



Digitalization-Environment Nexus: Dual Pathways Transforming Waste Management into Sustainable Development in Pakistan

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Abstract

Rapid urbanization in developing countries intensifies solid waste management (SWM) challenges. However, the parallel mechanisms through which SWM drives sustainable development remain underexplored, particularly how environmental practices and digitalization each independently transmit this effect. This study examines how environmental practices and digitalization, individually and jointly as parallel mediators, transmit SWM's effect on sustainable development within developing-economy public utilities. A quantitative, cross-sectional survey was administered to 406 employees across seven Water and Sanitation Companies (WASAs) in Khyber Pakhtunkhwa, Pakistan—structural Equation Modeling with bootstrapping procedures tested direct and indirect effects. SWM positively and significantly influenced sustainable development ($\beta = .41$, $p < .001$). Environmental practices and digitalization each significantly and partially mediated this relationship (specific indirect effects of .13 and .12, respectively), and the total indirect effect transmitted jointly through both parallel pathways was .25 (the sum of the two specific effects), which was also significant. These results indicate that environmental practices and digitalization function as two distinct, additive mediating mechanisms rather than as a statistically interacting or synergistic pair; no interaction term or serial-mediation path was estimated, so no claim of synergy or amplification is made. This study is among a relatively small number to model environmental practices and digitalization jointly, as parallel mediators, within a single structural model in a developing-economy public-utility context, offering evidence that resource-constrained municipalities can strengthen sustainability outcomes by investing in both mechanisms concurrently rather than treating them as substitutes.

Keywords: *Solid Waste Management, Sustainable Development, Digitalization, Environmental Practices, Circular Economy, Public Utilities, Structural Equation Modeling*

INTRODUCTION

The imperative for sustainable development has emerged as a defining challenge of the twenty-first century, compelling governments, businesses, and societies globally to confront the ecological, social, and economic repercussions of escalating industrialization and urbanization (World Bank, 2010). In this landscape, solid waste management (SWM) is a critical concern for developing countries (Addas et al., 2024; Maalouf & Agamuthu, 2023).

Mismanaged waste contributes to soil contamination, greenhouse gas emissions, and public health hazards, while also undermining social well-being and economic efficiency (Awino & Apitz, 2024; Yatoo et al., 2024). The World Bank projects a 70% increase in global waste generation by 2050, with low- and middle-income nations disproportionately affected (Kaza et al., 2018; Maalouf & Agamuthu, 2023; Yatoo et al., 2024).

Pakistan generates over 48.5 million tons of waste annually; roughly half is collected, and a substantial share remains untreated (Maalouf & Agamuthu, 2023; Shah et al., 2025). This situation contrasts with global frameworks such as the United Nations 2030 Agenda, particularly Goal 11 (sustainable cities and communities) and Goal 12 (responsible consumption and production),

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which position effective SWM as central to long-term sustainability (Awino & Apitz, 2024; Louis, 2004; Maalouf et al., 2020; Maalouf & Agamuthu, 2023; United Nations, 2022).

A growing body of scholarship argues that SWM cannot be treated as an isolated municipal function; instead, it should be examined alongside environmental practices and digital tools (Addas et al., 2024; Idrissi et al., 2025; Zyoud & Zyoud, 2025). Environmental practices, pollution prevention, regulatory compliance, and staff training are theorized to translate operational waste-handling routines into ecological outcomes (Daily et al., 2012).

Digitalization dashboards, route optimization, tracking systems, and citizen-facing applications are theorized to improve transparency, efficiency, and stakeholder engagement across waste-management systems (Bressanelli et al., 2017; Centobelli et al., 2020; Rosa et al., 2020). Because both mechanisms plausibly operate alongside SWM in the same organizations, this study evaluates them jointly, within a single statistical model, as two separate and additive (parallel) pathways rather than assuming in advance that they interact or reinforce one another; whether such an interaction exists is an empirical question this design does not test, and this scope boundary is stated explicitly rather than implied.

To provide a theoretical scaffold, the study draws on three complementary perspectives: the Resource-Based View (RBV), Stakeholder Theory, and the Circular Economy (CE) framework. Each perspective is mapped, in the Literature Review, to a specific causal path in the model rather than treated as generally applicable background theory; this mapping is intended to address the more general question of why three theories are needed and what each one specifically explains.

Four distinct, if related, gaps motivate this study. The empirical gap concerns the limited number of published studies that examine environmental practices and digitalization together, using primary survey data from public utilities in a developing-economy setting such as Pakistan. The theoretical gap concerns the absence, in prior work, of an explicit mapping between RBV, Stakeholder Theory, and CE and the individual causal paths of a combined SWM–ENV–DIG–SD model; without such a mapping, it is difficult to know which theory is doing which explanatory work.

The mechanism gap concerns whether environmental practices and digitalization should be modeled as two independent (parallel) mediators or as sequential (serial) or interacting mediators; prior studies have generally tested each mediator in a separate single-mediator model, which cannot distinguish between these possibilities. The practical gap is the lack of comparative evidence on the relative magnitude of the two pathways, which managers need to allocate limited resources between environmental and digital investments.

The present study addresses these four gaps by estimating environmental practices and digitalization as parallel mediators within one structural model, reporting each specific indirect effect separately as well as their total (summed) contribution, and by refraining from characterizing that sum as evidence of synergy or interaction unless a corresponding interaction or moderated-mediation term is estimated.

Empirically, the study draws on a quantitative, cross-sectional survey of 406 employees across seven Water and Sanitation Service Companies (WSSCs) operating in Pakistan's Khyber Pakhtunkhwa province. The study used Structural Equation Modeling (SEM) to test the hypothesized direct and mediated relationships. This context is relevant because Pakistan, like many developing countries, faces inadequate infrastructure, fragmented waste segregation, and constrained financial resources (Iqbal & Khan, 2023), while policymakers and managers increasingly recognize that durable sustainability requires integrating environmental stewardship with digital transformation rather than pursuing either in isolation (Asim et al., 2022).

In light of these gaps, the study addresses three research questions: (1) To what extent does solid waste management influence sustainable development? (2) How do environmental practices

and digitalization, modeled as parallel mediators, individually and jointly transmit the effect of SWM on sustainable development? (3) What theoretical and practical implications follow from testing environmental practices and digitalization together, as parallel rather than assumed-synergistic mechanisms, in a developing-economy public-utility context?

The study's contribution is therefore framed around the mechanism actually tested: two additive, parallel mediating pathways, rather than a claim of complementarity or synergistic amplification, which would require a different statistical specification.

Research Objectives

Corresponding to these three research questions, the study pursues three research objectives, each of which is addressed directly by a specific part of the Results, Discussion, or Conclusion reported below: (RO1) to determine the extent to which solid waste management exerts a direct effect on sustainable development, tested through H1 and reported in the Results (Table 5); (RO2) to determine how environmental practices and digitalization, modeled as parallel mediators, individually and jointly transmit the effect of solid waste management on sustainable development, tested through H2, H3, and H4 and reported in the Results (Tables 5 and 6); and (RO3) to identify the theoretical and practical implications that follow from testing environmental practices and digitalization as parallel, rather than assumed-synergistic, mechanisms in a developing-economy public-utility context, addressed in the Theoretical Implications and Practical Implications subsections of the Conclusion. The Results section reports findings for all three objectives, confirming that the study's empirical scope matches what it sets out to achieve.

LITERATURE REVIEW

Solid Waste Management and Sustainable Development

Solid waste management (SWM) is increasingly recognized as a driver of sustainable development, particularly in rapidly urbanizing societies ([Ali et al., 2021](#); [Kaza et al., 2018](#)). Effective SWM contributes to environmental protection, economic efficiency, and social well-being, reflecting the triple-bottom-line logic of economic, social, and environmental performance ([Elkington, 1998](#); [Alhaddi, 2019](#)).

Inadequately managed waste, by contrast, has been linked to soil and water contamination, elevated greenhouse gas emissions, and reduced urban quality of life ([Ferronato & Torretta, 2019](#); [Marshall & Farahbakhsh, 2013](#)). Integrated SWM approaches that prioritize recycling, re-use, and recovery reduce environmental damage while generating employment and enhancing urban competitiveness ([Marshall & Farahbakhsh, 2013](#)).

These challenges are pronounced in Pakistan, where limited infrastructure, weak regulatory frameworks, and constrained financial resources compound systemic issues ([Iqbal & Khan, 2023](#)). Embedding SWM into organizational strategy allows municipalities to contribute to the Sustainable Development Goals while strengthening organizational legitimacy ([Guerrero et al., 2013](#); [United Nations, 2022](#)).

H1: Solid waste management has a positive and significant effect on sustainable development.

Environmental Practices as a Mediator

Environmental practices include organizational routines, policies, and initiatives that mitigate environmental harm and ensure compliance with environmental standards, such as pollution prevention, waste minimization, resource efficiency, and staff environmental training ([Daily et al., 2012](#)). Organizations that adopt certified environmental management systems, such as ISO 14001, are better positioned to turn waste-management efforts into competitive advantage and

sustainability outcomes (Testa et al., 2014).

Within public-sector organizations, stringent environmental practices have been shown to improve service quality, build stakeholder trust, and support regulatory compliance (Zhang et al., 2020). At the same time, superficial adoption of environmental certification without genuine enforcement risks greenwashing rather than substantive ecological improvement (Testa et al., 2014), a caveat this study keeps in mind when interpreting self-reported environmental-practice scores. In developing-country contexts, environmental training is a comparatively low-cost way to strengthen SWM's sustainability impact (Asim et al., 2022).

H2: Environmental practices mediate the relationship between solid waste management and sustainable development.

Digitalization as a Mediator

Digitalization reshapes sustainability transitions by enabling organizations to reconfigure processes, improve operational efficiency, and strengthen stakeholder engagement (Bressanelli et al., 2017; Rosa et al., 2020). In waste management specifically, Geographic Information Systems (GIS), the Internet of Things (IoT), mobile applications, and data dashboards are used to optimize collection routes, track waste volumes, and increase transparency (Bressanelli et al., 2017; Centobelli et al., 2020; Rosa et al., 2020).

In developing countries, lightweight digital tools, such as citizen-facing applications for reporting waste issues, can improve service quality without major infrastructure investment (Centobelli et al., 2020). Digitalization alone, however, does not resolve structural governance problems; without institutional reform and capacity-building, digital adoption risks creating superficial efficiencies or digital divides (Idrissi et al., 2025). Digitalization also aligns with circular-economy principles by improving the traceability of material flows and supporting recycling and reuse (Kumar et al., 2021).

H3: Digitalization mediates the relationship between solid waste management and sustainable development.

Combined (Parallel) Mediation

Because environmental practices and digitalization are both plausible transmission mechanisms between SWM and sustainable development, this study estimates them together in a single structural model as parallel mediators: each mediator receives a direct path from SWM and sends an independent direct path to sustainable development, with no hypothesized path linking the two mediators to one another and no interaction term between them.

Under this specification, the joint contribution of the two mediators is captured by the total indirect effect, defined as the sum of the two specific indirect effects (SWM→ENV→SD and SWM→DIG→SD). This is a materially different and more modest claim than a claim of statistical interaction, synergy, or serial mediation, and the hypothesis is stated accordingly.

H4: Environmental practices and digitalization function as parallel mediators of the solid waste management–sustainable development relationship, such that the total indirect effect transmitted jointly through both pathways is statistically significant.

This study does not test, and therefore does not claim, that environmental practices and digitalization interact, reinforce, or amplify one another beyond the additive sum of their individual effects; establishing such an interaction would require an explicit interaction term or a moderated-

mediation index, which is identified below as a direction for future research rather than a claim made by the present model.

Theory to Hypothesis Mapping

To clarify why three theoretical perspectives are invoked and what each one specifically explains, Table 0 maps each causal path in the model to the theoretical mechanism that motivates it.

Path	Hypothesis	Theoretical mechanism
SWM → ENV	(component of H2)	RBV: routinized SWM operations generate the internal resources and managerial attention from which formal, VRIN-type environmental practices are built (Barney, 1991).
SWM → DIG	(component of H3)	RBV / dynamic capabilities: operational waste data and processes create the demand and organizational readiness for digital tools (Teece, 2018).
ENV → SD	(component of H2)	Stakeholder Theory: environmental compliance and transparency build legitimacy and trust with regulators, communities, and employees (Freeman et al., 2010).
DIG → SD	(component of H3)	Circular Economy: digital traceability of material flows enables recycling, reuse, and recovery, generating measurable sustainability outcomes (Kirchherr et al., 2018).
ENV + DIG → SD (total, parallel)	H4	RBV: two distinct VRIN-type resources jointly raise the organization's total capability base; their combined magnitude is additive under this specification, not multiplicative or interactive (Barney, 1991).

Theoretical Framework

This study is grounded in three complementary theoretical perspectives, each mapped above to a specific path. The Resource-Based View (RBV) posits that organizations gain competitive advantage through valuable, rare, inimitable, and non-substitutable resources ([Barney, 1991](#)); here, environmental practices and digital capabilities are treated as two such resources that build on SWM operations and jointly, but additively, enhance sustainability outcomes.

Stakeholder Theory holds that organizations must account for the interests of multiple stakeholders, including governments, communities, employees, and customers ([Freeman et al., 2010](#)); environmental practices and digital tools are each theorized to build legitimacy and trust through different channels: regulatory compliance and transparency, respectively.

The Circular Economy (CE) framework emphasizes resource recovery, re-use, and recycling as strategies for long-term sustainability ([Kirchherr et al., 2018](#)); digitalization is theorized to enable the traceability that CE strategies require. Together, these perspectives explain why SWM, environmental practices, and digitalization are theoretically connected, while the parallel-mediation specification tested here determines the empirical form that connection takes.

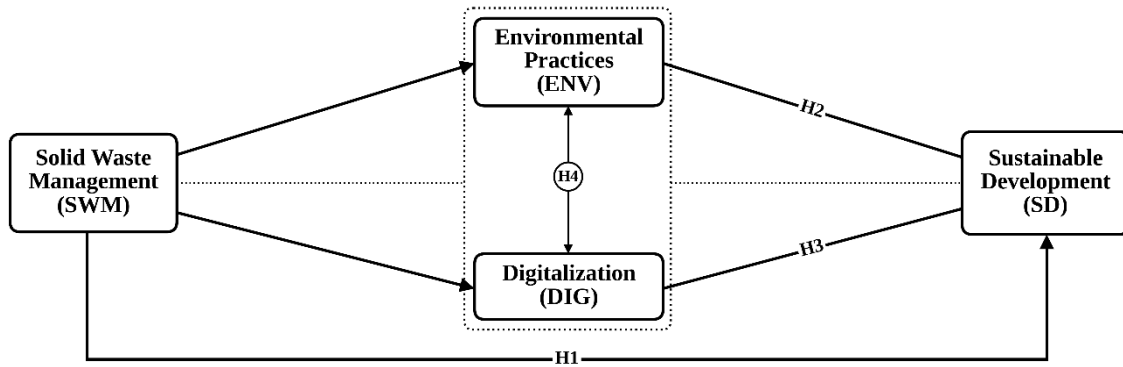


Figure 1. Theoretical Framework

RESEARCH METHOD

Research Design and Sampling

This study employed a quantitative, cross-sectional research design to test the hypothesized relationships between solid waste management (SWM), sustainable development (SD), environmental practices (ENV), and digitalization (DIG). The study used a quantitative paradigm because it is well suited to measuring latent constructs with validated instruments and testing hypotheses through statistical modeling (Creswell & Creswell, 2018).

A cross-sectional design provides a snapshot of organizational practices and sustainability outcomes but cannot establish the temporal ordering that causal claims, or formally, mediation claims, require; associations reported below should be read as concurrent statistical relationships consistent with the hypothesized theory rather than as proof of causal sequence (Levin, 2006).

The target population comprised employees of seven Water and Sanitation Companies (WASAs) operating in Khyber Pakhtunkhwa (KPK) province, the region's primary institutions responsible for municipal water supply, sewerage, and solid waste management. Human-resource rosters obtained from the seven WASAs indicated a combined workforce of approximately 3,850 permanent and contractual employees at the time of data collection.

Employees were stratified into three hierarchical strata: management/officers (approximately 12% of the workforce, $n \approx 460$), supervisory staff (approximately 23%, $n \approx 890$), and frontline/operational personnel (approximately 65%, $n \approx 2,500$), and proportional allocation was applied within each WASA so that the number of questionnaires distributed to each stratum matched its share of that WASA's workforce.

Within each stratum, respondents were selected using random selection from the HR roster. With a population of approximately 3,850, Krejcie and Morgan's (1970) table indicates a minimum required sample of 350 for a 95% confidence level; 450 questionnaires were distributed across the seven WASAs to accommodate anticipated non-response, and 406 usable responses were obtained, a response rate of 90.2%. This high response rate reflects the institutional support obtained from WASA management and the researchers' direct engagement with local officials during distribution.

Measurement Instrument

The survey instrument was developed by adapting items from established, validated scales, with wording modified only to fit the WASA organizational context (e.g., substituting generic organizational terms with WASA-specific terminology); no items were newly written or reverse-scored. Two bilingual subject-matter experts forward-translated the items into Urdu, and an independent third translator back-translated them into English; they resolved discrepancies through discussion before pilot testing.

A five-point Likert scale, ranging from 1 ("strongly disagree") to 5 ("strongly agree"), was

used throughout. Solid Waste Management (SWM) was measured with eight items adapted from [Guerrero et al. \(2013\)](#) and [Marshall and Farahbakhsh \(2013\)](#), covering collection efficiency, disposal practices, source segregation, and recycling. Sustainable Development (SD) was measured with nine items spanning three three-item sub-dimensions economic, social, and environmental adapted from [Elkington \(1998\)](#) and refined following [Geissdoerfer et al. \(2018\)](#).

Environmental Practices (ENV) was measured with six items adapted from [Testa et al. \(2014\)](#), covering regulatory compliance, pollution prevention, employee training, and environmental reporting. Digitalization (DIG) was measured with seven items adapted from [Bressanelli et al. \(2017\)](#) and [Centobelli et al. \(2020\)](#), covering ICT tool use, waste tracking systems, route optimization software, and citizen engagement platforms. The full item wording and sub-dimension structure are available from the corresponding author upon request. A pilot study with 30 respondents preceded main data collection and informed minor wording refinements.

Validity and Reliability Assessment

Three academics specializing in environmental management and research methodology reviewed the instrument for content validity, evaluating item relevance, clarity, and comprehensiveness; adjustments were made before pilot testing. Construct validity was assessed through Confirmatory Factor Analysis (CFA), examining convergent and discriminant validity. Convergent validity was established through factor loadings (> 0.60), Average Variance Extracted (AVE > 0.50), and Composite Reliability (CR > 0.70) ([Hair et al., 2019](#)).

Discriminant validity was evaluated using the Fornell-Larcker criterion, which requires that the square root of AVE for each construct exceed its highest correlation with any other construct ([Fornell & Larcker, 1981](#)). Internal consistency was evaluated using Cronbach's alpha (threshold 0.70) and corroborated with Composite Reliability.

Respondent Suitability

Because SWM, ENV, DIG, and SD were assessed as organization-level perceptual constructs rather than as individual job performance, employees at every hierarchical level were treated as capable informants regarding practices they routinely observe or are affected by waste collection procedures, environmental training participation, use of digital tracking tools, and visible sustainability outcomes. Nonetheless, frontline employees may have less visibility into organization-wide policy than managers, and the study acknowledges this asymmetry in informant knowledge as a limitation rather than assuming it away.

Data Collection, Common Method Bias, and Missing Data

Data collection took place over four months, from January to April 2025. Official permission was secured from WASA management prior to distribution. To mitigate common method bias (CMB), respondents were assured of anonymity and confidentiality, survey items were arranged and separated by construct, and questionnaires were self-administered with research assistants available to clarify questions ([Podsakoff et al., 2012](#)).

Harman's single-factor test was applied as an initial diagnostic; no single factor accounted for more than 35% of total variance. Because Harman's test alone is a relatively weak safeguard against CMB, it was supplemented by comparing the fit of the hypothesized four-factor measurement model against a constrained single-factor model; the four-factor model fit significantly better, providing additional, though not conclusive, evidence that CMB does not seriously threaten the results.

As no marker variable was included in the design, residual CMB risk cannot be fully excluded and is noted as a limitation. Missing values, present in less than 2% of cases, were addressed using

the Expectation-Maximization (EM) algorithm rather than mean substitution, since mean substitution can artificially deflate variance and distort the covariance structure that SEM estimation relies on (Hair et al., 2019).

Ethical Considerations

The study protocol received institutional ethical clearance before data collection, and all participants provided written informed consent. Respondents were informed of the voluntary nature of participation and their right to withdraw at any time without consequence. Participant anonymity and data confidentiality were maintained throughout collection, storage, and analysis, and the identity of individual WASAs and respondents is not disclosed in reporting the results.

Mediation Specification

Environmental practices and digitalization are specified as parallel mediators of the SWM–SD relationship: each mediator receives a direct path from SWM and sends an independent direct path to SD, with no path modeled between ENV and DIG. This specification tests H2 and H3 as two separate specific indirect effects (SWM→ENV→SD and SWM→DIG→SD). It tests H4 as the total indirect effect transmitted jointly through both mediators, computed as the sum of the two specific indirect effects ($a_1b_1 + a_2b_2$).

The model does not include an interaction term between ENV and DIG, a moderated-mediation index, or a serial path between the two mediators; therefore, the results reflect the combined magnitude of two additive pathways, not statistical synergy, amplification, or complementarity between the mediators. Both Baron and Kenny's (1986) causal-steps approach and bootstrapped, bias-corrected confidence intervals (Preacher & Hayes, 2008; 5,000 resamples) were used to evaluate each specific indirect effect and the total indirect effect.

Dataset Limitations

Several limitations of the dataset are acknowledged at the methods stage and revisited more fully in the Conclusion. Reliance on self-reported responses introduces the possibility of social desirability bias despite the procedural and statistical remedies described above. The sample is drawn from seven WASAs within a single province, limiting regional variation and constraining generalizability to other provinces or countries. The cross-sectional design precludes causal inference. The exclusion of three multivariate outliers to achieve normality may marginally affect representativeness, though the effect is expected to be minimal given the small number of exclusions.

Analytical Strategy

Data analysis was performed using SPSS 26 and AMOS 24 for Structural Equation Modeling (SEM), following a three-stage approach.

1. Data screening: The dataset was screened for missing values, outliers, and normality. Missing data (< 2%) were addressed using the EM algorithm. Outliers were identified using Mahalanobis distance and removed where influence was significant.
2. Measurement model assessment: Confirmatory Factor Analysis (CFA) assessed construct validity, including convergent and discriminant validity, as detailed above. Reliability was evaluated using Cronbach's alpha and Composite Reliability.
3. Structural model testing: The structural model tested the hypothesized relationships via SEM, specifying environmental practices and digitalization as parallel mediators, and allowing simultaneous assessment of direct effects, specific indirect effects, and the total indirect effect. Bootstrapping with 5,000 resamples generated bias-corrected confidence intervals for all

indirect effects ([Preacher & Hayes, 2008](#)).

FINDINGS AND DISCUSSION

Preliminary Analysis

Initial data screening confirmed the dataset's suitability for further analysis. From 450 distributed questionnaires, 406 usable responses were obtained (response rate 90.2%). Missing data (< 2%) were addressed using the EM algorithm. Multivariate outliers, identified via Mahalanobis distance, led to the exclusion of three cases, yielding a final analytic sample of N = 403.

Descriptive statistics showed construct means ranging from 3.45 to 3.82 on the 5-point scale, indicating moderate-to-high agreement. Skewness and kurtosis values for all variables fell within ± 2.0 , supporting the normality assumption ([Kline, 2015](#)) and the use of parametric testing.

Table 1. Descriptive Statistics and Correlations

Construct	SWM	SD	ENV	DIG
SWM	1.00	0.62	0.55	0.58
SD	0.62	1.00	0.59	0.61
ENV	0.55	0.59	1.00	0.54
DIG	0.58	0.61	0.54	1.00

Measurement Model

Table 2. Measurement Model Reliability and Convergent Validity

Construct	Items	Cronbach's α	CR	AVE
Solid Waste Management	8	0.89	0.91	0.62
Sustainable Development	9	0.91	0.93	0.65
Environmental Practices	6	0.87	0.89	0.59
Digitalization	7	0.88	0.90	0.61

Note. CR = Composite Reliability; AVE = Average Variance Extracted.

A Confirmatory Factor Analysis (CFA) validated the proposed measurement model. The fit indices met conventional thresholds ([Hu & Bentler, 1999](#)): $\chi^2/df = 2.14$ (< 3.0), CFI = .94, TLI = .93, RMSEA = .051, and SRMR = 0.046. All factor loadings exceeded 0.60, supporting convergent validity at the item level.

Table 3. Measurement Model Fitness (CFA)

Fit Index	Recommended Threshold	Obtained Value
χ^2/df	< 3.0	2.14
CFI	> .90	.94
TLI	> .90	.93
RMSEA	$\leq$.08	.051
SRMR	< .08	.046

Discriminant validity was established using the Fornell-Larcker criterion ([Fornell & Larcker, 1981](#)); as shown in Table 4, the square root of AVE for each construct exceeded its highest correlation with any other construct, confirming that each latent variable is distinct.

Table 4. Discriminant Validity (Fornell-Larcker Criterion)

	SWM	SD	ENV	DIG
Solid Waste Management	0.79			
Sustainable Development	0.62	0.81		
Environmental Practices	0.55	0.59	0.77	
Digitalization	0.58	0.61	0.54	0.78

Structural Model and Hypothesis Testing

The structural model was tested using SEM. Overall fit indices were satisfactory ($\chi^2/df = 2.25$, CFI = .93, TLI = .92, RMSEA = .054, SRMR = .049), indicating that the theoretical model adequately represents the observed data.

H1: SWM demonstrated a statistically significant positive direct effect on SD ($\beta = .41$, $p < .001$), supporting H1; enhanced SWM practices are directly associated with sustainable development outcomes.

H2: Environmental Practices significantly mediated the SWM–SD relationship; the specific indirect effect was .13 ($p < .01$), supporting H2.

H3: Digitalization significantly mediated the SWM–SD relationship; the specific indirect effect was .12 ($p < .01$), supporting H3.

H4: The total indirect effect of SWM on SD, transmitted jointly through the two parallel mediators, was significant (total indirect effect = .25, $p < .01$), supporting H4. This value equals the sum of the two specific indirect effects (.13 + .12 = .25). Because no interaction term or moderated-mediation index was estimated, this result indicates that the two pathways are jointly consequential in an additive sense; it is not evidence of statistical synergy, amplification, or complementarity between the mediators, and no such claim is made.

The paths from SWM to the mediators were also significant: SWM positively influenced ENV ($\beta = .46$, $p < .001$) and DIG ($\beta = .44$, $p < .001$), and both ENV ($\beta = .29$, $p < .001$) and DIG ($\beta = .27$, $p < .001$) significantly influenced SD.

Table 5. Structural Model Results

Hypothesis	Path	β	P-Value	Result
H1	SWM → SD	.41	< .001	Supported
H2	SWM → ENV → SD	.13	< .01	Supported
H3	SWM → DIG → SD	.12	< .01	Supported
H4	SWM → ENV + DIG → SD (Total, parallel)	.25	< .01	Supported

To further validate the mediation hypotheses, bootstrapping with 5,000 resamples generated bias-corrected confidence intervals for the indirect effects (Preacher & Hayes, 2008). As shown in Table 6, the 95% confidence intervals for all indirect effects (SWM→ENV→SD; SWM→DIG→SD; and the SWM→ENV+DIG→SD total effect) excluded zero, confirming the statistical significance of both specific and total indirect effects. Because the direct path between SWM and SD remained significant alongside the indirect effects, the mediation is classified as partial rather than full for both mediators.

Table 6. Bootstrapping Mediation Results

Mediation Path	Indirect Effect	95% CI (LL–UL)	Significance
SWM → ENV → SD	0.13	0.07 – 0.21	Significant
SWM → DIG → SD	0.12	0.06 – 0.20	Significant

SWM → ENV + DIG → SD (Total)	0.25	0.16 – 0.34	Significant
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Discussion

This study provides empirical evidence that solid waste management significantly affects sustainable development, both directly and indirectly through two parallel, additive mediating pathways: environmental practices and digitalization. Together, these two mediators account for a total indirect effect of .25, alongside a significant direct effect. The findings support the view that waste management functions as more than a technical or cost-centric process, contributing instead to broader sustainability transitions through both ecological and digital channels.

A central contribution of this study is demonstrating that environmental practices and digitalization can be estimated together, within a single structural model, as two statistically independent mediating mechanisms, rather than assuming a priori that their joint effect is non-additive. The total indirect effect (.25) is numerically larger than either specific indirect effect taken alone (.13 or .12), but this is a mathematical property of summing two positive indirect effects (.13 + .12 = .25) and should not be interpreted as evidence of interaction, mutual reinforcement, or synergy between the mediators. Testing such an interaction would require an explicit interaction term or a moderated-mediation index, which falls outside the parallel-mediation design used here and is identified below as a priority for future research.

The relative magnitude of the two pathways is plausible within the Khyber Pakhtunkhwa public-utility context. WASAs operate under regulatory oversight from provincial environmental agencies while simultaneously participating in donor- and government-funded digitalization initiatives common to Pakistani municipal services during the study period.

Employees in such organizations are consequently likely to experience environmental compliance requirements and digital tool adoption as parallel, externally driven initiatives rather than as a single integrated program, which is consistent with a parallel rather than a serial or interactive mediation structure, and helps explain why the two mediators, though positively correlated, retain distinguishable and additive rather than overlapping effects on sustainable development.

From a theoretical standpoint, the findings are consistent with the Resource-Based View (RBV): environmental practices and digitalization function as two distinct, valuable, and comparatively inimitable resources that each add to the benefits derived from SWM (Barney, 1991), without requiring that the two resources combine multiplicatively to have an effect. From a stakeholder theory perspective (Freeman et al., 2010), environmental practices and digital tools appear to build stakeholder trust through two separate channels, regulatory compliance and transparency, respectively, operating in parallel rather than in sequence.

The results are also consistent with the Circular Economy framework (Kirchherr et al., 2018): digitalization supports the traceability of material flows, while environmental practices support eco-efficiency, and both appear to support the shift from a linear "collect-dispose" model toward a more circular one, each through its own mechanism.

The contribution of this study rests on three more modest, and more precisely stated, dimensions than a claim of synergy would imply. First, it is among a relatively small number of studies to model environmental practices and digitalization jointly, as parallel mediators, within a single structural equation model in the SWM-sustainability context. Second, it provides comparative evidence on the relative and combined magnitude of the two pathways, information that a single-mediator study cannot provide without asserting that the two mediators interact statistically.

Third, it situates this parallel-mediator model within a developing-economy public-utility context, offering context-specific evidence from a setting where resource constraints make the

relative allocation of effort between environmental and digital investment especially consequential for managers.

CONCLUSIONS

This study examined the effect of solid waste management (SWM) on sustainable development (SD), including the parallel mediating roles of environmental practices and digitalization. Using data from 406 employees of Water and Sanitation Companies (WASAs) in Khyber Pakhtunkhwa, Pakistan, the findings show that SWM directly contributes to sustainability outcomes, and that its effectiveness is enhanced when it operates alongside proactive environmental practices and digital tools, each contributing an independent, additive pathway rather than a jointly interacting one.

Empirically, the study contributes evidence from an emerging-economy public-utility context that has received limited direct attention in prior single-mediator studies. The theoretical and practical implications of these findings, corresponding to the third research objective, are presented separately below.

Theoretical Implications

Theoretically, the study extends the Resource-Based View by showing that two distinct VRIN-type resources, environmental and digital capabilities, can be assessed jointly within one model without assuming they combine multiplicatively; extends Stakeholder Theory by showing that legitimacy-building (via environmental compliance) and transparency-building (via digital tools) operate as parallel rather than sequential routes to stakeholder trust; and extends Circular Economy thinking by showing that ecological and digital levers each independently support movement from linear to circular practice.

Collectively, these three extensions show that the theoretical perspectives mapped in the Literature Review explain distinct, additive causal paths rather than a single, interacting mechanism, which directly answers the theoretical half of the study's third research question.

Practical Implications: Managerial and Policy Implications

Practically, the study offers actionable, appropriately scoped insights for managers and policymakers, framing waste management as a platform for sustainable business models that can be strengthened through one or both of two distinct, complementary but non-interacting mechanisms; this addresses the practical half of the study's third research question.

The following recommendations are consistent with the study's findings and the broader literature. Several specific tools mentioned below (e.g., QR-coded bins, waste-to-energy projects, public-private partnerships, and ESG reporting) were not directly measured as variables in this study. They should be read as illustrative applications and recommendations rather than as direct empirical implications of the reported results.

Municipal Authorities and Managers should integrate environmental routines, pollution-prevention training, compliance audits, and eco-reporting to strengthen the sustainability benefits of SWM operations. They should separately invest in accessible digital tools, route-optimization applications, waste-tracking systems, and citizen-complaint dashboards to improve service quality and accountability.

Because the two pathways were found to be additive rather than dependent on one another, managers facing binding resource constraints can expect meaningful gains from strengthening either pathway individually. In contrast, gains from strengthening both are expected to accumulate rather than multiply. Investment in circular-economy initiatives such as recycling hubs, community

composting, and (where feasible) waste-to-energy projects is recommended as a complementary application of these findings, though such initiatives were not directly tested.

Policymakers and Sustainability Leaders should develop policy incentives and regulatory frameworks that encourage WASAs and private waste-management companies to invest in digital infrastructure and environmental training, and should consider public-private partnerships to accelerate adoption of digital waste tracking.

National waste-management policy should be explicitly aligned with the Sustainable Development Goals and Pakistan's climate commitments. Incorporating waste digitalization and environmental-performance metrics into ESG reporting is offered as a recommendation consistent with the study's themes, rather than as a finding of the study itself.

LIMITATION & FURTHER RESEARCH

This study acknowledges several limitations beyond those noted in the Methodology. First, measurement relied on single-informant, self-reported, perceptual data; frontline employees may have less visibility into organization-wide policy than managers, and we collected no supervisor-rated or archival data to cross-validate responses. Second, employees were nested within seven WASAs, and this organizational clustering was not modeled using multilevel techniques; if meaningful intra-organization correlation is present, standard errors may be modestly underestimated.

Third, and most importantly, the cross-sectional design cannot establish the temporal ordering that mediation, in a strict causal sense, requires; the statistical patterns reported here are consistent with the hypothesized theory but do not by themselves prove causal sequence. Fourth, the reliance on cross-sectional, self-reported data carries residual risk of common method bias despite the procedural and statistical remedies applied.

Fifth, the study was confined to WASAs in Khyber Pakhtunkhwa, which may limit generalizability to other provinces or countries. Sixth, the parallel-mediation model tested here does not assess whether environmental practices and digitalization interact statistically; any such synergy remains untested and should not be inferred from the present results.

Future research should address these limitations directly: (1) collecting multi-source or supervisor-rated data to reduce single-informant bias; (2) applying multilevel SEM to account for employee clustering within WASAs or other organizations; (3) using longitudinal or panel designs, or quasi-experimental approaches, to establish causal ordering; and (4) explicitly testing whether environmental practices and digitalization interact via an interaction term or a moderated-mediation index rather than assuming or asserting synergy based on an additive total effect.

Additional promising directions include comparative research across regions or countries; examining the roles of organizational culture, leadership, governance quality, or financial mechanisms; assessing the implementation of emerging technologies such as AI-based predictive analytics, blockchain traceability, and IoT-based monitoring; and engaging citizens, NGOs, and regulators to provide multi-stakeholder perspectives on sustainability transitions.

Addressing these areas would strengthen the theoretical and practical foundations of sustainable business models and offer more precise pathways for integrating waste management, environmental stewardship, and digital transformation.

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