

Research Paper

Advancing Sustainable Waste Management through National Recycling Rate under SDG 12.5.1

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Abstract. Solid waste management remains a pressing environmental challenge in both developed and developing nations. Recycling has been promoted globally as a key pathway to sustainability, yet recycling rates often provide only a partial picture of performance. In many contexts, challenges such as poorly regulated recycling policies, informal sector dominance, and practices that prioritize profit over environmental sustainability limit progress towards Sustainable Development Goal (SDG) 12.5.1, which tracks the national recycling rate. This study investigates the extent to which recycling rates reflect sustainable waste management and identifies the underlying factors that influence their effectiveness. The major objective of this study is to evaluate recycling rates as an indicator of sustainable waste management. This is further specified by: (i) examining recycling practices in selected countries (Germany, South Korea, USA, Brazil, and India), (ii) identifying key drivers and barriers that influence recycling performance, and (iii) assessing the implications of recycling rates for sustainable waste management systems. The study employed a mixed-methods approach, combining secondary data analysis, comparative country assessment, and policy review. Results show that recycling rates are useful but insufficient as a stand-alone measure of sustainability, since they are influenced by broader elements such as policy enforcement, economic incentives, public participation, and market structures. The findings highlight that Nigeria's recycling rate remains significantly low compared to leading economies, underscoring the need for integrated waste management reforms. This research contributes to environmental management discourse by demonstrating that while recycling rates provide a benchmark for SDG 12.5.1 monitoring, they must be interpreted alongside contextual drivers to ensure meaningful progress towards sustainable waste management.

Keywords: Sustainable Waste Management, National Recycling Rate, SDG 12.5.1, Circular Economy, Waste Policies, Recycling Trends

1. Introduction

Effective waste management is one of the key pillars of global sustainability initiatives [1]. Waste generation is on the rise owing to growing urbanization, industrialization, and population growth, necessitating an effective waste management strategy and its implementation towards minimizing the degradation of natural resources [2], [3]. Goal 12: Ensure sustainable consumption and production patterns; specifically, target 12.5 is about waste generation and the prevention, reduction, recycling, and reuse of waste related to sustainability. SDG Indicator 12.5.1 defines a national recycling rate as a

key parameter of sustainable waste management progress. This is where the implementation of circular economy (CE) (Figure 1) principles starts becoming important, as SDG 12.5.1 expresses the need for resource efficiency and proper waste disposal alternatives, avoiding landfills and incineration [2]. In order to have higher recycling rates, and increase the collection efficiency rate and improve the waste management infrastructure, many countries are developing policies and programs [4], [5]. Despite this, waste management initiatives continue to be hampered by serious problems such as poorly regulated recycling businesses, informal sector dominance, and practices that prioritize profit over environmental sustainability, minimal public involvement, lack of regulatory compliance and little knowledge of recycling compliance [6], [7].

Many research examines case studies to highlight global best practices and the challenges of achieving higher recycling rate. Waste management is still one of the most pressing environmental issues in many countries, with pollution, greenhouse gas emissions and the loss of valuable resources due to inadequate disposal. Although the national recycling rate is an important metric in sustainable waste management, many countries fight to make progressive steps because of systemic immaturities and political loopholes [8-10]. Recycling rates are widely used as a benchmark for progress in waste management under SDG 12.5.1. However, they often present a narrow view, as they may increase even where recycling systems are environmentally unsound, poorly managed, or socially inequitable. The problem therefore lies in relying solely on recycling rates as defenders of sustainability, without considering the broader elements that determine their effectiveness, such as policy frameworks, market conditions, and public behavior. This gap forms the basis of this study. This study highlights the current limitations of waste management systems and outlines a path forward considering national recycling rates to incentivize sustainable waste management services. Such analysis will help understand the barriers and enablers to achieving higher recycling rates and will offer important recommendations for policymakers, waste management authorities, and environmental sustainability stakeholders.

The major objective of this research is to evaluate recycling rates as a reliable indicator of sustainable waste management under SDG 12.5.1.

The specific objectives are:

1. To compare recycling performance across selected countries (Germany, South Korea, USA, Brazil, and India).
2. To identify key drivers and barriers influencing recycling outcomes.
3. To assess implications of recycling rates for strengthening sustainable waste management systems globally.

The results will help inform policymakers, environmental agencies, and waste management practitioners regarding successful recycling strategies and areas for improvement through data-driven insights. Furthermore, the findings will promote public understanding of the significance of recycling and the role it plays in attaining sustainable development. This paper explores policies, infrastructure, technology, and public engagement efforts that play a role in recycling successes or failures. The review focuses only on secondary data sources, which included accounts from international organizations, governmental entities, and academic literature.

2. Literature Review

Waste management as an environmental issue on a global scale is also relevant when it comes to Sustainable Development Goal (SDG) 12.5.1: Sustainable waste management refers specifically to waste management practices that minimize the negative effects of waste [11]. The national recycling rate, a metric that tracks recycling and composting over time, is an important measure of progress in the field of waste management, as it reflects the effectiveness being achieved in a country's move toward a circular economy. Recycling can reduce the negative impact of excessive waste on the environment, promote resource efficiency, save energy, and boost the economy [7]. Sustainable waste management follows the principles of the circular economy, where the focus is on using materials for longer and extracting as much value as possible before products are recycled and regenerated at the end of their life cycle [12]. Legislation plays an important role in achieving national recycling rates: a comprehensive legal framework for waste, well-developed waste management infrastructure, and awareness campaigns to encourage sorting and participation in recycling schemes lead to high recycling rates [13].

2.1. Theoretical Frameworks and Models

Sustainable waste management is underpinned by several theoretical models, including the circular economy, waste hierarchy, Extended Producer Responsibility (EPR), Life Cycle Assessment (LCA), and Behavior Change Theories. These frameworks guide policy development and implementation strategies to improve recycling rates globally [8], [11].

2.1.1. Circular Economy

The Circular Economy (CE) is a broad conceptual framework for a holistic approach to building a good-for business, society, and the environment economic system. The CE attempts to reduce waste and produce the maximum value by closing material loops and rejuvenating natural systems [14]. Unlike the traditional linear economy with a "take-make-dispose" approach, the CE is concerned with waste design out, product and material keeping in use, and natural system restoration. These are practices such as extending product life, material recovery, and industrial symbiosis that are employed in using principles of CE in waste management. These practices have been put into practice in reducing the consumption of primary resources and environmental pollution. These three fundamental principles of CE as proposed by the Ellen MacArthur Foundation (2013) [15] are those that are mostly driving the current trend towards promoting recycling and responsible waste systems.

2.1.2. Waste Hierarchy Model

The priority of the University of Edinburgh Waste Strategy is given to waste prevention, before reuse, recycling, recovery (e.g., energy), and disposal (e.g., landfill) [16]. The model is used by governments and organizations to establish policies and plans to prevent waste initiation and further waste production. The Waste Hierarchy is a principle in waste management that promotes reducing waste at its source, so less waste is generated and less waste treatment is required. Because recycling generates fewer greenhouse gas emissions and uses fewer natural resources than landfilling, the model rewards recycling [17].

2.1.3. *Extensive Producer Duty (EPR)*

Extended producer responsibility (EPR) is an environmental policy that holds producers responsible for the financial or physical treatment and disposal of end-of-life products [18]. Extended producer responsibility (EPR) aims to encourage producers to create more sustainable and recyclable products and hold them accountable for their products from the cradle to the grave. Extended Producer Responsibility (EPR) systems have been adopted across a range of industries, such as electronics, packaging, and automotive sectors, to facilitate waste minimization and boost recycling rates. This shift in responsibility for waste management from municipalities to manufacturers encourages innovation in sustainable product design and materials management [19].

2.1.4. *Life Cycle Assessment (LCA)*

Life Cycle Assessment (LCA) is a methodological approach developed to evaluate a final product, process, or service throughout its life cycle, from raw material extraction to disposal [20]. LCA is widely used in waste management to assess the sustainability of different waste disposal/disposal alternatives, such as landfilling and incineration, and recycling options. By assessing environmental impacts, including greenhouse gas emissions, energy use, and resource depletion, LCA provides insights to decision-makers to help them choose the most environmentally preferable waste management options. It also supports CE principles by providing insights into ways to reduce environmental impacts at each stage of a product's life cycle [21].

2.1.5. *Behavior Change Theories*

Public attitudes and behavior are key to the success of recycling programs and other sustainable waste management. Several behavior change theories have been used to promote waste reduction and recycling behavior, including the Theory of Planned Behavior (TPB), the Norm Activation Model (NAM) [22], and Community-Based Social Marketing (CBSM) [23]. According to the TPB, behavior is affected by attitudes, subjective norms, and perceived behavioral control [24]. Factors influencing recycling participation: In terms of recycling participation, people will participate more in recycling if they believe recycling is beneficial (attitude), if they feel social pressure to recycle (subjective norms), and if they believe they have the capacity and resources to recycle (perceived control). The NAM emphasizes the importance of personal norms and a sense of moral obligation in predicting pro-environmental behavior [25]. It implies that people are more inclined to recycle if they feel responsible for it, particularly when they know what happens if they fail to act. This is a social marketing strategy that applies behavioral psychology in order to promote more sustainable behaviors (CBSM). It is about identifying barriers and benefits to a target behavior and leveraging tools like prompts, commitments, and social norms to pull behavior change [26].

2.1.6. *Towards Zero Waste: The Importance of National Recycling Rates*

The national recycling rate (an indicator under SDG 12.5.1) provides an indication of the effectiveness of a country's waste management efforts. Countries with favorable recycling rates tend to have robust policy measures in place, for example, Extended Producer Responsibility (EPR) schemes that make it mandatory for manufacturers to take responsibility for end-of-life products [19]. For example, Sweden has successfully combined EPR and Waste-to-Energy (WtE) policies, leading to recycling rates over 50%

[27]. However, developing countries generally have low recycling rates, resulting from a lack of infrastructure, financing, and enforcement [28]. In many cities, especially in Africa and South Asia, the waste recovery system relies on informal waste pickers who, while providing a valuable service in recovering recyclable materials, often do so outside the boundaries of government support and safety regulation [29]. The national recycling program's success, therefore, depends on multiple converging factors, including supportive government policies, technological innovations, and community involvement [30].

2.2. National Recycling Rates: Challenges & Opportunities

While the rewards for high national recycling rates are considerable, numerous obstacles stand in the way of their widespread adoption. An effective approach faces many obstacles, including economic constraints, limited awareness from the public, and technological limitations, especially in low-income countries [31]. In addition, volatility in the global markets for recyclable materials can challenge the financial sustainability of recycling programs and deter investment in waste processing infrastructure [32]. But more efficient methods of waste sorting, public-private initiatives, and innovations in policy are opening up avenues for deterring generalization of recycling rates around the world. Digital devices, including smart bins and AI-based waste separation, are proven to have the potential to enhance processes like waste collection and recycling [33]. Also, agreements made between nations as well as knowledge-sharing initiatives have allowed nations to form best practices to deal with waste management and recycling [34]. The national recycling rate is an important indicator for evaluating the sustainable waste management efforts. Although developed countries are making fast progress with systems and technologies based up to this date, developing countries are facing issues for which some strategic intervention is required. Through regulatory reinforcement, infrastructure investment, and by promoting public engagement, countries can improve recycling rates, contributing towards global sustainability objectives. Future research should explore innovative waste management strategies and policy mechanisms to further recycling and waste reduction [2], [11].

3. Materials and Methods

This study adopts a mixed-methods approach. Quantitative data were sourced from the UN SDG Global Database, OECD Waste Statistics, the World Bank, and Eurostat. Five countries were selected for comparative analysis: Germany, South Korea, the United States, India, and Brazil. Qualitative data were collected through policy document reviews and literature analysis. Quantitative analysis involved time-series evaluation of recycling rates (2010–2022) and GDP-recycling correlations. Qualitative analysis focused on policy effectiveness, stakeholder engagement, and institutional frameworks influencing recycling rates.

3.1. Research Design and Framework

The research follows an exploratory and comparative design. It seeks to identify patterns and differences in national recycling rates and waste policies. The selection of countries was based on

geographic diversity, income level, recycling performance, and data availability. The five case countries - Germany, South Korea, the United States, Brazil, and India - represent a broad spectrum of development and waste management maturity. The framework used to guide the research integrates the circular economy, SDG 12.5.1 metrics, and institutional and behavioral theories. This approach allows for a comprehensive analysis of how various components - policy, behavior, infrastructure, and governance - interact to influence recycling performance.

3.1.1. Data Collection Methods

The research used secondary data sources for both qualitative and quantitative analysis. Quantitative data were extracted from the following databases: UN SDG Global Database, OECD Waste Statistics, Eurostat, and World Bank Open Data. These sources provided consistent indicators on national recycling rates, waste generation per capita, and economic performance. Data ranged from the years 2010 to 2022 to allow trend analysis.

Qualitative data were collected through:

- National waste policy documents and legislation
- Reports by UNEP, OECD, and the Ellen MacArthur Foundation
- Peer-reviewed academic studies focused on SDG 12.5.1 and circular economy practices.

3.1.2. Data Analysis Techniques

The data analysis process included:

- Time series analysis of recycling rate performance (2010–2022)
- Comparative policy analysis among the five countries
- Correlation analysis between GDP per capita and recycling performance
- Thematic analysis of qualitative documents to identify recurring policy instruments, challenges, and best practices

Findings were synthesized and interpreted using the waste hierarchy and circular economy principles, ensuring that the analysis aligns with international sustainability frameworks. Triangulation was applied to strengthen the validity of findings. Data triangulation was used by drawing from multiple secondary sources, including UN reports, World Bank statistics, and national waste management data. Methodological triangulation was applied through a comparative country analysis, trend review, and policy document evaluation. Theoretical triangulation was reflected in the use of sustainability frameworks and waste hierarchy principles to interpret recycling performance. These approaches ensured that the estimates derived from recycling rates were validated against multiple sources and analytical lenses. While the recycling data itself has limitations due to reporting inconsistencies, cross-checking across several international databases improved accuracy and reliability.

3.1.3. Limitations of the Methodology

Some limitations were encountered during the study:

- Inconsistent or missing data for certain developing countries, particularly in the informal waste sector

- Variability in how different countries define and calculate “recycling rate”
- Policy documents often reflect intent rather than enforcement or effectiveness

Despite these limitations, the triangulation of data sources ensured a robust and credible comparative analysis.

4. Results and Discussion

This section presents and interprets the key findings from both the quantitative analysis of national recycling data and the qualitative assessment of policy and institutional frameworks. The results are organized by country and thematic focus areas.

4.1. National Recycling Rate Performance

The comparative analysis of the five countries shows significant disparities in recycling performance (Figure 1.):

- Germany consistently achieves the highest national recycling rate, exceeding 65%. This success is attributed to its well-established Extended Producer Responsibility (EPR) system, mandatory source separation, and circular economy legislation.
- South Korea also maintains a high recycling rate (around 60–65%), driven by its Volume-Based Waste Fee (VBWF) system and strict enforcement policies.
- The United States shows moderate recycling performance (~32%), hindered by fragmented state-level policies and lack of national legislation.

Brazil and India fall below 15%, with recycling largely driven by the informal sector and minimal government enforcement. These trends reveal a strong link between comprehensive policy implementation and recycling outcomes (Table 1.).

	Country	Key Policy	Impact on Recycling
1	Germany	Circular Economy Act	+10% increase since 2012
2	South Korea	Volume-Based Waste Fee System	Consistent growth
3	India	Solid Waste Management Rules	Minimal improvement
4	United States	Resource Conservation and Recovery Act (RCRA)	Moderate recycling growth; fragmented policies
5	Brazil	National Solid Waste Policy (PNRS)	Low national rates (~13%); informal sector crucial

Table 1. National Waste Policy with SDG Targets

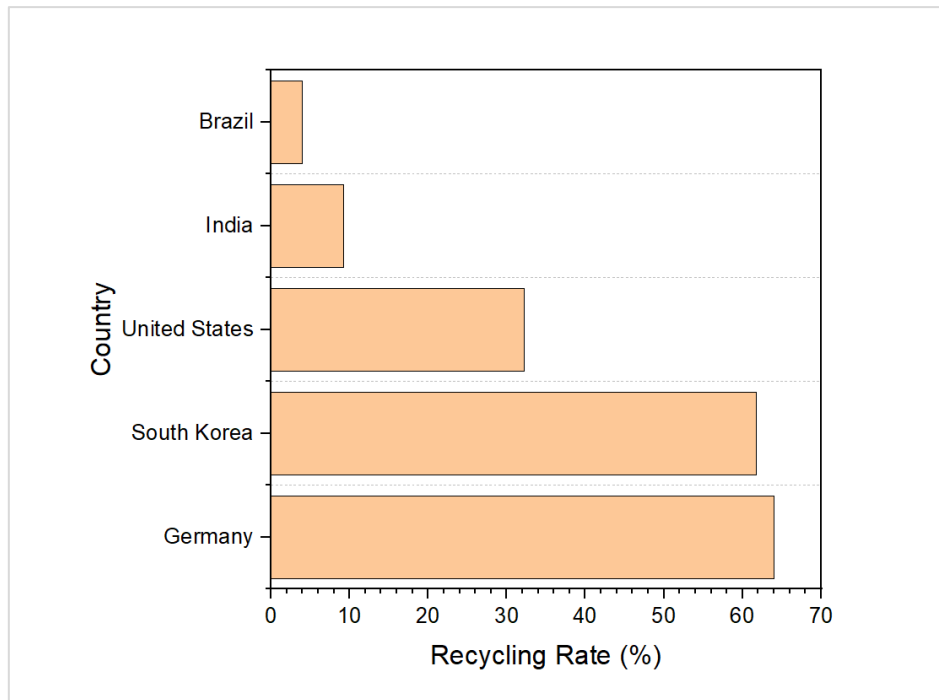


Figure 1. Recycling Rate Data (2020)

4.2. Policy and Institutional Drivers

Successful countries implement a combination of regulatory, economic, and informational instruments:

- Germany's Packaging Ordinance and Circular Economy Act enforce mandatory recycling targets and hold producers accountable.
- South Korea's VBWF system reduces waste generation and increases recycling through user-pays principles.
- The USA lacks federal coordination, resulting in inconsistent practices and data collection.
- Brazil and India have policies on paper (e.g., Brazil's National Solid Waste Policy), but enforcement and funding are weak.

Institutional capacity and transparency also influence performance. Germany and South Korea have robust monitoring systems and consistent public reporting, while India and Brazil struggle with underreporting and fragmented data.

4.3. Public Participation and Awareness

Countries with continuous public education and community participation initiatives show higher compliance. For instance:

- Germany promotes environmental education from early schooling.
- South Korea runs regular media campaigns and supports citizen monitoring groups.
- In contrast, Brazil and India lack structured awareness programs and depend heavily on NGOs or informal systems.

This highlights the importance of behavioral change strategies, as described by Ajzen's Theory of Planned Behavior, in improving recycling compliance.

4.4. Role of Informal Sector

In Brazil and India, informal waste pickers (also called "catadores" or "kabadiwalas") play a crucial role in recovering recyclable materials. However, they are often:

- Undervalued
- Excluded from official data
- Operating in poor conditions without legal or social protection

Integrating informal workers into the formal system - as seen in Brazil's city-level operative programs - can significantly improve recycling rates and livelihoods.

4.5. Data Quality and Monitoring Challenges

Reliable measurement of SDG 12.5.1 is hindered by:

- Lack of standardized definitions (e.g., what constitutes "recycled material")
- Poor integration of informal sector data
- Disparities in reporting formats across countries

The Digital Economy Report (2024) [35] recommends that governments invest in digital reporting platforms and collaborate with local stakeholders to improve data accuracy and coverage.

5. Conclusions

This study has demonstrated that SDG 12.5.1, which measures the national recycling rate and tons of material recycled, serves as a vital tool for evaluating the effectiveness of Sustainable Waste Management Services (SWMS). Based on comparative analyses of Germany, South Korea, the United States, Brazil, and India, - we found that the top-performing countries share a number of common characteristics. These include strong institutional frameworks, effective policy implementation, public involvement, and significant investment in infrastructure.

The results for Germany and South Korea show how the implementation of regulation, extended producer responsibility, and a circular economy can drive national recycling performance. However, Brazil and India have weak regulation, exclusion of the informal sector, poor infrastructure, and limited public education, which clearly contribute to low recycling rates.

In our findings, we stressed that, while legislation is essential, it must be complemented by implementation capacity, sustainable funding, transparent data systems, and stakeholder participation. Integrating informal waste processors into the formal economy and improving the accuracy of recycling data are critical steps for developing countries to achieve SDG 12.5.1.

Conflicts of Interests

The authors declare no conflict of interest.

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