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Integrating Digital Technologies into Solid Waste Management for Achieving Sustainable Development Goals (SDGs): A Case Study of KPK Water & Sanitation Services Companies (WSSCs), Pakistan

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Abstract

Solid Waste Management (SWM) is one of the most pressing challenges for urban centers in developing countries, with significant implications for environmental quality, economic growth, and public health. In Pakistan, particularly in Khyber Pakhtunkhwa (KPK), municipal service providers such as Water & Sanitation Services Companies (WSSCs) face increasing waste volumes, resource constraints, and operational inefficiencies. The rapid evolution of digital technologies, including Internet of Things (IoT), Geographic Information Systems (GIS), Artificial Intelligence (AI), blockchain, and data analytics, presents transformative opportunities to improve SWM systems. This study investigates the mediating role of Digital Technology Adoption in the relationship between SWM and the achievement of Sustainable Development Goals (SDGs). A cross-sectional survey was conducted with employees of all seven WSSCs in KPK, using a structured questionnaire. Data analysis employed descriptive statistics, reliability and normality checks, Pearson correlation, simple linear regression, and mediation analysis through the PROCESS macro (Model 4). Results indicate a significant positive relationship between SWM, digital technology adoption, and SDG achievement. Moreover, digital technology adoption partially mediates the SWM SDG link, highlighting the necessity of integrating technological solutions in waste management practices. The paper proposes policy reforms, capacity building, and joint government-non-government partnerships to speed up the digitalization of the Pakistani waste sector, which can lead to advancement in Pakistan reaching the 2030 Agenda.

Keywords: Solid Waste Management, Digital Technology Adoption, Sustainable Development Goals, Water & Sanitation Services Companies.

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Introduction

SWM is a multi-faceted and resource-demanding service that supports city health, environment, and economic prosperity (Momodu et al., 2011). By 2050, over 6 billion citizens will live in towns (Ritchie & Roser, 2018), and they will produce unprecedented amounts of waste. Sharma et al. (2021) posit that by the middle of the century, the global generation rate of municipal solid wastes will exceed 3.40 billion metric tons a year. The issue of waste management is eminent in all parts of the world, but the poor structural, financial, and technological capabilities cause unprecedented inefficiencies, environmental degradation, and create health hazards in developing nations like Pakistan.

The Agenda 2030 of the United Nations focuses on waste minimization, recycling, and environmentally sound modes of disposal within several of the SDGs, including Goal 6 (Clean Water & Sanitation), Goal 11 (Sustainable Cities & Communities), Goal 12 (Responsible Consumption & Production), and Goal 13 (Climate Action). To achieve these, it is vital to have systemic innovations in SWM that would go beyond policy changes and behavioral modifications to consider technological improvements (Lee et al., 2023).

New digital technologies, such as the use of Internet of Things (IoT) smart bins and AI-based route optimization, GIS mapping, blockchain technology to track waste, and big data analytics, are changing the face of urban waste management (Fatimah et al., 2020; Anagnostopoulos et al., 2017). The tools can increase operational efficiency, transparency, and real-time decision-making, advancing toward SDGs. Nevertheless, their usage in the Pakistani context is limited, including in the urban centers, such as the WSSCs of KP, which serve ~15 million people.

This research translates the current literature on the relationship between SWM and sustainability development and makes it specific to the role of Digital Technology Adoption. The present research produces empirical evidence of how technology integration will lead to the performance optimization of the SWM systems and national SDG targets through an analysis of the operational reality of seven WSSCs in KP.

Objectives of the Study

1. To investigate the connection between the solid waste management, digital technologies adoption, and attainment of Sustainable Development Goals (SDGs).
2. To analyze the direct influence of the solid waste management on the achievement of the SDGs in KPK WSSCs.
3. To determine the mediation effect of the adoption of digital technology on solid waste management and SDG achievement.

Literature Review

Solid Waste Management (SWM)

Solid waste is the discarded material that is a result of human activity, such as household refuse, commercial waste, construction waste, also known as construction debris, and industrial by-products (Christensen, 2011). Though normally regarded as

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solid, some wastes can also be in the form of sludge or semi-liquid. The World Bank (Kaza et al., 2018) estimates that annual global solid waste generation will rise from 2.01 billion metric tons in 2016 to 3.40 billion metric tons by 2050. The primary objective of SWM is to collect, transport, treat, and dispose of waste in ways that protect public health and the environment while conserving resources (Sharma et al., 2021).
In developing countries, including Pakistan, SWM faces multiple barriers: insufficient infrastructure, poor enforcement of regulations, low public awareness, and limited adoption of modern technologies (Guerrero et al., 2013). Ineffective SWM contributes to environmental degradation, disease outbreaks, and loss of economic opportunities, while effective systems can stimulate employment, reduce pollution, and support circular economy models.

Sustainable Development Goals (SDGs) and SWM
The 2030 Agenda for Sustainable Development, adopted by the United Nations in 2015, outlines 17 SDGs that encompass environmental, social, and economic dimensions. SWM is directly relevant to several goals, especially:

SDG 6: Clean Water and Sanitation — prevention of water pollution from waste leachate.

SDG 11: Sustainable Cities and Communities — improved urban waste services.

SDG 12: Responsible Consumption and Production — waste minimization, recycling, and reuse.

SDG 13: Climate Action — reduction of greenhouse gas emissions from waste.

Proper SWM contributes to these targets by reducing environmental pollution, conserving resources, and promoting urban resilience (Elsheekh et al., 2021).

Digital Technologies in Solid Waste Management
Digitalization is the use of digital tools and technologies in an attempt to modify business operations and service delivery. In the industry, efficiency and sustainability are driven by Industry 4.0 technologies, i.e., IoT, AI, blockchain, GIS, drones, and big data analytics (Fatimah et al., 2020; Cheah et al., 2022).

Examples include:

IoT-filled Smart Bins: Smart Bins have sensors to detect fullness and need to be emptied (Anagnostopoulos et al., 2017).

Artificial Intelligence - Routing: The routes of routes are optimized with the help of AI to travel with the least amount of fuel and environmentally harmful emissions (Hannan et al., 2020).

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GIS Mapping: The spatial data can facilitate in design of collection areas and the self-management of places of illegal dumps (Misra et al., 2018).

Blockchain Systems: Establish greater traceability of the waste streams, preventing waste that appears illegally (Ruohomaa & Ivanova, 2019).

Data Analytics Platforms: Shorten the time it takes to perform predictive maintenance of waste facilities and forecast waste generation trends.
When combined with SWM, these technologies enhance the precision of operational decision-making, increase transparency, and allow in-time service corrections, thus contributing to SDGs.

Linkages Between SWM, Digital Technology Adoption, and SDGs
There is no secret connection between SWM and SDGs, but through the adoption of technology, it becomes a transformational enabler. Digital technologies make the process of data gathering more precise, resources more efficiently distributed, and citizens more involved through the usage of mobile applications and reporting systems (Garmann-Johnsen et al., 2020). In the Pakistani scenario, where most SWM activities are still conducted manually, adopting digital solutions into this system can help increase their overall efficiency and speed up the pace of achieving the SDGs.

Theoretical Framework
The theoretical framework applied in the study is the Technology-Organization-Environment (TOE), which explains how the adoption of technological innovations in organizations takes place. This study theorizes that
Independent Variable (IV): Solid Waste Management

Mediator (M): Digital Technology Adoption

Dependent Variable (DV): Achievement of Sustainable Development Goals (SDGs)

Solid Waste Management → Digital Technology Adoption → Sustainable Development Goals

This model assumes that while SWM directly impacts SDGs, the adoption of digital technologies strengthens and partly mediates this effect.

Hypotheses
Based on the literature, the following hypotheses are formulated:
H1: The relationship between solid waste management and the adoption of digital technology is significantly positive concerning the attainment of Sustainable Development Goals.
H2: Solid waste management can contribute to a large extent to the Sustainable Development Goals.
H3: The effect of solid waste management on achieving Sustainable Development Goals greatly depends on digital technology adoption.

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Methodology

Research Design

This study employs a cross-sectional survey research design in analyzing the connection between Solid Waste Management (SWM) and the realization of Sustainable Development Goals (SDGs), with Digital Technology Adoption as the mediating step. The method is appropriate when there are hypothesized relationships that one wants to examine among variables and enables the collection of primary data from a large sample within a given period of time (Zikmund et al., 2010).

Population and Sample of the Study

The focus population of the proposed study is the employees of the seven Water and Sanitation Services Companies (WSSCs) existing in the provincial headquarters of Khyber Pakhtunkhwa (KP), Pakistan. These WSSCs are incorporated with the Securities and Exchange Commission of Pakistan (SECP), and they look after the collection, transportation, and disposal of Municipal waste in their respective cities.
According to the official reports, there are 6944 total employees working at these seven WSSCs. Taking a sample size has been done based on the table presented by Krejcie & Morgan (1970), which suggests a sample size of 361 in the population of this size. The G Power 3.1 software was also used further to indicate the minimum sample of 158 to give proper statistical power at the 95 percent confidence level and a medium effect size.
To ensure robust results, **411 questionnaires** were distributed proportionately across the seven WSSCs, and **406 complete and valid responses** were received, yielding a response rate of 98.78%.

Research Instrument

The structured questionnaire used in this study comprised two sections:
Section A: Demographic and organizational information (e.g., age, gender, education, years of service, department).
Section B: Scales measuring the three constructs — SWM, Digital Technology Adoption, and SDG achievement — using a **seven-point Likert scale** ranging from 1 = Strongly Disagree to 7 = Strongly Agree.

Measurement Scales

Solid Waste Management (SWM):

- Adopted from Sarbassov et al. (2019) and Trondillo et al. (2018), covering awareness & practice, attitude, and operational status.
- 38 items in total.

Digital Technology Adoption (DTA)

- Adapted from Fatimah et al. (2020), Anagnostopoulos et al. (2017), and Cheah et al. (2022).

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- Items assess the availability, usage, and perceived effectiveness of IoT devices, GIS mapping, AI-based route optimization, blockchain tracking, and data analytics in SWM operations.
- 14 items in total.

Sustainable Development Goals Achievement (SDGs)

- Adapted from Asiri (2017) and Sola & Sunny (2019), focusing on SDG-related outcomes such as improved environmental quality, reduced carbon emissions, enhanced recycling, and community well-being.
- 13 Items in total.

Validity and Reliability of Instruments

To ensure content validity, the questionnaire was reviewed by three academic experts in environmental management and municipal governance, as well as two senior WSSC managers with experience in technology adoption. A pilot test involving 30 respondents from WSSCs was conducted, and Cronbach's Alpha values exceeded the minimum acceptable threshold of 0.70 for all constructs, indicating good internal consistency (Nunnally, 1978).

Data Collection Procedure

The data collection process was carried out with official permission from the WSSCs' management. Questionnaires were distributed both physically and via the organization's digital communication channels (e.g., email, WhatsApp groups). Respondents were assured of confidentiality and anonymity to encourage honest responses. The data collection spanned over six weeks.

Data Analysis Tools and Techniques

The collected data were analyzed using IBM SPSS Statistics v26. The following statistical procedures were applied;

Descriptive Analysis: To summarize demographic information and variable characteristics.

Normality Tests: Skewness and kurtosis values were assessed, with acceptable thresholds of ±3 (Kline, 2005).

Reliability Analysis: Cronbach's Alpha values were computed to ensure internal consistency.

Correlation Analysis: Pearson's Product-Moment Correlation Coefficient was used to test H1.

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Simple Linear Regression: Used to test the direct impact of SWM on SDG achievement (H2).

Mediation Analysis: Hayes' PROCESS macro (Model 4) was employed to test the mediating role of Digital Technology Adoption (H3), including total, direct, and indirect effects with bootstrapped confidence intervals (5,000 samples).

Results and Discussion

Demographic Profile of Respondents

A total of 406 valid responses were obtained from employees of the seven WSSCs in KPK. The demographic profile shows that **82.5%** of respondents were male and **17.5%** were female. The majority of respondents (46.3%) fell within the age group of **31–40 years**, followed by 28.1% in the 21–30 age group, 18.2% in the 41–50 age group, and 7.4% above 50 years. Regarding education, 54.7% held a bachelor's degree, 31.5% a master's degree, and the remainder had intermediate or diploma qualifications.

Reliability Analysis

Construct	Number of Items	Cronbach's Alpha	Interpretation
Solid Waste Management (SWM)	38	0.948	Excellent
Digital Technology Adoption (DTA)	14	0.927	Excellent
Sustainable Development Goals (SDGs)	13	0.936	Excellent

All Cronbach's Alpha values exceed the threshold of 0.70 (Nunnally, 1978), confirming that the scales are internally consistent and reliable

Descriptive Statistics

Variable	N	Mean	Std. Deviation	Skewness	Kurtosis
SWM	406	5.12	0.81	-0.21	-0.38
DTA	406	4.89	0.87	-0.18	-0.29
SDGs	406	5.04	0.79	-0.25	-0.32

The skewness and kurtosis values fall within the acceptable range of ±3 (Kline, 2005), indicating that the data are normally distributed.

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Correlation Analysis

Variable	SWM	DTA	SDGs
SWM	1	0.701**	0.684**
DTA	0.701**	1	0.753**
SDGs	0.684**	0.753**	1

Note: p < 0.01 (two-tailed)

The correlation results show strong positive relationships among all three variables, supporting **H1** that SWM, DTA, and SDG achievement are significantly related.

Regression Analysis

H2: SWM significantly influences SDG achievement.

Model	β	t	Sig.	R^2
SWM → SDGs	0.684	19.13	0.000	0.468

The regression analysis reveals that SWM has a strong and significant effect on SDG achievement (**β** = 0.684, **p** < 0.001), explaining 46.8% of the variance in SDG achievement. **H2** is therefore supported.

Mediation Analysis (PROCESS Macro – Model 4)

H3: Digital Technology Adoption mediates the relationship between SWM and SDG achievement.

Path Coefficients

- **Path a** (SWM → DTA): β = 0.701, p < 0.001
- **Path b** (DTA → SDGs): β = 0.513, p < 0.001
- **Path c (Total effect)** (SWM → SDGs): β = 0.684, p < 0.001
- **Path c' (Direct effect)** (SWM → SDGs controlling for DTA): β = 0.324, p < 0.001

Indirect Effect

Bootstrapped estimate (5,000 samples) = **0.360**, 95% CI [0.291, 0.434] does not include zero, indicating a significant mediation effect.

These results indicate **partial mediation** — meaning that while SWM directly impacts SDG achievement, a substantial portion of this effect is transmitted through the adoption of digital technologies. This validates **H3** and underscores the importance of technological integration in enhancing SWM outcomes.

Discussion

The findings are consistent with global literature emphasizing the transformative role of technology in municipal waste management. The significant positive correlation between SWM and DTA supports prior studies (Fatimah et al., 2020; Cheah et al.,

2022), highlighting that effective SWM systems are more likely to integrate technological innovations. The mediation results align with the Technology–Organization–Environment (TOE) framework, suggesting that the adoption of digital tools acts as an organizational capability that strengthens the impact of SWM on SDG progress.
In the case of KPK's WSSCs, the adoption of IoT-enabled bins, AI-based route planning, and GIS tracking can reduce operational inefficiencies, minimize fuel consumption, and enhance transparency, thereby directly contributing to SDGs 6, 11, 12, and 13.

Conclusion

This paper has analyzed the association between Solid Waste Management (SWM) and the accomplishment of Sustainable Development Goals (SDGs), through Digital Technology Adoption (DTA) as an intermediate variable, in the context of Water & Sanitation Services Companies (WSSCs) in Khyber Pakhtunkhwa. Based on the cross-sectional survey of 406 respondents, the findings validate the argument that SWM has a positive effect on SDG attainment, whilst digital technologies have a considerable impact on the relationship as a partial mediator.
These results show the necessity of technological innovation to overcome the operational and environmental issues of waste management in developing countries. Although more advanced and innovative SWM processes will not replace the processes employed in the past, their combination with technologies like IoT-powered smart bins, GIS mapping, AI-powered route optimization, blockchain tracking of waste, and data analytics will bring the process a significant step forward, enhancing efficiency, visibility, and community interaction.
Through implementing such innovations, WSSCs in KPK would be able to intertwine them with the national developmental priorities of Pakistan and fast-track the achievement of SDGs 6, 11, 12, and 13. The biased mediation that has been revealed in this study implies that, though SWM directly influences long-term development, the implementation of digital technologies can increase this influence and make the results more noticeable and quantifiable.

Recommendations

Based on research results, the following recommendations concerning policymakers, municipal authorities, and WSSC management can be offered:

1. **Develop a Digital Transformation Roadmap for WSSCs**
   Establish a strategic plan outlining the adoption and integration of IoT, GIS, AI, and blockchain technologies in waste collection, transportation, and disposal.

2. **Invest in Infrastructure and Smart Technologies**
   Deploy IoT-enabled smart bins, GPS-based fleet tracking, and AI-based route optimization tools to enhance operational efficiency and reduce environmental impact.

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3. **Capacity Building and Training**
   Conduct regular training programs for WSSC staff to improve technical skills and ensure effective use of digital tools.
   Introduce digital literacy workshops for waste management field teams.

4. **Public–Private Partnerships (PPPs)**
   Engage with technology providers, startups, and research institutions to co-develop cost-effective and scalable waste management solutions.

5. **Strengthen Data-Driven Decision Making**
   Create centralized data platforms for real-time monitoring of waste generation, collection, and disposal patterns.
   Use predictive analytics to anticipate waste trends and allocate resources more effectively.

6. **Community Engagement Through Digital Platforms**
   Develop mobile apps and web portals that enable citizens to report uncollected waste, illegal dumping, and participate in recycling programs.

7. **Policy and Regulatory Support**
   Formulate provincial and municipal policies that mandate the integration of digital tools in SWM operations, with clear performance benchmarks.

Limitations and Future Research Directions

This study is limited by its cross-sectional design, which restricts causal inference. Furthermore, the data are based on self-reported perceptions, which may be subject to bias. Future research could employ longitudinal designs to track changes in digital adoption and SWM outcomes over time, or comparative studies between provinces to understand regional differences in technology integration.

Additionally, further studies could explore the cost–benefit analysis of digital technology investments in SWM, as well as the role of citizen digital participation in enhancing municipal service delivery.

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