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Evaluation of A Sludge Management Monitoring System for Sustainable Waste Disposal

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ABSTRACT: The increasing generation of sludge from wastewater treatment facilities creates environmental, operational, and regulatory challenges, particularly when monitoring and disposal rely on manual procedures. This study developed and evaluated a sludge management monitoring system designed to improve sludge tracking, operational efficiency, documentation, and environmental compliance. A descriptive-evaluative and correlational design was used with 200 personnel from five commissaries in the Philippines. Data were gathered through a validated questionnaire and analyzed using frequency, percentage, mean, standard deviation, and Pearson correlation. Results indicated that the system received very high ratings in usefulness, ease of use, relevance, technical requirements, effectiveness, and acceptability. The system improved sludge tracking, workflow efficiency, documentation, and environmental compliance while reducing manual errors and delays. Findings also indicated potential for the beneficial reuse of properly treated sludge as a soil additive, subject to applicable safety and environmental requirements. Overall, the system provided an effective and user-friendly technology-based approach for sustainable sludge management.

KEYWORDS: Sludge Management, Wastewater Treatment, Digital Monitoring, Technology Management, Operational Efficiency, Environmental Compliance, Sustainability

INTRODUCTION

The increasing production of sewage sludge has created environmental and operational concerns because improper handling, treatment, storage, transportation, and disposal may cause pollution, health risks, and resource loss. Effective sludge management therefore requires accurate monitoring and systematic documentation of activities throughout the management process.

Digital technologies provide opportunities to improve sludge tracking, record-keeping, reporting, and decision-making through timely and reliable operational information. Real-time monitoring can reduce manual errors, improve process visibility, and strengthen environmental compliance.

Despite advances in wastewater treatment, many facilities still experience difficulties associated with manual documentation, limited monitoring capabilities, resource constraints, and appropriate sludge disposal. These challenges demonstrate the need for an accessible and user-friendly monitoring system that can support efficient and sustainable sludge management.

The study therefore focused on developing and evaluating a technology-assisted sludge management monitoring system that could improve operational efficiency, transparency, accountability, regulatory compliance, and potential resource recovery.

LITERATURE REVIEW

The study was anchored on the Technology Acceptance Model (TAM), Systems Theory, Circular Economy Theory, and Technology-Organization-Environment (TOE) Framework. TAM explains user acceptance through perceived usefulness and ease of use. Systems theory views sludge management as an interconnected process requiring coordination among handling, treatment, storage, transportation, documentation, and disposal activities.

Circular Economy Theory emphasizes waste reduction, resource recovery, reuse, and sustainable utilization of materials, while the TOE Framework highlights the importance of technological capability, organizational readiness, and environmental requirements in technology implementation.

The study was also supported by relevant Philippine environmental laws, particularly Republic Act No. 9275 (Philippine Clean Water Act of 2004), Republic Act No. 9003 (Ecological Solid Waste Management Act of 2000), Republic Act No. 11038, Presidential Decree No. 1586, DENR Administrative Order No. 2016-08, and Republic Act No. 11898. Collectively, these frameworks emphasize the importance of effective technology, environmental protection, sustainable waste management, organizational readiness, and regulatory compliance.

OBJECTIVES

1. Determine the existing status of sludge handling, monitoring, and disposal before system implementation.
2. Assess the effectiveness of the Sludge Management Monitoring System.
3. Determine its operational efficiency in wastewater treatment processes.
4. Assess its acceptability among users.
5. Determine whether a significant relationship existed between system effectiveness and user acceptability.

MATERIALS AND METHODS

The study employed a descriptive-evaluative and correlational research design to assess the effectiveness, operational efficiency, and acceptability of the Sludge Management Monitoring System. It involved 200 personnel directly engaged in sludge-related activities, including plant crews, engineers, environmental personnel, and other authorized users.

The study was conducted in five commissaries located in Danao, Cebu, Bacolod, Cagayan de Oro, and Davao. These sites represented varied wastewater treatment environments and provided suitable settings for evaluating technology-assisted sludge management.

A researcher-developed questionnaire was used to assess existing practices, system effectiveness, operational efficiency, technical requirements, and user acceptability. The instrument underwent expert validation and reliability testing. A five-point rating scale was applied.

Data gathering included securing permissions, assessing baseline practices, demonstrating and implementing the system, administering the questionnaire, and reviewing relevant operational records. Ethical procedures involving informed consent, confidentiality, anonymity, and voluntary participation were observed.

Data were analyzed using frequency, percentage, mean, weighted mean, standard deviation, and Pearson product-moment correlation. Qualitative responses and observations were also examined thematically to identify operational issues and recommendations.

RESULTS AND DISCUSSIONS

Figure 1. The study has significant implications for the **environment** because the Sludge Management Monitoring System provides a technology-based approach to improving the monitoring, handling, documentation, and disposal of sludge. By enabling real-time monitoring, accurate recording, systematic reporting, and regulatory documentation, the system can help reduce environmental risks associated with improper sludge management and strengthen compliance with environmental requirements. The reported **51.7% improvement in environmental compliance** further indicates that the system can contribute to pollution prevention, environmental protection, and more responsible wastewater management. Moreover, the system may support sustainable resource recovery through the potential reuse of properly treated and characterized sludge as a soil additive, provided that applicable health, safety, and environmental requirements are satisfied.

Figure 2. The findings of the study have important implications for wastewater treatment operations, technology management, environmental compliance, and sustainable waste disposal. The results demonstrated that the Sludge Management Monitoring System can address limitations associated with manual and fragmented sludge management practices by providing more accurate monitoring, systematic documentation, real-time tracking, and timely reporting. The system obtained very high ratings in perceived usefulness, ease of use, relevance, and technical and functional requirements, indicating that digital monitoring can serve as a practical technology-assisted approach for improving sludge management operations.

For wastewater treatment facility management, the findings imply that investment in digital monitoring systems can improve operational workflow and decision-making. The system reduced manual handling and errors, streamlined sludge processing activities, and facilitated timely decisions. The reported 42.2% improvement in operational workflow efficiency suggests that technology integration can contribute to more organized and responsive sludge management operations.

For environmental management and regulatory compliance, the findings indicate that digital documentation and monitoring can strengthen accountability and environmental oversight. The system improved compliance with environmental regulations by 51.7%, while also supporting environmental audits and reducing potential compliance risks. This is particularly relevant to the implementation of environmental requirements under Republic Act No. 9275, Republic Act No. 9003, and DENR Administrative Order No. 2016-08.

For technology management, the high ratings for perceived usefulness, ease of use, technical functionality, and acceptability imply that successful technology adoption depends not only on the availability of hardware and software but also on how well the system fits users' operational needs. The findings support the relevance of the Technology Acceptance Model and the Technology-Organization-Environment Framework in understanding technology adoption within wastewater treatment environments.

For sustainable waste management, the study implies that sludge should not be viewed solely as a waste material requiring disposal. Proper monitoring, treatment, characterization, and regulatory control may create opportunities for resource recovery, including potential use as a soil additive when demonstrated to be safe and compliant with applicable requirements. Thus, digital monitoring can contribute not only to disposal management but also to broader circular-economy objectives.

The findings were strongly informed by personnel directly engaged in the daily handling, monitoring, and processing of sludge, while the participation of engineers and environmentalists provided technical and environmental perspectives on system functionality and compliance. This distribution supports a balanced assessment of the Sludge Management Monitoring System from operational, technical, and environmental viewpoints. The composition is consistent with Systems Theory, which emphasizes the interaction of different roles within an interconnected operational process, and with the Technology-Organization-Environment (TOE) Framework, which recognizes that successful technology implementation depends on technological capability, organizational readiness, and environmental requirements. Thus, the representation of the three respondent groups provided relevant perspectives for evaluating the system's effectiveness, operational efficiency, and acceptability.

Thematic Statement. Pre-Implementation Sludge Management Practices. Before implementation, sludge management was generally manual, conventional, and fragmented. Monitoring relied on visual inspection, intermittent measurements, and paper-based documentation. These practices contributed to delayed reporting, limited tracking, recording errors, and difficulties in regulatory monitoring, demonstrating the need for an integrated digital system.

Table 2 – Perceived Usefulness, Ease of Use, and Relevance

The system obtained a very high overall rating (M = 4.42, SD = 0.60). Perceived usefulness ranked highest (M = 4.43), followed by ease of use (M = 4.42) and relevance (M = 4.40), indicating that users viewed the system as useful, accessible, and relevant to daily operations.

Table 3 – Technical and Functional Requirements

The system received a very high rating (M = 4.47, SD = 0.59) for its technical and functional requirements. Real-time monitoring, high-precision sensors, and real-time data acquisition were among the highest-rated features, confirming their importance for accurate and timely sludge management.

Table 4 – Effectiveness in Improving Sludge Tracking

The system was highly effective in improving sludge tracking, with ratings ranging from 4.50 to 4.60. It improved recording accuracy, provided real-time tracking, and supported automated logging and reporting, thereby reducing errors and increasing transparency.

Table 5 – Effectiveness in Improving Operational Workflow

The system demonstrated high effectiveness in improving operational workflow, with ratings ranging from 4.45 to 4.55. It reduced manual handling, minimized errors, streamlined processing activities, and supported faster decision-making.

Table 6 – Effectiveness in Ensuring Environmental Compliance

The system was highly effective in supporting environmental compliance, with ratings ranging from 4.45 to 4.55. It strengthened regulatory monitoring, improved documentation, supported environmental audits, and reduced potential compliance risks.

Table 7 – Acceptability of the System

The monitoring system achieved a very high level of acceptability, with ratings ranging from 4.50 to 4.60. Respondents found the system user-friendly, reliable, responsive, practical, and easy to integrate into daily wastewater treatment operations.

Table 8 – Difference Before and After Implementation

The results demonstrated a significant improvement in sludge management practices after implementation. Improvements were observed in sludge tracking accuracy, operational workflow, and environmental compliance, confirming the positive contribution of digital monitoring.

Table 9 – Overall Improvement in Sludge Management

The system produced substantial improvements in sludge management. Environmental compliance improved by 51.7%, sludge tracking accuracy by 48.4%, and operational workflow efficiency by 42.2%. These findings demonstrate that digital monitoring reduced manual errors, improved efficiency, and strengthened regulatory compliance.

FIGURES

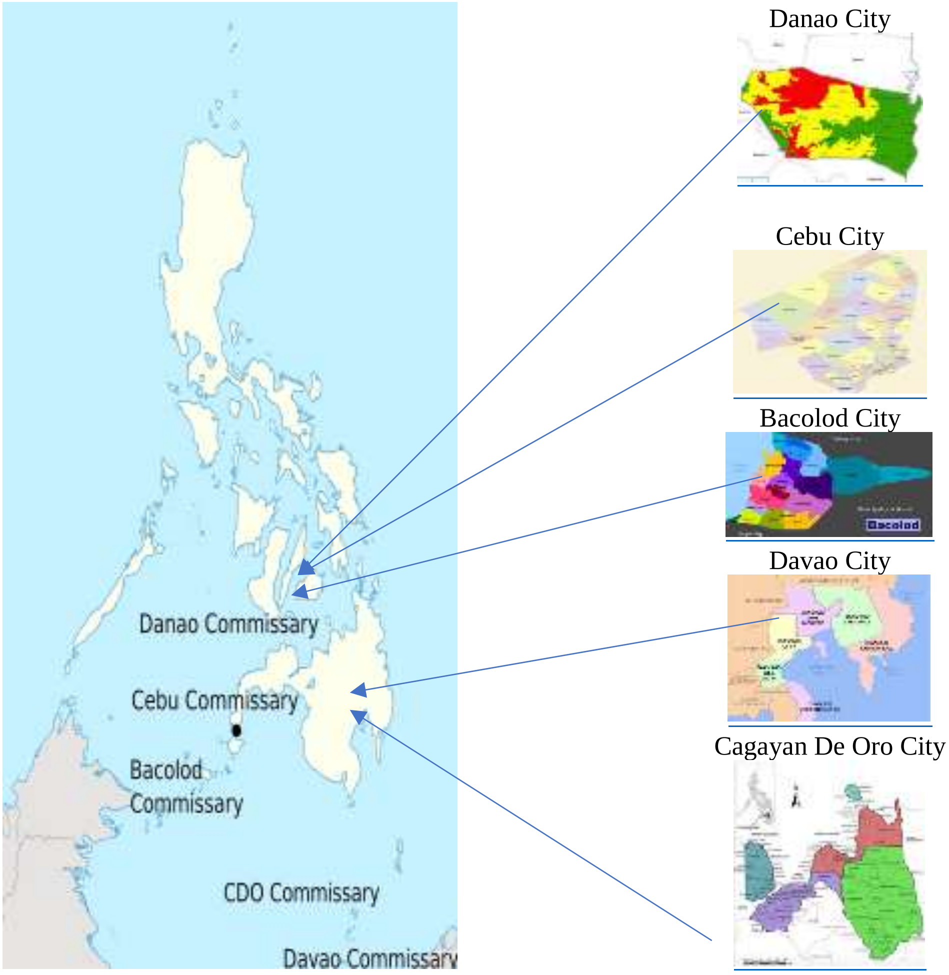

Figure 1. Location Map of Research Environment

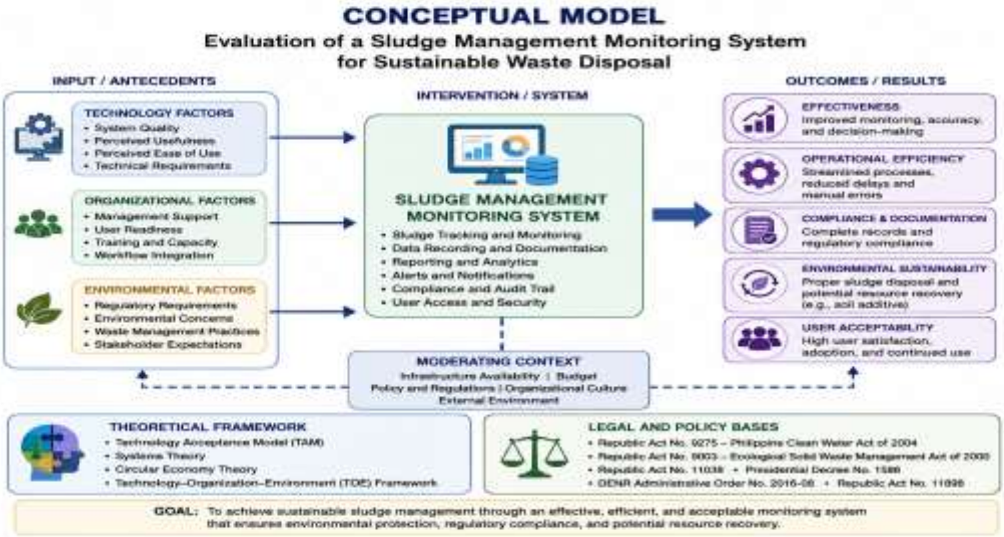

Figure 2. Conceptual Model

TABLES

Table 1: Distribution of Respondents

N=200

Respondents	Sample Size (n)	Percentage (%)
Plant Crews	120	60
Plant Engineers	20	10
Plant Environmentalist	60	30
Total	**200**	**100**

Table 2: ACCEPTABILITY EVALUATION SCORING

Acceptability Scoring (5-Point Hedonic Scale): Participants rated each sensory attribute based on personal preference using the following scale:

Score	Range	Verbal Description	Interpretation
5	4.21-5.00	Very Highly Acceptable (VHA)	Outstanding acceptability of the system
4	3.41-4.20	Highly Acceptable (HA)	High level of acceptability
3	2.61-3.40	Moderately Acceptable (MA)	Average or satisfactory acceptability
2	1.81-2.60	Acceptable (A)	Basic acceptability, needs minor improvement
1	1.00-1.80	Not Acceptable	Poor acceptability, requires significant improvement

Table 3: EFFECTIVENESS EVALUATION SCORING

Acceptability Scoring (5-Point Hedonic Scale): Participants rated each sensory attribute based on personal preference using the following scale:

Score	Range	Verbal Description	Interpretation
5	4.21-5.00	Very Highly Effective	System performs exceptionally in achieving intended outcomes
4	3.41-4.20	Highly Effective	System performs very well with minor limitations
3	2.61-3.40	Moderately Effective	System performs satisfactorily with some limitations
2	1.81-2.60	Effective	System performs at a basic functional level
1	1.00-1.80	Not Effective	System fails to meet intended objectives

Table 4: Perceived Usefulness, Ease of Use, and Relevance of the Developed Sludge Management Monitoring System

N = 200

Dimension	Indicators	Mean	SD	Verbal Interpretation
Perceived Usefulness	Enhances accuracy in monitoring sludge	4.55	0.52	Very Highly Useful
	Improves efficiency of plant operations	4.45	0.61	Very Highly Useful
	Supports compliance with environmental regulations	4.30	0.68	Very Highly Useful
Sub-Total	Perceived Usefulness	4.43	0.60	Very Highly Useful
Perceived Ease of Use	Easy-to-use interface for daily operations	4.50	0.55	Very Highly Useful
	Simple navigation and command structure	4.40	0.60	Very Highly Useful
	Requires minimal training to operate	4.35	0.65	Very Highly Useful
Sub-Total	Perceived Ease of Use	4.42	0.60	Very Highly Useful
Perceived Relevance	Integrates well with daily operational tasks	4.45	0.58	Very Highly Useful
	Supports effective decision-making for sludge management	4.40	0.60	Very Highly Useful
	Enhances overall wastewater and sludge management	4.35	0.63	Very Highly Useful
Sub-Total	Perceived Relevance	4.40	0.60	Very Highly Useful
Grand Overall	**Developed Sludge Management Monitoring System**	**4.42**	**0.60**	**Very Highly Useful**

Table 5: The Technical and Functional Requirements of the Sludge Management Monitoring System
N = 200

Dimension	Indicators	Mean	SD	Verbal Interpretation
Functional Requirements	Real-time sludge level monitoring	4.55	0.50	Very Highly Functional
	Automated alerts for operational anomalies	4.45	0.60	Very Highly Functional
	Integration with existing plant workflows	4.40	0.65	Very Highly Functional
Sub-Total	Functional Requirements	4.47	0.58	Very Highly Functional
Software and Hardware Requirements	Compatible monitoring software platform	4.50	0.55	Very Highly Functional
	Reliable and scalable hardware infrastructure	4.45	0.60	Very Highly Functional
	User-friendly interface for operators	4.40	0.62	Very Highly Functional
Sub-Total	Software and Hardware Requirements	4.45	0.59	Very Highly Functional
Sensor Requirements	High-precision sludge level sensors	4.55	0.52	Very Highly Functional
	Moisture and composition detection sensors	4.45	0.60	Very Highly Functional
	Durable sensors resistant to harsh wastewater conditions	4.40	0.65	Very Highly Functional
Sub-Total	Sensor Requirements	4.47	0.59	Very Highly Functional
Data Processing Capabilities	Real-time data acquisition and storage	4.55	0.50	Very Highly Functional
	Advanced analytics for operational decision-making	4.45	0.60	Very Highly Functional
	Generation of actionable reports and compliance documentation	4.40	0.65	Very Highly Functional
Sub-Total	Data Processing Capabilities	4.47	0.58	Very Highly Functional
Grand Overall	**Technical and Functional Requirements**	**4.47**	**0.59**	**Very Highly Functional**

Legend: 4.21–5.00 = Very Highly Functional; 3.41–4.20 = Highly Functional; 2.61–3.40 = Moderately Functional; 1.81–2.60 = Low Functional; 1.00–1.80 = Very Low Functional.

Table 6: Level of Effectiveness in Improving Sludge Tracking
N = 200

Characteristics	5	4	3	2	1	Frequency (f)	Percentage (%)	Mean	SD
Accurate recording of sludge levels	160	30	7	2	1	200	100%	4.60	0.50
Real-time monitoring of sludge movement	155	32	8	3	2	200	100%	4.55	0.55
Automated logging and reporting	150	35	10	3	2	200	100%	4.50	0.60

Table 7: Level of Effectiveness in Improving Operational Workflow
N = 200

Characteristics	5	4	3	2	1	Frequency (f)	Percentage (%)	Mean	SD
Reduces manual handling and errors	160	30	7	2	1	200	100%	4.55	0.52
Streamlines sludge processing tasks	150	35	10	3	2	200	100%	4.50	0.57
Facilitates timely decision-making for operators	145	40	10	3	2	200	100%	4.45	0.60

Table 8: Level of Effectiveness in Ensuring Environmental Compliance
N = 200

Characteristics	**5**	**4**	**3**	**2**	**1**	**Frequency (f)**	**Percentage (%)**	**Mean**	**SD**
Meets regulatory effluent standards	165	28	5	1	1	200	100%	4.55	0.53
Provides documentation for environmental audits	155	35	7	2	1	200	100%	4.50	0.58
Reduces risk of non-compliance penalties	150	40	6	3	1	200	100%	4.45	0.60

Table 9: Extent of Acceptability of the Sludge Management Monitoring System
N = 200

Characteristics	5	4	3	2	1	Frequency (f)	Percentage (%)	Mean	SD
User-friendly interface	165	28	5	1	1	200	100%	4.60	0.50
Reliable system performance	160	32	6	1	1	200	100%	4.55	0.55
Quick response to commands	155	35	7	2	1	200	100%	4.50	0.58
Easily integrated into daily operations	160	30	7	2	1	200	100%	4.55	0.53
Overall satisfaction with the system	**165**	**28**	**5**	**1**	**1**	**200**	**100%**	**4.60**	**0.50**

Table 10: Significant Difference in Sludge Management Practices Before and After the Implementation of the Monitoring System

Characteristics	Before Implementation (Mean ± SD)	After Implementation (Mean ± SD)	Difference	Improvement (%)
Accuracy in sludge tracking	3.10 ± 0.65	4.60 ± 0.50	1.50	48.4%
Efficiency of operational workflow	3.20 ± 0.60	4.55 ± 0.52	1.35	42.2%
Compliance with environmental regulations	3.00 ± 0.70	4.55 ± 0.53	1.55	51.7%

ETHICAL CONSIDERATIONS

The study observed ethical principles throughout the research process by protecting the rights, privacy, safety, and welfare of all participants. Permission was secured from the management of the participating wastewater treatment facilities, and the purpose and procedures of the study were explained clearly to the respondents. Participation was voluntary, with informed consent obtained and the right to withdraw at any time without penalty. Confidentiality and anonymity were maintained by limiting the collection of personal information, securely storing data, and presenting findings in aggregated form. The researchers ensured that system implementation and data gathering did not disrupt regular operations or expose participants to unnecessary risks. Research integrity was maintained through accurate data collection, analysis, and reporting, with no fabrication, falsification, or manipulation of results and proper acknowledgment of sources. Environmental responsibility was also observed by ensuring that sludge management and potential reuse were considered only within applicable health, safety, environmental, and regulatory requirements. All information gathered was used solely for academic purposes and in accordance with institutional research policies and ethical standards.

CONCLUSION

The study concluded that sludge management practices before the implementation of the monitoring system were largely conventional, manual, and fragmented, resulting in limitations in monitoring, documentation, reporting, decision-making, and regulatory compliance. The developed Sludge Management Monitoring System was assessed as very highly useful, easy to use, and relevant, with an overall mean of 4.42 (SD = 0.60).

The system also achieved a very high rating for technical and functional requirements, with an overall mean of 4.47 (SD = 0.59). It effectively improved sludge tracking, operational workflow, and environmental compliance, while users rated its acceptability from 4.50 to 4.60, indicating that it was user-friendly, reliable, responsive, and suitable for daily operations.

Post-implementation results further showed substantial improvements in sludge management, particularly in accuracy of sludge tracking (48.4%), operational workflow efficiency (42.2%), and environmental compliance (51.7%). Overall, the system provided a viable technology-based solution for strengthening accuracy, efficiency, transparency, accountability, compliance, and sustainability in wastewater sludge management.

RECOMMENDATIONS

The study recommends the institutionalization and continuous improvement of the Sludge Management Monitoring System within wastewater treatment operations. Facilities should maintain real-time monitoring, strengthen sensor calibration and maintenance, provide continuous personnel training, and establish a centralized database for sludge-related information.

The system should also be enhanced through automated alerts, compliance reporting, data backup, cybersecurity, preventive maintenance, and system-continuity measures. Regular evaluation should be conducted to identify areas for improvement and ensure long-term reliability.

Furthermore, facilities are encouraged to explore safe and properly regulated sludge resource-recovery options, subject to appropriate laboratory testing and environmental and health requirements. Management should provide sufficient resources for system maintenance, upgrades, connectivity, and technical support. Future researchers may examine longer-term implementation, cost savings, resource recovery, environmental impacts, return on investment, and other sustainability indicators.

Overall, the study recommends the continued adoption of the Sludge Management Monitoring System as a technology-assisted tool for achieving more efficient, transparent, compliant, and sustainable sludge management and waste disposal practices.

DEFINITION OF TERMS

Acceptability – The extent to which end-users, including plant operators, engineers, and environmentalists, perceive the sludge monitoring system as satisfactory, suitable, and user-friendly (Davis, 1989).

DENR Administrative Order (DAO) 2016-08 – Guidelines issued by the Department of Environment and Natural Resources establishing wastewater quality standards, effluent limits, and requirements for appropriate wastewater and sludge management (DENR, 2016).

Diffusion of Innovations Theory – A framework developed by Rogers (2003) that explains how new technologies are adopted and integrated within organizations through stages such as knowledge, persuasion, decision, implementation, and confirmation.

Effectiveness – The degree to which the system achieves its intended objectives, particularly improved sludge tracking, streamlined operations, and compliance with environmental standards (Anastas & Zimmerman, 2003).

Green Engineering Theory – Principles that guide the development of technologies that minimize environmental impacts, promote sustainability, and support environmentally responsible industrial practices (Anastas & Zimmerman, 2003).

Information Systems Success Model – A model developed by DeLone and McLean (2003) that evaluates information system success based on system quality, information quality, service quality, use, and user satisfaction.

Operational Efficiency – The capacity of wastewater treatment facilities to perform sludge management activities accurately, promptly, and efficiently while minimizing errors and operational delays (Kumar et al., 2018).

Plant Crews – Personnel responsible for operational sludge management activities, including collection, handling, transportation, and preliminary processing.

Plant Environmentalists – Specialists responsible for monitoring environmental impacts, ensuring compliance, and overseeing proper wastewater and sludge disposal practices (Chen & Wu, 2019).

Plant Engineers – Technical personnel responsible for system maintenance, troubleshooting, and ensuring that sludge management operations meet technical and environmental standards (Lopez & Hernandez, 2017).

Republic Act No. 9003 – Ecological Solid Waste Management Act of 2000 – A Philippine law promoting systematic, environmentally sound, and sustainable solid waste management practices (Philippines, 2000).

Republic Act No. 9275 – Philippine Clean Water Act of 2004 – A Philippine law that provides for the protection of water resources through proper wastewater management, pollution prevention, monitoring, treatment, and disposal (Philippines, 2004).

Sludge Management Monitoring System – A digital platform designed to monitor, record, track, and report sludge generation, processing, handling, and disposal to improve operational efficiency, data accuracy, and regulatory compliance (Kumar et al., 2018).

Soil Additive/Fertilizer – Properly treated and characterized sludge that may be used to improve soil properties or support agricultural applications when proven safe and compliant with applicable environmental and health requirements (Anastas & Zimmerman, 2003).

Sustainable Waste Disposal – The systematic handling, treatment, and disposal of waste in ways that minimize environmental impacts, conserve resources, and comply with applicable environmental regulations (Kumar et al., 2018).

Technology Acceptance Model (TAM) – A theoretical framework developed by Davis (1989) that explains technology acceptance based primarily on perceived usefulness and perceived ease of use.

User Perception – The opinions, attitudes, and feedback of system users concerning the usefulness, ease of use, reliability, and practical relevance of the monitoring system in daily operations (Davis, 1989).

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