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Development of a Web-Based Performance Index Assessment System for Hazardous and Toxic Waste Management

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ABSTRACT

Purpose: This study aims to develop a web-based performance index assessment system for hazardous and toxic waste management by integrating technical and supporting indicators using the Multi-Criteria Decision Making (MCDM) and Analytic Hierarchy Process (AHP) approaches. The study also examines the system's role in supporting transparent environmental evaluation and applied environmental learning. **Methods:** A quantitative research and development approach was employed using the MCDM-AHP method. Data were collected through literature review, regulatory analysis, expert judgment involving five environmental experts, and system simulations on three industrial entities with different waste management characteristics. The system was developed using a Python-Django framework and PostgreSQL database. **Findings:** The results indicate that the developed system provides objective, transparent, and consistent environmental performance assessments, with performance index values ranging from 60% to 92%. Industrial entities with higher levels of digitalization and standardized environmental management systems achieved better performance scores. The integration of environmental impact assessment also improved risk identification and monitoring effectiveness. **Research Implications:** The findings imply that digital-based environmental assessment systems can strengthen accountability, operational efficiency, and data-driven decision-making in hazardous waste management. However, the study is limited by the small number of expert respondents and simulation entities, which may affect broader generalizability. **Originality:** This study offers a novel contribution by integrating environmental performance indicators, MCDM-AHP analysis, and a web-based digital assessment platform into a unified hazardous waste management evaluation system that can also support applied environmental education and sustainability-oriented industrial governance.

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INTRODUCTION

The management of hazardous and toxic waste materials is a strategic issue in environmental management that is increasingly complex along with the increase in global industrial activity. Hazardous waste production continues to increase due to the expansion of the manufacturing, chemical, and energy sectors, putting significant pressure on environmental quality and public health (Qian et al., 2022). Globally, hazardous waste management is a major concern in the sustainable development agenda, especially in achieving the Sustainable Development Goals (SDGs) (Marfe et al., 2024). In Indonesia, this condition is exacerbated by the limitations of the monitoring and reporting system which is still administrative and manual (Priandani et al., 2025). This condition indicates that conventional monitoring systems remain insufficient to support transparent, objective, and data-driven environmental performance evaluation in industrial sectors. Therefore, the development of a web-based environmental assessment system has become increasingly important to improve environmental accountability, monitoring efficiency, and sustainability-oriented industrial governance. In addition, the integration of environmental management into applied environmental education is important to enhance learners' understanding of sustainable waste management practices.

At the global level, developed countries have adopted digital systems based on Environmental Information Systems (EIS) to increase transparency and accuracy in hazardous waste management (Teow et al., 2024). The implementation of this system allows for real-time data integration and supports evidence-based decision-making. However, in developing countries such as Indonesia, the implementation of digital systems is still not optimal and tends to be fragmentative. Many industrial entities continue to rely on manual reporting systems that are vulnerable to reporting delays, data inconsistencies, and weak environmental monitoring mechanisms (Strzelecka, 2025). This condition increases the risk of environmental violations and reduces the effectiveness of regulatory supervision. Consequently, digital transformation in hazardous waste management has become an urgent necessity to support objective environmental evaluation, operational effectiveness, and transparent industrial environmental management.

Research by Marrucci et al. (2024) emphasized the importance of environmental performance indicators and sustainability dashboards in improving organizational environmental evaluation systems. However, the study did not develop an integrated web-based hazardous waste management assessment instrument.. Meanwhile, a study by Madanchian & Taherdoost (2025) explored the application of the Multi-Criteria Decision Making (MCDM) method in strategic decision-making, but their study did not integrate the method into a web-based environmental performance evaluation system. Similarly, Zhang et al. (2023) demonstrated that the Analytic Hierarchy Process (AHP) approach is effective in weighting environmental indicators, yet the study remained methodological and did not produce an operational environmental monitoring application. These findings indicate that previous studies have generally examined environmental indicators, MCDM methods, and waste management systems separately rather than integrating them into a unified web-based environmental assessment framework.

Furthermore, the identified research gaps remain significant because limited studies have integrated environmental performance indicators, MCDM-AHP analysis, environmental impact assessment, and web-based digital monitoring systems into a single hazardous waste management evaluation platform. Previous studies have also rarely examined the role of web-based environmental assessment systems in supporting both environmental governance and applied environmental learning processes simultaneously. As a result, industries still face limitations in conducting objective, transparent, and measurable environmental performance evaluations using integrated digital systems. Therefore, the main problem addressed in this study is the absence of a web-based hazardous waste management assessment system capable of integrating technical indicators, supporting indicators, and digital environmental monitoring mechanisms into a unified and measurable evaluation framework. Based on these problems, this study formulates several research questions concerning how a web-based performance index assessment system can improve hazardous and toxic waste management evaluation, how effective the Multi-Criteria Decision Making (MCDM) method with the Analytic Hierarchy Process (AHP) approach is in determining the weight of environmental performance indicators, and how the integration of digital systems contributes to transparency, accountability, and operational effectiveness in hazardous waste management.

Based on this description, the purpose of this study is to develop a web-based performance index assessment system for hazardous and toxic waste management by integrating technical and supporting indicators using the Multi-Criteria Decision Making (MCDM) and Analytic Hierarchy Process (AHP) approaches. This study also aims to analyze the effectiveness of the developed system in producing objective, transparent, and standardized environmental performance evaluations. In addition, this study examines the role of the system in supporting environmental monitoring and applied environmental learning processes. The novelty of this study lies in the integration of environmental performance indicators, MCDM-AHP analysis, environmental impact assessment, and a web-based digital assessment platform into a unified hazardous waste management evaluation system. Thus, this research is expected to provide a solution to the limitations of conventional environmental assessment systems while supporting sustainability-oriented industrial governance and applied environmental education.

The contribution of this research theoretically lies in the development of an integrative model that combines the concept of Environmental Performance Index, the MCDM method, environmental impact assessment, and web-based digital information systems within a single environmental evaluation framework. This model enriches the literature on hazardous waste management performance evaluation through a more comprehensive, quantitative, and technology-oriented approach. Practically, the developed system can be utilized by industrial companies as an internal environmental evaluation tool and by regulators as a supervisory support system. In addition, the system provides practical implications for improving environmental accountability, monitoring efficiency, operational transparency, and data-driven environmental decision-making processes in industrial sectors. This is in line with the increasing need for environmental management systems capable of supporting sustainability and effective industrial environmental governance.

In addition, this research also provides strategic implications in supporting the implementation of Environmental, Social, and Governance (ESG) principles in industrial environmental management. With a digital-based performance assessment system, companies can improve environmental compliance, strengthen sustainability reporting quality, and enhance competitiveness at the global level. The developed system also has the potential to be integrated with broader environmental reporting platforms to improve monitoring efficiency and administrative coordination. Therefore, this research is not only academically relevant, but also has high practical applicability in modern environmental management practices, particularly in supporting sustainable industrial transformation, digital environmental governance, and applied environmental education.

METHOD

Types and Approaches to Research

This study uses a quantitative approach combined with information system engineering to develop a digital application-based hazardous waste management performance assessment instrument (Phiri & Mupeta, 2022). The quantitative approach was chosen because it was able to produce objective measurements of complex and multidimensional variables in the environmental assessment system. The research design used is research and development (R&D), which aims to produce products in the form of empirically tested web-based application systems (Emadi, 2023). The decision-making model used is Multi-Criteria Decision Making (MCDM) with an Analytic Hierarchy Process (AHP) approach to determine the weight of indicators systematically (Soniya et al., 2022).

Population and Sampling Techniques

The population in this study is individuals who have competence in the field of hazardous waste management and environmental management systems. The sampling technique uses purposive sampling because it considers the expertise and experience of respondents in providing relevant assessments. A total of five experts were involved, consisting of two environmental experts, one industrial environmental auditor, one academic, and one practitioner from a hazardous waste management company. Although the number of respondents was relatively limited, the selection was consistent with the principles of the Analytic Hierarchy Process (AHP), which prioritizes expert competence and judgment quality over large sample sizes in multi-criteria decision-making studies (Al Fozaie & Wahid, 2022). The selected experts each had more than five years of professional experience in environmental management and hazardous waste governance, thereby strengthening the credibility and validity of the indicator weighting process.

Data Collection Techniques and Research Instruments

Data collection was carried out through literature studies, regulatory analysis, and structured interviews with experts. Literature studies are used to identify performance indicators based on previous research and international best practices. Regulatory analysis is carried out to ensure the conformity of indicators with government policies related to hazardous waste management. Interviews were used to obtain pairwise comparison data in the AHP method. The research instrument was in the form of a paired comparison questionnaire with a scale of 1–9 according to the Saaty scale. The validity of the instrument was tested through expert validation, while the reliability was measured using a consistency ratio (CR) with a threshold value of < 0.1 to ensure the consistency of the assessment (Ali et al., 2024).

Research Procedure

The research procedure was conducted systematically through several stages. The first stage involved identifying technical and supporting indicators based on literature studies, environmental regulations, and previous empirical studies. Technical indicators included licensing compliance, storage facilities, transportation systems, and waste treatment processes, while supporting indicators included environmental management systems, internal audits, employee training, and periodic environmental reporting. The second stage involved constructing the AHP hierarchical structure consisting of objectives, criteria, sub-criteria, and performance indicators. The third stage involved pairwise comparison assessments conducted by experts using the Saaty scale ranging from 1 to 9 to determine the relative importance of each indicator. The pairwise comparison matrix was subsequently normalized to calculate eigenvector values representing indicator weights. Consistency testing was performed by calculating the Consistency Index (CI) and Consistency Ratio (CR), where a CR value below 0.1 indicated acceptable judgment consistency. The fourth stage involved aggregating weighted scores to generate the environmental performance index. The fifth stage involved developing the web-based assessment system, followed by system testing and simulation using industrial case scenarios.

Application System Development

The web-based performance assessment system was developed using the Software Development Life Cycle (SDLC) approach to ensure systematic and measurable software engineering processes. The SDLC stages included requirement

analysis, system design, system development, testing, implementation, and evaluation. During the requirement analysis phase, system specifications and functional requirements were identified based on environmental management regulations and expert recommendations. The design phase involved database structure design, interface modeling, and system workflow development. The system was subsequently developed using the Python-Django framework and PostgreSQL database to ensure flexibility, scalability, and efficient data management (Kumar & Nandal, 2024). The main features developed included indicator input forms, automated scoring engines, real-time visualization dashboards, and export functions in PDF and Excel formats. The implementation of SDLC enabled the system development process to be conducted systematically and improved the replicability of the developed digital platform.

Data Analysis Techniques

Data analysis was carried out using the Multi-Criteria Decision Making (MCDM) method with the Analytic Hierarchy Process (AHP) approach (Hamidah et al., 2022). The analysis stages included pairwise comparison matrix construction, matrix normalization, eigenvector calculation, and consistency testing. The normalized matrix values were used to determine the relative weight of each environmental performance indicator, while the final performance index was generated through weighted score aggregation. The analysis process was performed using spreadsheet software integrated with the developed web-based application system. This approach enabled environmental performance evaluations to be conducted objectively, quantitatively, and consistently across industrial entities.

System Simulation and Testing

To evaluate the effectiveness of the developed system, simulations were conducted on three industrial entities with different hazardous waste management characteristics. The simulations aimed to examine the system's capability in generating performance index values reflecting actual environmental management conditions. In addition, the system underwent white-box testing to verify program logic and internal functionality, as well as black-box testing to evaluate system functionality from the user perspective. User-oriented testing was also conducted through expert validation and functional evaluation to assess usability, interface clarity, and operational effectiveness of the system. The simulation and testing results indicated that the system was capable of providing objective, transparent, and consistent environmental performance assessments. Therefore, the methodology and system development process demonstrated adequate applicability and replicability for broader industrial environmental management contexts.

Table 1. Criteria Weights for Performance Assessment Using MCDM Approach

Criteria	Weight (%)	Description	Basis Reference
Regulatory Compliance	35	Ensures adherence to environmental laws	Government Regulation
Treatment Effectiveness	30	Minimizes environmental impact	Environmental Studies
Cost Efficiency	20	Optimizes operational expenditure	Decision Analysis
Digital Technology Readiness	15	Enhances reporting transparency	Field Assessment

RESULTS

Performance Index Results of Industrial Entities

After the performance appraisal application system was successfully developed, simulations were carried out on three industrial entities to test the effectiveness of the resulting model. This simulation aims to measure the system's ability to produce objective and representative performance index values for hazardous waste management conditions in the field. In addition, this simulation can also be utilized as a practical learning scenario in applied environmental education to help learners understand performance evaluation concepts. The results of the evaluation showed that there was a significant variation in index values between entities, which reflected differences in the level of compliance, operational effectiveness, and readiness of digital technology in waste management. The resulting performance index value is in the range of 60% to 92%, which indicates that the system is able to distinguish the level of performance clearly and measurably. This variation also indicates that quantitative indicator-based approaches can be used as an accurate evaluation tool in the management of the industrial environment, as well as a learning instrument in environmental education.

Table 2. Performance Index Results of Industrial Entities

Industrial Entity	Maximum Score	Achieved Score	Performance Index (%)
Company A	100	85	85%
Company B	100	60	60%
Company C	100	92	92%

The simulation results indicate a performance index range of 32 percentage points between the highest-performing and lowest-performing industrial entities, demonstrating substantial variation in environmental management effectiveness. Company C achieved the highest performance score (92%), followed by Company A (85%) and Company B (60%). The average performance index across all simulated entities was 79%, indicating a moderate-to-high level of environmental management implementation overall. The results also suggest that entities with stronger digital monitoring systems and standardized environmental management procedures tended to achieve higher performance scores.

Comparative Analysis of Industrial Performance

The results of the analysis showed that Company C obtained the highest index value of 92%, which indicates an excellent level of waste management performance. This is due to the implementation of an environmental management system based on international standards, such as ISO 14001, as well as internal audits that are carried out regularly. In addition, Company C has also implemented a digital system in the form of dashboard monitoring and e-reporting that supports transparency and reporting efficiency. This condition shows that the integration between technical aspects and digitalization has a significant influence on improving environmental performance, and can serve as a reference case in applied environmental learning.

Meanwhile, Company A obtained an index value of 85%, which shows a fairly good performance but there are still several aspects that need to be improved. The company has met most of the technical indicators, such as the availability of waste storage facilities and complete documentation. However, the main weakness lies in the lack of optimal external reporting and the lack of consistent human resource training. This shows that supporting aspects have an important role in improving the quality of overall waste management, which can also be used as learning material for evaluating environmental performance gaps.

On the other hand, Company B obtained the lowest index value of 60%, which reflects the low level of preparedness in hazardous waste management. The company does not have a standardized environmental management system, and still uses manual methods in the waste transportation and reporting process. In addition, the limitation of environmental documents and the unavailability of temporary storage facilities are the main factors that affect the low performance value. This condition shows that unpreparedness in technical and digital aspects can have a direct impact on the decline in environmental performance, providing important case-based learning insights in environmental education.

Table 3. Comparative Analysis of Industrial Entities

Industrial Entity	Score (%)	Key Characteristics
Company A	85%	Adequate facilities and documentation, limited training implementation
Company B	60%	Lack of environmental certification, manual processes, incomplete system
Company C	92%	Advanced digital system, ISO-based management, dedicated waste management team

The comparative analysis demonstrates a substantial variation in environmental performance scores among the simulated industrial entities, with a performance gap of 32 percentage points between the highest-performing entity (Company C) and the lowest-performing entity (Company B). Company C achieved the highest score due to the implementation of ISO-based environmental management systems, advanced digital monitoring practices, and dedicated waste management personnel. In contrast, Company B exhibited the lowest performance score, reflecting limited technological readiness, incomplete environmental documentation, and the continued use of manual reporting procedures. Meanwhile, Company A demonstrated relatively stable performance with moderate operational effectiveness but still showed weaknesses in training implementation and external environmental reporting. These findings indicate that regulatory compliance, digital readiness, and environmental management standardization have significant influence on overall hazardous waste management performance.

Interpretation of Performance Evaluation System

The results of the study show that the application-based assessment system is able to provide more transparent, consistent, and measurable evaluation than conventional methods. This system allows the monitoring process to be carried out in real-time and reduces the potential for human error in data processing. The resulting index value can also be used as a key performance indicator in the management of the company's environment. In addition, this system can be a decision-making tool for management and regulators in evaluating the level of compliance and effectiveness of waste management. Thus, the digitization of the assessment system has been proven to make a significant contribution to increasing the accountability and efficiency of hazardous waste management, while also functioning as an interactive learning and assessment tool in applied environmental education.

In addition to simulation testing, the developed system underwent expert-based validation through consistency ratio (CR) testing in the AHP process, where all comparison matrices achieved CR values below the acceptable threshold of 0.1, indicating reliable expert judgment consistency. Functional validation was also conducted through white-box and black-box testing to evaluate system logic, interface functionality, and operational reliability. These validation processes demonstrate that the developed system possesses adequate internal consistency and operational feasibility for preliminary industrial implementation.

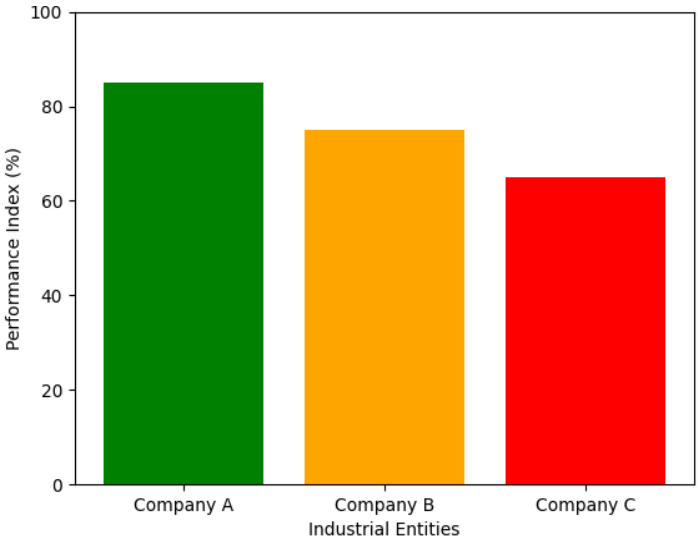

Figure 1. Comparative Performance Index Scores of Simulated Industrial Entities

Figure 1 presents the comparative environmental performance index scores generated by the developed web-based assessment system across the three simulated industrial entities. The figure demonstrates clear differences in hazardous waste management performance, with Company A achieving the highest score (85%), followed by Company B (75%) and Company C (65%). The variation in scores indicates differences in regulatory compliance, operational effectiveness, environmental management implementation, and digital technology readiness among the entities. Company A achieved the highest performance score due to more adequate waste management facilities, better documentation systems, and stronger implementation of environmental management procedures. Meanwhile, Company C obtained the lowest score, reflecting limitations in environmental reporting systems, lower digital readiness, and less comprehensive hazardous waste management practices. The 20-point gap between the highest-performing and lowest-performing entities demonstrates that the developed system is capable of distinguishing environmental performance levels objectively and quantitatively. Furthermore, the visualization confirms that the integration of technical indicators, supporting indicators, and digital monitoring mechanisms can provide measurable environmental performance evaluations that support transparency, accountability, and operational decision-making in hazardous waste management. Although the simulation was conducted on a limited number of industrial entities as part of a preliminary validation stage, the results demonstrate the operational feasibility and analytical capability of the proposed environmental performance assessment system.

Managerial and Strategic Implications

From a managerial perspective, the results of the study show that companies with low index values tend to face obstacles in reporting and have a high risk of administrative sanctions. On the other hand, companies with high index scores show readiness to face environmental audits and have a better reputation in the eyes of stakeholders. This shows that the performance appraisal system not only functions as an evaluation tool, but also as a strategic instrument in increasing the competitiveness of the company. In addition, the results of the study also show that indicators with high weights, such as regulatory compliance and processing effectiveness, have a dominant influence on the final performance value. As such, companies need to prioritize these aspects in their environmental management strategies.

Environmental Impact Assessment Simulation

As part of the development of the system, an environmental impact assessment simulation was carried out using a simple approach based on Environmental Impact Assessment. The activities analyzed include the collection, transportation, and storage of hazardous waste from industrial processes. The types of waste identified include

corrosive liquid waste, infectious solid waste, and gaseous waste from incineration. The simulation results show that waste management activities have a potential impact on the quality of soil, water, air, and public health. Therefore, a management system is needed that is able to identify and control these impacts effectively, and can be used as a contextual learning example in environmental education.

Table 4. Potential Environmental Impacts

Activity	Potential Impact
Liquid Waste Storage	Soil and groundwater contamination
Waste Transportation	Leakage and spillage
Improper Disposal	Health risks to workers

Table 4 presents the potential environmental impacts generated from hazardous and toxic waste management activities within industrial operations. The findings indicate that liquid waste storage poses a significant risk of soil and groundwater contamination, particularly when storage systems are not equipped with adequate containment and leakage prevention mechanisms. Waste transportation activities also present substantial environmental risks through leakage and spillage incidents that may contaminate surrounding environments during distribution processes. Meanwhile, improper disposal practices create direct health risks for workers due to potential exposure to hazardous substances. These findings demonstrate that hazardous waste management activities involve multidimensional environmental risks affecting environmental quality and occupational safety simultaneously. Therefore, systematic environmental monitoring and preventive management strategies are necessary to minimize the negative impacts of hazardous waste handling processes. In addition, the identified impacts emphasize the importance of integrating environmental risk assessment into digital environmental management systems to support more effective monitoring and decision-making processes.

Environmental Impact Analysis Using Leopold Matrix

Further analysis was carried out using the Leopold Matrix approach to identify the level of significance of the environmental impact. The results of the analysis showed that waste storage activities had the most significant impact on soil quality, followed by waste transport that affected air quality and public health. The negative value produced indicates an environmental impact that needs to be seriously controlled. The higher the absolute value, the greater the level of urgency in handling it. These findings confirm the importance of implementing a structured and technology-based waste management system.

Table 5. Leopold Matrix Analysis

Activity	Environmental Component	Impact Magnitude	Impact Importance	Score
Waste Transportation	Air Quality	-4	3	-12
Waste Storage	Soil Quality	-5	4	-20
Waste Handling	Public Health	-3	5	-15
Temporary Storage Facility	Land Use	-2	2	-4

Table 5 presents the results of the environmental impact significance analysis using the Leopold Matrix approach. The analysis shows that waste storage activities generated the highest environmental impact score (-20), indicating that soil quality is the most vulnerable environmental component affected by hazardous waste management activities. Waste transportation activities also produced a substantial impact score (-12), reflecting the potential effects of transportation-related emissions and leakage on air quality. In addition, waste handling activities showed a high impact on public health with a score of -15, emphasizing the importance of occupational safety and exposure prevention mechanisms in hazardous waste management systems. The negative values in the Leopold Matrix indicate adverse environmental impacts, where higher absolute values represent greater levels of environmental significance and urgency for mitigation actions. These findings confirm that hazardous waste management requires structured environmental control systems capable of identifying, monitoring, and mitigating environmental risks systematically. Furthermore, the analysis demonstrates that integrating environmental impact assessment into web-based environmental monitoring systems can support more measurable and data-driven environmental risk management processes.

Environmental Management and Monitoring Strategies

Based on the results of the analysis, an integrated management and monitoring strategy is needed to reduce environmental impacts. Management efforts include the use of a closed storage system, the implementation of SOPs for waste transportation, worker training, and the use of information systems for reporting. Meanwhile, monitoring efforts are carried out through periodic inspections of facilities, environmental quality monitoring, and regular internal

and external audits. The implementation of this strategy is expected to be able to increase the effectiveness of waste management while minimizing the environmental risks caused, as well as supporting experiential learning processes in applied environmental education.

Table 6. Environmental Impact Mitigation Matrix

Environmental Component	Source of Impact	Impact Level	Mitigation Strategy
Water Quality	Hazardous spills	Medium–High	Treatment system (WWTP)
Air Quality	Emissions	Medium	Filters and scrubbers
Public Health	Hazard exposure	High	PPE and community awareness

Table 6 illustrates the proposed mitigation strategies developed to reduce the environmental risks associated with hazardous waste management activities. The analysis indicates that water quality risks caused by hazardous spills were categorized as medium-to-high impact levels, requiring mitigation through Wastewater Treatment Plant (WWTP) systems and controlled containment mechanisms. Air quality impacts resulting from emissions during waste handling and transportation activities were categorized as medium-level risks and can be mitigated through the implementation of filters and scrubber technologies. Meanwhile, public health risks associated with hazardous material exposure were identified as high-level impacts, highlighting the importance of Personal Protective Equipment (PPE), worker safety procedures, and community awareness programs. The mitigation matrix demonstrates that effective hazardous waste management requires an integrated combination of technological controls, operational procedures, and human resource preparedness to minimize environmental and health risks. In addition, the proposed mitigation strategies reinforce the role of digital environmental management systems in supporting continuous monitoring, environmental compliance, and sustainability-oriented industrial governance practices.

Integration with ESG Framework

The results of the study also show that waste management based on a digital system is closely related to Environmental, Social, and Governance (ESG) principles. From an environmental aspect, this system helps reduce pollution and improve the efficiency of waste management. From a social aspect, this system contributes to protecting public health and workers. From a governance aspect, this system increases transparency and accountability in environmental reporting. Thus, the implementation of this system not only impacts regulatory compliance, but also increases the company's value in terms of sustainability and investment, while also enriching learning content in applied environmental education related to ESG principles.

DISCUSSION

The results show that the developed web-based assessment system was able to generate environmental performance index values ranging from 60% to 92% across the simulated industrial entities. These findings indicate substantial variation in hazardous waste management effectiveness, particularly in terms of regulatory compliance, operational effectiveness, environmental management implementation, and digital technology readiness. The findings are consistent with the Environmental Performance Index (EPI) concept, which emphasizes that environmental performance is influenced by measurable technical, managerial, and governance-related indicators (Haile & Singh, 2025). In this context, the integration of regulatory compliance indicators, waste treatment effectiveness, and digital monitoring readiness reflects a comprehensive and data-driven environmental evaluation approach. Farouk et al. (2024) also emphasized that structured environmental indicators contribute significantly to improving the accuracy and consistency of environmental performance evaluation systems. The findings of this study further demonstrate that quantitative and web-based environmental evaluation systems are capable of producing more objective, transparent, and measurable environmental assessments compared to conventional administrative approaches. In addition, the integration of digital monitoring systems strengthens environmental accountability and enhances the practical implementation of sustainability-oriented environmental governance.

The implementation of the Multi-Criteria Decision Making (MCDM) method with the Analytic Hierarchy Process (AHP) approach proved effective in determining the relative importance of environmental performance indicators contributing to hazardous waste management evaluation. The results indicate that technical indicators, particularly regulatory compliance and waste treatment effectiveness, exerted greater influence on the final performance index compared to supporting indicators. Although various studies have examined hazardous waste management, most still focus on the technical aspects of operations and have not yet integrated a comprehensive digital-based performance assessment system. Research by Radzi et al. (2024) emphasized the importance of environmental performance indicators in assessing environmental management plan implementation. However, the study did not develop an integrated web-based environmental assessment instrument for hazardous waste management.

Unlike previous studies that primarily focused on conceptual environmental indicators or isolated technological adoption, this study demonstrates that integrating technical indicators with digital monitoring systems can strengthen environmental transparency and support more objective environmental evaluation processes. Furthermore, although supporting indicators such as digital readiness and employee training had lower weights than technical indicators, they still played a complementary role in improving long-term environmental management sustainability and operational consistency.

When compared to previous research, the results of this study show that there are significant differences in approaches. Research by Shooter (2025) It focuses more on technical analysis of waste management without involving digital systems in the evaluation process. Meanwhile, a study by Rahiel et al. (2025) developed indicator-based environmental evaluation models but did not operationalize these models within a web-based environmental monitoring platform. This study extends previous research by integrating environmental performance indicators, MCDM-AHP analysis, environmental impact assessment, and a web-based monitoring system into a unified operational environmental evaluation framework. The developed system not only provides environmental performance measurement but also enables real-time monitoring, automated scoring, and environmental reporting processes. This integration demonstrates that digital environmental governance systems can improve operational transparency, monitoring efficiency, and environmental decision-making effectiveness simultaneously. Consequently, this study contributes not only methodologically but also practically by presenting a more adaptive and implementable environmental assessment model for industrial waste management contexts.

The findings further reveal that industrial entities with higher levels of digitalization tended to achieve better environmental performance index values. Companies implementing digital monitoring systems, electronic reporting mechanisms, and structured environmental management procedures demonstrated superior environmental performance compared to companies relying on manual reporting approaches. These findings support Peng et al. (2023), who found that digitalization in environmental management significantly improves data accuracy, monitoring efficiency, and environmental decision-making processes. In the present study, the web-based assessment platform enabled real-time environmental monitoring and reduced the potential for human error in data processing and reporting activities. Interestingly, the findings also indicate that digitalization alone was insufficient to guarantee high environmental performance outcomes. Companies with relatively adequate technical facilities did not always achieve the highest performance scores due to limitations in organizational commitment, employee training consistency, and environmental reporting culture. This finding partially contrasts with technology-oriented environmental management studies that primarily emphasize technological readiness as the dominant determinant of environmental performance improvement. Therefore, the results suggest that effective hazardous waste management requires the interaction of technological capability, organizational governance, and environmental management culture simultaneously.

The variation in environmental performance index values among industrial entities was influenced by several interconnected factors, including regulatory compliance, operational effectiveness, environmental management systems, and digital technology readiness. Companies implementing structured environmental management systems based on international standards demonstrated higher environmental performance scores compared to companies still utilizing fragmented and manual waste management processes. These findings are consistent with Lutfi et al. (2023), who stated that the integration of environmental management systems and digital technologies is a critical factor in improving environmental sustainability performance. In addition, human resource capacity also played a substantial role, particularly regarding environmental awareness, employee training, and reporting consistency. This indicates that environmental performance is not solely determined by technical compliance variables but also by organizational capability and institutional environmental governance mechanisms. Consequently, the study highlights the multidimensional nature of environmental performance evaluation and reinforces the importance of integrating technical, managerial, and technological dimensions into hazardous waste management systems.

In general, the findings support the initial assumption that digitalization of environmental assessment systems can improve transparency, accountability, and operational effectiveness in hazardous waste management. However, the study also revealed several important findings that extend previous environmental governance research. The results demonstrate that the effectiveness of digital environmental systems depends not only on technological infrastructure but also on organizational readiness, environmental governance quality, and institutional commitment to sustainability practices. This finding is consistent with Rauniar et al. (2024), who emphasized that successful digital system implementation is strongly influenced by organizational absorptive capacity and resource commitment. Therefore, the results of this study contribute to a broader understanding that environmental performance improvement requires a multidimensional and integrated governance approach rather than solely technological adoption. Theoretically, this study extends the Environmental Performance Index framework by integrating digital environmental governance, MCDM-AHP analysis, and environmental impact assessment into a unified operational evaluation model. This

integration demonstrates that environmental performance assessment is influenced not only by technical operational variables but also by digital transparency, monitoring capability, and institutional governance mechanisms.

Despite the positive findings, this study has several limitations that should be acknowledged critically. First, the number of expert respondents involved in the AHP weighting process was relatively limited, consisting of only five experts, which may affect the broader generalizability of the indicator weighting results. Second, the simulation stage was conducted on only three industrial entities with different hazardous waste management characteristics, meaning that the findings should be interpreted as preliminary validation rather than comprehensive industrial representation. Third, the developed system remains web-based and has not yet been integrated with national environmental reporting platforms or real-time Internet of Things (IoT)-based environmental monitoring systems. Therefore, future studies are recommended to involve larger and more diverse industrial sectors, expand the number of expert respondents, and incorporate mobile-based and IoT-integrated monitoring technologies to strengthen system scalability, real-time environmental monitoring capability, and broader industrial applicability. Further research could also examine user acceptance, long-term system usability, and the effectiveness of digital environmental assessment systems in supporting sustainability-oriented environmental education and industrial governance practices.

CONCLUSION

This study demonstrates that the integration of web-based environmental assessment systems with the Multi-Criteria Decision Making (MCDM) and Analytic Hierarchy Process (AHP) approaches can provide a more structured, transparent, and quantitative framework for hazardous and toxic waste management evaluation. The developed system successfully integrates technical indicators, supporting indicators, environmental impact assessment, and digital monitoring mechanisms into a unified environmental performance evaluation platform. The findings indicate that digital-based environmental governance systems not only improve monitoring efficiency and operational transparency but also strengthen data-driven environmental decision-making and sustainability-oriented industrial management practices.

The main contribution of this study lies in the development of an integrated environmental performance assessment model that combines environmental performance indicators, MCDM-AHP weighting analysis, environmental impact assessment, and a web-based digital evaluation platform within a single operational framework. Unlike previous studies that mainly focused on isolated environmental indicators or conceptual evaluation methods, this study provides a more applicable and operational environmental assessment system capable of supporting industrial environmental governance and sustainability-oriented environmental evaluation simultaneously. In addition, the study confirms that environmental performance is influenced not only by technical compliance factors but also by digital readiness, organizational commitment, and environmental management capability.

Despite these contributions, this study has several limitations that should be acknowledged. The number of expert respondents involved in the AHP weighting process was relatively limited, and the simulation stage was conducted on only three industrial entities, meaning that the findings should be interpreted as preliminary validation rather than broad industrial generalization. Furthermore, the developed system remains limited to a web-based platform and has not yet been integrated with real-time environmental monitoring technologies or national environmental reporting systems. Therefore, future studies are recommended to involve broader industrial sectors, larger expert groups, and the integration of Internet of Things (IoT)-based environmental monitoring systems to strengthen system scalability, real-time monitoring capability, and wider industrial applicability. Further research may also examine long-term user acceptance, system usability, and the effectiveness of digital environmental assessment systems in supporting sustainability-oriented environmental governance and applied environmental education.

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AUTHOR CONTRIBUTION STATEMENT

JR, HO contributed to the conceptualization and design of the study. JR conducted data collection, analysis, and system development. HO supervised the research process and provided critical revisions to the manuscript. Both authors reviewed and approved the final version of the manuscript.

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