Innovative Technology of Solid Waste Management in Various Nations for Sustainable Development

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Abstract

Effective management of solid waste is crucial for the conservation of the ecosystem, although it presents challenges for many countries. Technological progress offers possible alternatives, but the adoption and execution of these innovations depend on particular local conditions. The aim of this study is to examine and compare the techniques employed in the generation and management of solid waste in 30 countries, classified according to their level of income. The data provided pertaining to various waste categories, encompassing household waste, plastic waste, food waste, and miscellaneous waste. Countries were classified into low, lower-middle, upper-middle, and high-income categories. The findings revealed substantial associations between specific waste categories and identified varied correlations between types of waste and income brackets. The investigation unveiled clear categorizations based on wealth, signifying differences in the composition of these groups. Wealthy nations exhibited more efficacy in waste management; however intra-country inequalities were also seen. The efficacy of solid waste management varies globally in correlation with the degree of economic development. While recycling and waste-to-energy technologies show promise, it is essential to adopt customized local solutions that consider socio-economic considerations, especially in developing areas. Comparative evaluations provide vital information to facilitate the advancement of sustainable waste management methods.

Keywords:

Waste management, Solid waste, Environmental risk, Developing countries, Effective management.

1. INTRODUCTION

Rapid urbanization, population growth, economic development, and changing consumption patterns make solid waste management (SWM) a global issue (Shekdar, 2009). Due to finance, infrastructure, and technical capacity gaps, high- and low-income countries implement SWM differently, despite its importance to public health, environmental sustainability, and economic efficiency (Nanda & Berruti, 2021). Urbanization increases waste volumes and complexity, overwhelming systems and resulting in low collection rates, open dumping, and poor landfilling, causing contamination, ecological damage, and health risks in developing countries. Domestic waste in Tunisia is expected to rise from 2.4 to 2.6 million tons per year (2.5% growth) (Henaien et al., 2024).

Healthcare costs, land degradation, and resource loss from inefficient SWM also cost money (Kaza et al., 2018; Cook & Velis, 2021). Medical and plastic waste increased during the COVID-19 pandemic, straining fragile systems (Roy et al., 2021). New technologies like Waste-to-Energy (incineration, gasification, anaerobic digestion) reduce landfilling and generate energy (Das, 2022). AI and sensor-based sorting improve recycling (Das, 2022; RecyclingInside, 2023; Taneepanichskul et al., 2022), and IoT-enabled smart bins and routing improve collection.

Limitations remain on context-specific strategies for low-income settings. Research favors high-income contexts (Esmaeilian et al., 2018), and waste stream data gaps hinder planning (Bin Mokaizh, 2022). SWM routing and resource allocation applications underuse bio-inspired metaheuristics like MOSOA and SHO, which are promising for optimization (Dhiman et al., 2021; Dhiman & Kumar, 2017).This study examines correlations between national income levels and waste management approaches. It aims to identify optimal SWM strategies for low-income countries that accommodate financial and technological constraints while advancing global sustainability goals, guided by two research questions:

i. How does municipal solid waste (MSW) composition differ among high-, middle-, and low-income countries?

ii. Which sustainable waste management approaches prove most effective for low-income nations given their technological and budgetary limitations?

2. LITERATURE REVIEW

According to recent studies, waste management and technology are crucial to solving global issues like urbanization and public health (Rada et al., 2021). Blockchain technology is revolutionizing waste security and transparency. COVID-19 has impacted solid waste management, highlighting the need for flexible frameworks and strong regulations. Pakistan, a developing nation, has inefficiencies that require stronger regulations. High-income nations struggle with strict regulations and new technologies like biodegradable plastic sorting. Though waste segregation is difficult, behavioral interventions in low-income urban areas may be cost-effective (He et al., 2022). The literature emphasizes technological innovation, adaptable policies, and community engagement in global waste management. Previous study objectives and findings are summarized in Table 1.

Table 1: summarizing the key objectives and findings of the previous research.

Reference	**Key Objectives**	**Key Findings**	**Implications / Recommendations**
Zheng et al., 2017	Provide a comprehensive overview of blockchain technology, its architecture, and consensus algorithms.	Blockchain is an immutable ledger for decentralized transactions; key challenges include scalability and	Pursue research on scalability and security; leverage blockchain to enhance transparency in

		security; future trends and technical advances are outlined.	supply chains and waste tracking.
Yadav et al., 2023	Study and list effective waste management policies during COVID-19 across various economies.	Diverse global strategies adopted; WHO guidelines widely followed; some sustainable practices are suitable for permanent adoption to bolster pandemic response.	Integrate pandemic-specific waste policies into permanent frameworks; strengthen health and safety protocols in waste handling.
Taneepanichskul et al., 2022	Review identification and sorting technologies for compostable/biodegradable plastics.	Surveys gravity, flotation, image-based, and other sorting methods; details benefits and limitations; underscores proper sorting's role in a circular economy.	Promote advanced sorting tech; develop standards to improve sorting efficiency; encourage innovation in the recycling industry.
Roy et al., 2021	Analyze solid waste generation trends in high-income countries (HICs) and treatment processes.	HICs generate substantial MSW; enforce strict management guidelines; adopting emerging techniques is critical for sustainability and circularity.	Incentivize emerging sustainable technologies; prioritize circular economy integration to minimize waste.

2.1. Sustainable Waste Management

Originating in the 1970s, the concept of environmental sustainability has evolved into a comprehensive framework that encompasses social, economic, and environmental goals (Giovannoni & Fabietti, 2013). Solid waste management (SWM) is a key, interdisciplinary issue with significant implications for global sustainable development (Oo et al., 2024). Within the SWM framework, sustainability emphasizes the adoption of waste reduction, recycling, and recovery practices to decrease environmental harm while promoting social and economic benefits. Studies show that sustainable waste management systems must be adapted to local conditions, considering each region's unique environmental, economic, and social factors (Aloysius et al., 2025). For example, low-income countries often lack the financial and technological resources needed for effective solid waste management, leading to common practices such as open dumping and informal waste collection (Pires et al., 2011). Conversely, high-income nations have adopted advanced technologies and regulations that support more efficient and environmentally friendly waste management practices (Nepal et al., 2023). SWM provides a unique opportunity to reduce environmental impacts while also supporting emission reduction efforts reduction

2.2 Technological innovation

Technological advances are improving waste management by addressing inefficiencies and environmental issues. Real-time waste bin monitoring by IoT optimises collection routes and lowers operational costs (John et al., 2022). Blockchain technology improves waste tracking transparency and accountability, preventing recyclables from going to landfills and encouraging stakeholder collaboration (Permana & Rahman, 2022; Zheng et al., 2017). Solid waste management is increasingly using AI to sort waste, predict outcomes, and optimize resources (Abdallah et al., 2020; Guo et al., 2021). Artificial neural networks have solved complex problems like waste composition analysis and treatment optimization (Guo et al., 2021). However, high implementation costs and poor data infrastructure prevent developing countries from adopting these technologies (Abdallah et al., 2020). Waste-to-Energy (WTE) technologies, which incinerate, gasify, or anaerobic digest waste, are promising. They are widely used in high-income countries but expensive and difficult to implement in low-income regions (Kumar, 2023). WTE adaptations for these settings should reduce costs, build capacity, and engage local communities (Das, 2022). Table 2 lists these technologies' pros and cons.

Table 2. Summarizing the previous studies about the Innovation Technologies of Solid Waste Management Strategies.

Citation	Technology	Waste Types	Advantages	Disadvantages	Alleged Outcome
Farooq et al., 2022	Blockchain, IoT, AI	All	Improves traceability, transparency, efficiency; reduces waste, conserves resources, protects environment	Neglects consumer perspective; lacks empirical validation	More transparent and efficient waste management
Taylor et al., 2020	Blockchain	All	Tracks/trace waste; payments/rewards; improves transparency; reduces fraud/corruption	Unclear definition of sustainable WM; blockchain limits in solving crises	Reduced fraud and corruption
Permana & Rahman, 2022	Blockchain	All	Tracks waste; payments/rewards; transparency; reduces fraud/corruption	Focus on adoption over economics; high costs and long-term commitments; data standardization gaps	Potentially more transparent, efficient, affordable SWM; challenges remain
Ferronato & Torretta, 2019	Recycling	MSW	Less landfill waste; conserves resources; lowers GHG emissions	Energy/resources for processing; economic feasibility varies; contamination reduces effectiveness	Reduced waste volumes, GHGs; recovery of valuable resources

Mousavi et al., 2023	IoT	MSW	Efficiency, cost savings; lower environmental impact; higher recycling; better public health/safety	High upfront costs; data privacy risks; tech dependence; potential job loss	Improved energy efficiency; reduced GHGs; better waste management; supports circular economy
Nwosu & Chukwueloka, 2020	GPS, GIS, Remote Sensing, RFID, Comms	MSW	More accurate and efficient operations	High upfront costs; privacy concerns; tech dependence	Lower costs; better public health/safety; reduced environmental impact
Abubakar et al., 2022	Landfills, Incineration, Composting	MSW	Landfills: sanitary disposal; Incineration: volume reduction + energy; Composting: nutrient-rich amendment	Landfills: methane; Incineration: air pollutants; Composting: space/time needs	Sustainability requires balancing environmental, social, economic factors

2.2.1. Artificial Intelligence (AI)

AI-based models are becoming increasingly important in medicine, linguistics, and engineering. Limited computational methods and AI advances drive this growth (Kalogirou, 2003). AI modeling excels at managing noisy, complex datasets, making it popular in environmental engineering. AI addresses air pollution, water/wastewater treatment, soil remediation, groundwater contamination, and strategic planning. The Adaptive Neuro-Fuzzy Inference System (ANFIS) can predict pollutant and particulate levels (Roy, 2012).

AI methods for Solid Waste Management (SWM) are becoming powerful alternatives to computational methods. A comprehensive literature review by Abdallah et al. (2020) shows AI's growing use in SWM.Cutting-edge bio-inspired metaheuristics, such as the Emperor Penguin Optimizer (EPO) (Kaur et al., 2020), the Tunicate Swarm Algorithm (Dhiman et al., 2018), and the Seagull Optimization Algorithm (Dhiman & Kumar, 2019), offer novel frameworks for tackling complex, non-linear waste logistics problems. These algorithms enhance AI-driven SWM systems by enabling rapid convergence under multifaceted constraints, such as balancing cost against environmental impact.

The convergence of cyber-physical systems, the Internet of Things (IoT), and blockchain technologies significantly accelerates the development of efficient waste management frameworks (Bharadwaj et al., 2016). Early innovations, like the multi-layer SWM architecture using RFID and sensors developed by Chowdhury and Chowdhury (2007), automated waste identification, weight measurement, and bin theft detection. Real-world implementation of such IoT concepts is evident in South Korea's nationwide volume-based waste fee system, heavily reliant on RFID tags for household waste billing, significantly reducing landfill volumes (Wang et al., 2023). Jiang et al. (2020) further proposed an IoT and data-mining framework to analyze residential waste trends, informing policy decisions. Singapore exemplifies this approach, utilizing sensor data from smart bins city-wide to dynamically optimize collection schedules and reduce operational costs (National Environment Agency [NEA] Singapore, 2021). Esmaeilian et al. (2018) emphasized the necessity of tracking and data-sharing technologies, proposing an IoT framework linking waste practices throughout a product's lifecycle. Japan's advanced waste tracking systems, integrating sensors across collection and processing facilities, demonstrate this lifecycle data integration in practice (Earth.org., 2025).

Globally, AI's significance in SWM is highlighted by its varied national applications: predicting waste generation patterns (e.g., predictive analytics models used in major European cities like Copenhagen (Bello and Odiete, 2022) optimizing collection routes (as seen in Singapore's AI-powered garbage truck routing (NEA Singapore, 2021), identifying optimal locations for waste treatment facilities (utilized in urban planning across the USA, (Denekos et al., 2021)) and simulating complex waste conversion processes (pioneered in countries like Sweden for waste-to-energy efficiency (Islam, 2025)).

2.2.2. Blockchain

Blockchain technology is globally recognized as a transformative force in the digital revolution, catalyzing economic growth across nations. Its potential advantages have spurred significant investment from corporations and governments worldwide (Gillpatrick, 2022). Initially designed for financial transactions, blockchain now demonstrates versatile applications spanning banking, food safety, healthcare, logistics, and supply chain management (Crosby et al., 2016). Its core architecture – an immutable, time-ordered ledger maintained across distributed networks – uniquely enhances transparency and efficiency in supply chains, including waste management systems (Kainuma & Tawara, 2006). Sweden exemplifies this through blockchain-tracked waste-to-energy conversions, where real-time monitoring of waste origins and energy outputs has reduced landfill dependence by 32% since 2020 (Islam 2025).

The strategic implementation of blockchain in waste management fundamentally transforms accountability across stakeholders. Singapore's national blockchain platform for e-waste tracking has increased recyclable recovery rates by 27% by creating immutable records of disposal responsibilities (Rotabi and Ali, 2021). This technology minimizes landfill reliance by enhancing traceability and enabling circular economy models. For processing complex blockchain data, bio-inspired optimization algorithms like the Binary Emperor Penguin Optimizer (BEPO) prove invaluable in managing high-dimensional datasets within smart city infrastructures (Dhiman et al., 2021).

Blockchain integration fosters unprecedented collaboration between governments, regulators, and businesses, leading to more resilient waste management standards. The UAE's "Recycle to Earn" initiative (2023) demonstrates this synergy, using a private blockchain where municipalities, manufacturers, and consumers jointly verify recycling claims, reducing contamination rates by 41% (Berigüete et al., 2024). Platform selection (public vs. private) remains contingent on project complexity and security requirements (Pongnumkul et al., 2017). Blockchain’s application in reverse logistics is particularly impactful, with the Hashcash algorithm enabling tamper-proof recording of recyclables. Japan's Plastic Resource Circulation initiative (2022) utilizes this approach, creating shared ledgers for cross-border plastic waste shipments that increased compliance transparency by 98% (Earth.org., 2025).

PwC research (2020) projects blockchain could add $1.76 trillion to global GDP this decade. However, significant disparities exist in adoption capabilities. While advanced economies like Germany integrate blockchain into municipal waste contracts (Ameer, 2025), developing nations like Rwanda face infrastructure gaps – only 45% of waste handlers have reliable internet access essential for blockchain participation (Ameer, 2025). This technological asymmetry risks amplifying the global "digital divide," potentially excluding vulnerable regions from circular economy benefits.

3. METHODS

3.1 Study area and gathering data

The criteria were devised to select study countries for the construction of the profiling approach, considering population size and economic status, with a focus on low- and middle-income countries (refer to Fig. 1, Table 3). The sample encompasses extensive latitudes (−40.9 in New Zealand to 34.8 in Syria) and longitudes (−72.3 in Haiti to 174.9 in New Zealand), and varies from India (approximately 1.4 billion) to Oman (over 4 million).

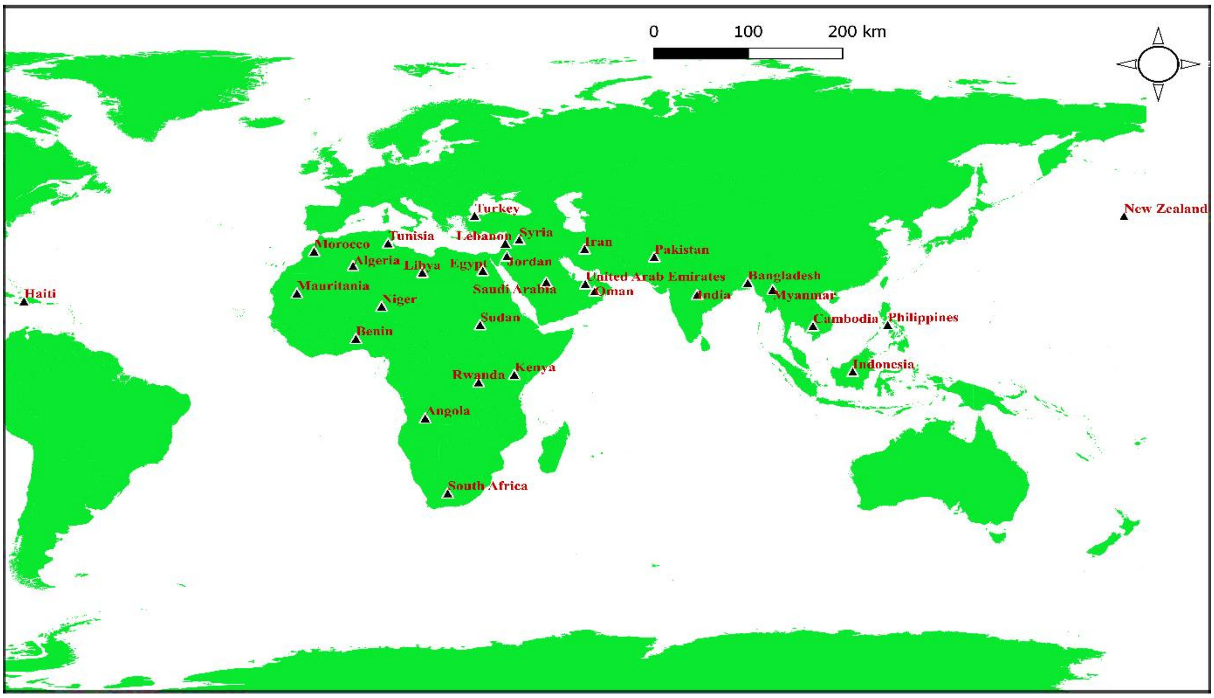

Fig.1: Map showing the selected countries in this study.

Variations in solid waste production indicate economic advancement and quality of life. The GDP per capita in Table 3 varies from 53,757.90 USD (high-income) to 533.0 USD (low-income). A higher Human Development Index (HDI) is associated with increased waste generation, with average HDI values of 0.885 (high), 0.748 (upper-middle), 0.643 (lower-middle), and 0.505 (low), as illustrated in Table 3.

The analysis was based on data collection encompassing various waste categories: household, plastic, organic food, retail, glass, paper, home consumption, metal, and others. Data were obtained from an online database (BANK, 2022), with country classification by GDP provided by the World Bank (worldbank., 2015). A minimum of four countries were categorized within each income group, resulting in the following classifications:

i. Low-income economies with a GNI per capita of $1,135 or less.
ii. Lower-middle-income economies with a GNI per capita ranging from $1,136 to $4,465.
iii. Upper-middle-income economies with a GNI per capita ranging from $4,466 to $13,845.
iv. High-income economies with a GNI per capita of $13,846 or more.
v. The inclusion of only countries with recent Solid Waste Management (SWM) data ensures that the representation is informative rather than definitive.

Table 3: Population, GDP, HDI and the continent of the selected countries.

Entity	Classification	Population	GDP	HDI
Oman	High income	4,576,298	25,056.80	0.816
Saudi Arabia	High income	36,408,820	30,436.30	0.875
New Zealand	High income	5,124,100	48,249.30	0.937
United Arab Emirates	High income	9,441,129	53,757.90	0.911
Sudan	Low income	46,874,204	1,102.10	0.508
Syria	Low income	22,125,249	537.2	0.577
Niger	Low income	26,207,977	533	0.4
Rwanda	Low income	13,776,698	966.3	0.534
Algeria	Lower middle income	44,903,225	4,273.90	0.745
Egypt	Lower middle income	110,990,103	4,295.40	0.731
Iran	Lower middle income	88,550,570	4,387.80	0.774

Jordan	Lower middle income	11,285,869	4,204.50	0.72
Lebanon	Lower middle income	5,489,739	4,136.10	0.706
Morocco	Lower middle income	37,457,971	3,527.90	0.683
Tunisia	Lower middle income	12,356,117	3,776.70	0.731
Bangladesh	Lower middle income	171,186,372	2,688.30	0.661
Angola	Lower middle income	35,588,987	2,998.50	0.586
Mauritania	Lower middle income	4,736,139	2,190.70	0.556
Benin	Lower middle income	13,352,864	1,303.20	0.525
Myanmar	Lower middle income	54,179,306	1,095.70	0.585
Cambodia	Lower middle income	16,767,842	1,786.60	0.593
Haiti	Lower middle income	11,584,996	1,748.30	0.535
India	Lower middle income	1,428,627,663	2,388.60	0.633
Kenya	Lower middle income	54,027,487	2,099.30	0.575
Philippines	Lower middle income	115,559,009	3,498.50	0.699
Pakistan	Lower middle income	235,824,862	1,596.70	0.544
Libya	Upper middle income	6,812,341	6,716.10	0.718
Indonesia	Upper middle income	275,501,339	4,788.00	0.705
South Africa	Upper middle income	59,893,885	6,776.50	0.731
Türkiye	Upper middle income	85,341	10,616.10	0.838

3.2 Data analysis

Statistical analyses and graphical displays were conducted using R software version 4.2.2, specifically utilizing the "vegan" package (Oksanen et al., 2019). Map created using the Free and Open Source QGIS software version 3.36 [http://qgis.org].

The initial examination of the data involved a Kolmogorov-Smirnov test (Johnson et al., 2000), indicating a non-normal distribution. Consequently, a non-standard parametric test was utilized in the subsequent statistical analysis. Spearman's correlation coefficient measurements were employed to identify associations among urban variables, with statistical significance set at $p < 0.01^{**}$ and $0.05 > p > 0.01^{*}$. A multivariate analysis study of variables linked to solid waste, such as domestic, plastic, organic food, retail, glass, paper, home consumption, metal, and other content, was undertaken, classifying these countries according to income.

Bray-Curti’s dissimilarity and permutation ($n = 999$) in a non-metric multidimensional scaling (NMDS) analysis were used to assess how groups differed by country based on their income levels. The "metaMDS" package in R software was utilized for NMDS analyses (McCune & Grace, 2002). A PERMANOVA test (Anderson, 2001) was conducted to assess the statistical significance of the NMDS models, with 999 permutations.

Principal Component Analysis (PCA), a multivariate statistical method, was employed to simplify input variable complexity and mitigate multicollinearity. PCA was used to uncover significant waste patterns associated with different income groups. The Bartlett's test of sphericity (Bartlett, 1937) assessed the suitability of the original data for factor analysis.

4. RESULTS AND DISCUSSION

In this section, the study's findings are categorized into three main aspects: solid waste composition, regional differences between groups (PCA), and solid waste constraints on groups (NMDS).

3.1. Solid waste composition

Table 4 illustrates how differing lifestyles across the studied countries lead to various solid waste management systems. Non-parametric Spearman correlation tests were conducted on waste variables, all showing significant deviations from normal distribution ($p \leq 0.05$). The analysis revealed statistically significant but generally weak positive and negative correlations. Specifically, there is a strong negative correlation between glass and organic food waste with household and retail consumption, with coefficients of -0.36 (p ≤ 0.001) and -0.44 (p ≤ 0.05), respectively. In contrast, paper waste correlates positively with retail waste (r = 0.34, p ≤ 0.01), and organic food waste shows a strong negative relationship with other waste types (r = -0.55, p ≤ 0.001).

These findings align with prior research. The negative correlation between glass and organic food waste supports conclusions by Cai et al. (2024) and Kaza et al. (2020), suggesting higher organic food waste influences glass waste separation. The negative relationship between organic food and retail waste, and the positive link between organic food, household waste, and plastic (Edjabou et al. (2015), though the latter two correlations were not statistically significant here.

Moreover, the total organic food content appears to have little effect on waste distribution patterns, a finding consistent with recent studies on waste composition across cultures (Sharma et al., 2024; Dawar et al., 2025). Together, these results underscore the complexity of waste management systems and emphasize the importance of culturally specific policies tailored to local waste practices.

Table 4: Correlation matrix of solid waste categories.

Solid Waste Category	Household	Home Consumption	Retail	Plastic	Food Organic	Glass	Metal	Composition Other	Paper
Household	1								
Home Consumption	0.18	1							
Retail	-0.36***	-0.2	1						
Plastic	-0.32	0.09	0.15	1					
Food Organic	0.06	0.06	-0.21	0.08	1				
Glass	-0.1	-0.14	0.21	-0.04	-0.44*	1			
Metal	0.11	-0.12	0.11	-0.12	-0.27	0.67*	1		

Composition Other	0.09	0.12	-0.16	0.05	-0.55***	0.27	0.04	1	
Paper	-0.19	0.04	0.34**	-0.1	-0.45	0.2	0.16	-0.22	1

$^{***}p\leq0.001$, $^{**}p\leq0.01$, $^{*}p<0.05$

3.2. Regional differences of solid waste between groups (PCA)

Principal Component Analysis (PCA) minimizes dataset dimensionality by converting correlated variables into a reduced number of linearly uncorrelated components, thereby maintaining critical information (Field, 2013; Li et al., 2019). The first principal component has the most data variation, while later components optimize residual variance oppositely (Fadhullah et al., 2022).

Bartlett's test confirmed the data's suitability for PCA ($p \leq 0.001$). In Hutcheson and Sofroniou's (1999) waste classification using PCA, close variables had positive correlations and far variables had negative correlations. (Fig.2) showed that PC1 and PC2 explained 26.8% and 20.5% of the variance, totaling 47.3%. Important patterns emerged: Retail paper waste increases in high-income countries and decreases in residential waste. Positive correlation between glass-metal waste and negative correlation with organic food waste in upper-middle-income countries. A positive correlation exists between household consumption and home consumption in low-upper-middle-income groups, but organic waste is inverse. This supports previous research on income-dependent waste patterns in Nigeria, India, and Istanbul (Mama et al., 2021; Sharma, 2019). The unique income-level patterns show that multi-objective optimization frameworks like Multi-objective Spotted Hyena Optimizer (Dhiman and Kumar, 2017) can create customized solid waste management strategies that balance cost, coverage, and environmental risk. Superior financial resources that enable cost recovery through taxes and fees, decentralized implementation supported by private investment, and advanced technologies that improve coverage and foster innovation make high-income countries' solid waste management more effective than low-income countries.

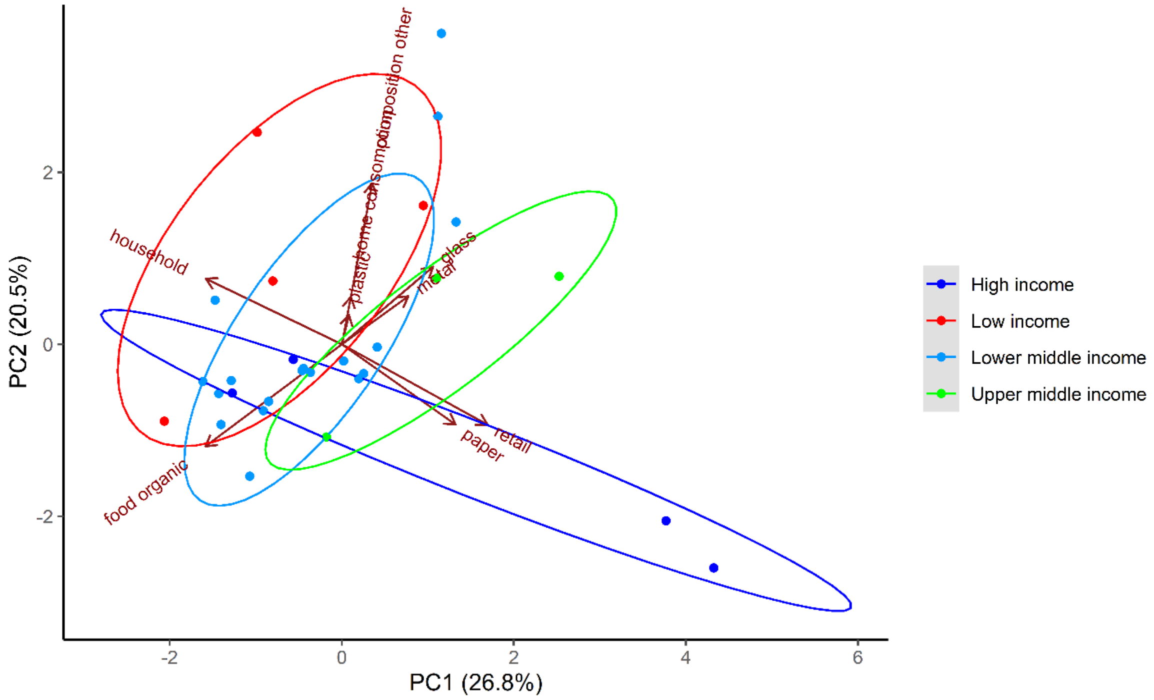

Fig.2: Principal Component Analysis (PCA) presented the solid waste categories related to the groups.

3.3. Solid waste constraints on groups

The nonmetric multidimensional scaling (NMDS) analysis (Fig.3) showed country income-based clustering patterns, highlighting significant differences between the four groups. The Adonis (Permanova) test confirmed significant differences in solid waste composition among income groups (ANOSIM, R = 0.26, $p \leq 0.05$). The observed findings confirmed significant differences in solid waste classifications among the fourth group of countries ($P \leq 0.001$; Anderson, 2001, Table 3). Thus, high-income nations have very different solid waste compositions and volumes. Low-income countries struggle to establish effective waste management systems (Iyamu et al., 2020), and source separation is less common.

Population growth, especially in high-income countries, drives waste production. Zambrano-Monserrate et al. (2021) found that high-income countries generate more solid waste per capita than low-income countries, as shown in Figure 3. Several factors may explain these differences. Rich people in middle- or low-income countries follow high-income trends (Johnson et al., 2000; Ezeudu & Bristow, 2024). Geographic location, food habits, cultural norms, climate, and profession also affect waste generation (Dikole & Letshwenyo, 2020; Kala & Bolia, 2020).

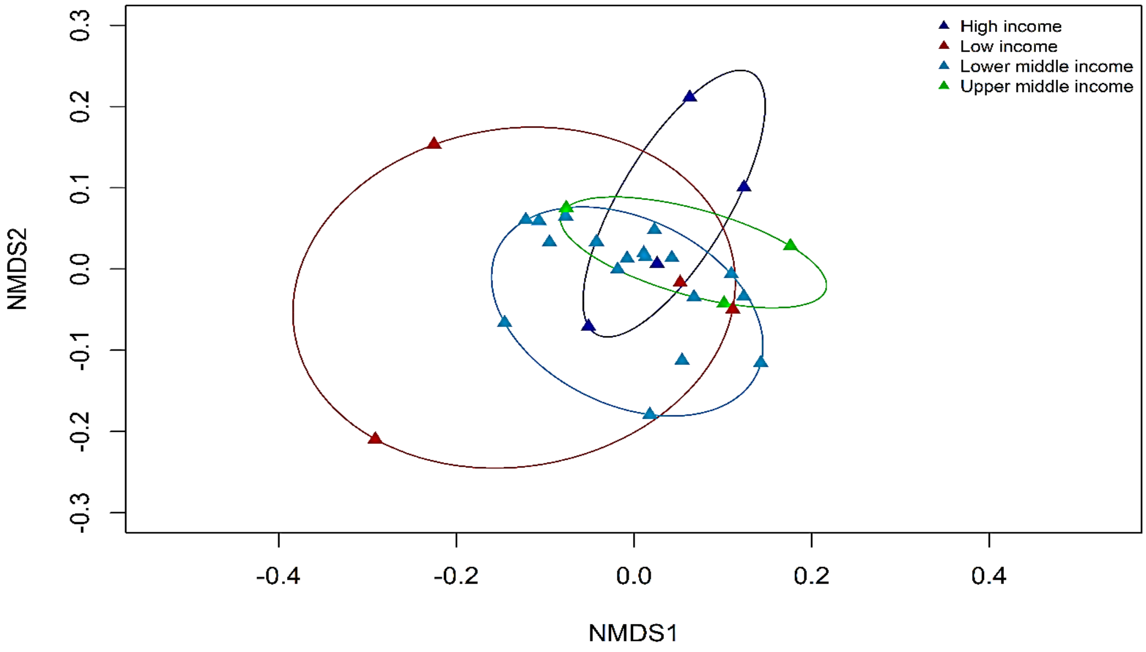

Fig.3: Nonmetric multidimensional scaling (NMDS) plots showing the clustering by the GDP per capita.

3.4 Health and Environmental Risks

Poor solid waste management (SWM) degrades environmental and occupational health regulations in developing countries, endangering workers and the public (OSHwiki, 2014; McAllister, 2015). Uncollected waste can clog drains and cause flooding, and collection is dangerous (McAllister, 2015). Children under 16 live in open dumps with poor water and sanitation as informal pickers (Zohoori & Ghani, 2017). Most micro and small recyclers sort manually without washing, baling, dust control, or safety gear (OSHwiki, 2014).

Over the past 20 years, union advocacy has improved SWM OHS regulations and OHS in many developed countries (OSHwiki, 2014). The industry now has lighter containers, lower-loading vehicles, mandatory gloves and high-visibility vests, sorting plants with dust suppression, enclosed conveyors, ventilation, and air-quality monitoring (Fig. 4), modern landfill machinery with rollover protection and climate-controlled cabs, and better training and noise reduction.

Targeted public awareness campaigns and country-specific factors influencing technologies and legal frameworks in the Global South can reduce health and environmental harms from inadequate SWM (Abubakar et al., 2022). Policies should include separation laws, incentives, and outreach; companies should adopt circular economy practices and audit waste; authorities should partner with local businesses, expand recycling/composting, and use IoT for route optimization; and lower-income contexts should prioritize cost-benefit cases, accessible finance, and recycling jobs. Through composting, sustainable SWM improves public health, reduces landfill-related greenhouse gases, and supports environmental, health, and economic goals.

Fig.4: The difference between solid waste collecting according to the GDP per capita: a) High income; b) Upper middle income; c) Lower middle income; d) Low-income countries.

5. CONCLUSION

The analysis of solid waste management plans in 30 countries shows income-related challenges and opportunities. Due to financial and institutional barriers, low- and middle-income countries struggle with inadequate collection services, unsafe working conditions, and limited access to modern technologies. High-income nations benefit from advanced infrastructure and decentralized systems that improve efficiency. Instead of using one-size-fits-all approaches, waste-to-energy and circular economy models must be tailored to local economic and social contexts. Effective governance, targeted financing, and incremental technology adoption are essential for developing nations. Formal recognition and support for informal waste workers can improve environmental outcomes and livelihoods. Practical technology transfer pathways, inclusive policy frameworks for informal sectors, and detailed behavioral studies to reduce waste at the source should be studied in the future. Strengthening public-private partnerships is key to scaling investments and innovations. Sustainable solid waste management requires context-specific, inclusive frameworks that balance economic feasibility, social equity, and environmental protection.

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CONTRIBUTION STATEMENT

Methodology (study design; statistical framework incl. Spearman analysis, PCA, NMDS, PERMANOVA) (T.J.K.I & A.H.). Data curation (T.J.K.I. & J.H. & H.R.). Software (T.J.K.I). Investigation (A.H. & J.H. & H.R. & A.M.A.). Data sources; institutional access; tools) (T.J.K.I. & A.M.A). Writing – original draft: (T.J.K.I&A.H). Writing – review: All authors

CONFLICTS OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the finding of this study is available in the Bank world 2022 and 2015 at https://datahelpdesk.worldbank.org/knowledgebase/articles/906519 and https://datahelpdesk.worldbank.org/knowledgebase/articles/378834-how-does-the-world-bank-classify-countries, respectively.

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