




Article

Integrating Sustainability Dimensions and Stakeholder Engagement in Solid Waste Management in Developing Countries: Evidence from Pakistan Using Structural Equation Modeling

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Abstract

Rapid urbanization and population growth have intensified solid waste management (SWM) challenges in developing countries, where institutional capacity and stakeholder participation remain limited. Existing studies, particularly in the context of Pakistan, largely examine isolated technical or environmental aspects, with limited integration of sustainability dimensions and stakeholder dynamics. This study develops and empirically validates an integrated structural equation modeling (SEM) framework to examine the interrelationships among sustainable solid waste management systems (SSWM), stakeholder engagement (SE), and solid waste management strategies (SWMS). Primary data were collected from 420 stakeholders representing diverse groups. The measurement model demonstrated strong reliability and validity, while the structural model exhibited excellent fit indices. Results indicate that economic, social, technical and environmental and institutional dimensions significantly shape SSWM. Structural path analysis reveals that SSWM significantly influences SE and SWMS, while SE has a significant effect on SWMS. Mediation analysis confirms that SE partially mediates the relationship between SSWM and SWMS, highlighting the critical role of participatory governance. The findings demonstrate that achieving sustainable waste management requires the integration of system-level capacity, stakeholder engagement, and strategic implementation. This study contributes to the sustainability literature by providing a holistic framework and providing understanding for policymakers to promote circular economy practices and resource efficiency in developing countries.



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1. Introduction

Solid waste management (SWM) stands at the forefront of contemporary environmental challenges, representing the comprehensive approach of collecting, disposing, and treating solid waste materials generated by human activities. Due to low waste collection efficiency, incapable reuse and recycling infrastructure, and inefficient SWM practices, a

large amount of waste exists in dumpsites and uncontrolled landfills in developing countries [1,2]. Urbanization and economic growth lead to a rapid and uncontrolled increase in municipal SWM generation. The urban waste management system needs to be optimized to stop large-scale environmental contamination from uncollected municipal solid waste (MSW) [3]. Conventional garbage disposal techniques put community infrastructure at risk and cause other issues like greenhouse gas emissions, soil damage, groundwater contamination, and air pollution. Recent evidence also indicates that methane emissions from solid waste disposal sites may be underestimated, suggesting that improved landfill monitoring and locally adapted mitigation strategies are important opportunities for reducing waste-related greenhouse gas emissions, particularly in developing countries [4]. Adopting a successful and efficient MSW management system guarantees a decrease in handling expenses, including investment, operating, and recycling costs [3,5,6]. In the context of developing countries, there is an urgent need to adopt the concept of sustainable development while considering waste management. The concept of sustainable development (SD) is strengthened by shifting from a conventional linear approach to a circular economy (CE) [3,7].

Due to a lack of financial stability, ineffective technology, and poor technical expertise, municipalities in developing countries have yet to achieve efficient MSW collection services. For instance, Singh et al. [8] reported that rapid growth and mismanagement of MSW in developing countries worsen environmental issues such as air, water, and soil pollution. They identified key challenges in collection and transportation (C&T) processes, including limited technology, poor planning, and low public participation. While developed countries tailor C&T systems to local conditions, achieving sustainable outcomes, developing countries often adopt outdated, uniform approaches that fail. The study emphasized integrating information and communication technology (ICT) for monitoring, tracking, and data management, alongside infrastructure and socio-economic considerations, to improve MSW management in resource-limited settings. Ezeudu and Ugochukwu [9] examined waste management financing in developing countries, using Anambra State, Nigeria, as a case study. They observed that user fees and government subsidies are the primary funding sources; however, barriers such as inadequate cost–revenue models, economic instability, reluctance to pay, and insufficient transparency impede sustainability. They suggest using behavioral incentives, neoliberal policies, and bringing in informal waste pickers to lower costs and help a circular economy. Yusuf et al. [10] pointed out that Liberia has problems with managing its urban waste. For example, only 40% of the waste is collected, and illegal dumping has gone up by 25% in five years. The Whein Town landfill (582 t/day) is almost full and does not have any leachate or gas controls. Healthcare waste is expected to grow by 15% each year, with an average of 0.137 kg/bed/day. The situation is made worse by a lack of laws, poor funding, and weak enforcement. Barbosa et al. [11] looked at 199 Brazilian MSW services from 2013 to 2022 using a dynamic slacks-based measure model. They found that the average efficiency was 61.9% and there were cumulative productivity losses. Recyclable material recovery had an adverse impact on the efficiency of selective collection and technological progress. On the other hand, population density, GDP, and COVID-19 influenced the results. Golzary et al. [12] look at the problems that Tehran's city government has with managing its trash because the city is growing rapidly. Some of the main problems are poor data tracking, ineffective source separation, not enough storage, too many collections, bad composting, unregulated informal waste picking, problems with landfills, and weak management. Weißert et al. [13] examine waste management issues in sub-Saharan Africa, highlighting the necessity for sustainable innovations that align with SDGs and engage stakeholders. Their methodology, utilized in a composting initiative in Ethiopia, demonstrates that local participation enhances outcomes while also indicating var-

ied sustainability effects, thereby identifying opportunities for enhancement. This method helps with sustainable innovation in municipal waste. Tahiru et al. [14] investigated the incorporation of Waste-to-Energy (WtE) into the compromised waste management system of Tamale. Even though there are policy, financial, and social barriers, working together and learning from each other helps things move forward. A stakeholder-validated WtE framework within Integrated Solid Waste Management aims to boost sustainability, energy, and support UN SDGs, guiding Tamale and similar cities. Eneh's [15] study investigated the challenges and solutions related to municipal solid waste recycling and resource recovery (MSW3R) in Enugu, Nigeria, a city facing growing waste generation and limited infrastructure. Key challenges identified based on Principal Component Analysis include inadequate infrastructure, poor public awareness, and policy gaps, alongside eight key solutions including improved waste management policies, public education, and enhanced recycling systems. Rafiquee and Shabbiruddin [16]'s study in Patna, India, finds an Internet of Things (IoT)-based door-to-door waste management system to be the most effective and cost-efficient solution, with social acceptance as a key factor. Knbanaza [17] examined solid waste management challenges in Alexandra, Johannesburg, South Africa, using qualitative and quantitative methods. Findings showed unreliable waste collection and transportation, mainly due to limited resources and equipment. Leknoi et al. [18] examined waste segregation practices in Bangkok. Attitude primarily influenced intention, whereas intention and trust in the recycling system predominantly affected behavior. Differences between lifestyle groups show that targeted strategies are needed. This is useful information for policymakers in megacities of developing countries. Kwakye et al. [19] looked at how solid waste is handled in Oforikrom, Ghana. They found a moderate SWAi score (50.8%) with good collection and transport but poor sorting (14%) and disposal (21%). Limited funding, vehicle breakdowns, and low public awareness, food waste (40%) and plastics (5.5%) were the key challenges.

Structural equation modeling (SEM) is a strong statistical method that is often used in behavioral sciences to describe and understand how different parts of a system are related to each other. A standard SEM framework consists of observed variables, which are measured directly, and latent variables, which are derived from observed data. In solid waste and environmental behavior research, SEM has been applied to explore factors affecting solid waste separation behaviors at source among industrial staff in Ahvaz, Iran [20]; residents' behavior in participating in smart waste sorting system in Chinese major cities [21]; assessing the community perception in San Jose, Occidental Mindoro, of proper waste disposal [22]; and to improve the plastic waste management performance [23] and financial support in E-waste management within a circular economy [24]. Related SEM-based waste-management studies have also shown that stakeholder attitudes, behavioral norms, incentive policies, professional ethics, waste-management behavior, and source-planning practices significantly influence waste sorting and waste reduction outcomes [25,26]. These studies show that SEM can be used in a lot of different ways to investigate complicated relationships in the areas of sustainability and waste management.

Pakistan's SWM system faces significant operational and structural challenges, characterized by low collection efficiency, inadequate infrastructure, and limited financial and institutional capacity [27–29]. In major urban areas, only a portion of municipal solid waste is formally collected, while the remaining waste is often disposed of through open dumping or uncontrolled landfilling, leading to environmental degradation and public health risks [30–32]. Waste segregation at source is largely absent, restricting recycling and resource recovery potential [27,30]. Furthermore, municipalities operate under financial constraints with limited cost-recovery mechanisms, making economic factors (EC) a critical determinant of system performance [28]. Institutional fragmentation and weak policy

enforcement further hinder effective waste management, while low public awareness and limited stakeholder participation reduce the effectiveness of sustainability initiatives [30,33].

Despite these well-documented challenges, existing studies on SWM in Pakistan remain fragmented, mainly focusing on isolated dimensions such as policy, governance, technical interventions, or environmental impacts. There is still a lack of comprehensive empirical frameworks that integrate economic, institutional, technical, environmental, and social dimensions within a unified analytical model. Furthermore, the role of stakeholder engagement in influencing sustainable waste management outcomes remains underexplored, particularly in developing-country contexts, and its potential mediating role in linking sustainability systems to strategic waste management outcomes has received limited empirical attention.

Therefore, the main aim of this study is to develop and empirically validate an integrated SEM framework for examining the interrelationships among sustainable solid waste management systems (SSWM), stakeholder engagement (SE), and solid waste management strategies (SWMS) in the context of Pakistan as a representative developing-country case. Specifically, this study seeks to (i) evaluate the contribution of economic, technical, environmental, institutional, and social dimensions to SSWM; (ii) examine the influence of SSWM on SE and SWMS; (iii) assess the effect of stakeholder engagement on SWMS; and (iv) test the mediating role of SE in the relationship between SSWM and SWMS. By addressing these objectives, this study provides empirical evidence for improving waste management planning, stakeholder participation, and circular economy-oriented policy implementation in Pakistan and similar developing-country contexts.

2. Materials and Methods

2.1. Conceptual Framework and Hypotheses Development

Based on the literature review and identified research gaps, this study formulates hypotheses to examine the interrelationships among the principal dimensions of sustainable solid waste management. The hypotheses are structured around three main constructs: sustainable solid waste management systems (SSWM), stakeholder engagement (SE), and solid waste management strategies (SWMS), each representing a distinct dimension of waste management systems. To ensure conceptual clarity, SSWM reflects system-level sustainability outcomes, encompassing economic, technical, environmental, institutional, and social performance. In contrast, SE represents the behavioral and participatory dimension, capturing the extent of stakeholder involvement, access to information, and collaboration in decision-making and implementation processes. SWMS, on the other hand, refers to the operational and strategic mechanisms through which waste is managed, including resource recovery, waste processing, technological adoption, and policy frameworks.

Although some dimensions may appear conceptually related, they differ in their functional roles within the framework. For instance, social factors (SO) under SSWM represent societal attitudes and acceptance of sustainable practices, whereas community contribution (CC) under SWMS reflects active participation in operational waste management activities. Similarly, operational involvement (OI) under SE captures stakeholder participation in planning and execution, while operational efficiency (OE) under SWMS represents the effectiveness of system performance. This distinction ensures that each construct captures a unique aspect of the waste management system while maintaining theoretical consistency and avoiding conceptual overlap.

Table 1 shows that the hypotheses are further subdivided into quantifiable factors under each construct. The hypotheses collectively integrate economic, technical, environmental, institutional, social, and strategic dimensions into a unified analytical framework. This study seeks to confirm the interaction and contribution of these factors to the effi-

cacy and sustainability of solid waste management practices, particularly in developing country contexts. Figure 1 illustrates the conceptual framework for sustainable solid waste management.

Table 1. Development of hypotheses.

Category	Hypothesis Statement	Supporting Literature
Sustainable Solid Waste Management Systems (SSWM)	H1a: Economic factors (EC) positively influence SSWM.	Ezeudu & Ugochukwu [9]; Alremeithi et al. [34]; Van Fan et al. [35]
	H1b: Technical factors (TE) positively influence SSWM.	Golzary et al. [12], Shanta et al. [36]; Galavote et al. [37]
	H1c: Environmental considerations (EN) positively influence SSWM.	Singh et al. [8]; Yusuf et al. [10]; Knbanaza [17], Peng et al. [38]
	H1d: Institutional capacity (IC) positively influences SSWM.	Weißert et al. [13]; Munawir et al. [39]
Stakeholder Engagement (SE)	H1e: Social factors (SO) positively influence SSWM.	Leknoi et al. [18]; Eneh [15]; Weißert et al. [13]
	H2a: Policy access (PA) positively influences SE.	Tahiru et al. [14]; Mukhlis et al. [40]
	H2b: Information access (IA) positively influences SE.	Rafiquee & Shabbiruddin [16]; Battaglia et al. [41]
	H2c: Local participation (LP) positively influences SE.	Weißert et al. [13]; Savi-Bortolotto et al. [42], Wang et al. [43]
	H2d: Stakeholder impact (SI) positively influences SE.	Tahiru et al. [14]; Knbanaza [17]
	H2e: Operational involvement (OI) positively influences SE.	Singh et al. [8]; Mersico et al. [44]
Solid Waste Management Strategies (SWMS)	H3a: Resource recovery (RR) positively influences SWMS.	Barbosa et al. [11]; Eneh [15]
	H3b: Processing of waste (PW) positively influences SWMS.	Golzary et al. [12]; Galavote et al. [37]
	H3c: Smart tools (ST) positively influence SWMS.	Rafiquee & Shabbiruddin [16]
	H3d: Waste disposal (WD) positively influences SWMS.	Yusuf et al. [10]; Knbanaza [17]
	H3e: Ecological impact (EI) influences SWMS.	Singh et al. [8]; Yusuf et al. [10]
	H3f: Financial independence (FI) positively influences SWMS.	Ezeudu & Ugochukwu [9]; Novais and Tavares [45]
	H3g: Economic gains (EG) positively influence SWMS.	Barbosa et al. [11]; Pati and Agrawal [46]
	H3h: Community education (CE) positively influences SWMS.	Eneh [15]; Leknoi et al. [18]
	H3i: Community contribution (CC) positively influences SWMS.	Singh et al. [8]; Andaya et al. [47]; Alremeithi et al. [34]
	H3j: Operational efficiency (OE) positively influences SWMS.	Kwakye et al. [19]; Suryawan et al. [48]
Inter-Construct Hypotheses	H3k: Policy framework (PF) positively influences SWMS.	Tahiru et al. [14]; Lakhout et al. [49]; Galavote et al. [37]
	H3l: Resource availability (RA) positively influences SWMS.	Knbanaza [17]; Kwakye et al. [19]
	H4: SSWM positively influences SE.	Weißert et al. [13]; Tahiru et al. [14]
	H5: SSWM positively influences SSWMS.	Barbosa et al. [11]; Golzary et al. [12]
	H6: SE positively influences SWMS.	Rafiquee & Shabbiruddin; Leknoi et al. [18]

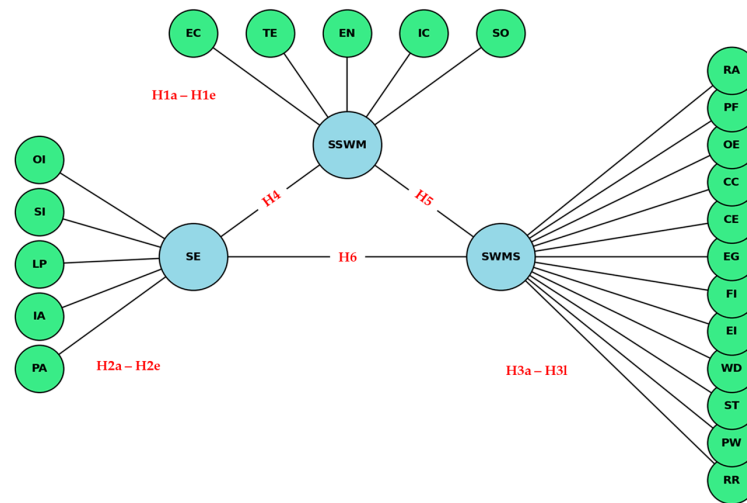


Figure 1. Conceptual framework for sustainable solid waste management.

2.2. Design of Questionnaire

The questionnaire was structured into two main sections and is provided as Supplementary File S1. The first section collected demographic and professional information from respondents, including occupation, organizational affiliation, years of experience, age, and email. This information was used to make sure that all groups of stakeholders were diverse and represented. The second part was about how to measure the study's proposed constructs (Table 1), which were SSWM, SE, and SWMS. These constructs were evaluated using a five-point Likert scale, where 1 represented "very low" and 5 represented "very high." The use of a five-point scale was based on prior studies recommendations [50], as it provides an optimal balance between response accuracy and respondent cognitive load, making it well-suited for capturing perceptions in survey-based research.

2.3. Respondent Selection and Data Collection

An intentional yet diverse sampling strategy was used to ensure that the collected responses represented the key stakeholder groups involved in sustainable solid waste management (SSWM). The inclusion of different stakeholder categories was consistent with the study's conceptual framework, which is based on three latent constructs: sustainable solid waste management systems (SSWM), stakeholder engagement (SE), and solid waste management strategies (SWMS).

Government and municipal waste management representatives were included as a key stakeholder group because they play a fundamental role in policy implementation, waste collection planning, landfill operation, recycling initiatives, resource allocation, monitoring, and enforcement of waste management regulations. Their responses were particularly important for assessing operational and strategic dimensions of SWMS, including resource recovery, process efficiency, waste disposal, policy framework, and resource availability. Health professionals contributed to the SSWM construct by highlighting the environmental and public health risks associated with ineffective waste management, including pollution, disease exposure, and community health impacts. Their responses helped reinforce the importance of environmental and social sustainability dimensions. Academics and researchers provided theoretical and empirical perspectives on sustainable waste management, particularly in relation to institutional capacity, technical feasibility, environmental performance, and the validity of the proposed conceptual framework. Representatives of non-governmental organizations (NGOs) contributed to the SE construct by emphasizing inclusivity, public awareness, access to information, and collective participation in decision-making and implementation processes. Finally, members of the general public represented the community-level perspective,

as their responses reflected household waste practices, waste segregation behavior, recycling participation, and cooperation with municipal programs.

According to the 2023 census, Peshawar's population was reported at 2,412,000 (<https://www.pbs.gov.pk/>). With a 5% margin of error and a 95% confidence level, the sample size required was found to be 384 [51]. A total of 550 questionnaires were sent through several channels, such as Google Forms, email, postal services, and in-person meetings, to make sure there was enough representation. A total of 420 valid responses were received, with a response rate of 76.36%, suitable for SEM analysis.

2.4. Structural Equation Modeling (SEM)

The SEM procedure was conducted in the following steps. First, confirmatory factor analysis (CFA) was done to make sure that the observed variables were a good fit for the latent constructs they were supposed to be. Cronbach's alpha and composite reliability (CR) were performed to check the reliability of collected data. Validity of data was analyzed through average variance extracted (AVE). The heterotrait–monotrait (HTMT) correlation ratio was used to check for discriminant validity. To analyze how well the structural model worked, the fit indices were examined. These included the Tucker–Lewis Index (TLI), Comparative Fit Index (CFI), Bentler–Bonett Normed Fit Index (NFI), Bentler–Bonett Non-Normal Fit Index (NNFI), Bollen's Incremental Fit Index (IFI), Relative Noncentrality Index (RNI), Bollen's Relative Fit Index (RFI), and Parsimony Normed Fit Index (PNFI). Standard regression coefficients at a 0.05 significance level were used to test the hypotheses. R^2 values were also computed to determine the explanatory power of each construct. All the analyses were performed on jamovi 2.7.6, an open-source statistical software.

3. Results

There were 420 valid responses collected, with municipal waste management experts comprising the largest share (47%) as shown in Figure 2. This reflects their direct involvement in planning, operational management, and oversight of solid waste management systems. Academics and researchers accounted for 24% of the respondents, providing theoretical understandings, analytical perspectives, and validation of sustainability constructs. NGO representatives comprised 17% of the sample, emphasizing their role in community mobilization, advocacy, and policy support. However, members of the general public represented 12%, confirming the presence of household-level behaviors, societal attitudes, and citizen perspectives on waste management. The balanced mix of professional experts and community voices makes the findings more representative and reliable because it includes both technical knowledge and real-life experiences.

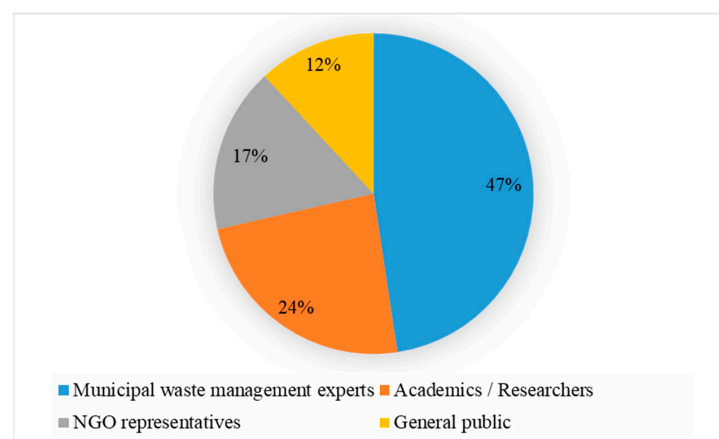


Figure 2. Received responses (%).

3.1. Confirmatory Factor Analysis (CFA)

CFA results are summarized in Table 2. It shows that the latent variables and their respective indicators shape SSWM, SE, and SWMS. All factor loadings exceeded the minimum threshold of 0.40 [52], indicating that each indicator meaningfully contributes to its underlying construct; therefore, no item was excluded from the analysis.

Table 2. Summary of confirmatory factor analysis.

Construct/Latent Variable	Indicator	Factor Loading (Estimate)	Z-Value	Probability (p)-Value	Cronbach's Alpha	Composite Reliability (CR)	Average Variance Extracted (AVE)
SSWM	EC	0.585	17.4	<0.001	0.85	0.83	0.64
	TE	0.547	16.3	<0.001			
	EN	0.516	15.9	<0.001			
	IC	0.524	15.8	<0.001			
	SO	0.543	16.2	<0.001			
SE	PA	0.487	14.8	<0.001	0.81	0.79	0.55
	IA	0.529	15.4	<0.001			
	LP	0.528	15.5	<0.001			
	SI	0.496	14.3	<0.001			
	OI	0.45	12.7	<0.001			
	RR	0.523	16.2	<0.001			
	PW	0.455	14.2	<0.001			
	ST	0.518	15.4	<0.001			
	WD	0.412	12	<0.001			
	EI	0.432	12.9	<0.001			
SWMS	FI	0.485	14.8	<0.001	0.90	0.91	0.52
	EG	0.469	14.2	<0.001			
	CE	0.483	14.7	<0.001			
	CC	0.527	15.3	<0.001			
	OE	0.497	15	<0.001			
	PF	0.484	14.5	<0.001			
	RA	0.546	16.5	<0.001			

The economic (EC), technical (TE), environmental (EN), institutional (IC), and social (SO) dimensions of the SSWM construct all had factor loadings between 0.516 and 0.585, and the Z-values were very high, ranging from 15.8 to 17.4 ($p < 0.001$). The SE construct also had significant positive loadings, with values between 0.450 and 0.529 for indicators like participation (PA), information access (IA), local partnership (LP), stakeholder influence (SI), and organizational involvement (OI). The SWMS construct also had factor loadings between 0.412 and 0.546, and indicators like recycling and reuse (RR), waste disposal (WD), energy initiatives (EI), and resource allocation (RA) all showed statistically significant relationships.

Cronbach's alpha values ranged from 0.81 to 0.90 (SE and SWMS, respectively), exceeding the recommended cutoff of 0.70 [53]. In addition, CR values ranged from 0.79 to 0.91 across all constructs, meeting Hair et al. [54]'s benchmark of 0.70. The results suggest that these constructs dominate high internal consistency. Additionally, the AVE for SSWM, SE, and SWMS demonstrated convergent validity, yielding AVE values of 0.64, 0.55, and 0.52, respectively. It shows that a substantial proportion of variance in the observed indicators can be explained by latent constructs as all AVE values exceeded 0.50. So, based on these results, it can be concluded that the proposed model is robustly supported, providing confidence in its use in SEM analysis and hypothesis testing.

3.2. Heterotrait–Monotrait (HTMT) Ratio of Correlations

To assess discriminant validity, the HTMT ratio was used. HTMT assesses the degree to which latent constructs are different from one another. The values below 0.90 are indicative of satisfactory discriminant validity as suggested by Gold et al. [55]. The HTMT ratios computed in this study are presented in Table 3 for the latent constructs. It shows that SSWM and SE have HTMT values of 0.54; SSWM and SWMS have HTMT values of 0.55. Correspondingly, SE and SWMS have HTMT values of 0.58. These values are well below the threshold of 0.90, indicating a sufficient degree of distinctness and lack of multicollinearity. These results provide robust evidence of discriminant validity, affirming that each construct represents various aspects of sustainable solid waste management without significant overlap.

Table 3. Discriminant validity using the heterotrait–monotrait ratio of correlations (HTMT) ratio.

Latent	SSWM	SE	SWMS
SSWM	1	0.54	0.55
SE	0.54	1	0.58
SWMS	0.55	0.58	1

3.3. Model Fit Indices

The assessment of model fit, as summarized in Table 4, shows that the SEM fits the observed data very well. According to Hu and Bentler [56], values above 0.90 are generally considered acceptable, while values exceeding 0.95 reflect a strong model fit. CFI reached a value of 0.999, which means that the proposed model explains the observed covariances very well. The TLI and NNFI both showed values of 0.999, which means that the model is still strong even after accounting for complexity. The RNI (0.999) backs this up even more by showing that it almost perfectly matches the data. The NFI (0.995) and RFI (0.994) also went above the 0.90 mark, which means they did a lot better than a null model. The IFI, which is also 0.999, support these results by showing that almost all possible improvements in explaining covariance have been made. The PNFI was 0.887, which is a little less than 0.90 but still in an acceptable range. This shows that the model strikes a good balance between fit and parsimony. These results show substantial evidence that the proposed model exhibits exceptional goodness of fit, thereby affirming the structural relationships among the latent constructs.

Table 4. Summary of model fit statistics.

	Model
CFI—Comparative Fit Index	0.999
TLI—Tucker–Lewis Index	0.999
NNFI—Non-Normed Fit Index (Bentler–Bonett)	0.999
RNI—Relative Noncentrality Index	0.999
NFI—Normed Fit Index (Bentler–Bonett)	0.995
RFI—Relative Fit Index (Bollen)	0.994
IFI—Incremental Fit Index (Bollen)	0.999
PNFI—Parsimony-Adjusted NFI	0.887

3.4. Structural Model Assessment

The structural model was evaluated through standardized regression weights (β), 95% confidence intervals, z-statistics, and R^2 values, which together indicate the explanatory power and predictive accuracy of the latent constructs. The results are summarized in Table 5, while Figure 3 shows the illustration of the model with a path diagram. Mostly,

all observed indicators demonstrated statistically significant loadings ($p < 0.001$), thereby supporting the hypothesized relationships across all constructs. For SSWM, the results reveal that economic (EC), technical (TE), environmental (EN), institutional (IC), and social (SO) factors are all significant contributors, with β ranging between 0.776 and 0.817. The R^2 values for these indicators (0.602–0.667) highlight their strong explanatory power in capturing the multidimensional nature of SSWM. Therefore, hypotheses H1a–H1e are supported, confirming that sustainability in waste management depends on the integration of economic efficiency, technological capacity, environmental considerations, institutional strength, and social acceptance.

Table 5. Summary of hypothesis testing results from structural equation modeling.

Construct/Latent Variable	Indicator (Hypothesis)	Estimate	β	β 95% Confidence Intervals		z	p-Value	R^2	Hypothesis Remarks
				Lower	Upper				
SSWM	EC (H1a)	1.000	0.817	0.762	0.872	-	-	0.667	Supported
	TE (H1b)	0.956	0.781	0.719	0.843	19.5	<0.001	0.610	Supported
	EN (H1c)	0.976	0.797	0.733	0.861	19.1	<0.001	0.635	Supported
	IC (H1d)	0.950	0.776	0.713	0.839	19.1	<0.001	0.602	Supported
	SO (H1e)	0.994	0.812	0.751	0.872	19.9	<0.001	0.659	Supported
SE	PA (H2a)	1.000	0.743	0.674	0.812	-	-	0.552	Supported
	IA (H2b)	1.049	0.779	0.712	0.847	15.7	<0.001	0.607	Supported
	LP (H2c)	1.061	0.788	0.722	0.855	15.4	<0.001	0.622	Supported
	SI (H2d)	0.992	0.737	0.665	0.809	14.2	<0.001	0.543	Supported
	OI (H2e)	0.884	0.657	0.574	0.740	12.5	<0.001	0.432	Supported
SWMS	RR (H3a)	1.000	0.773	0.721	0.825	-	-	0.598	Supported
	PW (H3b)	0.918	0.710	0.644	0.776	18.3	<0.001	0.504	Supported
	ST (H3c)	0.967	0.748	0.694	0.802	22.3	<.001	0.559	Supported
	WD (H3d)	0.802	0.620	0.546	0.695	15.8	<0.001	0.385	Supported
	EI (H3e)	0.846	0.655	0.583	0.726	16.4	<0.001	0.428	Supported
	FI (H3f)	0.937	0.725	0.661	0.788	19.1	<0.001	0.525	Supported
	EG (H3g)	0.897	0.694	0.621	0.766	16.4	<.001	0.481	Supported
	CE (H3h)	0.944	0.730	0.670	0.789	19.1	<0.001	0.532	Supported
	CC (H3i)	0.941	0.728	0.673	0.783	22.1	<0.001	0.530	Supported
	OE (H3j)	0.939	0.726	0.666	0.786	18.7	<0.001	0.527	Supported
	PF (H3k)	0.924	0.714	0.651	0.777	18.7	<0.001	0.510	Supported
	RA (H3l)	1.020	0.789	0.741	0.837	24.7	<0.001	0.623	Supported

In the case of SE, the indicators policy access (PA), information access (IA), local participation (LP), stakeholder impact (SI), and operational involvement (OI) all demonstrated significant positive effects, with loadings between 0.657 and 0.788. The R^2 values, however, were slightly lower compared to SSWM, ranging from 0.432 to 0.622. Among these, OI showed the weakest explanatory power ($R^2 = 0.432$), suggesting that while engagement mechanisms are in place, direct stakeholder participation remains a challenge. However, all five hypotheses (H2a–H2e) were supported, affirming that SE is a critical enabler in sustainable waste management processes.

For SWMS, twelve indicators were examined, including resource recovery (RR), waste processing (PW), smart tools (ST), waste disposal (WD), ecological impact (EI), financial independence (FI), economic gains (EG), community education (CE), community contribution (CC), operational efficiency (OE), policy framework (PF), and resource availability (RA). All indicators significantly influenced SWMS with factor loadings between 0.620 and 0.789. The R^2 values varied between 0.385 and 0.623, where WD showed the lowest explanatory power, while RA appeared as the strongest contributor. These results provide robust support for hypotheses H3a–H3l, highlighting that those comprehensive strategies,

supported by both technical and socio-economic dimensions, are necessary for effective waste management practices.

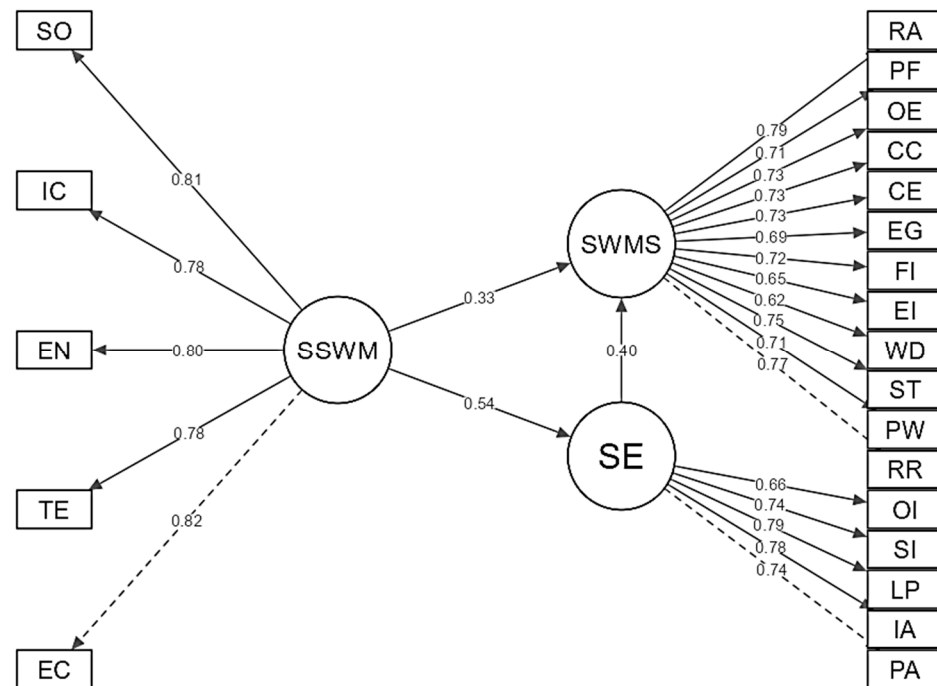


Figure 3. Structural equation model (SEM) path diagram showing standardized path coefficients (β) between latent constructs and their observed indicators.

3.5. Structural Path and Mediation Analysis

The structural model results provide strong support for the hypothesized relationships among the latent constructs, as presented in Table 6. The path from SSWM to SE is positive and statistically significant ($\beta = 0.543, p < 0.001$), indicating that sustainability-oriented waste management systems significantly enhance stakeholder engagement. The magnitude of this relationship suggests that improvements in system-level sustainability dimensions contribute to increased participation, information exchange, and collaboration among stakeholders.

Table 6. Structural path and mediation effects.

Effect	Paths	Estimate	β	95% Confidence Intervals		Z	p	Hypothesis Remarks
				Lower	Upper			
Direct	SSWM \rightarrow SE (H4)	0.493	0.543	0.396	0.590	9.97	<0.001	Supported
	SE \rightarrow SWMS (H6)	0.421	0.405	0.305	0.538	7.08	<0.001	Supported
	SSWM \rightarrow SWMS (H5)	0.314	0.331	0.212	0.416	6.04	<0.001	Supported
Indirect	SSWM \rightarrow SE \rightarrow SWMS	0.208	0.220	0.145	0.271	6.456	<0.001	Significant (Partial mediation)
Total	SSWM \rightarrow SWMS	0.522	0.551	0.434	0.609	11.676	<0.001	Significant

Similarly, the path from SSWM to SWMS is significant ($\beta = 0.331, p < 0.001$), demonstrating that SSWM directly influences the development and implementation of waste management strategies. This confirms the role of sustainability systems as key drivers of strategic actions, where enhanced institutional, economic, and environmental capacities translate into more effective operational practices. The relationship between SE and SWMS is also positive and statistically significant ($\beta = 0.405, p < 0.001$). This indicates

that stakeholder engagement plays a central role in strengthening the effectiveness of waste management strategies, contributing more strongly than the direct influence of SSWM alone.

In addition to the direct effects, the mediation analysis reveals a significant indirect pathway from SSWM to SWMS through SE ($\beta = 0.220$, $p < 0.001$). This indicates that SSWM influences SWMS not only directly but also indirectly by enhancing stakeholder engagement. The total effect of SSWM on SWMS remains significant ($\beta = 0.551$, $p < 0.001$), confirming the combined influence of both direct and mediated relationships. The presence of significant direct and indirect effects indicates partial mediation, where SE serves as an important mechanism linking sustainability systems to strategic waste management outcomes.

4. Discussion

The findings of this study provide a comprehensive understanding of the complex interrelationships among sustainable solid waste management systems (SSWM), stakeholder engagement (SE), and solid waste management strategies (SWMS). The validated SEM framework demonstrates strong measurement and structural properties, confirming the multidimensional nature of SSWM and highlighting the combined importance of institutional capacity and community-driven participation in achieving sustainability outcomes.

A key understanding from the results is the significant influence of SSWM dimensions, particularly economic and social factors, in shaping sustainability performance. The standardized regression weights indicate that the economic dimension ($\beta = 0.817$, $R^2 = 0.667$) and social dimension ($\beta = 0.812$, $R^2 = 0.659$) are the most influential contributors. This suggests that effective waste management systems must ensure financial viability, affordability, and community-oriented approaches. These findings are consistent with Mishra and Das [57], who emphasized that cost-effectiveness and societal inclusion are fundamental to sustainable urban waste management. Similarly, He et al. [58] highlighted that neglecting social engagement can undermine otherwise technically efficient systems, reinforcing the importance of integrating social dimensions into sustainability frameworks.

Stakeholder engagement (SE) also emerges as a critical component, with local participation (LP, $\beta = 0.788$, $R^2 = 0.622$) and information access (IA, $\beta = 0.779$, $R^2 = 0.607$) identified as the strongest predictors. These results emphasize the importance of inclusive governance structures and transparent communication in building trust and encouraging compliance among stakeholders. Fontaine et al. [59] and Muheirwe et al. [60] similarly emphasized that participatory mechanisms enhance collaboration among municipalities, private entities, and communities, leading to improved waste collection, recycling, and disposal outcomes. However, the relatively lower explanatory power of operational involvement (OI, $\beta = 0.657$, $R^2 = 0.432$) indicates that while stakeholders are increasingly involved in decision-making processes, their direct participation in operational activities remains limited. This observation aligns with Leknoi et al. [61], who emphasized that active community involvement in practices such as waste segregation and local monitoring is essential for long-term sustainability.

The analysis of SWMS further highlights the importance of resource availability (RA, $\beta = 0.789$, $R^2 = 0.623$) and smart tools (ST, $\beta = 0.748$, $R^2 = 0.559$) as key enablers of efficient waste management. These findings reflect a transition from traditional disposal-oriented systems toward resource-efficient and technology-driven approaches. Marshall and Safferman et al. [62] similarly emphasized that investments in advanced processing technologies, such as composting, anaerobic digestion, and digital monitoring systems, significantly reduce reliance on landfills and improve operational efficiency. In contrast, the relatively lower explanatory power of waste disposal (WD, $\beta = 0.620$, $R^2 = 0.385$) suggests

that disposal remains a weak component within sustainability frameworks. This supports the perspective of Awino et al. [63], who argued that landfilling should be considered the least preferred option within integrated waste management hierarchies.

The structural relationships further confirm the interconnected nature of the proposed framework. SSWM significantly influences both SE ($\beta = 0.543, p < 0.001$) and SWMS ($\beta = 0.551, p < 0.001$), indicating that well-structured sustainability systems enhance stakeholder participation while simultaneously strengthening strategic waste management practices. Moreover, SE exerts the strongest influence on SWMS ($\beta = 0.584, p < 0.001$), highlighting the central role of participatory governance in translating sustainability principles into operational outcomes. When stakeholders are actively involved in planning and decision-making processes, waste management strategies become more effective, transparent, and sustainable. These findings are supported by Cox et al. [64] and Etim et al. [65], who demonstrated that awareness initiatives and participatory approaches significantly improve waste segregation and recycling performance.

Importantly, the mediation analysis reveals that SSWM influences SWMS both directly and indirectly through SE, confirming the presence of partial mediation. This indicates that while system-level improvements play a direct role in enhancing waste management strategies, their effectiveness is further amplified through stakeholder engagement. This complementary relationship highlights the importance of integrating institutional capacity with participatory governance mechanisms to achieve sustainable outcomes. Such an integrated dynamic is consistent with the framework proposed by UN-Habitat [66], which emphasizes that long-term sustainability is achieved through the synergy between structured systems and community involvement.

Beyond the empirical findings, this study provides several practical implications for Pakistan's municipal solid waste management system. Municipal authorities should prioritize financial sustainability through dedicated waste-management budgets, improved cost-recovery mechanisms, subsidies, and extended producer responsibility schemes where feasible. In addition, strengthening institutional coordination, transparent decision-making, and stakeholder participation can improve public trust and implementation effectiveness. Investments in source segregation, recycling facilities, composting, smart monitoring tools, and circular economy practices are also essential to reduce dependence on landfilling and improve system efficiency. However, these measures require addressing local barriers such as institutional fragmentation, weak enforcement, limited technical capacity, unstable financing, and low public trust. These recommendations align with Bittencourt et al. [67], who emphasized the importance of adaptive management and iterative feedback systems in delivering sustainable urban services.

In summary, the findings highlight that sustainable waste management requires a multidimensional approach that simultaneously integrates economic, social, technological, and governance factors. By embedding stakeholder engagement within system design and implementation, municipalities can achieve not only environmental sustainability but also broader socio-economic benefits, including improved public health, job creation, resource efficiency, and enhanced urban resilience.

5. Conclusions

This study developed and empirically validated an integrated structural equation modeling (SEM) framework to examine the interrelationships among sustainability dimensions, stakeholder engagement, and solid waste management strategies in a developing-country context, with empirical evidence from Pakistan. The findings confirm that sustainable solid waste management is inherently multidimensional and is shaped by the combined influence of economic, technical, environmental, institutional, and social factors. Among

these dimensions, economic viability and social acceptance emerged as the most influential determinants of sustainability performance.

The structural model demonstrates that sustainable solid waste management systems (SSWM) significantly influence both stakeholder engagement (SE) and solid waste management strategies (SWMS). In addition, SE significantly strengthens SWMS, confirming the importance of participatory governance in translating sustainability principles into practical waste management outcomes. The mediation analysis further reveals that SE partially mediates the relationship between SSWM and SWMS, indicating that stakeholder participation acts as a key mechanism through which system-level improvements are converted into effective operational strategies.

The main contribution of this study lies in integrating sustainability dimensions, stakeholder engagement, and waste management strategies into a single empirically validated SEM framework. Unlike studies that examine isolated technical, institutional, or environmental aspects, this study demonstrates how these dimensions interact within a unified model. The findings are particularly relevant for Pakistan, where solid waste management is constrained by limited municipal finance, weak institutional coordination, inadequate recycling infrastructure, low public participation, and reliance on disposal-based practices.

From a practical perspective, the findings suggest that policymakers and urban managers should prioritize financial sustainability, institutional strengthening, inclusive stakeholder participation, source segregation, recycling facilities, composting, smart monitoring tools, and circular economy practices. These measures can help reduce dependence on landfilling and improve resource recovery, public health, and urban resilience. However, successful implementation requires addressing local barriers such as institutional fragmentation, weak enforcement, limited technical capacity, unstable financing, and low public trust.

Despite its contributions, this study has some limitations. The data were collected from a single geographic context, which limits direct generalization to other cities or developing countries. The cross-sectional survey design also restricts the ability to infer long-term causal relationships among SSWM, SE, and SWMS. In addition, this study did not conduct subgroup SEM comparison or additional robustness checks such as marker-variable testing for common method bias. Future research should validate the framework across multiple cities and countries, use longitudinal data, include informal waste pickers and other stakeholder subgroups more explicitly, and apply multi-group SEM, sensitivity analysis, clustering, Bayesian networks, or predictive modeling to capture dynamic sustainability transitions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18136405/s1>, File S1: Questionnaire used for data collection.

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Institutional Review Board Statement: The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and was reviewed by the Secretary Board of Advanced Studies and Research (BOASAR), University of Engineering and Technology Peshawar, Pakistan. Based on the anonymous, voluntary, questionnaire-based nature of the study, and because it did not involve clinical intervention, medical treatment, biological samples, vulnerable participants, invasive

procedures, or the collection of personally identifiable information, the study was considered minimal risk and was exempted from full ethical review. The ethical review exemption/waiver was issued by BOASAR, UET Peshawar, under reference No. 293/BOASAR/UET. Informed consent was obtained from all participants prior to participation.

Informed Consent Statement: Informed consent was obtained during filling of questionnaire from all subjects involved in the study. The questionnaire is provided as supplemental attachments.

Data Availability Statement: The supporting data is uploaded to Mendely Data repository. <https://data.mendeley.com/datasets/5tc5nm5wy/1> (accessed on 1 September 2025).

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