials, while metals, wood, and glass can be reused or repurposed, thereby supporting the principles of the circular economy (European Commission, 2020).

Table 14 : Global Distribution of Construction and Demolition Waste (2023)

Region	Annual Waste Volume (Million Tons)	Share of Total Waste (%)
European Union	450	35
Asia-Pacific	350	25
North America	250	20
Other Regions	240	20
World Total	1290	100

Source: World Bank. 2023. European Commission. 2020.

Table 14, presents the global regional distribution of construction and demolition (C&D) waste for 2023. The European Union accounts for the largest share, generating approximately 450 million tons, which represents 35% of the global total. The Asia-Pacific region follows with 350 million tons (25%), while North America contributes 250 million tons (20%). The remaining regions collectively produce 240 million tons, also accounting for around 20% of the total. Overall, global C&D waste generation is estimated at approximately 1.29 billion tons annually. This distribution underscores the predominant role of developed regions in global waste generation and highlights the necessity for region-specific policies and sustainable management strategies to handle such substantial volumes effectively.

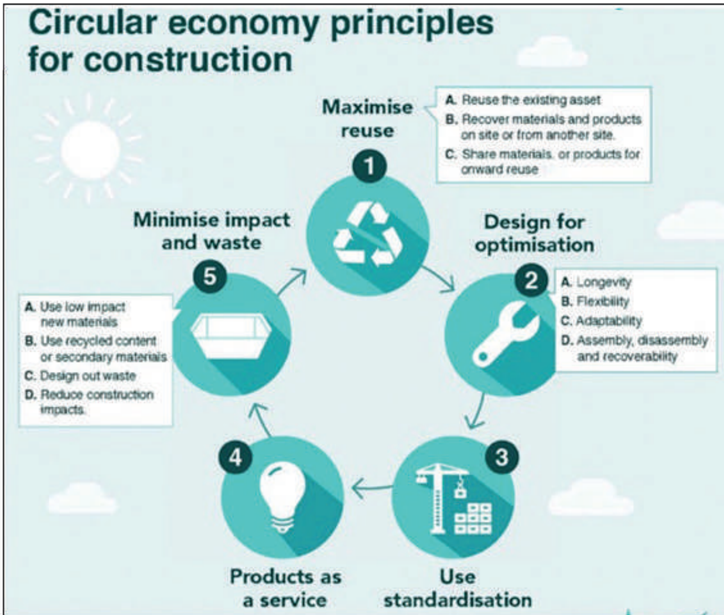

Figure 13 : Integration of Construction and Demolition Waste into the Circular Economy

Source: UK Green Building Council. (2025).

The main objective illustrated in Figure 13 is to achieve sustainability by moving away from the traditional "take–make–dispose" model toward a system based on reuse, design optimization, standardization, product-as-a-service approaches, and impact-driven waste minimization. This framework emphasizes a closed-loop resource cycle, where materials are continuously circulated within the economy to reduce waste generation and enhance overall resource efficiency.

2.2.6. Technological (E-) Waste

E-waste refers to discarded electronic devices that have reached the end of their useful life. This category includes computers, mobile phones, televisions, and various household appliances (Forti et al., 2020).

E-waste contains valuable metals such as gold, copper, and rare earth elements, offering significant economic recovery potential. However, it also includes toxic substances like lead and mercury, which pose serious environmental and health hazards. Therefore, e-waste management represents both an economic opportunity and an environmental challenge, requiring integrated policies for safe recycling and resource recovery (Forti et al., 2020).

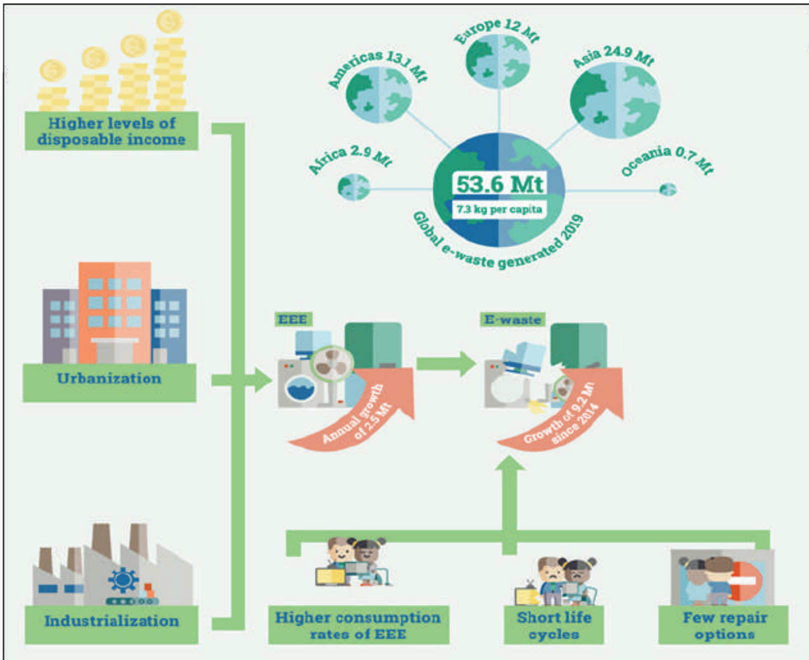

Figure 14 : Global E-Waste Generation and Key Determining Factors (2019)

Source: Forti, Baldé, Kuehr & Bel 2020, Global E-waste Monitor 2020

In 2019, the world generated an estimated 53.6 million tons (Mt) of electronic waste (e-waste), corresponding to an average of 7.3 kilograms per capita. Global e-waste generation increased by 9.2 Mt since 2014 and is projected to reach 74.7 Mt by 2030, nearly doubling within just sixteen years. The escalating volume of e-waste is primarily driven by rising consumption rates of electrical and electronic equipment (EEE), short product life cycles, and limited repair options.

Asia accounted for the largest share of global e-waste in 2019, generating 24.9 Mt, followed by the Americas (13.1 Mt)and Europe (12 Mt), while Africa (2.9 Mt) and Oceania (0.7 Mt) contributed smaller portions. However, in terms of e-waste generation per capita, Europe ranked first globally with 16.2 kg per person, followed closely by Oceania (16.1 kg) and the Americas (13.3 kg), whereas Asia (5.6 kg) and Africa (2.5 kg) recorded substantially lower figures. These statistics highlight the unequal distribution of e-waste generation across regions and emphasize the need for region-specific recycling and management frameworks to mitigate future environmental impacts.

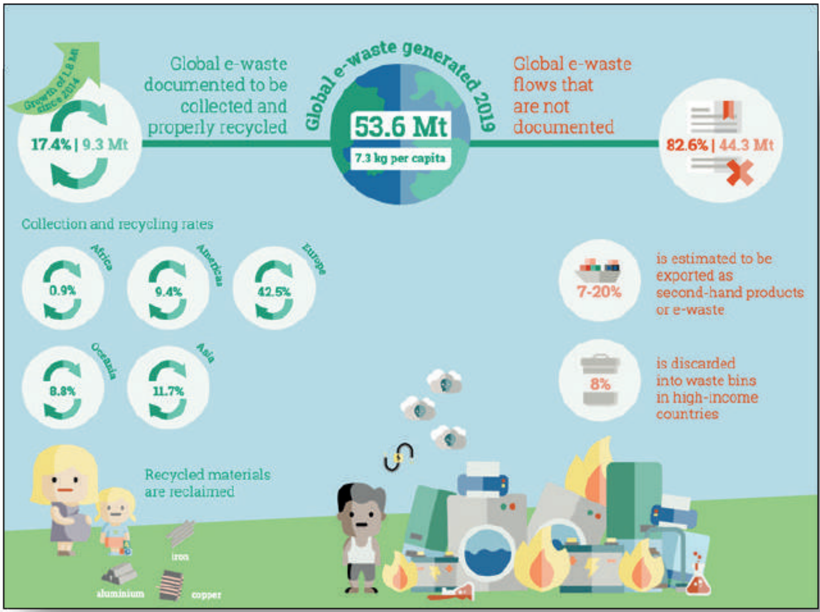

Figure 15 : Global Collection and Recycling Rates of Electronic Waste (2019)

Source: Forti, Baldé, Kuehr & Bel (2020), Global E-waste Monitor 2020

Figure 15, illustrates the global collection and recycling performance of e-waste in 2019. The formally documented collection and recycling amounted to 9.3 million tons (Mt), representing only 17.4% of the total e-waste generated worldwide. Although this figure increased by 1.8 Mt compared to 2014—an average annual growth of 0.4 Mt—the overall generation of e-waste expanded by 9.2 Mt, nearly 2 Mt per year. This growing disparity indicates that recycling activities have not kept pace with the accelerating global production of e-waste.

At the regional level, Europe recorded the highest collection and recycling rate at 42.5%, followed by Asia (11.7%). The Americas (9.4%) and Oceania

(8.8%) demonstrated comparable performance, while Africa showed the lowest rate, with only 0.9% of its e-waste formally collected and recycled. As Figure 2.6 reveals, these differences highlight the uneven global progress in e-waste management and underline the urgent need for enhanced recycling infrastructure and regulatory frameworks, particularly in developing regions.

2.3. The Recycling Process of Waste

The recycling process of waste materials consists of a series of systematic and sequential stages designed to promote raw material efficiency and environmental sustainability. Initially, waste is collected separately at its source and transported to recycling facilities. Upon arrival, the materials are sorted according to type, then compressed and baledfor further processing. This is followed by a shredding phase, where the waste is reduced into smaller particles.

Subsequently, the cleaning or washing process removes dirt and impurities to ensure the materials are suitable for the next stage. During the melting and reformation phase, these processed materials are converted back into raw material form and prepared for manufacturing new products. In the final stage, the recovered materials are reintroduced into the market as newly produced goods, thereby completing a closed-loop cycle that generates both economic benefits and environmental protection (Shakti Plastic Industries, 2023).

As illustrated in Figure 16, this process systematically depicts the entire pathway—from waste collection to the production of new goods—highlighting the interlinked stages that enable a sustainable circular system.

Figure 16 : Main Stages in the Waste Recycling Process

Source: Shakti Plastic Industries, 2023

2.4. Global Statistics and Trends in Waste Generation

At the global level, waste generation has shown a steady upward trend in recent years. According to the World Bank's What a Waste 2.0 Report, approximately 2.01 billion tons of municipal solid waste (MSW) were generated worldwide in 2016, and this figure is projected to reach 3.40 billion tons by 2050 (World Bank, 2018). This growing trend is directly linked to urbanization, economic expansion, and changing consumption patterns.

Not only the total volume but also the per capita generation of waste draws attention. In high-income countries, the average daily waste generation per person is around 2.2 kilograms, whereas in low-income countries, it remains below 0.6 kilograms (World Bank, 2018). This disparity reveals a strong correlation between income levels and waste generation, indicating that wealthier nations tend to produce more waste per capita due to higher consumption levels.

Another notable global trend is the variation in municipal waste quantities across countries. According to 2022 data, the United States is the largest producer of municipal waste, generating 265.2 million tons, followed by Germany (49.7 Mt) and Japan (40.95 Mt), while Turkey's total municipal waste generation stands at 32.42 million tons. Although smaller nations produce lower total quantities, their per capita waste generation is relatively high. For instance, in Oceania, waste generation per person reaches significantly elevated levels.

The following table 15 summarizes the total waste generation, population, and annual per capita waste productionacross selected countries, providing a comparative perspective on global municipal waste patterns.

Table 15 : Municipal Waste Generation and Per Capita Values by Country (2022)

Country	Municipal Waste (Million Tons)	Population (Million)	Per Capita Waste (kg/year)
United States (2018)	265,2	327	811,0092
Germany	49,7	83	598,7952
Japan (2021)	40,95	126	325
France	36,61	67	546,4179
Turkey	32,42	84	385,9524
United Kingdom	29,36	66	444,8485
Italy (2021)	29,25	60	487,5
South Korea (2021)	22,7	52	436,5385
Spain	22,29	47	474,2553
Australia (2021)	13,95	25	558
Poland	13,42	38	353,1579
Netherlands	8,37	17	492,3529
Israel	6,19	9	687,7778
Denmark	4,64	6	773,3333
New Zealand	3,6	5	720
Saudi Arabia (2020)	2,5	34	73,52941
Costa Rica	1,62	5	324

Source: Statista, 2022

Table 15 demonstrates that the United States remains the undisputed leader in municipal waste generation, while European countries stand out with higher per capita figures (World Bank, 2018; Statista, 2022).

The composition of waste also reveals significant global patterns. According to the OECD's Global Plastics Outlook Report (2022), approximately 353 million tons of plastic waste were generated worldwide in 2020, yet only 9% of this amount was successfully recycled. Similarly, the increase in electronic waste (e-waste) represents another major concern. The United Nations' Global E-Waste Monitor (2020) reported that in 2019, the world produced 53.6 million tons of e-waste, of which only 17.4% was recycled. By 2030, global e-waste generation is projected to reach 74 million tons(Forti, Baldé, Kuehr, & Bel, 2020).

These data indicate that the rising volume of waste constitutes not only an environmental challenge but also an economic and social issue. The persistently low recycling rates underscore the urgent necessity of scaling up circular economy practices at the global level to achieve the Sustainable Development Goals (SDGs) (UNEP, 2021).

2.5. Economic Costs of Waste Management

Waste management generates not only environmental but also significant economic implications. According to the World Bank's What a Waste 2.0 Report, the collection and disposal of municipal solid waste constitute one of the largest expenditure categories in local government budgets. These costs vary depending on the collection, transportation, recycling, and landfill processes, and place considerable pressure on municipal budgets—particularly in low-income countries where financial resources are limited (World Bank, 2018).

The global waste management market size is analyzed in terms of both service types and waste sources. The following figure 17 illustrates the market size by service category, showing how the costs of collection, disposal, and transportation services are expected to evolve between 2023 and 2033. This projection highlights the rising economic burden of waste services and underscores the growing importance of efficient and technology-driven waste management systems in achieving sustainable development objectives.

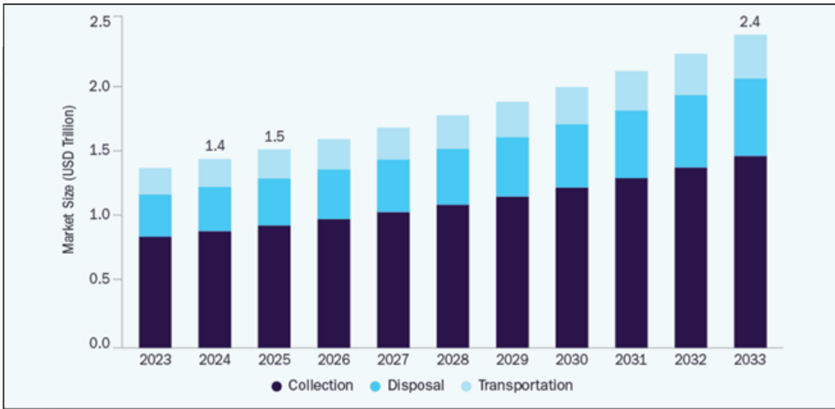

Figure 17 : Projected Global Waste Management Market by Service Type, 2023–2033 (Trillion USD)

Source: Waste Management Market Size ,2023

Figure 17 illustrates the steady increase in the costs of collection, disposal, and transportation services over time, indicating that the total market size of the global waste management industry is projected to reach USD 2.4 trillion by 2033 (Grand View Research, 2023). This upward trend reflects the combined effects of rising urbanization, regulatory requirements, and technological investments necessary for efficient waste handling and recycling.

Similarly, waste management costs vary significantly depending on the source of waste. The following figure 18 presents the market distribution by source type, showing how commercial, industrial, and household waste streams contribute differently to the overall cost structure of the global market between 2020 and 2035.

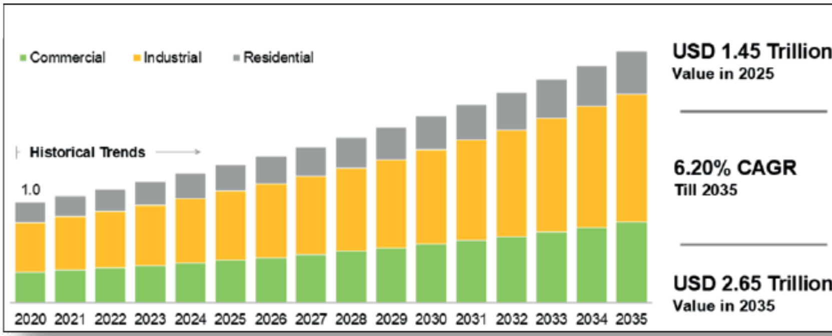

Figure 18 : Global Waste Management Market Size by Source Type, 2020–2035 (Trillion USD)

Source: Roots Analysis. 2025.

Figure 18 reveals that industrial waste accounts for the largest share of total costs within the global waste management market, which is projected to reach USD 2.65 trillion by 2035 (Roots Analysis, 2022). This projection underscores the dominant economic weight of industrial waste treatment and disposal, reflecting both the scale of production activities and the increasing complexity of compliance requirements in industrial sectors.

The economic dimensions of the waste management market are shaped not only by cost structures but also by competition intensity, innovation dynamics, and regulatory frameworks. The following figure (Figure 19) summarizes these sectoral dynamics, illustrating the interplay between market concentration, innovation rates, regulatory impact, and the presence of substitute or alternative solutions within the global waste management industry.

Figure 19 : Sectoral Dynamics of the Global Waste Management Market

Source: Waste Management Market Size ,2023

Figure 19 indicates that the global waste management market exhibits a moderate level of concentration, operates under a strong regulatory influence, and demonstrates a high degree of innovation capacity (Grand View Research, 2023). This structure reflects a competitive yet highly regulated industry, where technological advancement and policy frameworks jointly shape market performance and investment strategies.

Finally, the distribution of global waste management costs by waste type is summarized in the following figure (Figure 20), which provides a comparative overview of market shares by category for the year 2024.

Figure 20 : Global Market Share by Waste Type in 2024 (%)

Source: Waste Management Market Size ,2023

Figure 20 shows that industrial waste dominates the global market cost structure, accounting for over 70% of total expenditures, while municipal, electronic, and medical waste represent comparatively smaller shares (Grand View Research, 2024). These findings reveal that the economic costs of waste management are continuously increasing, while market dynamics are becoming more diverse in terms of both service categories and waste sources.

Consequently, waste management should no longer be viewed merely as an environmental necessity, but rather as a rapidly expanding global economic sector that integrates technological innovation, regulatory frameworks, and sustainability-oriented business models.

2.6. A General Perspective on the Waste Problem

The waste problem has evolved into a global crisis that encompasses not only environmental but also economic, social, and public health dimensions. According to the World Bank's What a Waste 2.0 Report, the total amount of municipal solid waste generated worldwide was 2.01 billion tons in 2016 and is projected to increase by 70%, reaching 3.40 billion tons by 2050 (World Bank, 2018). This rapid growth is particularly concentrated in fast-urbanizing regions, where waste volumes already exceed existing infrastructure capacities.

The United Nations Environment Programme (UNEP), in its Global Waste Management Outlook 2 report, highlights that inefficient waste management not only causes severe environmental degradation but also results in economic losses estimated between USD 80–120 billion annually. These losses are largely attributed to non-recycled plastics, electronic waste, and food waste (UNEP, 2021). Similarly, projections by the OECD (2022) indicate that plastic waste generation is expected to triple by 2060, warning that current policies are insufficient to manage this escalating trend.

The severity of the waste crisis is visibly reflected in many developing cities, where uncontrolled waste accumulationposes serious threats to both environmental quality and social well-being. Such conditions not only create visual and odor pollution, but also increase the risk of disease transmission and degrade overall living standards.

Figure 21 : Environmental Challenges Posed by Uncontrolled Urban Waste Accumulation in Developing Countries

Source: Adekola, P. O., Iyalombe, F. O., Paczoski, A., Abebe, S. T., Pawłowska, B., Bąk, M., & Cirella, G. T. 2021.

Figure 21 illustrates the pressures exerted on public health and the environment by the accumulation of waste in urban areas resulting from inadequate waste collection systems. The issue extends beyond its visual and aesthetic dimensions, encompassing a complex theoretical and systemic framework within the field of environmental management.

Improperly managed waste streams — including medical, electronic, and construction waste — generate cascading effects through uncontrolled dumping and open burning practices. These actions contribute to water, soil, and air pollution, the spread of infectious diseases, the proliferation of marine litter, and even global warming (European Commission, 2020).

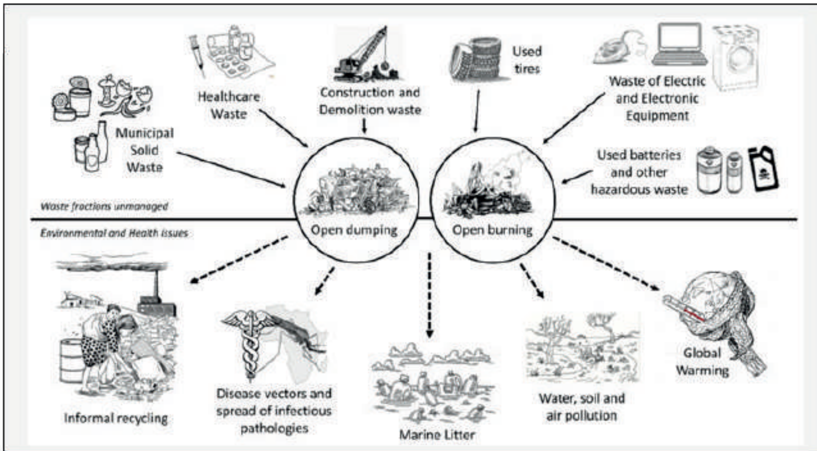

Figure 22: Sources of Pollution and Environmental Impacts Resulting from Improper Solid Waste Management

Source: Ferronato, N., & Torretta, V. (2019).

Figure 22 illustrates the multifaceted consequences of improper waste management practices, such as open dumping and open burning, which lead to environmental pollution, the spread of infectious diseases, the accumulation of marine litter, and the exacerbation of global warming.

Consequently, the waste problem represents a multidimensional challenge driven by factors such as overconsumption culture, unplanned urbanization, insufficient infrastructure, and limited public awareness. Addressing this complex issue requires the global implementation of circular economy principles, the integration of innovative technologies, and enhanced international cooperation to ensure sustainable management of waste and its long-term mitigation.

CHAPTER 3

Urbanization Challenges and the Waste Sector in Turkey

The process of urbanization in Turkey has accelerated particularly since the 1950s, resulting in the majority of the country's population now residing in cities. While this rapid transformation has created significant opportunities in terms of economic development and social change, it has also brought about multifaceted challenges such as inadequate infrastructure, housing shortages, unplanned construction, and increasing environmental pressures. One of the areas most directly affected by these challenges has been waste management. Rising population density and changes in consumption patterns have led to a growing volume of waste, creating both an economic burden for municipalities and a serious threat to environmental sustainability (World Bank, 2018; UNEP, 2021).

3.1. Dimensions of the Urbanization Problem

Urbanization, while a natural outcome of economic development and social modernization, can lead to multidimensional problems when it occurs in an uncontrolled and rapid manner. According to World Bank data, in developing countries such as Turkey, the rate of urbanization has sharply increased over the past 70 years, straining infrastructure capacity and threatening the achievement of sustainable development goals (World Bank, 2018).

From an economic perspective, although urbanization offers opportunities in terms of production and employment, it simultaneously exacerbates income inequalities and increases the cost of living. Moreover, the collection, transportation, and disposal of waste have become significant financial burdens on municipal budgets (UNEP, 2021).

From a social perspective, rapid population growth and insufficient housing production have led to the spread of informal settlements, deficiencies in infrastructure services, and issues of social exclusion. In this context, irregular waste disposal or the failure to collect waste adequately has had a negative impact on the quality of life in low-income areas (UN-Habitat, 2020).

From an environmental perspective, urbanization is directly linked to increased energy consumption, traffic congestion, and rising waste generation. Uncontrolled urban growth contributes to air, water, and soil pollution, as well as higher greenhouse gas emissions, thereby accelerating climate change (OECD, 2022).

Therefore, the issue of urbanization should not be viewed merely as a spatial transformation; rather, it must be understood as a multidimensional process that encompasses economic, social, and environmental dimensions, including the challenges of waste management.

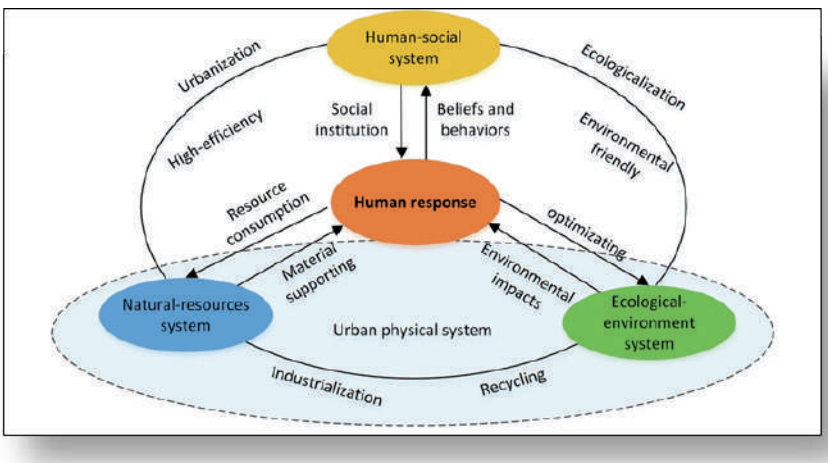

Figure 23 : Conceptual framework illustrating the economic, social, and ecological dimensions of the urbanization problem

Source: Li, Y., Beeton, R.J.S., Zhao, X. et al.2024

Figure 23 illustrates how human response shapes the multidimensional challenges of urbanization through societal institutions, resource consumption, and environmental impacts.

3.1.1. Economic Dimension

The economic dimension of urbanization in Turkey encompasses multifaceted dynamics that directly influence the country's sustainable development goals. Although the growing urban population expands opportunities for production and employment, it also contributes to income inequality and rising living costs. As shown in Table 16, key indicators such as GDP growth rates, foreign trade balance, unemployment, and inflation in Turkey during the 2015–2024 period have exhibited considerable fluctuations. These data indicate that economic vulnerabilities have intensified throughout the urbanization process, accompanied by increasing demand for urban services.

Table 16 : Indicators of Sustainable Development in Turkey (2015–2024)

Indicators	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
GDP Growth, Chain Volume Index, %	6,1	3,3	7,5	3	0,8	1,9	11,4	5,5	5,1	3,2
GDP, Current Prices, Billion TL	2351	2627	3134	3761	4318	5049	7256	10012	12646	13411
GDP, Current Prices, Billion $	867	859	859	798	760	717	808	906	1130	1322
Population, Thousand Persons	78948	79614	80483	82004	83267	84334	85042	85727	86571	87622
GDP per Capita, Current Prices, $	11085	10806	10696	9799	9208	8600	9601	10659	13243	15463
Exports (GTS, FOB), Million $	143	142	157	177	180	169	226	254	255	261
Exports (GTS)/GDP, %	17,4	16,7	18,3	22,2	23,8	23,7	27,9	28,2	22,6	21,4
Imports (GTS, CIF), Million $	213,6	202,2	238,7	231,2	210,3	219,5	271,4	363,7	362	344,6
Imports (GTS)/ GDP, %	27,8	27	28,7	29	27,6	30,6	33,6	40,2	32	28,2
Export-Import Coverage Ratio (%, GTS)	67,2	70,3	65,9	76,6	85,6	76,9	83	69,8	70,6	75,6
Tourism Revenues, Million $	31,5	22,1	26,3	29,5	34,5	12,1	25,3	38,8	54,3	63
Foreign Direct Investments (Gross), Million $	19,3	13,2	11,2	12,5	9,5	7,5	14,2	13,7	10,7	11
Current Account Balance (Billion $)	-32,1	-21,7	-40,6	-21,7	8,7	-36,7	-8,8	-48,6	-45,2	-31,8
Current Account Balance/GDP, %	-4,1	-2,4	-4,8	-2,8	1,2	-5	-1,1	-5,3	-3,9	-2,3

Labor Force Participation Rate, %	51,7	52,4	53,3	53,2	53	49,3	51,4	53,1	53,4	54,2
Unemployment Rate, %	10,2	10,9	10,9	11	13,7	13,1	12	10,4	9,4	8,5
Employment Rate, %	46,4	46,3	47,1	47,4	45,7	42,8	45,2	47,9	48,4	49,2
CPI (Annual Average Change, %)	7,67	7,78	11,14	16,33	15,18	12,28	19,6	72,31	53,86	58,9
CPI (%)	8,81	8,53	11,92	20,3	11,84	14,6	36,08	64,27	64,77	65,4
PPI (Annual Average Change, %)	5,28	9,94	15,82	27,01	17,56	12,18	43,86	128,47	49,93	41,1
PPI (%)	5,71	9,94	15,47	33,64	7,36	25,15	79,89	97,72	44,22	28,52

Source: TÜİK 2024

According to table 16, Turkey's GDP growth rate declined from 6.1% in 2015 to 0.8% in 2019, before rising sharply to 11.4% in 2021 following the post-pandemic recovery. However, by 2024, the growth rate had fallen again to 3.2%. The inflation rate increased dramatically from 7.67% in 2015 to 72.31% in 2023, and slightly decreased to 58.9% in 2024. Meanwhile, the unemployment rate fell from 10.2% in 2015 to 8.5% in 2024. These data suggest that the Turkish economy has been characterized by high inflation and volatile growth, both of which exert financial pressure on urbanization processes and waste management expenditures.

Furthermore, external economic balances significantly influence urbanization policies and the fiscal capacities of local governments. As shown in Table 17, the balance of payments data reveal that Turkey has remained under persistent economic pressure due to chronic current account and trade deficits. This situation constrains municipal budgets allocated for essential services such as infrastructure investment and waste management, thereby hindering the ability to address emerging environmental needs associated with ongoing urbanization.

Table 17 : Developments in Turkey's Balance of Payments (2024–2025)

Indicators	**May 2024**	**May 2025**	**Difference**	**Jan-May 2024**	**Jan-May 2025**	**Difference (Jan-May)**
I- Current Account Balance	-591	-684	-93	-15190	-21039	-5849
A. Foreign Trade Balance	-4192	-4804	-612	-12576	-15032	-2456
B. Services Balance	5242	4862	-380	14462	15004	542
C. Primary Income Balance	-1667	-1548	119	-6468	-7527	-1059
D. Secondary Income Balance	-152	-131	21	-1318	-1354	-36
II- Capital Account	0	1	1	22	20	-2
III- Financial Account	2032	647	-1385	-20902	-26624	-5722
Direct Investments	-410	-289	121	-1420	-2534	-1114
Net Asset Acquisition	713	375	-338	3239	4590	1351
Net Liability Formation	1123	1022	-101	4659	7055	2396
Capital	603	414	-189	1865	2285	420
Investment	611	425	-186	1792	2255	463
Liquidation	8	11	3	73	30	-43
Other Investments (Net)	331	792	461	4128	5759	1631
Real Estate (Net)	189	146	-43	1077	1243	166
Portfolio Investments	-6944	-2194	4750	-16702	-7732	8970
Other Investments	-8207	-5919	2288	-20394	-18099	2295
Reserve Assets	17593	12453	-5140	15410	9909	-5501
IV- Net Errors and Omissions	2636	1343	-1293	-5690	-5906	-216

Source: TÜİK 2024

As shown in the table 17, Turkey's current account deficit rose from USD 15.1 billion in the January–May period of 2024 to over USD 21 billion during the same period in 2025. The foreign trade deficit increased from –USD 12.6 billion in 2024 to –USD 15 billion in 2025. In contrast, the services balance maintained its strong positive contribution, recording a surplus of USD 14.6 billion in 2024 and USD 15 billion in 2025. The financial account showed a net outflow of –USD 20.9 billion in 2024, which further widened to –USD 26.6 billion in 2025. These figures indicate rising external economic pressures, which indirectly constrain the financial resources that municipalities can allocate to urban infrastructure and waste management investments.

The most tangible reflection of the economic dimension of urbanization, however, can be observed in the increasing volume of waste generation. As shown in Table 18, total municipal solid waste generation in Turkey rose from approximately 27 million tons in 2003 to over 52 million tons in 2023. The notable increase, particularly in industrial and commercial waste categories, clearly demonstrates the economic burden imposed by rapid urbanization. The expanding volume of waste represents not only an environmental challenge but also a significant economic concern, compelling municipalities to allocate a substantial share of their budgets to waste collection, transportation, and disposal activities.

Table 18 : Estimated Urban Solid Waste Generation in Turkey (2003–2023)

Source of Waste	2003 (Tons)	2010 (Tons)	2020 (Tons)	2023 (Tons)
Urban Settlements	12152306	15087209	18854323	19913958
Rural Settlements	6099800	6521337	6775735	6782885
Industry	3557994	5031798	8080831	9311489
Commercial–Institutional	5419099	7946504	13805801	16283167
Total	27229259	34586848	47516690	52291499

Source: TÜİK 2024

According to the table18, total solid waste generation in Turkey increased from 27.2 million tons in 2003 to 34.5 million tons in 2010, 47.5 million tons in 2020, and 52.3 million tons in 2023. The most significant increase is observed in urban settlement–based waste, which rose from 12.1 million tons in 2003 to 19.9 million tons in 2023. Industrial waste also grew substantially during the same period, increasing from 3.5 million tons to 9.3 million tons. Similarly, commercial–institutional waste almost tripled, rising from 5.4 million tons in 2003 to 16.2 million tons in 2023. In contrast, rural settlement–based waste exhibited only a modest increase, from 6.1 million tons to 6.7 million tons. These figures clearly indicate that urbanization has been the dominant driver of waste generation, leading to a considerable escalation in economic costs associated with waste management.

3.1.2. Social Dimension

The social dimension of urbanization in Turkey extends beyond economic development, directly influencing the quality of social life. The rapid urbanization process, intensified by rural-to-urban migration, has led to housing shortages, unplanned construction, and the expansion of informal settlements. According to UN-Habitat's World Cities Report 2020, the most evident outcome of rapid urbanization in developing countries is the imbalance between housing supply and population growth (UN-Habitat, 2020). Similarly, in Turkey, increasing population density—particularly in major cities—has deepened social inequalities and spatial segregation.

Another crucial aspect of the social dimension is the limited access to basic infrastructure services. Inadequate provision of electricity, water, and sewage systems adversely affects the quality of urban life. Waste management plays a critical role in this context. When social awareness and environmental consciousness are low, issues such as irregular waste disposal and illegal dumping sites emerge, increasing health risks and rendering the urban environment less livable (UNEP, 2021).

According to the Turkish Statistical Institute (TÜİK), the period between 2020 and 2024 reveals notable trends in social indicators. During this period, the total population increased from 83.6 million to 85.6 million, while the urban population ratio remained stable at around 93%, and the rural population fell below 7%. The average household sizedeclined from 3.30 to 3.12, whereas the proportion of single-person households rose from 17.9% to 21.1%. The median age increased from 32.7 to 34.2, reflecting a shift in age dependency ratios: the child dependency ratiodecreased from 33.7% to 31.9%, while the elderly dependency ratio rose from 14.1% to 15.4%. These indicators demonstrate that Turkey is gradually developing an aging population structure.

Table 19 : Social Indicators in Turkey (2020–2024)

Indicator	2020	2021	2022	2023	2024
Total population	83,614,362	84,680,273	85,279,553	85,372,377	85,664,944
Population living in provincial/district centers (%)	93.0	93.2	93.4	93.0	93.4
Population living in towns/villages (%)	7.0	6.8	6.6	7.0	6.6
Average household size	3.30	3.23	3.17	3.14	3.12
Single-person household rate (%)	17.9	18.9	19.9	20.4	21.1
Households consisting of a nuclear family (%)	65.2	64.4	63.5	63.0	62.3
Median age	32.7	33.1	33.5	34.0	34.2
Child dependency ratio (0–14 years)	33.7	33.0	32.6	32.1	31.9
Elderly dependency ratio (65+ years)	14.1	14.3	14.8	15.1	15.4

Source: TÜİK 2024

Furthermore, urbanization has brought to the forefront issues such as unemployment, the concentration of migrant populations, and social integration challenges. In major metropolitan areas, irregular migration often exceeds the capacity of urban services, thereby intensifying social pressures. This situation also places additional strain on waste management systems. For instance, in metropolitan cities such as Istanbul, Ankara, and Izmir, the rapid increase in the volume of daily collected waste illustrates how social problems have become intertwined with environmental challenges (TÜİK, 2022).

In conclusion, the social dimension of urbanization in Turkey is shaped by a combination of factors, including housing shortages, deficiencies in infrastructure services, unemployment, migration, and low levels of social awareness. These social dynamics are directly linked to the effectiveness of waste management policies. Therefore, enhancing public awareness and civic participation is essential for achieving sustainable urbanization.

3.2. Causes of the Urbanization Problem

The challenges emerging during the process of urban growth are rooted in interrelated structural, demographic, and governance deficiencies. In the context of Turkey, these problems primarily stem from insufficient housing production, rapid urbanization, high population growth, and the tolerance of illegal construction activities.

3.2.1. Insufficient Housing Production

The insufficiency in housing production represents one of the most prominent challenges in Turkey's urbanization process. Population growth and rural-to-urban migration have rapidly increased the demand for housing—particularly in major cities—while the supply has failed to keep pace. This imbalance has led to rising housing prices, escalating rental costs, and significant barriers for low-income households in accessing their fundamental right to adequate housing(Güven, 2023).

Table 20 : Share of Housing and Rent in Household Consumption Expenditures in Turkey (2019–2024)

Year	Housing & Rent (%)
2019	24,1
2020	24,1
2021	22,4
2022	22,4
2023	23,9
2024	26

Source: TÜİK 2024

Table 20 presents the share of housing and rent expenditures within total household consumption in Turkey between 2019 and 2024. The data reveal that housing and rent consistently account for over one-fifth of household budgets, with a steady increase from 24.1% in 2019 to 26.0% in 2024. This upward trend underscores the growing financial burden of housing costs, particularly for low- and middle-income households, and reflects persistent insufficiencies in affordable housing production.

The insufficiency in housing production in Turkey stems not only from quantitative shortages but also from qualitative deficiencies. A significant portion of the existing housing stock falls short of international standards in terms of energy efficiency, structural resilience, and quality of living conditions. Housing production in Turkey has often prioritized quantitative expansion rather than addressing social housing and affordable housing policies. As a result, low-income groups have been compelled to reside in informal and insecure settlements, lacking proper infrastructure and safety (Özdemir Sarı & Khurami, 2018).

The existence of informal housing areas (gecekondu regions) represents another major outcome of inadequate housing production. In the face of rapid migration waves, the state's inability to provide sufficient social housing has forced migrants to find their own shelter solutions. Most of these settlements are unregistered, infrastructure-deficient, and highly vulnerable to natural disasters. In the long term, such conditions exacerbate spatial segregation and deepen social inequalities within urban areas (Yücel & Bektaş, 2013).

Moreover, housing policies implemented in Turkey have predominantly followed a market-oriented approach, with urban transformation projects often shaped by profit-driven dynamics. These projects tend to create modern residential areas for high-income groups, while further marginalizing low-income households instead of addressing their housing needs. Consequently, the insufficiency in housing production represents not only a physical and spatial challenge but also a critical issue of social justice and urban sustainability (Güven, 2023; Özdemir Sarı & Khurami, 2018).

3.2.2. Rapid Urbanization

One of the most prominent aspects of Turkey's demographic and spatial transformation has been rapid urbanization. Beginning in the 1950s with large-scale migration from rural areas to cities, this process accelerated over subsequent decades, leading to the concentration of both economic activity and population in metropolitan regions. As of 2023, more than 93% of

Turkey's population resides in provincial and district centers. This ratio clearly illustrates a long-term structural shift from rural to urban living (Turkish Statistical Institute [TurkStat], 2024).

The high rate of urbanization has frequently exceeded the infrastructural, housing, and social service capacities of municipalities and national institutions. In major cities such as Istanbul, Ankara, and Izmir, rapid population growth has resulted in severe traffic congestion, insufficient public transportation, and increasing pressure on water supply and waste management systems. The mismatch between population growth and infrastructure capacity has deepened social inequalities and accelerated environmental degradation (Özdemir & Güzey, 2020).

Another significant consequence of rapid urbanization has been the proliferation of informal housing areas and unplanned neighborhoods. Migrant populations unable to access affordable housing often constructed gecekondu (informal dwellings) on public or private lands without legal authorization. Although these areas have later been subjected to various legalization and urban transformation projects, they continue to exist as a structural legacy of unmanaged urbanization, revealing persistent weaknesses in urban planning and governance (Karpat, 2022).

Table 21 : Urban and Rural Population Distribution in Turkey (2019–2024)

Year	Total Population	Urban Population (%)	Rural Population (%)	Population Density (per km²)	Annual Growth Rate (‰)
2019	83154997	92,8	7,2	108	13,9
2020	83614362	93	7	109	5,5
2021	84680273	93,2	6,8	110	12,7
2022	85279553	93,4	6,6	111	7,1
2023	85372377	93	7	111	1,1
2024	85664944	93,4	6,6	111	3,4

Source: Turkish Statistical Institute (TurkStat), İstatistiklerle Türkiye (Turkey in Statistics), 2020–2024.

Table 21 reveals that more than 93% of Turkey's population consistently resides in provincial and district centers. While the share of the rural population has fallen below 7%, population density has increased from 108 persons per square kilometer in 2019 to 111 persons in 2024. This trend demonstrates that the urbanization process has generated a permanent and structural transformation, while simultaneously intensifying pressure on infrastructure and service delivery systems.

Finally, rapid urbanization has also reinforced regional disparities. Metropolitan areas in the western regions have attracted the majority of migrant populations and benefited from concentrated investment and employment opportunities, whereas eastern regions have remained relatively underdeveloped. This imbalance has deepened economic and social inequalities within the country, underscoring the necessity of implementing regionally balanced urbanization policies to achieve sustainable development (World Bank, 2019).

3.2.3. Rapid Population Growth

Rapid population growth has been one of the most influential dynamics shaping the urbanization process in Turkeyover the past decades. The country's population increased from 70.6 million in 2007 to 85.4 million in 2023. However, the annual population growth rate declined significantly—from 13.1‰ in 2008 to 1.1‰ in 2023. This demographic shift indicates that while the total population continues to grow, the sharp decline in the growth rate has had a profound impact on urban planning, infrastructure development, and waste management systems (Turkish Statistical Institute [TÜİK], 2024).

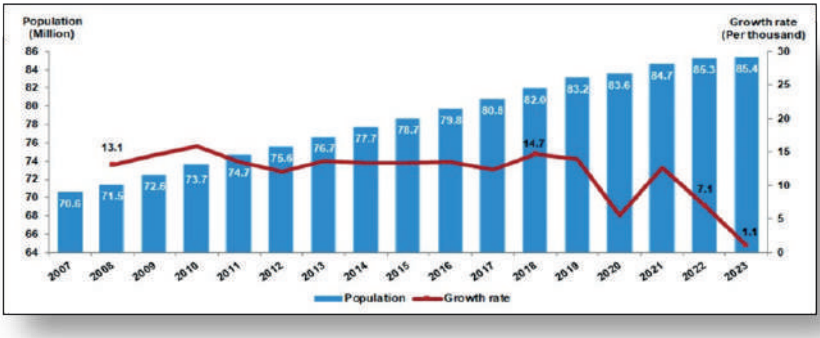

Figure 24 : Population and Annual Growth Rate in Turkey (2007–2023)

Source: Turkish Statistical Institute, 2022

Figure 24 illustrates the continuous growth of Turkey's population and the sharp decline in the annual growth rate observed after 2019. This trend has direct implications for housing demand, social services, and waste generation.

In addition to total population growth, the distribution between rural and urban populations clearly demonstrates the direction of this demographic transformation. The vast majority of Turkey's population now resides in urban centers. Metropolitan municipalities, in particular, continue to experience constant in-migration, which places increasing pressure on housing, transportation, and municipal services, while simultaneously contributing to the rise in urban waste volumes.

Table 22 : Urban vs. Rural Population Distribution in Turkey

Year	Total			Province and district centers			Towns and villages		
	Total	Male	Female	Total	Male	Female	Total	Male	Female
2007	70 586 256	35 376 533	35 209 723	49 747 859	24 928 985	24 818 874	20 838 397	10 447 548	10 390 849
2008	71 517 100	35 901 154	35 615 946	53 611 723	26 946 806	26 664 917	17 905 377	8 954 348	8 951 029
2009	72 561 312	36 462 470	36 098 842	54 807 219	27 589 487	27 217 732	17 754 093	8 872 983	8 881 110
2010	73 722 988	37 043 182	36 679 806	56 222 356	28 308 856	27 913 500	17 500 632	8 734 326	8 766 306
2011	74 724 269	37 532 954	37 191 315	57 385 706	28 853 575	28 532 131	17 338 563	8 679 379	8 659 184
2012	75 627 384	37 956 168	37 671 216	58 448 431	29 348 230	29 100 201	17 178 953	8 607 938	8 571 015
2013	76 667 864	38 473 360	38 194 504	70 034 413	35 135 795	34 898 618	6 633 451	3 337 565	3 295 886
2014	77 695 904	38 984 302	38 711 602	71 286 182	35 755 990	35 530 192	6 409 722	3 228 312	3 181 410
2015	78 741 053	39 511 191	39 229 862	72 523 134	36 376 395	36 146 739	6 217 919	3 134 796	3 083 123
2016	79 814 871	40 043 650	39 771 221	73 671 748	36 936 010	36 735 738	6 143 123	3 107 640	3 035 483
2017	80 810 525	40 535 135	40 275 390	74 761 132	37 470 193	37 290 939	6 049 393	3 064 942	2 984 451
2018	82 003 882	41 139 980	40 863 902	75 666 497	37 912 323	37 754 174	6 337 385	3 227 657	3 109 728
2019	83 154 997	41 721 136	41 433 861	77 151 280	38 660 605	38 490 675	6 003 717	3 060 531	2 943 186
2020	83 614 362	41 915 985	41 698 377	77 736 041	38 921 666	38 814 375	5 878 321	2 994 319	2 884 002
2021	84 680 273	42 428 101	42 252 172	78 908 631	39 481 794	39 426 837	5 771 642	2 946 307	2 825 335
2022	85 279 553	42 704 112	42 575 441	79 613 279	39 802 439	39 810 840	5 666 274	2 901 673	2 764 601
2023	85 372 377	42 734 071	42 638 306	79 399 292	39 664 342	39 734 950	5 973 085	3 069 729	2 903 356
2024	85 664 944	42 853 110	42 811 834	80 007 258	39 939 809	40 067 449	5 657 686	2 913 301	2 744 385

Source: Turkish Statistical Institute,2024

Table 22 presents the changes in the urban and rural population distribution in Turkey between 2007 and 2024. During this period, while the total population continued to grow, the urban population increased from 49.7 million to 79.3 million, whereas the rural population declined from 20.8 million to 5.6 million. This shift clearly illustrates the phenomenon of rapid urbanization and highlights the decisive role of rural-to-urban migration in shaping Turkey's demographic transformation (Turkish Statistical Institute [TÜİK], ADNKS 2007–2024).

Another significant aspect of rapid population growth is the changing age structure of the population. Although Turkey's population remains relatively young compared to European countries, the proportion of elderly citizens is steadily increasing. This dual demographic pattern simultaneously intensifies the demand for housing and employment among the younger population, while also increasing the need for healthcare and social services among the elderly.

Table 23 : Population by Age Groups in Turkey

Year	**Total age dependency ratio**	**Child dependency ratio (Age 0-14)**	**Elderly dependency ratio (Aged 65 and over)**
2007	50,4	39,7	10,7
2008	49,5	39,3	10,2
2009	49,2	38,8	10,5
2010	48,9	38,1	10,8
2011	48,4	37,5	10,9
2012	48,0	36,9	11,1
2013	47,6	36,3	11,3
2014	47,6	35,8	11,8
2015	47,6	35,4	12,2
2016	47,2	34,9	12,3
2017	47,2	34,7	12,6
2018	47,4	34,5	12,9
2019	47,5	34,1	13,4
2020	47,7	33,7	14,1
2021	47,4	33,0	14,3
2022	46,8	32,3	14,5
2023	46,3	31,4	15,0
2024	46,1	30,6	15,5

Source: TÜİK, Adrese Dayalı Nüfus Kayıt Sistemi (ADNKS), 2007-2024

Another important dimension of rapid population growth is the change in the age structure of the population. Although Turkey's population remains relatively young compared to European countries, the proportion of elderly individualshas been steadily increasing. This dual demographic pattern simultaneously drives higher housing and employment demand among the younger population, while also heightening the healthcare and social service needs of the elderly.

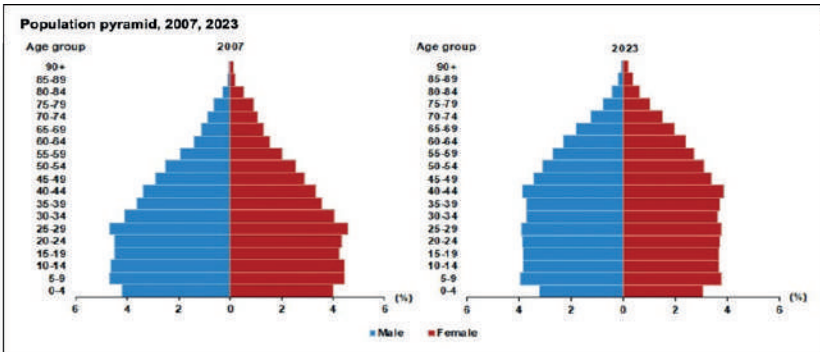

Figure 25 : Population by Age Groups in Turkey

Source: TÜİK, Adrese Dayalı Nüfus Kayıt Sistemi (ADNKS), 2007-2024

Figure 3.9 illustrates the distribution of Turkey's population by age and gender groups. While the proportion of young people was relatively high in 2007, by 2023 the share of the elderly population within the total population had noticeably increased. This trend reveals an aging tendency in Turkey's demographic structure, necessitating new adjustments in social and economic policy frameworks.

Regional population distribution also points to significant imbalances among provinces. Major metropolitan areas such as Istanbul, Ankara, and Izmir continue to absorb a substantial portion of national population growth, whereas some eastern and rural regions are experiencing stagnation or population decline. This imbalance exacerbates regional disparities in housing availability, employment opportunities, and waste management capacity (TÜİK, 2024).

Overall, Turkey's rapid yet uneven population growth presents both opportunities and challenges. On one hand, it fosters economic dynamism and accelerates urbanization; on the other hand, it increases social, environmental, and infrastructural costs, with particularly profound implications for waste generation and management.

3.2.4. Failure to Implement Laws (Illegal Construction)

One of the most critical challenges accompanying rapid urbanization in Turkey is the ineffective enforcement of zoning regulations and the consequent rise of illegal construction. Although legal frameworks are designed to ensure the planned development of urban areas, the lack of effective monitoring mechanisms and implementation deficiencieswithin local administrations have facilitated the widespread emergence of unregulated buildings. This situation not only undermines urban aesthetics, but also leads to inadequate infrastructure services, environmental degradation, and an increased risk of natural disasters (Turhan, 2021).

A significant dimension of illegal construction is its role in increasing vulnerability to natural disasters. In Turkey, particularly in cities located within seismic zones, buildings constructed in violation of zoning and construction codes significantly elevate the risk of loss of life and property. The aftermaths of the 1999 Marmara Earthquake and the 2023 Kahramanmaraş Earthquakes have vividly demonstrated the devastating consequences of unregulated and substandard construction practices (Erdik & Durukal, 2023).

Figure 26 : Collapsed Buildings in the Kahramanmaraş Earthquake: Consequences of Illegal and Non-Standard Construction

Source: Al-Aawsat 2024.

Moreover, illegal construction also generates profound social consequences. Residents living in unplanned and informally developed areas often face significant challenges in accessing basic public services such as transportation, healthcare, education, and infrastructure. This situation deepens urban inequalities and weakens social cohesion. At the same time, the emergence of such practices in violation of the rule of law undermines public trust in government institutions (Kuyucu & Ünsal, 2010).

The economic impacts of illegal construction are equally noteworthy. The proliferation of unlicensed buildingscontributes to informality in the real estate market, leads to revenue losses for municipalities, and hinders the effective implementation of sustainable urbanization policies (Özdemir, 2019). Therefore, strengthening legal enforcement, establishing efficient inspection mechanisms, and developing public awareness–raising policies are of critical importance for achieving sound and sustainable urban development in Turkey.

3.3. The Waste Sector in the Context of Urban Development in Turkey

The waste sector in Turkey has become one of the most critical components of sustainable urban development. Rapid industrialization, urbanization, and demographic growth have led to a substantial increase in both hazardous and non-hazardous waste volumes. Managing this growth effectively requires addressing industrial waste processing, municipal services, and recycling infrastructure within a comprehensive and integrated system framework.

As shown in Table 24, Turkey's total waste volume increased from 104.7 million tons in 2020 to 109.2 million tons in 2022. In 2022, the amount of hazardous waste was approximately 29.4 million tons, while non-hazardous wastereached 79.8 million tons. These figures clearly demonstrate the mounting pressure on waste management systems, particularly in urban areas with concentrated industrial activity.

Table 24 : Waste Generation in Turkey (2020–2022)

Waste generation, 2020, 2022 (Tonnes)

	Amount of total waste		Amount of hazardous waste		Amount of non-hazardous waste	
	2020	2022	2020	2022	2020	2022
Total	**104 739 181**	**109 237 232**	**30 770 088**	**29 380 898**	**73 969 093**	**79 856 334**
Manufacturing industry establishments	**23 867 866**	**27 969 021**	4 597 274	5 439 883	19 270 593	22 529 139
Thermal power plants	**24 375 356**	**27 815 548**	10 012	10 512	24 365 343	27 805 036
Mining establishments[1]	**27 581 875**	**26 309 170**	26 044 730	23 794 881	1 537 144	2 514 289
Organized industrial zones	**279 067**	**323 140**	116 720	127 268	162 347	195 872
Households[2]	**28 635 018**	**26 820 352**	1 352	8 354	28 633 665	26 811 998

Source: Turkish Statistical Institute,2023

Table 24 presents the changes in total, hazardous, and non-hazardous waste quantities in Turkey over time. The data reveal a clear upward trend, particularly in waste generated by industrial activities and households.

Industrial sub-sectors play a decisive role in overall waste generation. Table 25 displays the distribution of waste by manufacturing sub-sectors, while Figure 27 provides a graphical representation of this distribution. According to the data, the basic metals and fabricated metal products sector accounts for the largest share (51.4%), followed by the chemical, plastics, and pharmaceutical industries (21.9%). This distribution reflects the heavy industrial structure of the Turkish economy and highlights its implications for urban sustainability.

Table 25 : Waste Statistics by Manufacturing Sub-Sectors in Turkey (2022)

Waste statistics of manufacturing industry sub-sectors, 2020, 2022 (**Ton**-Tonnes)			
		Amount of waste generated	
NACE Rev. 2 divisions		2020	2022
C	Manufacturing industry	**23 867 866**	**27 969 021**
C10-C12	Manufacturing of food, beverage and tobacco products	1 191 621	1 385 195
C13-C15	Manufacture of textiles, wearing apparel and leather products	642 514	824 364
C16	Manufacture of wood and of products of wood and cork (except furniture)	190 157	426 438
C17-C18	Manufacture of pulp, paper and paper products and recorded media	1 112 229	1 346 807
C19	Manufacture of coke, refined petroleum products	51 582	67 194
C20-C22	Manufacture of chemicals, chemical products, basic pharmaceutical products, rubber and plastic products	5 565 587	6 129 198
C23	Manufacture of other non-metallic mineral products	1 205 416	1 275 497
C24-C25	Manufacture of basic metals and fabricated metal products	12 075 949	14 376 602
C26-C30	Manufacture of computur, electronic and optical products, electrical equipment, machinery and equipment, motor vehicles, trailers and semitrailers and other transport equipment	1 588 996	1 904 585
C31-C33	Manufacture of furniture, other manufacturing, repair and installation of machinery and equipment	243 815	233 141

Source: Turkish Statistical Institute,2023

Table 25 presents a comparative overview of the waste quantities generated by manufacturing sub-sectors. It is evident that the basic metal and chemical industries hold the largest shares in total industrial waste generation.

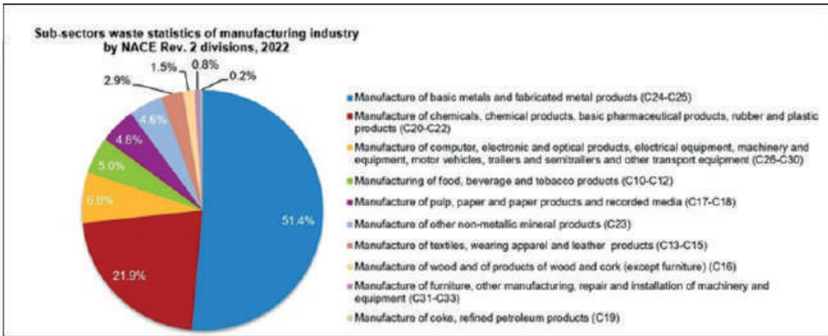

Figure 27 : Waste Statistics by Manufacturing Sub-Sectors in Turkey (2022)

Source: Turkish Statistical Institute,2023

Figure 27 illustrates the distribution of waste across manufacturing sub-sectors in percentage terms, highlighting the predominance of the metal and chemical industries.

Urban waste management, which falls under the responsibility of municipal authorities, has shown significant improvements in recent years. Table 26 presents the developments in municipal waste services, while Figure 28 depicts the changes in waste management methods. According to the data, the share of municipal waste sent to regular treatment facilities increased from 82.6% in 2020 to 85.9% in 2022, whereas the proportion of waste sent to municipal dumpsites declined from 17% to 13.5% during the same period. This trend indicates steady progress toward more sustainable practices in municipal waste management.

Table 26 : Municipal Waste Services in Turkey (2020–2022)

Municipal waste services statistics, 2022							
Province	Total municipal population	Total number of municipalities	Number of municipalities providing waste services	Population of municipalities served by waste services	(%) Rate of municipal population served by waste services in total municipal population (%)	Amount of waste collected (Tonnes)	Amount of waste per capita (Kg/ capita-day)
Türkiye	**80 785 141**	**1391**	**1389**	**80 319 403**	**99,4**	**30 283 757**	**1,03**
Adana	2 274 106	16	16	2 260 333	99,4	665 695	0,81
Adıyaman	487 642	23	22	483 209	99,1	179 724	1,02
Afyonkarahisar	588 048	60	60	585 217	99,5	198 273	0,93
Ağrı	314 539	12	12	314 120	99,9	181 116	1,58
Amasya	256 679	8	8	255 455	99,5	111 099	1,19
Ankara	5 782 285	26	26	5 778 930	99,9	1 956 586	0,93
Antalya	2 688 004	20	20	2 672 108	99,4	1 340 770	1,37
Artvin	107 965	9	9	107 965	100,0	61 276	1,55
Aydın	1 148 241	18	18	1 140 789	99,4	456 122	1,10
Balıkesir	1 257 590	21	21	1 257 257	100,0	445 066	0,97
Bilecik	197 441	11	11	197 441	100,0	61 157	0,85
Bingöl	199 384	11	11	196 854	98,7	47 638	0,66
Bitlis	243 880	13	13	243 480	99,8	82 236	0,93
Bolu	241 953	12	12	241 953	100,0	97 911	1,11
Burdur	203 435	15	15	203 381	100,0	128 243	1,73
Bursa	3 194 720	18	18	3 194 720	100,0	1 033 183	0,89
Çanakkale	415 159	23	23	405 707	97,7	256 932	1,74
Çankırı	146 791	16	16	143 919	98,0	79 136	1,51
Çorum	398 833	16	16	396 214	99,3	128 849	0,89
Denizli	1 056 332	20	20	1 049 800	99,4	342 621	0,89
Diyarbakır	1 804 880	18	18	1 772 283	98,2	739 224	1,14
Edirne	330 403	16	16	330 403	100,0	147 867	1,23
Elazığ	498 321	20	20	495 672	99,5	170 209	0,94
Erzincan	196 431	15	15	195 940	99,8	80 382	1,12
Erzurum	749 754	21	21	703 618	93,8	231 819	0,90
Eskişehir	906 617	15	15	903 401	99,6	307 569	0,93
Gaziantep	2 154 051	10	10	2 154 051	100,0	682 796	0,87
Giresun	325 647	24	24	316 154	97,1	110 881	0,96
Gümüşhane	109 655	14	14	109 632	100,0	26 002	0,65
Hakkari	176 468	8	8	176 061	99,8	58 530	0,91
Hatay	1 686 043	16	16	1 686 043	100,0	826 861	1,34
Isparta	356 469	22	22	355 958	99,9	154 602	1,19
Mersin	1 916 432	14	14	1 908 836	99,6	590 566	0,85
İstanbul	15 907 951	40	40	15 907 951	100,0	6 552 701	1,13
İzmir	4 462 056	31	31	4 457 705	99,9	1 983 465	1,22
Kars	145 215	9	9	144 792	99,7	105 499	2,00
Kastamonu	244 090	20	20	240 561	98,6	75 731	0,86

Kayseri	1 441 523	17	17	1 441 232	100,0	513 665	0,98
Kırklareli	307 853	21	21	306 806	99,7	111 986	1,00
Kırşehir	205 554	10	10	205 527	100,0	75 102	1,00
Kocaeli	2 079 072	13	13	2 079 072	100,0	622 287	0,82
Konya	2 296 347	32	32	2 286 298	99,6	823 070	0,99
Kütahya	462 886	28	28	462 886	100,0	146 765	0,87
Malatya	812 580	14	14	806 370	99,2	221 315	0,75
Manisa	1 468 279	18	18	1 468 279	100,0	634 997	1,18
Kahramanmaraş	1 177 436	12	12	1 170 805	99,4	405 167	0,95
Mardin	870 374	11	11	814 893	93,6	215 120	0,72
Muğla	1 048 185	14	14	1 044 022	99,6	582 240	1,53
Muş	239 760	23	22	237 064	98,9	83 973	0,97
Nevşehir	250 696	23	23	249 948	99,7	87 513	0,96
Niğde	300 538	29	29	293 425	97,6	103 303	0,96
Ordu	763 190	20	20	717 497	94,0	224 191	0,86
Rize	250 776	18	18	247 307	98,6	71 662	0,79
Sakarya	1 080 080	17	17	1 073 984	99,4	355 011	0,91
Samsun	1 368 488	18	18	1 312 802	95,9	397 195	0,83
Siirt	242 539	12	12	241 818	99,7	78 186	0,89
Sinop	139 531	9	9	138 787	99,5	62 942	1,24
Sivas	498 834	24	24	498 070	99,8	258 164	1,42
Tekirdağ	1 142 451	12	12	1 142 451	100,0	484 766	1,16
Tokat	477 701	37	37	474 320	99,3	162 972	0,94
Trabzon	818 023	19	19	812 248	99,3	213 415	0,72
Tunceli	58 230	9	9	56 319	96,7	26 507	1,29
Şanlıurfa	2 170 110	14	14	2 124 726	97,9	513 421	0,66
Uşak	297 315	11	11	297 274	100,0	123 553	1,14
Van	1 128 749	14	14	1 123 675	99,6	419 453	1,02
Yozgat	318 145	36	36	318 057	100,0	134 744	1,16
Zonguldak	434 560	25	25	433 058	99,7	141 243	0,89
Aksaray	356 625	22	22	354 758	99,5	99 331	0,77
Bayburt	60 265	5	5	60 265	100,0	21 392	0,97
Karaman	213 606	11	11	212 395	99,4	64 944	0,84
Kırıkkale	249 402	11	11	249 402	100,0	75 600	0,83
Batman	541 139	11	11	538 344	99,5	176 709	0,90
Şırnak	420 731	19	19	420 116	99,9	217 716	1,42
Bartın	110 451	8	8	109 791	99,4	74 890	1,87
Ardahan	41 120	7	7	41 120	100,0	26 146	1,74
Iğdır	134 419	7	7	134 419	100,0	57 229	1,17
Yalova	265 869	14	14	264 470	99,5	117 506	1,22
Karabük	198 467	7	7	198 298	99,9	51 400	0,71
Kilis	116 361	4	4	116 361	100,0	81 555	1,92
Osmaniye	468 665	14	14	468 665	100,0	131 002	0,77
Düzce	284 706	10	10	284 069	99,8	96 074	0,93

Source: TÜİK, Municipal Waste Services Statistics, 2022

Table 26 presents the amounts of waste collected and sent for processing by municipalities on an annual basis. The data highlight a noticeable increase in the capacity of municipal waste services during the 2020–2022 period.

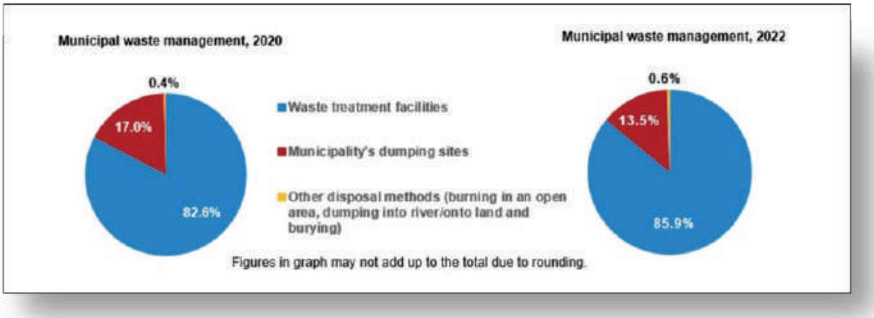

Figure 28 : Municipal Waste Management (2020–2022)

Source: TÜİK, Municipal Waste Statistics, 2022

Figure 28 presents the distribution of municipal waste by disposal methods. The increase in the rate of controlled landfilling reflects a positive development in terms of sustainable waste management practices.

Another important component of the sector is the development of waste disposal and recovery infrastructure. According to Table 27, the number of facilities increased from 2,752 in 2020 to 3,136 in 2022, while the amount of processed waste rose from 127.4 million tons to 133.1 million tons over the same period. Table 28 illustrates the capacity expansion of composting, co-incineration, and other recovery facilities. These developments indicate that Turkey has made notable progress in aligning its waste management system with European Union standards and the goals of a circular economy.

Table 27 : Waste Disposal and Recovery Facilities in Turkey (2020–2022)

	2020	2022
Number of waste disposal and recovery facilities	**2 752**	**3 136**
Number of waste disposal facilities	**184**	**200**
Controlled landfill site		
Number	174	191
Capacity (m^3)	1 208 369 189	1 408 773 786
Rest of capacity (m^3)	661 189 005	682 017 415
Total amount of waste landfilled (Tonnes)	77 762 423	80 996 500
Amount of hazardous waste landfilled (Tonnes)	31 884 941	28 845 805
Amount of non-hazardous waste landfilled (Tonnes)	45 877 482	52 150 694
Incineration plant		
Number	10	9
Capacity (Tonnes/year)	842 222	747 462
Total amount of waste incinerated (Tonnes)	570 980	449 532
Amount of hazardous waste incinerated (Tonnes)	c	c
Amount of non-hazardous waste incinerated (Tonnes)	c	c
Number of waste recovery facilities	**2 568**	**2 936**
Composting plant		
Sayısı - Number	9	11
Capacity (Tonnes/year)	651 150	722 253
Total amount of waste composted (Tonnes)	127 046	120 096
Compost produced (Tonnes)	34 834	30 152
Co-incineration plant		
Number	50	59
Total amount of waste co-incinerated (Tonnes)	1 298 579	3 154 270
Amount of hazardous waste co-incinerated (Tonnes)	542 127	621 281
Amount of non-hazardous waste co-incinerated (Tonnes)	756 452	2 532 989
Other recovery facilities		
Number	2 509	2 866
Total amount of waste recovered (Tonnes)	47 642 204	48 462 778
Amount of hazardous waste recovered (Tonnes)	1 810 315	1 736 972
Amount of non-hazardous waste recovered (Tonnes)	45 831 889	46 725 806

Source: TÜİK, Waste Disposal and Recovery Facilities Statistics, 2022

Table 27 illustrates the increase in the number of waste disposal and recovery facilities, as well as in the amount of waste processed. This growth clearly indicates an expansion in infrastructure capacity.

Table 28 : Waste Disposal and Recovery Facilities Indicators (2020–2022)

Waste disposal and recovery facilities indicators, 2020, 2022

	2020		2022	
	Number of facilities	Total amount of waste treated (Tonnes)	Number of facilities	Total amount of waste treated (Tonnes)
Waste disposal and recovery facilities	**2 752**	**127 401 232**	**3 136**	**133 183 175**
Waste disposal facilities	**184**	**78 333 403**	**200**	**81 446 031**
Controlled landfill sites	174	77 762 423	191	80 996 500
Incineration plants	10	570 980	9	449 532
Waste recovery facilities	**2 568**	**49 067 829**	**2 936**	**51 737 143**
Composting plants	9	127 046	11	120 096
Co-incineration plants	50	1 298 579	59	3 154 270
Other recovery facilities (1)	2 509	47 642 204	2 866	48 462 778

Figures in tables may not add up to totals due to rounding.
Imported waste is included.
(1) It includes the facilities which recover waste metal, plastic, paper, mineral etc.

Source: TÜİK, Waste Disposal and Recovery Facilities Statistics, 2022

Table 28 illustrates the developments in composting, co-incineration, and other recovery facilities, showing that Turkey has significantly enhanced its recycling capacity within the framework of waste management.

CHAPTER 4

The Technological Waste Economy in the Digital Era

The acceleration of digitalization on a global scale has not only transformed economic and social structures but also ushered in a new era in waste management and environmental sustainability. The growing diversity of electronic devices, their shortened life cycles, and shifting consumption habits have placed the technological waste economy at the core of sustainable development debates. Following the discussion of sustainability and urbanization issues in the previous chapters, this section explores how the waste economy is being reshaped within the opportunities and risks brought by the digital age. Accordingly, it demonstrates that technological waste possesses not only environmental but also economic and strategic dimensions, while addressing the integration of digital tools—such as Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, and big data—into waste management systems.

4.1. Defining the Technological Waste Economy

The technological waste economy is regarded as one of the most prominent environmental and economic phenomena of the digital era. This concept refers to the revaluation of waste generated throughout the lifecycle of electronic and digital devices—from production to end-of-use—within the economic value chain. In other words, the technological waste economy represents a multidimensional system situated at the intersection of digitalization, sustainable development, and circular economy principles (Forti, Baldé, Kuehr & Bel, 2020).

Technological or electronic waste (e-waste) encompasses electronic devices and components that have lost their functionality, are no longer in use, or have become technologically obsolete.

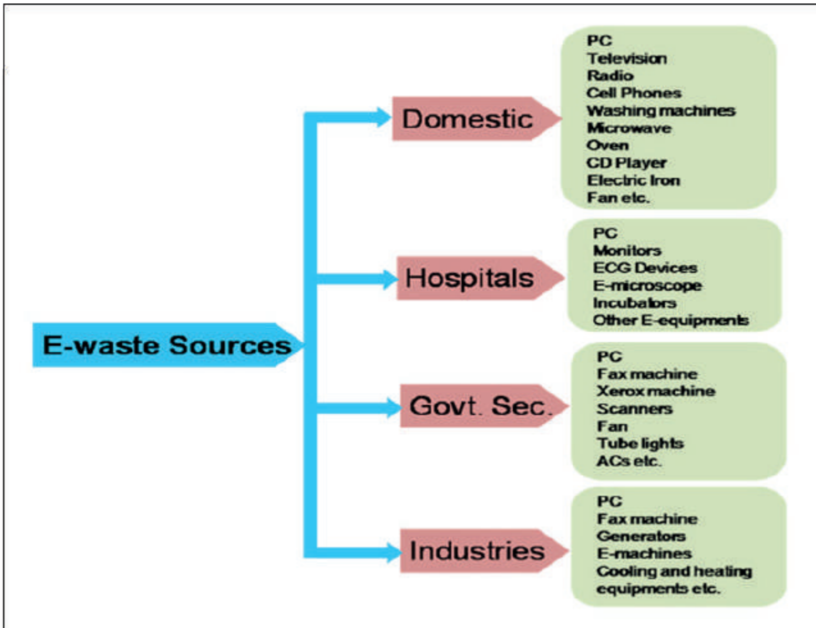

Figure 29 : Major Sources of Electronic Waste

Source: Ankit et al. (2021),

The figure 29 illustrates the four main sources of electronic waste: household, industrial, public, and healthcare sectors. This structure provides a conceptual framework by clearly classifying the economic and institutional domains in which e-waste is generated.

Computers, mobile phones, televisions, printers, cables, batteries, and small household appliances fall under these categories.

Table 29 : Global E-Waste Generation by Equipment Category (2022)

Category	E-Waste (billion kg)	Formal Collection (billion kg)	Collection Rate (%)	Share of Total (%)
Small equipment	20,4	2,4	12	30,1
Large equipment (excl. PV)	15,1	5,1	34	22,3
Temperature-exchange equipment	13,3	3,6	27	19,6
Screens & monitors	5,9	1,5	25	8,7
Small IT & telecommunication equipment (laptops & phones)	4,6	1	22	6,8
Lamps	1,9	0,1	5	2,8
Photovoltaic panels	0,6	0,1	17	0,9
Total	61,8	13,8	22	100

Source: United Nations University (UNU) & International Telecommunication Union (ITU). (2024).

Table 29 presents the distribution of globally generated electronic waste by equipment category in 2022. According to the data, small equipment accounts for 30% of total e-waste, followed by large equipment (22.3%) and temperature exchange equipment (19.6%). The category of small IT and telecommunication equipment—including laptops and mobile phones—draws attention with a 6.8% share.

The United Nations University (UNU) defines e-waste as “all discarded electrical and electronic equipment, and its components, that use electric currents or electromagnetic fields” (Baldé, Forti, Gray, Kuehr & Stegmann, 2017). This definition encompasses not only devices themselves but also the secondary waste generated throughout the production and consumption chain.

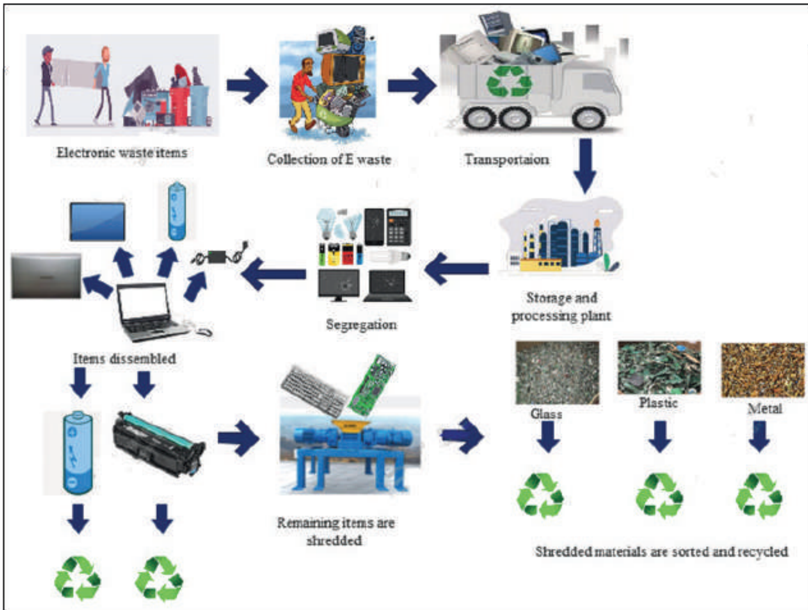

Figure 30 : Collection, Separation, and Recycling Process of Electronic Waste

Source: Islam, Khatun & Mourshed 2024.

The figure 30 illustrates the life cycle of electronic waste. The process begins with collection and proceeds through stages of transportation, separation, dismantling, shredding, and ultimately the recycling of materials such as glass, plastic, and metal.

The composition of e-waste is highly complex. For instance, a computer motherboard contains more than 60 types of metals, including high-value materials such as gold, silver, copper, and palladium, as well as toxic substances like lead, mercury, and cadmium (Cucchiella, D'Adamo, Koh & Rosa, 2015). Therefore, e-waste represents both a valuable source of raw materials and a major source of pollution when improperly managed.

This dual nature forms the core dynamic of the technological waste economy: on one hand, it serves as a resource contributing to the circular economy; on the other, when left uncontrolled, it becomes a significant ecological threat (UNEP, 2021).

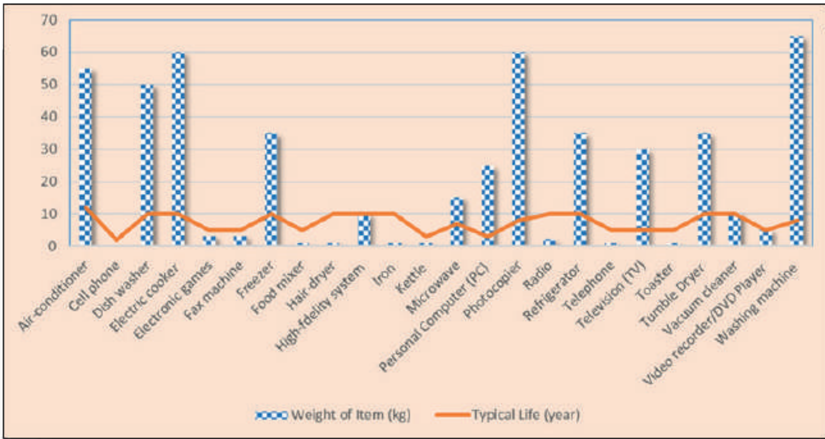

Figure 31 : Types of Electronic Devices and Their Average Lifespans

Source: Ankit et al. 2021.

The figure 31 illustrates the average weights and lifespans of various categories of electronic devices.

On a global scale, the generation of electronic waste has exhibited a pronounced upward trajectory in recent years. According to The Global E-Waste Monitor 2024, per capita e-waste generation in 2022 amounted to 17.6 kg in Europe, 16.1 kg in Oceania, 14.1 kg in the Americas, 6.4 kg in Asia, and 2.5 kg in Africa. In contrast, the quantities officially collected and recycled remain considerably lower—7.53 kg (42.8%) in Europe, 6.66 kg (41.4%) in Oceania, 4.2 kg (30%) in the Americas, 0.76 kg (11.8%) in Asia, and merely 0.018 kg (0.7%) in Africa (UNU & ITU, 2024).

These data underscore the persistent regional disparities in global e-waste management and emphasize the insufficiency of sustainable recycling systems, particularly in developing regions. The widening gap between e-waste generation and formal recovery highlights the urgent need for integrated international frameworks and advanced digital monitoring mechanisms to ensure effective waste governance.

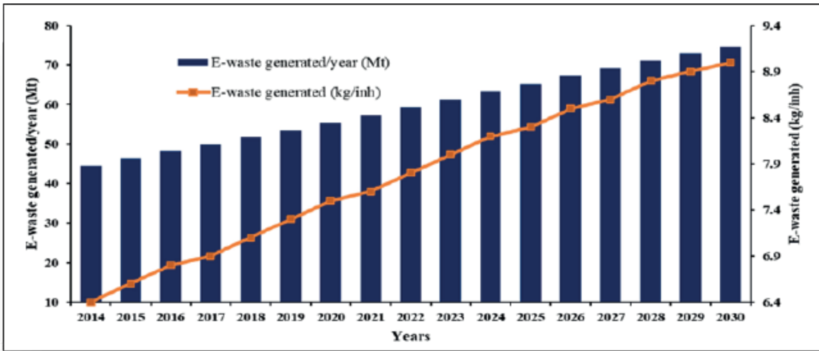

Figure 32 : Annual Growth in Global E-Waste Generation (2014 – 2030)

Source: Ankit et al. 2021.

The figure 32 illustrates the steady increase in global e-waste generation between 2014 and 2030. The data trend indicates that, in parallel with the acceleration of digitalization, global e-waste generation has risen at an average annual rate of approximately 3%.

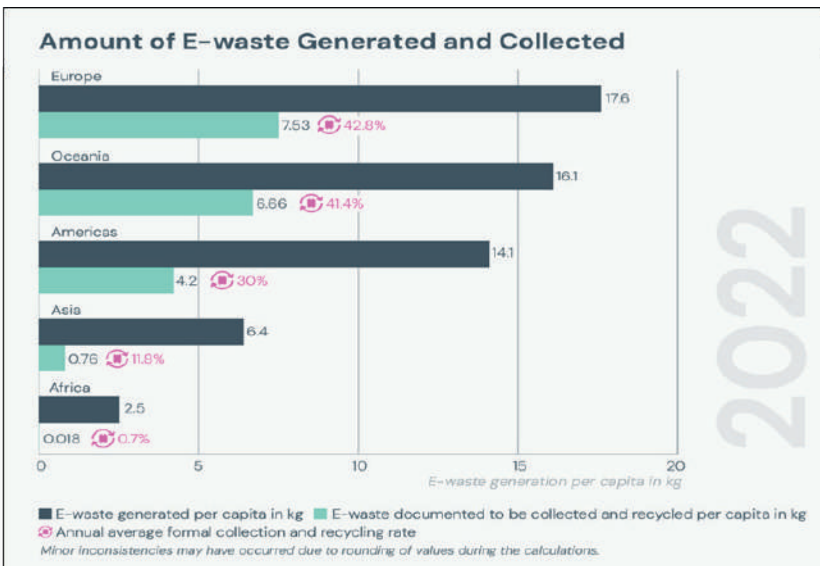

Figure 33 : Global E-Waste Generation and Official Collection Rates (2022)

Source: UNU & ITU, 2024.

The figure 33 presents the quantities of e-waste generated and officially collected per capita across different regions. Europe and Oceania stand out with relatively high recycling rates, whereas the notably lower rates in Asia and Africa reveal the structural inequalities embedded within the global waste economy.

The evolution of the e-waste economy supports not only environmental sustainability but also economic growth. Employment generation within the recycling sector, improvements in resource efficiency, and cost savings collectively strengthen the economic dimension of this process. The following figure summarizes the key economic benefits of e-waste recycling and highlights why the technological waste economy holds strategic significance for global sustainability agendas.

Figure 34 : The Economic Benefits of E-Waste Recycling

Source: 4THBIN 2024. The Economic Benefits of E-Waste Recycling

The Figure 34 illustration demonstrates the economic value generated by e-waste recycling in terms of job creation, resource conservation, recovery revenues, and the reduction of environmental impacts. These dimensions collectively underscore the significance of the technological waste economy within both economic growth and circular economy frameworks.

Future trends shaping the technological waste economy are closely linked to digital transformation, advancements in material technologies, and evolving regulatory frameworks. By 2025, the e-waste recycling sector is expected to witness notable progress in material recovery efficiency, an increase in the number of certified recyclers, strengthened policy mechanisms, and rising consumer awareness regarding sustainable waste practices.

Figure 35 : E-Waste Recycling: Trends and Predictions for 2025

Source: 4THBIN 2024. The Economic Benefits of E-Waste Recycling

The figure 35 illustrates the technological and policy developments projected for the e-waste recycling sector in 2025, with a particular focus on advancements in recovery technologies, consumer participation, and localization trends.

The technological waste economy represents not merely an environmental necessity but an economic opportunity positioned at the core of the digital era's sustainable development vision. Its success depends on the establishment of a robust regulatory framework, the integration of digital monitoring technologies, and the effective implementation of global cooperation mechanisms (World Bank, 2023).

4.2. Global Perspectives on the Technological Waste Economy

The technological waste economy has gained strategic importance in terms of both environmental sustainability and economic development, parallel to the global expansion of digitalization. The shortening life cycles of electronic devices, the surge in consumer demand, and the rapid renewal of production technologies have led to an unprecedented increase in global e-waste generation (Forti, Baldé, Kuehr & Bel, 2020). Today, e-waste is not only a matter of environmental policy but also a critical component of energy security, raw material supply, digital transformation strategies, and green growth policies (UNEP, 2021).

In this context, the technological waste economy represents a multidimensional system situated at the intersection of digitalization, sustainable development, and circular economy principles. This system is structured around a life cycle approach encompassing the stages of e-waste generation, consumption, collection, transportation, dismantling, recycling, and final disposal. E-waste management, therefore, extends beyond a purely technical process; it constitutes an integrated framework that includes policymaking, environmental engineering, and social responsibility dimensions.

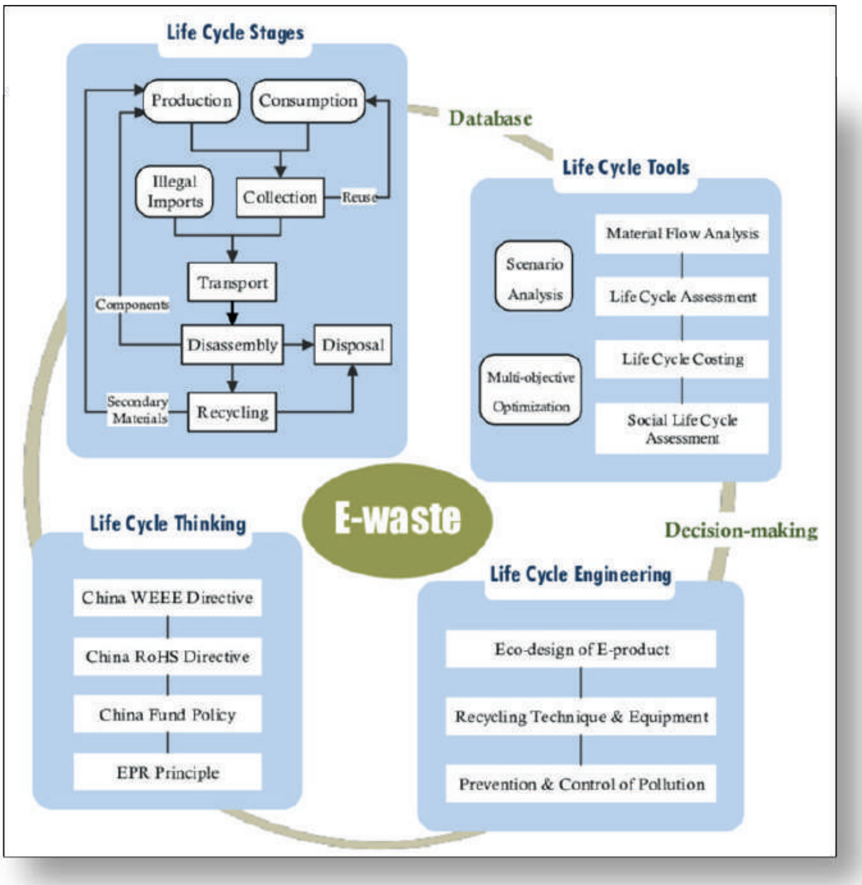

Figure 36 : Life Cycle and Management Process of E-Waste

Source: Song, X., Yang, J., Lu, B., & Yang, D. 2017.

The figure 36 illustrates e-waste management within a comprehensive Life Cycle Management framework. The "Life Cycle Stages" component encompasses processes ranging from production and consumption to collection and recycling, while "Life Cycle Tools" incorporates analytical and decision-making instruments such as Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and Social Life Cycle Analysis. "Life Cycle Thinking" represents the policy and regulatory dimensions (e.g., WEEE and RoHS Directives), and "Life Cycle Engineering" addresses eco-design, recycling technologies, and pollution prevention strategies. Together, these elements form a sustainable framework integrating the technical, legal, and environmental dimensions of e-waste management.

According to The Global E-Waste Monitor 2020 published by the United Nations University, approximately 53.6 million tons of e-waste were generated worldwide in 2019, of which only 17.4% was officially collected and recycled. This figure is projected to reach 74.7 million tons by 2030 (Forti et al., 2020), reflecting both the accelerating pace of digitalization and the expanding magnitude of the global waste economy. Regionally, Asia accounts for nearly half of global e-waste generation with 24.9 million tons, followed by the Americas (13.1 million tons) and Europe (12 million tons). Africa (2.9 Mt) and Oceania (0.7 Mt) generate comparatively smaller amounts. However, in terms of per capita generation, Europe ranks first with 16.2 kg, followed by Oceania (16.1 kg) and the Americas (13.3 kg) (Parajuly & Wenzel, 2017). These disparities clearly demonstrate the direct correlation between technological consumption levels and the degree of economic development.

Table 30 : Global E-Waste Generation and Regional Distribution (2015–2022)

Year	Global Total (Mt)	Official Recycling Rate (%)	Asia (Mt)	Americas (Mt)	Europe (Mt)	Africa (Mt)	Oceania (Mt)
2015	44,3	–	20,5	10,8	9,5	2,4	0,6
2016	45,8	–	21,3	11,2	10	2,5	0,7
2017	48	–	22,5	11,8	10,8	2,8	0,7
2018	50,4	–	23,6	12,4	11,5	2,9	0,7
2019	53,6	17,4	24,9	13,1	12	2,9	0,7
2022	62	22,3	28,5	15,2	13,2	3,3	0,8

Source: United Nations University,2024.

Between 2015 and 2022, as shown in Table 3.0, global e-waste generation increased by more than 40%. The official recycling rate, which stood at only 17.4% in 2019, rose to 22.3% by 2022. Regionally, Asia remains the largest producer, accounting for approximately 46% of global e-waste. While the Americas and Europe lead in per capita generation, Africa and Oceania continue to record much lower quantities. These trends reaffirm the direct relationship between technological consumption and the level of economic development.

The structure of the global e-waste economy is shaped by pronounced inequalities between developed and developing countries. Although advanced economies possess robust recycling infrastructures and well-established regulatory frameworks, a significant portion of e-waste is still exported to developing nations for processing (Baldé, Forti, Gray, Kuehr & Stegmann, 2017). In Africa, for instance, Ghana's Agbogbloshie region has become one of the world's largest informal e-waste processing hubs. Primitive metal recovery practices conducted there contribute to soil and water contamination, posing severe health hazards (UNEP, 2021). This situation underscores the necessity—within the framework of environmental justice—to establish a more equitable, inclusive, and sustainable global e-waste management system (Zeng, Li & Stevels, 2023).

The principal international legal framework regulating e-waste management is the Basel Convention, adopted in 1989, which aims to control the transboundary movement of hazardous wastes (Basel Convention, 2023). However, the rapid evolution of digital technologies and the increasing diversity of electronic devices have outpaced the scope of existing regulations. Consequently, the United Nations Environment Programme (UNEP) and the Organisation for Economic Co-operation and Development (OECD) have developed new cooperation mechanisms and policy models (UNEP, 2021; OECD, 2022). Within the European Union, the WEEE Directive (2012/19/EU) and the Circular Economy Action Plan (2020) have introduced the Extended Producer Responsibility (EPR) framework, which mandates producers to take active responsibility in waste management (European Commission, 2020). As a result, the EU's average e-waste collection rate has surpassed 45%, and recycling capacity continues to expand (European Environment Agency, 2023).

These global disparities deeply influence the structural transformation of the e-waste economy. In developing countries, most e-waste is processed within the informal sector under conditions of low technology and weak regulatory oversight. Conversely, in developed nations, waste management operates within a legally grounded, high-technology, and resource-efficiency-oriented framework (UNEP, 2021; OECD, 2022). The gap between these two systems makes it imperative to transition from a model that perceives e-waste as "pollution" to one that recognizes it as a high-value resource within a sustainable framework. As emphasized by Forti, Baldé, and Kuehr (2020), the future of e-waste management will be shaped by the transition from informal, labor-intensive activities to industrialized recycling infrastructures. Figure 37conceptually illustrates this transformation, revealing the evolution of the e-waste economy from a pollution-driven system into a resource-oriented structure.

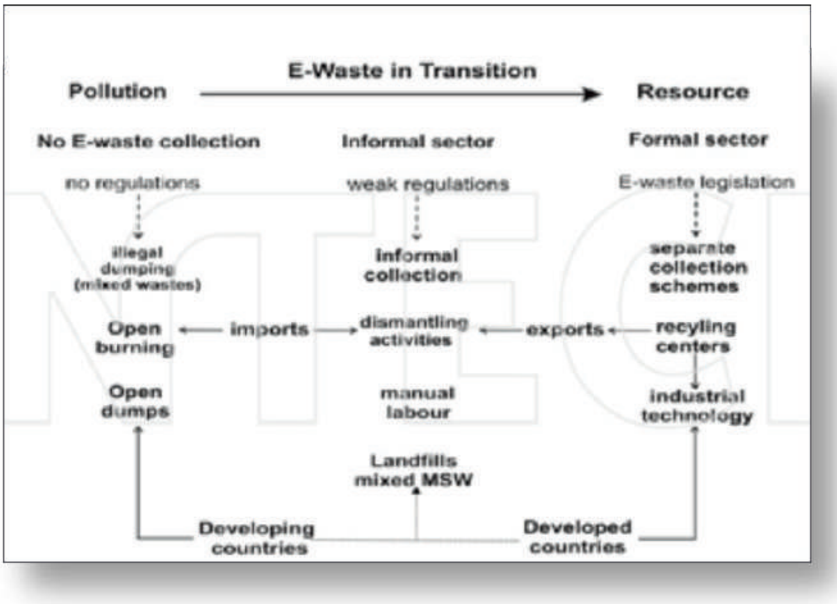

Figure 37 : Transition of the E-Waste System: From Pollution to Resource

Source: Mihai, F.-C. (Ed.) (2016). E-Waste in Transition: From Pollution to Resource. InTechOpen.

The technological waste economy holds significance not only in terms of environmental protection but also for its potential to generate substantial economic value. The total estimated value of recoverable materials—such as gold, silver, copper, cobalt, and rare earth elements—contained in e-waste amounts to approximately USD 57 billion annually (Forti et al., 2020).

Consequently, e-waste is often referred to as an "urban mine", positioned at the core of the circular economy framework (Zeng et al., 2023).

From a circular economy perspective, effective e-waste management encompasses not only recycling but also the processes of reduction (reduce), reuse, and remanufacturing. These approaches collectively enhance resource efficiency and foster sustainable transformation within global production and consumption systems (UNEP, 2021).

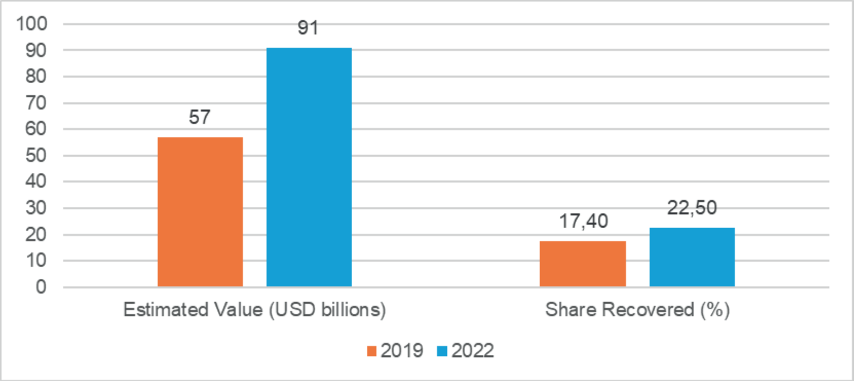

Figure 38 : Economic value of recoverable materials in global e-waste between 2019 and 2022

Source: UNITAR (2024). Global E-Waste Monitor 2024

The figure 38 illustrates the increase in the economic value of recoverable materials within global e-waste between 2019 and 2022. In 2019, the total value of recoverable raw materials was estimated at approximately USD 57 billion, rising to USD 91 billion by 2022. During the same period, the global recovery rate increased from 17.4% to 22.5%.

Digital technologies play a pivotal role in transforming the global e-waste economy. Artificial intelligence (AI)-based sorting systems, Internet of Things (IoT)-enabled sensor networks, big data analytics, and blockchain applications enhance traceability, transparency, and efficiency across waste management processes (Addas, Khan & Naseer, 2024). For example, blockchain-based supply chains document the entire journey of e-waste—from its origin to recycling facilities—thereby reducing illegal waste trade. Simultaneously, AI-driven classification technologies increase recycling efficiency and minimize material loss (UNEP, 2021). These advancements demonstrate that the technological waste economy is not merely an environmental policy domain but an integrated economic system where digital innovation and sustainable development converge (World Bank, 2023).

Looking ahead, the United Nations Sustainable Development Goals (SDG 12.4 and 12.5) call for the environmentally sound management of e-waste and the enhancement of recycling rates (UNEP, 2021). Achieving these objectives requires strengthened international policy coordination, improved data-sharing mechanisms, and enhanced financial support frameworks. In developing countries in particular, addressing infrastructure deficiencies, ensuring regulatory harmonization, and increasing public awareness are essential to establishing a sustainable global e-waste economy (World Bank, 2023).

Ultimately, the technological waste economy is characterized as a multi-layered system governing the complex interactions between production, consumption, technology, and the environment on a global scale. Digitalization functions as both the driving force and the solution mechanism of this system; thus, achieving a sustainable future depends on transforming the technological waste economy into an equitable, inclusive, and innovation-driven structure (OECD, 2022; UNEP, 2021).

4.3. The Technological Waste Economy in Turkey

In Turkey, the technological waste economy has rapidly evolved over the past two decades, driven by digitalization, urbanization, rising living standards, and shifts in consumption patterns. The widespread use of electronic devices, the growing ownership of smartphones and computers, and the digital transformation of the industrial and service sectors have significantly increased e-waste generation across the country.

As of 2020, Turkey produced approximately 847,000 tons of e-waste, ranking in the mid-range among European countries, with an estimated 10.1 kilograms of e-waste per capita (Forti, Baldé, Kuehr & Bel, 2020). Although this figure remains below the European average of 16 kilograms, it continues to rise annually in line with the country's accelerating pace of digitalization.

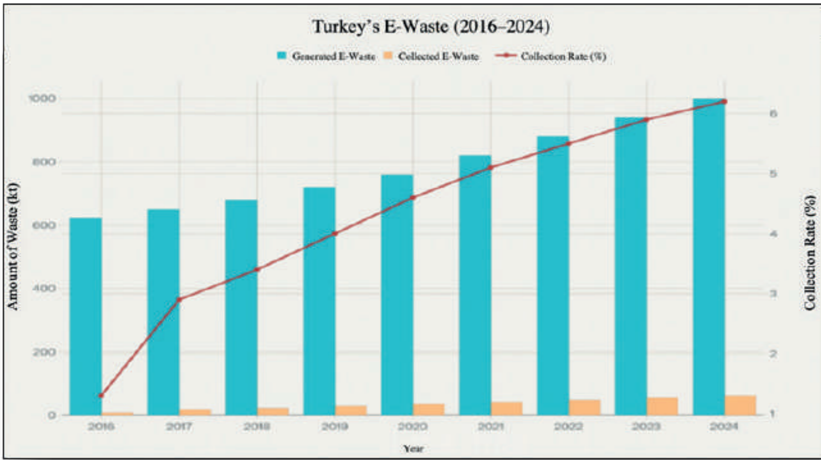

Figure 39 : Amount of E-Waste Generated and Collected in Turkey (2016–2024)

Source: TÜİK ,2024.

The figure 39 illustrates the annual changes in the quantities of e-waste generated and officially collected in Turkey between 2016 and 2024. The data reveal a steady increase in e-waste generation and a gradual, albeit limited, rise in official collection rates over the years.

For many years, e-waste management in Turkey remained fragmented; however, significant progress has been achieved since the 2010s in alignment with the European Union's environmental acquis. The Regulation on the Control of Waste Electrical and Electronic Equipment (AEEE Regulation), which entered into force in 2012, established the legal foundation for e-waste management in Turkey and introduced a framework consistent with the European Union's WEEE Directive (2012/19/EU) (Republic of Türkiye Ministry of Environment, Urbanization and Climate Change, 2023). The regulation introduced Extended Producer Responsibility (EPR) obligations for manufacturers and importers, governing the collection, transportation, recovery, and disposal of e-waste. In addition, environmental permitting and licensing systems were implemented to formalize and monitor these activities.

Institutionally, e-waste management in Turkey operates as a shared responsibility system among municipalities, Producer Responsibility Organizations (PROs), licensed recycling firms, and environmental agencies. Municipalities are responsible for the collection of e-waste from households and businesses, while producers bear the financial and recycling-related costs. Despite this regulatory framework, the overall efficiency of the system remains below the desired level. According to TÜİK (2022) data, only 12–15% of Turkey's annual e-waste is collected through official channels, while the remainder is handled informally. The main reasons for this low rate include unregistered collection activities, low public awareness, and regional disparities in recycling infrastructure (OECD, 2022).

Table 31 : Indicators Related to E-Waste Management in Turkey (2014–2030)

Year	Regulatory / Policy Framework	E-waste Generated (kt)	Per Capita (kg)	Formally Collected E-waste (t)	Collection Rate (%)
2014	Preparation phase before regulation	503	6,5		
2017	Implementation of EEE Waste Regulation; EPR introduced			19000	3
2020	Updated AEEE Regulation enforcement	847	10,1	67153	
2021	Shared institutional management (municipalities, PROs, recyclers)			52129	12,5
2022	Revision of AEEE regulation; start of digital monitoring systems	1000		62000	6,2
2025	National E-waste target (AEEE collection)				40
2030	EU Green Deal & Circular Economy alignment plans				65

Source: OECD, 2022

Table 31 summarizes the key indicators related to e-waste management in Turkey between 2014 and 2030. The data are evaluated based on the evolution of legislation, total e-waste generation, per capita e-waste levels, official collection rates, and national targets. The findings indicate that since the 2010s, Turkey has enhanced its institutional capacity in line with the European Union environmental acquis, yet official collection rates remain limited. The targets set for 2025 and 2030, aligned with circular economy and Green Deal policies, foresee a gradual increase in e-waste collection rates.

The informal sector holds a substantial share within Turkey's e-waste economy. In major metropolitan areas such as Istanbul, Ankara, Izmir, and Bursa, informal collection and dismantling activities are widespread alongside licensed facilities. While these activities provide short-term employment opportunities, they pose significant risks to both the environment and public health. Heavy metal leakage, open burning practices, and improper waste storage threaten environmental sustainability (UNEP, 2021). Consequently, the formalization of Turkey's e-waste economy and the strengthening of environmental policies and enforcement mechanisms are imperative.

From an economic standpoint, the e-waste sector in Turkey has emerged as a rapidly expanding sub-sector of the circular economy. According to TÜBİTAK (2021) data, the e-waste recycling industry generates an annual economic value of approximately USD 200 million and provides direct employment for over 5,000 individuals. However, this figure represents only about one-third of its full potential. The majority of collected e-waste consists of low-value materials, and the recovery rate of precious metals remains limited. In particular, the extraction of strategic metals such as gold, silver, copper, and cobalt has not yet reached the desired level due to insufficient technological investment and R&D capacity (Zeng, Li & Stevels, 2023).

Table 32 : Economic Indicators and Informality Share in Turkey's E-Waste Sector

Indicator	Value / Rate	Year	Source
Total e-waste generated	1,000,000 tons	2022	TURKSTAT (2022)
Officially collected e-waste	120,000 tons	2022	MoEU (2023)
Informally collected e-waste	≈ 880,000 tons	2022	TURKSTAT (2022)
Official collection rate	12%	2022	OECD (2022)
Economic value of the sector	USD 200 million / year	2021	TÜBİTAK (2021)
Direct employment	>5,000 persons	2021	TÜBİTAK (2021)
Recovery rate of valuable metals	Below 30%	2021	Zeng et al. (2023)

Source: TÜBİTAK (2021); TURKSTAT (2022); OECD (2022); Zeng, Li & Stevels (2023); UNEP (2021)

The table 32 presents the economic scale, employment impact, and informality share of Turkey's e-waste sector. The data indicate that the informal sector continues to maintain a significant presence, while official collection rates reflect only a limited share of the sector's full economic potential.

In recent years, Turkey has launched several initiatives aimed at improving e-waste management through digitalization and smart technology applications. Collaborations between municipalities, private enterprises, and universities have led to the development of smart waste collection systems, sensor-based container monitoring networks, AI-assisted sorting lines, and blockchain-based waste tracking platforms (Addas, Khan & Naseer, 2024). Pilot projects implemented in cities such as Istanbul, Konya, Gaziantep, and Kocaeli have enhanced collection efficiency, cost optimization, and traceability (World Bank, 2023). In addition, digital platforms integrated into the e-Government (e-Devlet) infrastructure guide citizens to e-waste drop-off points, contributing to higher levels of public awareness.

A major milestone in Turkey's environmental policy is the National Waste Management and Action Plan (2023–2030), which establishes goals for resource efficiency, waste reduction, recycling, and digital traceability in line with circular economy principles (Republic of Türkiye Ministry of Environment, Urbanization and Climate Change, 2023). Moreover, the Green Deal Action Plan (2021) aims to align Turkey with the European Green Deal (EU Green Deal) by promoting a transition toward a carbon-neutral and resource-efficient production system, recognizing e-waste management as one of the country's strategic priority areas (Republic of Türkiye Ministry of Trade, 2021).

Nevertheless, several structural challenges persist within Turkey's technological waste economy. Key issues include low collection rates, the large size of the informal sector, limited technological recycling capacity, gaps in the enforcement of existing legislation, and insufficient environmental awareness among the public (OECD, 2022; UNEP, 2021). Furthermore, the heavy reliance of e-waste management on the budgetary capacities of local governments restricts financial sustainability. In this context, enhancing private sector participation, promoting public–private partnership (PPP) models, and expanding the use of green finance instruments are essential for advancing Turkey's technological waste economy (World Bank, 2023).

4.4. Digitalization in Waste Management: AI, IoT, Blockchain, and Big Data

Digitalization represents one of the most significant structural transformations in waste management over the past decade. Traditional waste management approaches largely relied on manual operations, human labor, and limited data analysis. These systems often exhibited low operational efficiency, substantial resource waste, and considerable environmental impact. However, the rapid advancement of digital technologies—including Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, and big data analytics—has transformed waste management into a data-driven, predictive, and sustainable system (Addas, Khan & Naseer, 2024).

This transformation, supported by the digitalization of environmental policies, contributes directly to resource efficiency, carbon reduction, and the achievement of circular economy objectives (UNEP, 2021).

Table 33 : Applications of Digital Technologies in Waste Management (AI, IoT, Blockchain, Big Data): Policies, Pilots, and Quantified Impacts

No	Technology	Application / Use-case	Jurisdiction / Program	Year(s)	Indicator / Outcome	Notes	Source
1	IoT (RFID PAYT)	Food-waste smart bins with RFID & scales	Seoul Metropolitan Gov. (Pay-as-you-throw)	2010s	-40% waste amount; +100% recyclables collected	City evaluation after rollout	Seoul Solution (UNOSD, 2021)
2	IoT (Smart bins + compaction)	Solar smart-litter bins (city pilot □ rollout)	Dún Laoghaire–Rathdown (Dublin, IE)	2017–2018	-85% reduction in bins emptied daily (1st 12 months)	National Oversight & Audit Commission best-practice deck	NOAC (2018)
3	IoT (Smart bins, GIS tagging)	Citywide tagging & deployment metrics	Dublin City Council	2021	KPI tracked: # smart bins added; reduction in collections (ongoing)	Climate Action progress report	Dublin City Council (2021)
4	IoT + Analytics	Real-time sewer overflow monitoring	Hawthorne, CA (US)	2025	≈ $2 million avoided fines/ mitigation	US EPA "Smart Sewers" case	US EPA (2025)
5	Blockchain (Digital Product Passports)	Traceability for batteries & other products	EU (EC/EU Blockchain Observatory)	2024–	Lifecycle tracking & compliance (policy instrument)	Supports circularity & end-of-life mgmt.	EU Blockchain Observatory (2024)
6	Big Data / Digital Tracking	Mandatory Digital Waste Tracking service	UK (DEFRA)	2025–2026	National rollout timetable (receiving sites focus)	Gov policy pages (updates in 2025)	GOV.UK (2025)
7	Big Data (Global platform)	GWMO 2024 Data Platform	UNEP / ISWA	2024	Open datasets for MSW generation, costs, scenarios	Evidence-based policy foundation	UNEP (2024)
8	IoT (adoption baseline)	Enterprise use of smart devices/IoT	OECD measurement (Brazil example)	2021	14% of enterprises use IoT; 21% among large firms	Context for digital readiness	OECD Digital Economy Outlook (2023)
9	System performance baseline	Recycling rates (EU-27)	EEA indicator	2022	Packaging 65%; Municipal 49%; E-waste 32%	Benchmark for digital impacts	EEA (2022)

10	IoT + Policy (PAYT & data capture)	National waste-data & PAYT scheme	Republic of Korea (national case)	2010s	Mandatory bags; IoT/weight-based charging	UNOSD case deck	UNOSD (2021)
11	Digital enforcement tools	Technology for better enforcement (waste flows)	OECD (Env. Working Paper)	2024	Framework for digital tools vs. waste crime	Policy levers (not official OECD view)	OECD (2024)
12	Global evidence base	Global Waste Management Outlook	UNEP (GWMO 2024)	2024	Updated global waste generation & cost trajectories	Macro indicators & trends	UNEP (2024)

Source: Seoul Metropolitan Government (2021);NOAC (2018);Dublin City Council (2021);US EPA (2025);EU Blockchain Observatory (2024);DEFRA (2025);UNEP (2024);OECD (2023, 2024);EEA (2022);UNOSD (2021).

Table 33 demonstrates how the integration of digital technologies into waste-management processes has taken shape across different countries through measurable indicators. It comparatively presents the contributions of Internet of Things (IoT), blockchain, big data, and artificial intelligence (AI) applications to operational efficiency, resource utilization, carbon-emission reduction, and circular-economy objectives.

Among these, IoT-based systems represent the most widespread form of digital transformation in waste collection and monitoring. In South Korea's Pay-As-You-Throw (PAYT) model, smart containers equipped with RFID sensors have achieved a 40 % reduction in food waste and a 100 % increase in recyclable materials. Similarly, solar-powered smart bins introduced in cities such as Dublin and Seoul have reduced collection frequency by up to 85 %, generating substantial savings in both labor and carbon emissions. These findings demonstrate that IoT technologies have become a strategic instrument for data-driven decision-making and operational optimization in waste management.

Blockchain technology enhances transparency in recycling processes—particularly for batteries, electronic devices, and hazardous waste—through product-lifecycle traceability and digital product passports. Within the European Union, Digital Product Passport initiatives have evolved into a regulatory tool aimed at strengthening compliance and reducing illegal waste movements.

Big-data analytics and digital monitoring systems provide a comprehensive oversight mechanism at the policy level. The UK Department for Environment, Food and Rural Affairs (DEFRA) has implemented the Digital

Waste Tracking Service (2025–2026), enabling nationwide digital tracking of waste flows and offering an evidence-based foundation for environmental taxation policies. Likewise, the UNEP Global Waste Management Outlook (2024) established the GWMO Data Platform, which supplies open data on global waste volumes, costs, and carbon impacts—thereby deepening the analytical basis for scientific research.

Indicators from the OECD and the European Environment Agency (EEA) included in the table underscore that digital transformation is not only technical but also institutional and statistical in nature. According to OECD data, 14 % of enterprises actively use IoT-based devices, a figure rising to 21 % among large firms. In the European Union, as of 2022, 65 % of packaging waste, 49 % of municipal waste, and 32 % of electronic waste were recycled. These ratios confirm that the growing adoption of digital technologies has markedly improved performance indicators in modern waste-management systems.

The integration of digital technologies into waste management systems exerts a multi-layered impact across all stages—from production and consumption to final disposal. Artificial intelligence (AI) enables the automated classification of waste through image recognition and machine-learning algorithms, thereby reducing human error and significantly increasing recycling efficiency. Systems based on deep-learning models can distinguish among materials such as plastics, metals, glass, and paper with an accuracy rate of up to 95 % (Chen, Yu & Huang, 2023). This development has established a digitally grounded foundation for the waste economy, enhancing both economic efficiency and environmental quality. In Turkey, AI-based sorting systems have recently been implemented on a pilot scale in cities such as Istanbul, Konya, and Gaziantep, where they have reduced municipal operational workloads and improved material recovery rates (Republic of Türkiye Ministry of Environment, Urbanization and Climate Change, 2023).

The Internet of Things (IoT) constitutes another core component of the digital transformation in waste management. IoT technology employs sensor-enabled containers that measure fill levels as well as physical conditions such as temperature and humidity in real time, transmitting these data to cloud-based platforms for the optimization of waste-collection processes (Addas et al., 2024). This allows municipalities to dynamically plan collection routes, reduce fuel consumption, lower carbon emissions, and achieve cost savings of 20–30 % (World Bank, 2023). Beyond improving efficiency, these systems also enable the early detection of environmental risks. In hazardous-waste management, for example, IoT-based sensors make it possible to identify leaks, gas emissions, or fire hazards in advance (OECD, 2022). Within Turkey's Smart Waste Management Platform projects, IoT-based solutions have been increasingly adopted by both public institutions and the private sector.

Blockchain technology stands out as one of the most transformative innovations that digitalization has introduced into waste management. By storing data in immutable digital ledgers, blockchain enables the full traceability of waste flowsfrom the point of generation to recycling facilities (Teng, Zhang & Li, 2022). This system ensures transparent monitoring of waste movements, prevents illegal trafficking, and strengthens the implementation of the Extended Producer Responsibility (EPR) principle. The European Union's "CircularChain" initiative serves as a leading example in this field, while in Turkey, the National Waste Management Plan (2023–2030) developed by the Ministry of Environment, Urbanization and Climate Change includes ongoing efforts to establish blockchain-based monitoring infrastructures(Republic of Türkiye Ministry of Environment, Urbanization and Climate Change, 2023).

Big data analytics facilitates the incorporation of digital waste management systems into strategic decision-making processes. Millions of data points—covering waste-generation volumes, collection frequencies, recycling rates, population density, and consumption patterns—are analyzed through big-data algorithms, enabling the creation of city-level digital-twin models (Kumar, 2023). Through these digital replicas, urban waste-generation trends can be predicted, infrastructure investments can be planned in advance, and environmental impacts can be mitigated. Thus, big-data technology functions not merely as an administrative tool but as a core component of policy design and long-term environmental planning.

As summarized in Table 4.2, the integration of digital technologies into waste-management systems has yielded quantifiable economic and environmental improvements across diverse contexts.

Table 34 : Economic and Environmental Impacts of Digital Technologies on Waste Management (AI, IoT, Blockchain, Big Data)

Technology	Application Area	Country / Example Program	Period	Key Indicators	Economic Impact	Environmental Impact
Artificial Intelligence (AI)	Image recognition and automated waste classification	China / Smart Sorting Systems	2023	95% accuracy rate; reduction in human error	Lower labor costs, higher efficiency	Increase in recycling rate
Artificial Intelligence (AI)	Pilot smart sorting systems	Türkiye (Istanbul, Konya, Gaziantep)	2022–2023	Reduction in operational burden; increase in material recovery	Lower municipal costs	Higher resource efficiency
Internet of Things (IoT)	Sensor-based containers and fill-level monitoring	South Korea / PAYT Model	2010–	40% waste reduction; 100% increase in recyclables	20–30% reduction in collection costs	Decrease in carbon emissions
Internet of Things (IoT)	Hazardous-waste monitoring sensors	OECD Countries	2022	Early detection of environmental risks	Reduced insurance and maintenance costs	Decrease in leakage and fire risk
Blockchain	Traceability of waste flows; EPR applications	European Union / CircularChain	2023–2030	Higher traceability and transparency	Prevention of logistics losses	Reduction in illegal waste transport
Big Data	Digital-twin modeling at city scale	India / Urban Planning Model	2023	Analysis of consumption trends and infrastructure needs	Improved planning efficiency	Higher precision in environmental impact analysis
Big Data	National waste-data analytics	Türkiye / Green Deal Strategy	2024–	Integration of decision-support systems	Better policy design efficiency	Improved prediction of waste generation
Digitalization (General Impact)	All digital technologies (AI, IoT, BD, BC)	OECD / UNEP Countries	2022	15% reduction in collection costs; 25% increase in recycling	Global cost optimization	Decrease in CO_2 emissions; growth of green jobs

Source: Chen, Yu & Huang (2023); Ministry of Environment (2023); Addas et al. (2024); World Bank (2023); OECD (2022); Teng, Zhang & Li (2022); EC (2023); Kumar (2023).

Table 34 presents a multidimensional overview of the economic and environmental impacts of digital technologies on waste management. It provides quantitative evidence illustrating how core digital tools—Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, and big data analytics—enhance operational performance and align with environmental sustainability indicators.

AI-based systems enable the automated classification of waste through image recognition and machine-learning algorithms, increasing accuracy rates in recycling processes up to 95 % (Chen, Yu & Huang, 2023). This advancement represents a critical step in the digital transformation of the waste economy, reducing labor costs and boosting operational efficiency. Pilot projects conducted in Istanbul, Konya, and Gaziantep have demonstrated that AI-supported sorting systems significantly reduce municipal workloads while improving material recovery rates (Republic of Türkiye Ministry of Environment, Urbanization and Climate Change, 2023).

The Internet of Things (IoT) represents one of the most widely applied components of digital waste management. Sensor-enabled container systems continuously monitor fill levels, temperature, and humidity, supporting data-based decision-making and optimizing collection routes. South Korea's "Pay-As-You-Throw (PAYT)" model stands as one of the most successful examples: the system achieved a 40 % reduction in total waste generation and a 100 % increase in recyclable material collection (World Bank, 2023). Moreover, it reduced carbon emissions and generated 20–30 % savings in collection costs.

Blockchain (DLT) technology enhances the traceability of waste flows, thereby helping to prevent illegal waste transportation. The European Union's "CircularChain" initiative enables transparent data recording throughout all stages—from producers to recycling facilities—ensuring full visibility across the system (Teng, Zhang & Li, 2022). This approach strengthens the implementation of the Extended Producer Responsibility (EPR) principle. In Turkey, within the framework of the National Waste Management Plan (2023–2030), policy initiatives have been introduced to establish blockchain-based monitoring infrastructures.

Big data analytics serves as another key component guiding strategic decision-making in waste management. Big-data algorithms analyze millions of data points—such as waste-generation volumes, population density, collection frequencies, and consumption trends—to create digital-twin models of cities. These models allow policymakers to forecast waste-generation trends, plan infrastructure investments based on empirical data, and reduce environmental impacts (Kumar, 2023).

The table also incorporates comparative data from OECD (2022) and UNEP (2021), which indicate that digital waste-management practices reduce average waste-collection costs by approximately 15 % and increase recycling rates by up to 25 %. These findings demonstrate that digital technologies function not merely as operational tools but as value-generating components of an environmentally sustainable economic chain.

In summary, Table 34 reveals that the transformation driven by digital technologies in waste management is multidimensional, encompassing both economic efficiency and environmental performance. Digitalization has redefined waste management from a traditional environmental policy field into the foundation of a new "digital waste economy" paradigm—one that integrates green growth, circular economy, and decarbonization strategies.

The economic and environmental impacts of digitalization in waste management are increasingly evident both globally and within the Turkish context. According to OECD (2022) data, digital waste-management applications have reduced national waste-collection costs by an average of 15 %, while increasing recycling rates by up to 25 %. Simultaneously, the reduction of carbon emissions, optimization of resource utilization, and creation of new green employment opportunities have strengthened digitalization's contribution to the global economic value chain. The UNEP (2021)report estimates that integrating digitalization processes into environmental management could generate USD 1.2 trillion in global investment opportunities by 2030. In Turkey, ongoing AI-, big-data-, and IoT-based projects are being developed in alignment with Green Deal objectives, supporting the country's long-term circular economy vision.1

CHAPTER 5

Findings, Discussion, and Conclusions

5.1. Summary of Findings

The findings of this study demonstrate that sustainable development and the waste economy constitute interdependent pillars of contemporary economic systems. The equilibrium between economic growth and environmental sustainability has become a decisive factor shaping modern development strategies. Global data from 2020 to 2023 indicate that, although CO_2 emissions have continued to rise, the share of renewable energy and municipal waste recycling rates have shown a gradual upward trend. These developments signal an ongoing structural transition toward greener economies, yet the overall progress remains insufficient to fully mitigate escalating environmental pressures.

In the context of Turkey, despite steady increases in per capita income, key indicators related to waste managementand renewable energy utilization remain below the OECD average. The analysis reveals that Turkey's advancement toward sustainable development is constrained by institutional capacity limitations, regional imbalances, and high capital investment requirements. Nevertheless, policy efforts—such as the nationwide "Zero Waste Project" and the growing implementation of circular economy principles—reflect tangible progress in environmental performance and societal awareness, marking important steps toward the integration of sustainability within the national development agenda.

Waste has been recognized as a multidimensional phenomenon encompassing environmental, economic, and social dimensions simultaneously. Rapid population growth, industrialization, and urban expansion have collectively accelerated the generation of waste, producing both new employment opportunities and fiscal pressures on municipalities. Global projections indicate that municipal solid waste (MSW) volumes will increase by nearly 70% by 2050, while recycling rates remain critically low. Among the various waste categories—household, medical, hazardous, industrial, construction, and electronic—each poses unique yet interconnected challenges. The sharp rise in electronic waste (e-waste) highlights the environmental externalities of digitalization. In 2019, global e-waste generation reached 53.6 million tons, with only 17.4% officially recycled, underscoring both the significant potential and systemic inefficiencies within the sector.

At the national level, Turkey produces approximately 32.4 million tons of municipal waste annually, equivalent to around 386 kilograms per capita. The total waste volume reached 109.2 million tons in 2022, with 27% classified as hazardous. The manufacturing sector, particularly basic metals and chemical industries, accounts for over two-thirdsof industrial waste generation. Meanwhile, urbanization dynamics have further intensified these patterns: more than 93% of Turkey's population now lives in urban areas, and the volume of municipal solid waste has risen by nearly 90% between 2003 and 2023. This trajectory demonstrates how industrial structure and urban expansion interact to define the country's evolving waste profile.

The findings further indicate that waste management has evolved into one of the world's fastest-growing economic sectors. The global waste-management market is projected to reach USD 2.4 trillion by 2033, with industrial wasteaccounting for more than 70 percent of total costs. While municipal, medical, and electronic waste markets are smaller in scale, they are gaining substantial economic significance through value recovery, material reuse, and technological integration.

Digitalization has emerged as a transformative driver in the evolution of the waste economy. Advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, and big-data analytics are reshaping waste-management systems by enhancing traceability, reducing operational expenditures, and optimizing recycling efficiency. Empirical findings reveal that IoT-based collection systems can lower costs by 20–30 percent, while AI-assisted sorting technologies can increase recycling rates by up to 25 percent. These results confirm the strong synergy between digital transformation, circular-economy objectives, and green-growth strategies.

In Turkey, however, the digital waste sector remains in an early stage of development. Official e-waste collectioncovers only about 12 percent of the roughly 1 million tons generated annually. Nonetheless, pilot projects in major cities—such as Istanbul, Konya, and Gaziantep—have demonstrated the potential of digital tracking systems to enhance efficiency, transparency, and regulatory compliance. Scaling these systems to a national level would substantially advance Turkey's alignment with the European Green Deal and the United Nations Sustainable Development Goals.

Taken together, the results suggest that the modernization of the waste economy—through digital integration, institutional coordination, and policy innovation—constitutes a strategic pathway toward sustainable growth. Waste is no longer a passive by-product of economic activity but a quantifiable component of national wealth, environmental governance, and technological progress.

5.2. Interpretation and Discussion

The analyses indicate that sustainable development cannot be confined to environmental indicators alone; rather, it requires establishing a reciprocal balance among economic growth, technological innovation, and societal awareness. The findings further reveal that in Turkey and similar developing economies, economic growth continues to coincide with mounting environmental pressures—making green growth and carbon-neutral development strategies an urgent necessity. In particular, the rise in recycling rates across the European Union demonstrates the decisive role of regulatory frameworks and institutional capacity in achieving environmental success.

The waste economy clearly illustrates the extent to which environmental sustainability and economic growth dynamics are intertwined. Waste management has evolved beyond a disposal-oriented process into a strategic sectorthat promotes resource efficiency, job creation, and financial sustainability. However, the diverse risk profiles of waste categories necessitate differentiated policy and management instruments. The irregular disposal of household waste contributes to higher greenhouse gas emissions; industrial and hazardous wastes generate long-term toxic impacts; and medical waste—particularly during the pandemic period—has imposed severe strains on public health systems. These realities underscore the need for an integrated and interdisciplinary approach to waste management that unites environmental, economic, and technological dimensions within a cohesive sustainability framework.

Global data reveal a strong correlation between income levels and waste generation. In high-income countries, per capita waste production is more than three times higher than in low-income nations; however, these countries also exhibit higher recycling rates and greater levels of environmental awareness. This contrast demonstrates that economic development is not merely a process of increasing production volume but one that also shapes environmental consciousness and technological capacity.

In the case of Turkey, urbanization, industrialization, and population growth act as mutually reinforcing factors that are reshaping the waste economy. Rising population density, consumption levels, and economic activity have simultaneously placed pressure on municipal services and turned the waste sector into a rapidly expanding economic domain. Yet, the concentration of population in metropolitan areas has deepened spatial inequalities, making infrastructure and environmental investments increasingly essential. The fact that nearly all municipalities in Turkeynow provide waste-management services reflects a notable expansion in governance capacity; nevertheless, financial sustainability continues to represent a major structural challenge.

Economic data indicate that the fluctuating growth conditions between 2015 and 2024 have constrained environmental investment. Industrial waste—particularly from the metal and chemical sectors—accounts for more than two-thirds of total industrial waste, underscoring that the environmental impacts of structural transformation in production have not yet been fully managed. Nonetheless, the recent expansion in the capacity of recovery and recycling facilities demonstrates Turkey's gradual alignment with the European Union's circular economy policies. The interdependence between urbanization and the waste sector presents both opportunities and risks for sustainable development: while urbanization drives the increase in waste generation, the waste economy, in turn, fosters economic growth through new employment opportunities and investment channels.

Digital technologies have emerged as the transformative force behind this transition. Artificial intelligence (AI), the Internet of Things (IoT), blockchain, and big-data analytics not only optimize waste-management systems but also establish a new economic paradigm that integrates resource efficiency, data-driven governance, and sustainable growth principles. The fact that electronic waste simultaneously contains high-value metals (such as gold, silver, and cobalt) and toxic substances (such as lead, mercury, and cadmium) illustrates how digitalization embodies both opportunity and risk. This duality positions the technological waste economy as a "dual-impact domain"—one that generates economic potential while simultaneously deepening environmental responsibilities.

Digital waste management in Turkey is still in its developmental stage; however, pilot projects implemented in cities such as Istanbul, Konya, and Gaziantep demonstrate that AI-supported monitoring systems have significantly improved operational efficiency. These advancements indicate that Turkey can achieve its Green Deal objectives and circular economy vision through digital transformation.

Ultimately, the success of sustainable development depends on the simultaneous advancement of technology, the economy, and governance. The integration of digitalization with environmental policy will not only enhance economic resilience but also reduce environmental costs, thereby accelerating Turkey's green transformation process.

5.3. Policy Recommendations for Turkey and Beyond

Strengthening sustainable development and the digital waste economy in Turkey requires more than technical solutions; it demands a holistic and long-term governance framework. The findings demonstrate that environmental sustainability, economic competitiveness, and digital transformation must be treated as complementary and mutually reinforcing dimensions. To ensure the effectiveness of policies at both national and global levels, it is imperative to simultaneously enhance institutional capacity, financial sustainability, and international cooperation mechanisms.

First and foremost, strengthening institutional and digital capacity forms the foundation of a sustainable waste-management system. The widespread adoption of data-based monitoring platforms, sensor-supported collection technologies, and AI-driven predictive models within local governments will improve cost efficiency and promote standardization in service quality. In this context, reinforcing inter-municipal coordination mechanisms and advancing the technical capacity of municipal personnel are of critical importance.

Second, the circular economy legislation and regulatory framework must be updated and modernized. In alignment with the European Union's Circular Economy Action Plan, Turkey should establish binding national targets for recycling, reuse, and resource-efficiency indicators. The Extended Producer Responsibility (EPR) principle must be implemented effectively across all sectors, while the development of blockchain- and IoT-based digital infrastructuresensuring waste-flow traceability should be actively promoted.

Third, the diversification of green financing mechanisms and investment models is of critical importance. Through public–private partnerships (PPPs), long-term capital inflows should be directed toward waste-management infrastructure, and instruments such as green bonds, carbon credits, and sustainable investment funds should be utilized effectively. Supporting e-waste recycling, renewable-energy, and digital-infrastructure projects through these financial instruments will facilitate Turkey's integration with the European Green Deal objectives.

Fourth, enhancing public awareness is an indispensable prerequisite for the success of sustainable policies. Integrating themes such as environmental economics, resource efficiency, and digital transformation into educational curricula, alongside awareness campaigns conducted through media and civil society organizations, will foster behavioral change among consumers—encouraging waste reduction, reuse practices, and a broader culture of sustainability.

Fifth, addressing regional disparities must be prioritized to ensure equitable and sustainable waste management. In regions with limited infrastructure capacity—particularly Eastern and Southeastern Anatolia—investments should be directed toward the development of waste collection and recycling facilities. This approach will not only promote environmental justice but also expand opportunities for green employment and regional development.

Finally, international cooperation and knowledge exchange will strengthen Turkey's role in the global sustainability agenda. Collaborative initiatives should be pursued with organizations such as the OECD, UNEP, the European Environment Agency (EEA), and the European Commission. Active participation in technology transfer, data-sharing mechanisms, and green innovation networks will enable Turkey to evolve from being merely a policy implementer to a policy-shaping actor in the international sustainability landscape.

Overall, these policy recommendations aim to support Turkey's sustainable development by integrating its digital transformation with the objectives of the green economy, encompassing economic, environmental, and social dimensions. Such a strategic framework would enable the country to reduce environmental costs while simultaneously enhancing global competitiveness, thereby accelerating the transition toward a low-carbon and circular economic model.

5.4. Conclusions

The general findings indicate that the environmental, economic, and technological dimensions of sustainable development cannot be treated in isolation. The waste economy lies at the intersection of these three pillars, and when integrated with resource efficiency, renewable energy, and digital transformation, it becomes possible to sustain economic growth while minimizing environmental impacts. For Turkey, ensuring coherence between digital transformation and sustainable development policies has emerged as a strategic necessity for achieving green growth objectives.

This study demonstrates that waste management is not merely an environmental obligation but also a strategic sector with significant implications for economic growth, employment generation, and technological innovation. The findings show that when circular economy practices, digital technologies, and green financing instruments are applied synergistically, waste can be transformed into a valuable economic asset. Such a transformation would not only enhance resource efficiency but also reduce environmental costs, thereby strengthening sustainable production and consumption models.

Urbanization dynamics have become a decisive factor in shaping the development of Turkey's waste economy. Rising population levels and industrialization have dramatically increased municipal waste volumes, while simultaneously turning the waste sector into a new field of employment and investment-driven growth. However, environmental pressures in highly industrialized regions reveal the need for a comprehensive strategic framework to achieve Turkey's green transition goals. In this regard, establishing a delicate balance between economic growth, environmental protection, and digital transformation will form the foundation of sustainable urban economies in the future.

The digital waste economy represents one of the most critical transformation areas of the 21st century. The results reveal that digitalization has turned waste management into a data-driven, traceable, and cost-efficient system, while also generating a new economic paradigm. Yet, sustaining this transformation depends on regulatory harmonization, financial sustainability, and strengthening institutional capacity. To the extent that Turkey succeeds in integrating its digital infrastructure with green economy policies, it will both enhance its global competitiveness and advance toward carbon-neutral development objectives.

Ultimately, waste is no longer a mere environmental burden, but a strategic resource capable of generating economic value when managed effectively. Embracing this vision will unite environmental protection, economic growth, and digital innovation within a single sustainable framework—forming the foundation of the green and digital economy of the future.

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