



Performance Indicator Model for Environmental Management Plan in Sustainable Toll Road Construction in Riau, Indonesia: A Case Study of the Pekanbaru-Dumai Toll Road Using AHP and LCA

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ABSTRACT

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Toll road construction supports regional connectivity and economic growth in Indonesia, but poses significant environmental risks, particularly in peatland regions such as Riau Province. This study proposes a performance indicator model to evaluate the effectiveness of environmental management plan (EMP) implementation during the construction of the Pekanbaru-Dumai Toll Road. The model integrates the analytic hierarchy process (AHP) to prioritize environmental aspects based on stakeholder input and life cycle assessment (LCA) to quantify environmental impacts. A structured questionnaire was distributed to 100 selected stakeholders, including consultants, contractors, government officials, and academics. AHP results identified Soil and Land as the most critical aspect, followed by Water Quality and Ecology, highlighting concerns such as slope failure, erosion, and peatland degradation. LCA simulations validated these findings, showing that earthworks and asphalt paving contributed the highest greenhouse gas (GHG) emissions and ecological disturbance. Stakeholder perception analysis further revealed weaknesses in EMP enforcement, monitoring, and implementation fidelity. The resulting AHP-LCA-based model provides a structured and replicable framework for performance-based environmental monitoring in toll road infrastructure. It supports decision-makers in aligning mitigation priorities with actual environmental risks and enhances accountability in sustainable construction. The model is adaptable for broader use in ecologically sensitive infrastructure projects.

1. INTRODUCTION

The expansion of toll road infrastructure has become a cornerstone of Indonesia's national development strategy, aimed at improving interregional connectivity, reducing logistics costs, and driving economic growth [1]. Among the flagship projects is the Pekanbaru-Dumai Toll Road in Riau Province, which plays a strategic role in linking industrial centers across Sumatra. However, the development of large-scale infrastructure in ecologically fragile landscapes such as peatlands presents significant environmental challenges. Tropical peatlands are globally recognized carbon sinks and hydrological regulators, yet they are highly susceptible to land degradation, subsidence, biodiversity loss, and greenhouse gas (GHG) emissions when disturbed by construction activities [2, 3]. These challenges are particularly acute for linear infrastructure projects, where large-scale cut-and-fill operations and drainage modifications often exacerbate long-term ecological disruption.

To manage these risks, Indonesian regulations require the preparation and implementation of environmental management plans (EMPs) as part of the Environmental Impact Assessment (AMDAL) process, regulated under Law No. 32/2009 and Ministerial Regulation No. 10/2024 (KLHK).

EMPs are designed to guide mitigation actions, environmental monitoring, and compliance throughout the project lifecycle. Despite their legal significance, many EMPs are criticized for functioning primarily as formal documentation with limited practical implementation in the field. A common shortcoming is the lack of clear, measurable indicators to evaluate whether environmental commitments are effectively carried out during project execution [4, 5].

Environmental performance indicators (EPIs) are essential for translating mitigation objectives into actionable outcomes, enabling both project developers and regulators to monitor progress, ensure accountability, and support adaptive management [6, 7]. Yet in Indonesia, the adoption of such indicators in toll road projects remains inconsistent, particularly in high-risk environments like tropical peatlands. Furthermore, existing EMP evaluation methods are often generic, underutilize empirical environmental data, and insufficiently incorporate stakeholder perspectives, leading to limited applicability in site-specific contexts [8, 9]. This gap is especially significant in peatland toll roads, where conventional EMPs tend to underestimate issues such as peat oxidation, subsidence, and long-term hydrological change.

To address these limitations, this study proposes a performance indicator model that combines two

complementary methods: the analytic hierarchy process (AHP) and life cycle assessment (LCA). AHP allows for the prioritization of environmental aspects and sub-indicators based on expert judgment and stakeholder perspectives [10], while LCA quantifies the environmental impacts of construction activities, especially emissions and ecological disruption [11, 12]. The novelty of this research lies in combining AHP and LCA into a unified framework for EMP evaluation in tropical peatland road construction, bridging the gap between stakeholder-based priorities and empirical environmental evidence.

This hybrid approach is applied to the Pekanbaru-Dumai Toll Road as a representative case study of infrastructure development in a peatland-dominated landscape. The objectives of this study are threefold: (1) to identify and prioritize key environmental indicators relevant to EMP performance in toll road construction; (2) to quantify major environmental impacts during the construction phase using LCA; and (3) to develop a structured, replicable model that integrates stakeholder-based judgment and scientific data to support more effective EMP implementation. By advancing a practical and evidence-based monitoring tool, this research contributes to the broader goals of sustainable infrastructure governance in Indonesia and provides a methodological reference for similar projects in other tropical regions [13].

2. LITERATURE REVIEW

2.1 Environmental management plans in infrastructure projects

EMPs are essential instruments for implementing environmental safeguards in infrastructure development, serving as a bridge between impact assessments and actual mitigation efforts during both the construction and operational phases. As emphasized by Ibrahim and Shaker [7], EMPs play a vital role in translating environmental commitments into concrete actions on the ground, especially in large-scale infrastructure projects. Globally, EMPs are recognized as part of best practices in environmental governance, ensuring that impacts identified during AMDAL are addressed through measurable mitigation and monitoring strategies.

According to Karim et al. [5], a well-structured EMP not only outlines mitigation procedures but also assigns responsibilities, schedules, and reporting mechanisms, thereby functioning as a dynamic management tool rather than a static document.

In Indonesia, the EMP, locally known as *Rencana Pengelolaan Lingkungan* (RPL) is a compulsory component of the *Analisis Mengenai Dampak Lingkungan* (AMDAL), as regulated under Law No. 32/2009 and further detailed in Ministerial Regulation No. 10/2024 (KLHK) (Law No. 32/2009). The RPL outlines the type, scope, and frequency of environmental mitigation and monitoring activities, as well as the responsible parties and reporting mechanisms throughout a project's lifecycle. In the context of large-scale infrastructure, such as toll roads, the RPL is expected to manage diverse environmental risks, including deforestation, water contamination, erosion, and social disturbance.

Despite its regulatory significance, several empirical studies indicate that EMPs in Indonesia often remain underutilized or merely fulfill administrative requirements without translating into actionable site-level interventions [4, 6]. This issue is

especially apparent in regions with limited institutional capacity and minimal environmental oversight. Often, EMPs are developed as static documents to secure project approval, but lack the tools and frameworks necessary for adaptive management once the project begins. As a result, implementation tends to be inconsistent, fragmented, and reactive rather than proactive.

Ineffective EMP implementation is frequently attributed to the absence of clear, quantifiable performance indicators and the poor integration of environmental considerations into real-time decision-making processes at construction sites [7]. These problems are further exacerbated in developing countries by systemic challenges such as limited institutional capacity, insufficient funding, inadequate training, and weak enforcement mechanisms [3]. Without standardized performance metrics, EMP monitoring becomes subjective and difficult to audit, weakening regulatory enforcement and reducing accountability.

Recent studies have also highlighted stakeholder dissatisfaction with EMP performance in toll road projects. For instance, Oetari and Isworo [8] found that in the Solo-Yogyakarta toll project, the lack of stakeholder consultation and ineffective mitigation measures led to a credibility gap between official documentation and field implementation. Similarly, Radzi et al. [14] emphasized the need for key performance indicators (KPIs) in water infrastructure EMPs to provide clearer accountability and objective measurement of success. The situation is further complicated in projects located in ecologically fragile areas, where Makbul et al. [9] observed that inadequate EMP application contributed to uncontrolled land conversion and long-term environmental degradation, especially in agricultural zones affected by toll construction.

In infrastructure projects involving ecologically sensitive environments, such as roads built through peatlands, mangroves, or protected forest zones, the shortcomings of weak EMP execution are even more critical. In such contexts, ineffective mitigation not only leads to environmental degradation but also contributes to social resistance, regulatory disputes, and reputational risks for developers [2]. Strengthening the structure, implementation, and evaluation of EMPs through systematic indicator models is therefore essential for advancing sustainable infrastructure governance in Indonesia.

2.2 Environmental performance indicators

EPIs serve as measurable benchmarks for evaluating the effectiveness of mitigation strategies outlined in EMPs. As emphasized by Spencer et al. [2], EPIs function as critical tools for translating environmental objectives into quantifiable outcomes, allowing for systematic monitoring, evaluation, and corrective action. Ibrahim and Shaker [7] further highlighted that robust indicators should capture a range of environmental dimensions, including physical factors (such as air quality, water clarity, and noise levels), ecological variables (such as habitat integrity and biodiversity), and socio-environmental concerns (such as community health, safety, and public nuisance).

Despite their importance, the application of standardized EPIs in infrastructure development, particularly in Indonesia, remains limited. Rezk et al. [15] observed that many EMPs lack consistent performance indicators, resulting in fragmented reporting, weak oversight, and minimal

accountability in environmental compliance. Without a harmonized indicator system, stakeholders often struggle to compare progress across project phases or to assess whether mitigation measures are truly effective. This challenge is particularly relevant in toll road development projects, where environmental impacts are spatially and temporally distributed, making consistent monitoring both essential and complex.

In the context of toll road construction, commonly used indicators include particulate matter (dust) levels, turbidity or pollutant load in surface water runoff, incidence of soil erosion, loss of vegetation cover, frequency of wildlife disturbance, and exhaust emissions from heavy construction machinery. These indicators are directly tied to typical construction activities such as excavation, earthworks, and transportation of materials. However, as noted by Hardika and Aridiyanto [16], such general indicators are often insufficient in ecologically sensitive areas.

In tropical peatland regions like Riau, additional EPIs become necessary to capture site-specific risks. Liu et al. [3] emphasized that indicators such as land subsidence, peat oxidation rates, fire hazard levels, and hydrological disruption must be included to effectively monitor long-term ecological impacts. These indicators are not only relevant for environmental compliance but are also essential for anticipating disaster risks and protecting regional carbon stocks. Goulart et al. [17] further supported this position by arguing that EPI frameworks must be adapted to the land-based characteristics of transportation projects, especially in biodiverse and carbon-sensitive ecosystems. They propose that customized indicators reflecting land degradation, carbon release, and biodiversity pressure should be incorporated into the standard EMP design for transport infrastructure. Similarly, Radzi et al. [14] emphasized the need for key performance indicators (KPIs) that are both measurable and locally grounded to improve the objectivity and transparency of EMP evaluation in civil construction.

Integrating such location-specific indicators into EMP frameworks enhances their responsiveness and ensures that mitigation is both technically appropriate and ecologically relevant. Moreover, doing so can improve stakeholder confidence, reduce regulatory conflict, and align infrastructure development with broader sustainability and climate mitigation goals.

2.3 Life cycle assessment in road construction

LCA has become a robust and internationally standardized method to assess environmental impacts associated with the entire lifecycle of infrastructure systems, including roads and highways. As defined by ISO 14040 and elaborated by Hoxha et al. [11], LCA evaluates the cumulative environmental burdens from material extraction, transportation, construction, operation, maintenance, and eventual decommissioning. It encompasses indicators such as GHG emissions, energy consumption, resource depletion, and ecological disturbance, thereby supporting more informed and sustainable project planning.

Recent LCA applications in infrastructure highlight that the construction phase often contributes disproportionately to total environmental impacts. Wang et al. [18] found that in highway projects across Asia, earthworks, asphalt production, and material transportation can account for up to 70% of project-related GHG emissions. Similarly, Zhou et al. [19] noted that

heavy machinery use and long-haul aggregate transport are particularly carbon-intensive activities, especially in remote or underdeveloped regions. In the Indonesian context, Fauzi et al. [12] applied a performance evaluation framework on the Tebing Tinggi-Parapat Toll Road and found that early-phase construction activities contributed significantly to carbon output due to poor material efficiency and fuel-intensive operations.

In tropical environments, such as Southeast Asia's peatland regions, the environmental footprint of road construction is further amplified. Liu et al. [20] demonstrated that building roads over peat substrates can result in severe CO₂ emissions due to the oxidation of organic matter following land clearing and drainage. Supporting this, Liu et al. [3] emphasized that secondary impacts, such as land subsidence, hydrological alteration, and long-term peat decomposition, are often neglected in conventional EMPs but captured effectively through LCA modeling. Faleschini and Zanini [21] also highlighted that in the Trans-Sumatra Toll Road, failure to account for peatland sensitivity led to long-term land degradation and inadequate risk mitigation planning.

Several recent studies have advocated the integration of LCA into infrastructure environmental governance. According to Faleschini and Zanini [21], combining LCA with planning and design tools such as Building Information Modeling (BIM) or Geographic Information Systems (GIS) can improve material efficiency and environmental transparency. Furthermore, Faleschini and Zanini [21] illustrated that LCA can assist in selecting eco-friendly pavement alternatives, reducing life cycle costs and GHG emissions simultaneously. In a systematic review, Kriswardhana et al. [13] emphasized that the growing trend in transportation decision-making is the use of multi-criteria tools, particularly AHP and LCA in parallel, enabling planners to combine stakeholder input with empirical environmental modeling.

Integrating LCA into EMP evaluation frameworks thus provides a data-driven basis for identifying the most environmentally intensive stages of road construction. This enables project stakeholders to formulate mitigation strategies that are both cost-effective and targeted. In the case of the Pekanbaru-Dumai Toll Road, embedding LCA in EMP monitoring can support better-informed decisions around earthworks, drainage design, and peatland protection. As infrastructure development continues to expand in environmentally sensitive areas, the role of LCA will become increasingly indispensable in achieving long-term sustainability goals [19, 20].

2.4 Multi-Criteria Decision Making and the analytic hierarchy process

Environmental management decisions often involve evaluating diverse and conflicting criteria, ranging from ecological preservation and resource efficiency to economic viability and public acceptance. In response to this complexity, Multi-Criteria Decision Making (MCDM) methods have gained prominence as structured tools for evaluating and prioritizing competing factors in environmental planning. Among them, the AHP is one of the most widely applied due to its simplicity, transparency, and adaptability [15, 20].

AHP transforms subjective judgments from stakeholders into quantitative priority values through a systematic process of pairwise comparisons and consistency verification. The method decomposes complex decision problems into

hierarchical levels, typically involving goals, criteria, sub-criteria, and alternatives. It then calculates normalized weights and consistency ratios (CR) to ensure logical coherence in the responses [19]. These features make AHP particularly useful in participatory settings, where expert knowledge and stakeholder preferences must be integrated into a unified decision framework.

Recent applications of AHP in environmental and infrastructure sectors have demonstrated its versatility. For instance, Liu et al. [20] employed AHP to rank environmental risks in hydropower projects, while Wang et al. [18] used it to identify key environmental impact indicators in road construction projects across Malaysia.

In the Indonesian context, AHP has also been used in toll road infrastructure planning. Rifqi and Siallagan [22] utilized AHP to prioritize segments of the Trans-Sumatra Toll Road based on criteria such as environmental vulnerability, construction risk, and economic connectivity. Their findings demonstrated the value of AHP in transparently comparing alternatives under multi-objective trade-offs. Similarly, Hidayat et al. [10] applied AHP to develop a weighted success framework for public-private partnership (PPP) toll road procurement, integrating technical, financial, and environmental indicators. These examples illustrate that AHP is not only applicable at the environmental impact level but also at broader decision-making layers in project governance.

On a global scale, Khan et al. [23] provided a comprehensive AHP-based ranking of sustainability criteria for urban infrastructure, which included environmental resilience and public health as dominant factors. Their findings reinforce the relevance of AHP in developing structured and replicable evaluation tools in environmental engineering, especially when dealing with uncertainty and limited data. A systematic review by Kriswardhana et al. [13] confirmed that the use of AHP has expanded over two decades in transportation research, particularly for tasks involving indicator selection, stakeholder evaluation, and integrated risk modeling.

These studies collectively affirm the analytical power and methodological flexibility of AHP for complex environmental decisions, making it a strong candidate for inclusion in EMP evaluation models, particularly in projects like the Pekanbaru-Dumai Toll Road that intersect technical complexity with ecological sensitivity.

While previous studies have shown the utility of AHP in prioritizing environmental risks [18, 20], and the effectiveness of LCA in quantifying life cycle impacts [19, 21], both approaches have typically been applied in isolation. AHP-based models often lack empirical validation from environmental datasets, which can limit their credibility when used for policy or regulatory purposes. Conversely, LCA studies tend to be data-intensive and technically complex, but often fail to incorporate local stakeholder values and perceptions, leading to limited acceptance in practice. This fragmentation highlights a methodological gap where existing EMP evaluations either rely heavily on subjective stakeholder judgments or exclusively on technical modeling, without integrating both dimensions into a coherent framework.

2.5 Research gap

Although both LCA and the AHP are well-established methodologies in the field of environmental engineering, their combined application in evaluating the effectiveness of EMPs,

particularly in the context of toll road construction across tropical peatland regions, remains notably underexplored. Most prior research has tended to isolate either environmental impact quantification through LCA or stakeholder-based prioritization through AHP. As a result, there is a lack of integrative models that offer a comprehensive, multi-dimensional framework for EMP evaluation and decision support in infrastructure development [2, 15].

Furthermore, in countries such as Indonesia, where rapid infrastructure expansion increasingly overlaps with ecologically sensitive areas, including high-biodiversity peatlands and carbon-rich landscapes, the need for such hybrid approaches is becoming increasingly urgent. Liu et al. [3] argued that conventional EMPs in these regions are often too generic, lacking spatial specificity and adaptive capacity to reflect the unique risks posed by peatland disturbance, GHG emissions, and hydrological disruption. Mandia et al. [24] similarly emphasized that EMPs for the Trans-Sumatra Toll Road often fail to anticipate geomorphological sensitivities, leading to unmitigated land degradation and compliance issues. Without the incorporation of robust, context-sensitive performance indicators, EMPs risk becoming static documents with limited managerial value in the field.

Moreover, while AHP has been widely used for indicator prioritization, and LCA for impact measurement, there is limited literature that fuses these two methods within a single decision-support system tailored to infrastructure in tropical environments. As noted by the references [13, 23], the future of environmental planning lies in integrating multi-criteria judgment with quantitative sustainability assessment, yet very few empirical studies operationalize such integration in practice.

This study seeks to address the identified research gap by proposing an integrated AHP-LCA framework for the development of a performance indicator model specifically tailored to toll road construction in tropical peatland environments. Using the Pekanbaru-Dumai Toll Road in Riau Province as a case study, the framework combines stakeholder input and empirical impact analysis to produce a structured, data-driven tool for monitoring, evaluation, and policy decision-making. The resulting model contributes both methodologically and practically by bridging the gap between environmental assessment theory and implementation practice in sustainable infrastructure projects.

The novelty of this study lies in developing an integrated AHP-LCA framework that explicitly combines participatory prioritization with empirical impact quantification. Unlike conventional AHP-only approaches, this model ensures that prioritized indicators are validated against life cycle impact data, thereby enhancing both robustness and transparency. Similarly, compared to stand-alone LCA studies, the inclusion of stakeholder perspectives ensures that the resulting performance indicators remain context-specific, socially acceptable, and practically implementable. In the context of tropical peatland toll roads, where both ecological fragility and governance limitations intersect, this hybrid approach offers a unique and replicable tool for improving EMP performance evaluation.

3. METHODOLOGY

3.1 Study design

This study adopts a descriptive quantitative research design

to develop a structured and evidence-based performance indicator model for evaluating the implementation of EMPs in toll road construction. The research is framed within the context of sustainable infrastructure development in tropical peatland regions, where environmental risks are amplified and regulatory oversight is often limited. In Indonesia, the rapid expansion of toll road networks, including those traversing fragile ecosystems such as peatlands and agricultural zones, has intensified the urgency to adopt environmental monitoring tools that are both scientifically rigorous and contextually grounded [9].

The proposed model integrates two complementary methodological approaches: the AHP and LCA. AHP is used to determine the relative priority weights of environmental aspects and sub-indicators based on structured judgments from domain experts and key stakeholders. Through a systematic process of pairwise comparisons, AHP translates qualitative preferences into quantitative indicators, enabling transparent and consistent prioritization of mitigation targets. AHP has been widely applied in infrastructure sustainability planning, including toll road prioritization and risk evaluation frameworks in Indonesia [10, 22].

In parallel, LCA is applied to quantify environmental impacts associated with the construction phase of toll road development. This includes emissions from material production and transportation, fuel use in machinery, and ecological disturbances resulting from land clearing and drainage. LCA results serve to validate and complement the AHP outputs by identifying the most resource and carbon-intensive activities during implementation. According to Fauzi et al. [12], integrating LCA into performance measurement can improve material efficiency and highlight previously under-acknowledged emission sources, especially in asphalt production and earthworks. Furthermore, Mandia et al. [24] argued that failure to assess land sensitivity, such as peat oxidation risks, has led to significant ecological degradation in toll road development across Sumatra.

By combining AHP and LCA in a unified framework, this research produces a hybrid indicator model that reflects both stakeholder values and empirical impact data. The model is intended to improve monitoring, evaluation, and adaptive decision-making in the implementation of EMPs, particularly for toll road projects located in ecologically sensitive zones such as Riau Province. Ultimately, the study aims to contribute to the development of practical tools for performance-based environmental management in large-scale infrastructure projects, while also supporting Indonesia's broader transition toward low-carbon and climate-resilient development pathways [13].

The overall research was conducted between January and August 2025. Data collection through stakeholder questionnaires was carried out over a three-month period (February–April 2025), followed by data validation and life cycle inventory (LCI) development in May–June 2025. The integration and analysis of AHP and LCA results were finalized in July–August 2025.

3.2 Case study area

This study applies the proposed performance indicator model to the Pekanbaru-Dumai Toll Road in Riau Province, Indonesia, as a representative case of infrastructure development in ecologically sensitive landscapes. The project, which spans approximately 131 kilometers, forms part of the

larger Trans-Sumatra Highway network and is strategically significant for enhancing regional connectivity and accelerating economic development in Sumatra. However, the corridor also traverses peat-dominated zones, forest margins, and agricultural regions that are ecologically fragile and carbon-rich.

The selected toll road corridor traverses a diverse range of land cover types, including tropical peatlands, secondary forest edges, agricultural plantations, and settlement zones. These landscapes are characterized by high ecological fragility and carbon density, making them particularly vulnerable to environmental disturbances such as land subsidence, peat oxidation, water table alteration, biodiversity loss, and fire risk, especially during the dry season. Mandia et al. [24] emphasized that in similar Trans-Sumatra Toll Road segments, peatland degradation and erosion were common due to limited environmental safeguards during the construction phase.

Given these environmental sensitivities, the project is subject to the mandatory AMDAL process under Indonesian environmental law, including the preparation and implementation of a comprehensive EMP. However, as observed by Makbul et al. [9], EMPs in Indonesian toll projects often fall short in ensuring effective mitigation in high-risk landscapes, particularly where spatial indicators are absent or poorly contextualized. This reinforces the need for improved performance-based monitoring tailored to local conditions.

The integration of AHP in this study is used to prioritize environmental aspects and sub-indicators specifically relevant to the local context of Riau. Through structured stakeholder engagement involving government agencies, contractors, environmental consultants, and academics, the method captures expert judgments that reflect both regulatory expectations and on-the-ground realities. Hidayat et al. [10] noted that in PPP toll projects, integrating multi-stakeholder perspectives is essential to ensure long-term success and environmental accountability. The resulting weighted indicator hierarchy developed through AHP is intended to support performance-based monitoring of EMP implementation, offering a more adaptive and transparent framework for environmental decision-making during construction.

The Pekanbaru-Dumai Toll Road was selected not only due to its ecological complexity, but also because it exemplifies the challenges of balancing infrastructure expansion with environmental protection in peat-dominated tropical landscapes. Its location and regulatory status make it an ideal testbed for developing a replicable and scalable EMP performance evaluation model, particularly for infrastructure projects across Indonesia and Southeast Asia facing similar ecological and governance challenges [8, 23].

3.3 Data collection instrument

To support the development of the performance indicator model, a structured questionnaire was designed based on an extensive literature review, expert consultations, and relevant national regulatory frameworks, particularly Ministry of Environment and Forestry Regulation No. 10/2024 concerning environmental permits and monitoring. The instrument was developed to capture both quantitative inputs for the AHP and qualitative insights into the effectiveness and challenges of EMP implementation. The design of this questionnaire was

informed by prior studies in infrastructure environmental management that emphasize the importance of triangulating technical judgment with stakeholder perception [14, 17].

The questionnaire comprises four main sections structured as follows:

1. Section A - Respondent Profile:

This section gathers demographic and professional information, including position, gender, level of education, years of experience, type of organization, and prior involvement in toll road development or EMP preparation. This information supports respondent categorization and credibility analysis.

2. Section B - Pairwise Comparisons (AHP):

This section evaluates the relative importance of sub-indicators under the seven main environmental aspects: Soil and Land, Water Quality, Ecology, Air Quality, Waste and Pollution, Social and Safety, and Disaster and Climate Risk. Respondents were asked to compare indicators using Saaty's fundamental scale of 1 to 9, with the aim of generating weight values and CR ($CR \leq 0.1$) for each aspect.

3. Section C - EMP Implementation Effectiveness:

This section captures stakeholder perceptions of EMP implementation performance based on five key dimensions: monitoring system, expert involvement, sanctions and enforcement, institutional coordination, and budget allocation. Responses were recorded using a 5-point Likert scale, ranging from Strongly Disagree to Strongly Agree.

4. Section D - Policy Recommendations:

This final section seeks stakeholder views on broader environmental governance issues, including regulatory clarity, public participation, and inter-agency coordination. Open-ended items allow respondents to provide additional suggestions to improve EMP effectiveness.

The final version of the questionnaire was pre-tested and refined prior to full distribution. It was then administered to a total of 100 purposively selected respondents, representing a broad range of key stakeholder groups, including environmental consultants, project owners, construction contractors, regulatory agency officials, and academic experts. These respondents were selected based on their experience with EMP development, toll road planning, and environmental monitoring in Indonesia.

The survey was conducted over a three-month period, during which questionnaires were distributed in both printed and electronic formats. Respondents were given approximately three weeks to complete the instrument, with follow-ups conducted to ensure a high response rate.

The finalized instrument comprised 63 pairwise comparison items across seven environmental aspects, along with 20 Likert-scale statements aimed at capturing stakeholder perceptions and policy-related recommendations. The questionnaire was structured in accordance with the principles of the AHP and informed by national regulatory frameworks and field-level challenges observed in previous infrastructure projects. A complete version of the questionnaire, including the full set of pairwise matrices and perception questions is available as supplemental material. The content of this instrument was directly used to generate both the weighted performance indicators and the descriptive findings reported in this study.

3.4 Analytic hierarchy process

The AHP was applied in this study to determine the priority

weights of environmental aspects and sub-indicators within the EMP framework for toll road construction. This method was chosen for its ability to convert qualitative judgments into quantitative weights through a structured pairwise comparison process, enabling consistent prioritization based on expert and stakeholder input. The AHP has proven to be a robust decision-support tool in environmental planning and infrastructure project evaluation, particularly when stakeholder perspectives and technical complexity must be synthesized [13, 23].

Seven main environmental aspects were designated as the second-level criteria: Air Quality, Water Quality, Soil and Land, Ecology, Waste and Pollution, Social and Safety, and Disaster and Climate Risk. These aspects were selected based on national regulatory references, particularly the AMDAL and EMP regulatory framework, and were aligned with previous environmental indicator frameworks proposed in infrastructure sustainability studies [14, 17]. Each of these aspects was further detailed into five to eight sub-indicators, such as slope failure, sedimentation, biodiversity loss, and emissions from heavy equipment. These sub-criteria represent the measurable environmental components that are directly impacted by toll road construction activities.

To operationalize the AHP, each respondent completed a pairwise comparison matrix for the sub-indicators under each main aspect, using Saaty's fundamental 1–9 scale. These matrices reflected the perceived relative importance of each indicator in the context of EMP monitoring. To ensure the validity of the responses, a CR was calculated for each matrix. Only matrices with CR values of 0.10 or lower were included in the final analysis, following AHP methodological standards [10, 15]. This step helped eliminate biased or inconsistent judgments and improved the analytical rigor of the results.

The valid matrices were processed using the eigenvector method via Expert Choice or equivalent decision-support software. This yielded both local and global priority weights for each indicator, which were then aggregated across all respondents to generate final weighted scores. These scores form the basis of the proposed performance indicator model, providing a quantitative foundation for performance-based EMP evaluation and monitoring in toll road construction, particularly in ecologically sensitive regions such as Riau Province.

3.5 Life cycle assessment

To complement the stakeholder-based prioritization generated through the AHP, a simplified LCA was conducted to quantify the environmental burdens associated with the construction phase of the Pekanbaru-Dumai Toll Road. The LCA was developed in accordance with the methodological framework outlined in ISO 14040, covering four standard phases: goal and scope definition, LCI, Life Cycle Impact Assessment (LCIA), and interpretation.

In the goal and scope definition phase, the objective was to assess environmental impacts generated specifically during toll road construction activities. The functional unit was defined as the construction of one kilometer of toll road infrastructure within a tropical peatland context. The system boundary included land clearing, earthworks, material transport, asphalt and concrete application, and heavy equipment operation, components identified by prior research as dominant contributors to environmental burdens in linear infrastructure [12, 20].

During the LCI phase, input-output data were compiled primarily from secondary sources, including government environmental reports, academic studies on infrastructure in Sumatra, and prior toll road project evaluations. The inventory included major material and energy flows such as diesel fuel consumption, use of asphalt, cement, aggregates, steel reinforcement, and operating hours for construction machinery. This approach follows the precedent set by Mandia et al. [24], which conducted environmental risk assessments for the Trans-Sumatra Toll Road using empirical site-level data and construction activity logs.

To ensure the reliability of the inventory data, a calibration process was conducted. Construction material and energy use estimates were cross-validated with official project reports, environmental monitoring records from the Ministry of Environment and Forestry (KLHK), and empirical data from previous toll road studies in Sumatra. Where discrepancies occurred, average values were adopted, and sensitivity analysis was performed to test the robustness of assumptions.

The LCIA focused on four key environmental impact categories relevant to infrastructure development in ecologically sensitive regions: (1) GHG Emissions, measured in CO_{2e}, resulting from fuel combustion and material production; (2) Land Use Change and Peatland Disturbance, reflecting the effects of clearing peat-rich land and altering natural drainage; (3) Habitat Loss and Biodiversity Disruption, including impacts on flora and fauna due to forest fragmentation and corridor intrusion; and (4) Water Pollution and Sedimentation Risk, particularly runoff contamination during earthworks and slope exposure.

In the interpretation phase, the results of the LCA were analyzed to cross-validate the prioritization outcomes obtained from AHP. The magnitude of impacts observed, particularly those related to GHG emissions and peatland disruption, aligned with stakeholder concerns expressed in the pairwise comparisons. This convergence between expert perception and empirical impact strengthened the reliability of the model, confirming the elevated weights assigned to Soil and Land and Water Quality indicators. As noted by previous studies [13, 15], such triangulation between judgment-based and data-based approaches enhances the robustness of decision-support tools in infrastructure sustainability assessment.

This hybrid AHP-LCA approach allows for a more comprehensive understanding of EMP performance by linking perceptual insights with quantifiable evidence. It also supports more adaptive environmental governance, particularly in toll road projects located in peat-rich landscapes such as Riau, where unmanaged impacts may contribute disproportionately to regional carbon emissions and ecosystem degradation [3, 17].

Figure 1 illustrates the methodological framework adopted in this study, combining the stages of AHP (stakeholder-based prioritization) and LCA (impact quantification), along with the integration and triangulation process leading to the final EMP performance indicator model.

3.6 Descriptive analysis of stakeholder perception

To complement the quantitative results derived from the AHP and LCA, a descriptive statistical analysis was conducted to examine stakeholder perceptions regarding the implementation of EMPs. This analysis was based on responses from Sections C and D of the structured questionnaire, which captured both evaluative and prescriptive insights from experts and practitioners involved in toll road infrastructure and environmental management.

The analysis employed basic descriptive statistics, including frequency distributions, mean scores, and standard deviations, to identify key patterns in stakeholder feedback. This approach aligns with perception-based environmental assessments used in infrastructure governance, where respondent diversity and experiential knowledge provide insight into implementation realities [8, 14]. Three primary dimensions were assessed:

1. Perceived strengths and weaknesses in current EMP implementation, including the availability of monitoring systems, technical expert support, and the effectiveness of enforcement mechanisms;
2. Institutional and technical barriers, such as budget limitations, lack of inter-agency coordination, and insufficient regulatory clarity, which are often cited in infrastructure projects across developing contexts [2, 10];
3. Stakeholder preferences regarding policy improvements, including recommendations for strengthening public participation, improving sanction mechanisms, and enhancing the accountability framework for EMP execution.

These perception-based insights were subsequently triangulated with the findings from the AHP (stakeholder-driven prioritization) and LCA (empirical environmental burden quantification) to develop a more comprehensive understanding of both practical and structural challenges in EMP implementation. The integration of stakeholder perceptions adds significant value, particularly in contexts like Indonesia, where institutional fragmentation and limited enforcement capacity often impede the effective realization of environmental policies [13, 23].

By combining quantitative ranking, environmental modeling, and stakeholder-based evaluation, the study is able to formulate evidence-based recommendations for improving EMP performance and accountability. This is especially relevant for toll road projects located in ecologically sensitive regions such as Riau Province, where robust environmental governance mechanisms are essential to prevent long-term ecological degradation.

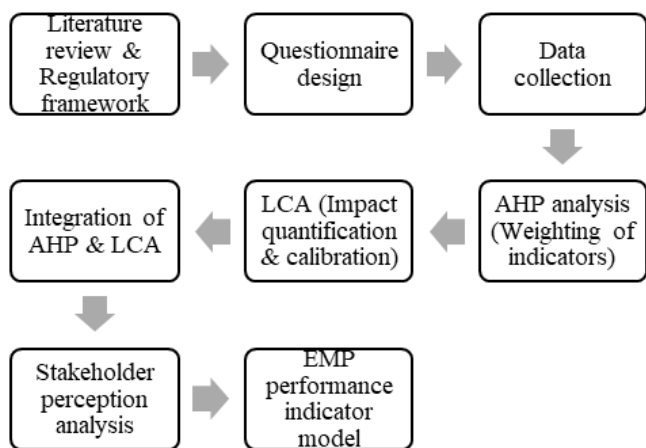


Figure 1. Flowchart of the research methodology (AHP-LCA framework)

4. RESULTS AND DISCUSSION

4.1 Stakeholder-based prioritization of environmental aspects (analytic hierarchy process results)

The AHP was applied to identify and prioritize the most critical environmental aspects influencing the effectiveness of EMPs in toll road construction. A total of 100 expert respondents completed pairwise comparison matrices, which were evaluated for logical consistency using a CR threshold of ≤ 0.10 . Only responses meeting this threshold were retained for analysis. The final priority weights were calculated using the eigenvector method, and the results are presented visually in Figure 2.

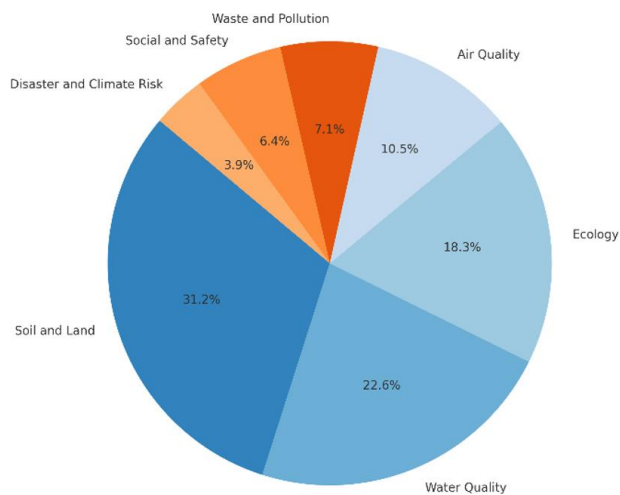


Figure 2. Priority weights of environmental aspects (analytic hierarchy process (AHP) results)

As illustrated in Figure 2, Soil and Land was perceived as the most important aspect, receiving 31.2% of the total weight. This reflects strong stakeholder concern regarding peatland degradation, erosion, and slope instability, which are prevalent issues in the Riau region where the project is located. Water Quality ranked second at 22.6%, emphasizing the risks of sedimentation, turbidity, and contamination of surface water during earthworks. The third-highest priority, Ecology (18.3%), highlights perceived threats to biodiversity, including habitat fragmentation and wildlife disturbance due to construction activities.

Lower priority weights were assigned to Air Quality, Waste and Pollution, Social and Safety, and Disaster and Climate Risk, though all were still considered relevant to EMP effectiveness. These results suggest that mitigation and monitoring efforts should focus primarily on land stability and hydrological protection, especially given the ecological sensitivity of tropical peatland ecosystems. The emphasis on soil-related concerns aligns with previous studies showing that land disturbance from road construction is a major contributor to long-term ecological degradation and GHG emissions in tropical regions [11, 20].

Furthermore, this prioritization supports findings of Mandia et al. [24], which reported similar stakeholder concerns in the Trans-Sumatra Toll Road project, where inadequate soil and peat management led to slope failure and hydrological disruption. It also echoes the conclusions of Goulart et al. [17], which argued that sustainability assessment frameworks in land transport must give higher weight to land-based environmental indicators in sensitive ecological contexts.

In addition to the aspect-level priorities illustrated in Figure 2, Table 1 presents the complete ranking of sub-indicators across all seven environmental aspects, as derived from stakeholder pairwise comparisons. These results provide a more granular view of the specific environmental concerns prioritized during EMP implementation.

Table 1. Priority weights of environmental aspects and sub-indicators based on analytic hierarchy process (AHP) results

Environmental Aspect	Sub-Indicator	Priority Weight (%)
Soil and Land	slope failure	10.20
	over-excavation and fill	8.50
	agricultural land degradation	7.80
	erosion and sedimentation	1.70
Water Quality	runoff pollution	7.10
	blocked drainage	6.60
	water turbidity increase	4.50
	sediment accumulation	4.40
	habitat fragmentation	6.40
Ecology	vegetation loss	6.20
	disruption of wildlife movement	5.70
	dust generation	3.10
Air Quality	equipment emissions	4.10
	noise and vibration	3.30
	chemical/oil spills	2.50
Waste and Pollution	construction waste mismanagement	2.80
	open burning	1.80
	on-site construction accidents	1.90
Social and Safety	public health risk	2.60
	traffic safety disturbance	1.90
	peat oxidation risk	2.70
Disaster and Climate Risk	flood risk from drainage alteration	0.80
	greenhouse gas emissions	0.40

Among the seven environmental aspects, Soil and Land emerged as the top priority. A deeper analysis was therefore conducted to evaluate its sub-indicator structure, as presented in the following section.

To ensure the reliability of the AHP results, CR were calculated for each respondent's matrix. Table 2 summarizes the number and percentage of valid and invalid matrices for each environmental aspect. Over 90% of responses met the CR threshold (≤ 0.10), confirming the robustness of the stakeholder judgments used in the final prioritization.

Table 2. Summary of analytic hierarchy process (AHP) consistency ratios (CR)

Environmental Aspect	Valid Matrices (CR ≤ 0.10)	Invalid Matrices (CR > 0.10)	Validity Rate (%)
Soil and Land	92	8	92
Water Quality	90	10	90
Ecology	88	12	88
Disaster and Climate Risk	91	9	91

As shown in Table 2, the validity rate across all environmental aspects was consistently high, with most aspects exceeding 90% of valid matrices (CR ≤ 0.10). This indicates a strong level of logical consistency in stakeholder

responses, enhancing the methodological rigor of the prioritization process. The high CR validity supports the credibility of the resulting weights and confirms that stakeholder judgments were stable and reliable across different environmental dimensions.

4.2 Sub-indicator ranking for Soil and Land aspect

Following the identification of Soil and Land as the highest-priority environmental aspect, a more detailed AHP analysis was conducted to evaluate its constituent sub-indicators. The pairwise comparison results revealed that slope failure was considered the most critical issue, receiving the highest priority weight at 22.8%. This was followed by excessive excavation and fill (18.7%) and erosion and sedimentation (17.4%). These top-ranked concerns are closely associated with the geomorphological instability of tropical peatlands, where road construction often involves large-scale cut-and-fill operations, drainage modifications, and changes in topographic relief.

Other sub-indicators, such as agricultural land degradation (14.3%), peatland disturbance (13.5%), forest clearing (7.8%), and topographic alteration (5.5%), were also assigned substantial weights, indicating their relevance to environmental risk in the project area. Although these sub-indicators ranked lower than slope failure, they collectively represent critical processes that can lead to long-term soil degradation, hydrological imbalance, and carbon emissions if not adequately addressed during project planning and execution. These sub-indicator rankings are summarized visually in Figure 3.

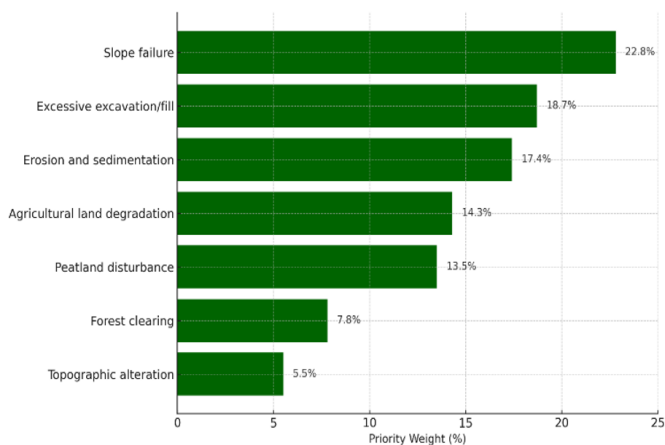


Figure 3. Sub-indicator priority under Soil and Land aspect

These results underscore the technical and environmental complexity of constructing road infrastructure on peat-dominated terrain. In such contexts, slope instability can rapidly lead to localized landslides, embankment failure, and even disruption of adjacent drainage systems. Additionally, excessive excavation or unbalanced fill volumes increase the risk of differential settlement, posing structural and ecological hazards.

Effective EMP implementation in such environments must therefore prioritize: Proactive slope stabilization techniques (e.g., geosynthetics, staged embankment construction); Controlled earthwork volumes through precise engineering design; and Integrated land-use management strategies that maintain hydrological balance and prevent unregulated clearing.

These findings are consistent with the conclusions drawn by Mandia et al. [24] in their evaluation of the Trans-Sumatra Toll Road, which highlighted slope instability and peat degradation as recurring environmental issues. Furthermore, Song et al. [25] emphasized that climate adaptation planning for highways must consider land subsidence and erosion sensitivity, particularly when peat soils are involved. In the Indonesian context, Rifqi and Siallagan [22] also identified land degradation and fill imbalance as primary environmental constraints in toll road prioritization studies.

These findings are further reinforced by the LCA results, where earthworks and excavation were identified as the single largest source of GHG emissions (33.5% of the total CO₂e/km). Since slope failure and excessive cut-and-fill operations are directly linked to intensive earthworks on peat soils, the convergence between AHP and LCA outcomes demonstrates that stakeholder concerns are well-aligned with measurable environmental burdens. This alignment validates the prioritization of Soil and Land management as the most critical dimension of EMP implementation in peatland toll road projects.

4.3 Life cycle assessment results - simulated construction impacts

To complement the stakeholder-based prioritization obtained through AHP, a simplified LCA was conducted to estimate the environmental burdens associated with the construction phase of toll road development. Using secondary data from similar infrastructure projects in Sumatra, the analysis focused on four key impact categories: GHG emissions, land use change, peatland disturbance, and biodiversity disruption.

The LCA simulation revealed that construction activities generated approximately 2,450 tons of CO₂e/km of roadway. As illustrated in Figure 4, the largest share of these emissions originated from earthworks and excavation (33.5%), primarily due to diesel-intensive operation of heavy machinery and soil movement. Asphalt paving and hot mix production contributed 27.4%, followed by material transportation (19.2%), concrete casting and formwork (12.3%), and site clearing and deforestation (7.6%). These quantitative results are detailed in Table 3, which summarizes the estimated GHG emissions and percentage contribution of each major construction activity.

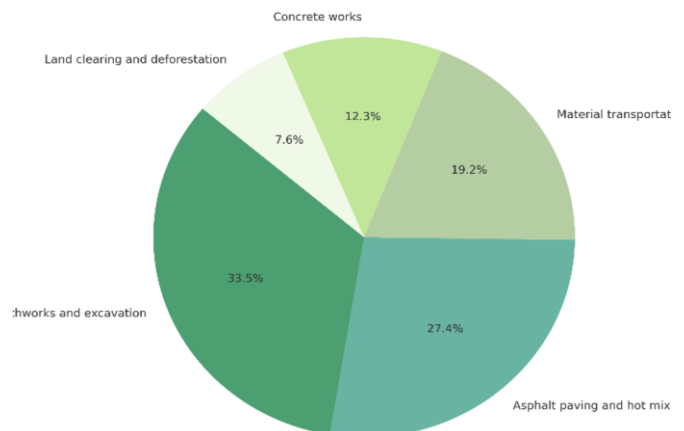


Figure 4. Greenhouse gas (GHG) emissions by construction activity (LCA results)

Table 3. Estimated greenhouse gas (GHG) emissions by construction activity based on LCA

Construction Activity	Emission (kg CO ₂ e/km)	Contribution (%)	Remarks
Earthworks	820	33.5	peat disturbance + heavy machinery
Asphalt paving	670	27.4	asphalt mixing and heating
Material transport	470	19.2	diesel truck operation
Concrete and steel	300	12.3	cement, rebar
Site clearing (land use change)	190	7.6	peatland deforestation
Total	2,450	100.0	

In addition to emissions, the LCA also highlighted significant impacts related to land use change. It was estimated that approximately 13.2 hectares of peatland and mixed vegetation were permanently disturbed for every 10 kilometers of road alignment. Based on peat oxidation emission factors, this disturbance could result in an additional 500–1,000 tons of CO₂ per hectare, depending on peat depth, water table alteration, and post-construction surface treatment [3, 20]. These findings support the stakeholder-driven AHP ranking, which emphasized Soil and Land impacts as the top priority for EMP monitoring and mitigation.

These findings strongly support the AHP-derived ranking, which emphasized Soil and Land impacts as the top priority for EMP performance monitoring. The alignment between the empirical results of LCA and the stakeholder judgments from AHP reinforces the relevance and reliability of the proposed performance indicator model.

In practical terms, these results underscore the need for mitigation measures targeting earthwork-related impacts. These include: optimizing cut-and-fill volumes through 3D terrain modeling and balanced mass haul planning, using low-emission equipment (e.g., Tier 4 diesel engines or hybrid machinery), preserving native vegetation buffers to reduce peat exposure and biodiversity disruption, avoiding over-compaction in high-risk peat zones to maintain hydrological balance.

Several previous studies reinforce these recommendations. For example, Zhou et al. [19] emphasized that early-stage design decisions, particularly in material logistics, and embankment strategies can significantly influence carbon footprints in road infrastructure. Similarly, Song et al. [25] proposed incorporating LCA into national highway adaptation planning to identify trade-offs between engineering efficiency and ecological resilience. LCA-informed decision-making is key for toll road projects to meet sustainable development targets without compromising ecosystem functions [26].

4.4 Descriptive analysis of stakeholder perception

Stakeholder perceptions of EMP implementation effectiveness were assessed using responses from Section C of the structured questionnaire. Respondents were asked to evaluate five operational dimensions of EMP execution: (1) monitoring systems, (2) inter-agency coordination, (3) budget

availability, (4) enforcement of sanctions, and (5) involvement of environmental experts. A 5-point Likert scale was used, ranging from 1 (strongly disagree) to 5 (strongly agree), allowing for quantitative analysis of implementation strengths and weaknesses.

Stakeholders were asked to rate their agreement with 10 statements related to EMP implementation using a 5-point Likert scale. Table 4 presents the mean scores and standard deviations for selected key items. The results indicate moderate agreement on expert involvement and EMP conformity, while perceived weaknesses are evident in sanction enforcement and adoption of environmentally friendly construction technologies. Table 4 summarizes stakeholder responses across the five core EMP implementation dimensions.

Table 4. Descriptive statistics of stakeholder perceptions on environmental management plan (EMP) implementation effectiveness

Statement	Mean Score	Standard Deviation
Budget for EMP implementation is sufficient	3.21	1.12
Environmental experts are actively involved	3.68	0.94
Mitigation measures are implemented according to the EMP	3.45	1.01
Routine supervision is conducted	3.19	1.18
Sanctions are enforced firmly	2.84	1.34
Coordination with environmental agencies is effective	3.09	1.07
Environmentally friendly technologies are applied	2.97	1.22

To visualize the relative ratings across the five main performance dimensions, Figure 5 provides a bar chart summary based on the same Likert-scale responses.

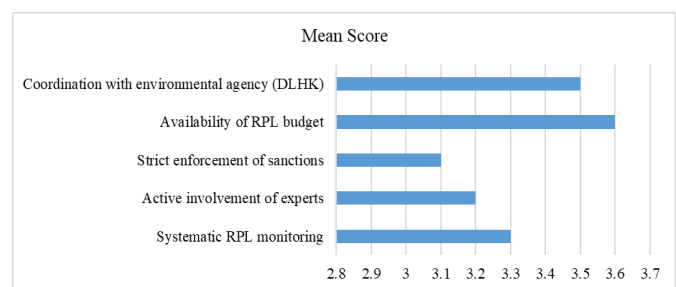


Figure 5. Stakeholder perceptions of environmental management plan (EMP) implementation effectiveness

As illustrated in Figure 5, the two most favorably rated components were: Availability of EMP budget (mean score = 3.6); and Coordination with environmental agencies (mean = 3.5).

These scores suggest that institutional arrangements and financial resource allocation are beginning to improve in toll road projects, at least from the perspective of key stakeholders. However, the lowest-rated dimension was enforcement of sanctions (mean = 3.1), which reflects ongoing concerns over regulatory weakness, low deterrence, and insufficient legal follow-up in cases of environmental non-compliance. This issue has been highlighted in previous studies as a persistent weakness in Indonesia's infrastructure governance [5, 14].

Mean scores of five EMP performance dimensions, based on a 5-point Likert scale. Budget availability and inter-agency coordination were rated highest, while enforcement of sanctions received the lowest score.

Other notable gaps included: Limited involvement of environmental specialists (mean = 3.2); and Lack of systematic monitoring and documentation (mean = 3.3).

These findings point to a persistent technical capacity gap, especially in field-level implementation, where environmental controls are often left to undertrained personnel or subcontractors with limited environmental expertise [4, 10].

Notably, only 41% of respondents agreed that EMP implementation on-site was aligned with the content of approved environmental documents. This reveals a substantial implementation gap between the planning and execution phases of EMPs. Causes identified through open-ended responses include: Fragmented oversight responsibilities; Unclear lines of authority between central and regional agencies; and Minimal third-party supervision during construction.

These results underscore the critical need for strengthened regulatory enforcement, clear institutional mandates, and continuous capacity-building for EMP field implementation. Transparency and public access to monitoring outcomes can also serve as indirect pressure mechanisms to increase contractor compliance and agency responsiveness [8].

In line with best practices identified in international literature, the integration of performance-based evaluation tools, independent audits, and real-time digital monitoring platforms is recommended to ensure that EMPs function not merely as administrative checklists, but as proactive environmental management instruments [15, 23].

In addition to assessing EMP implementation effectiveness, stakeholders were also asked to rate policy-level recommendations that could improve environmental governance in toll road construction. Table 5 presents the ranked preferences based on mean scores.

Table 5. Stakeholder policy priorities

Policy Recommendation	Mean Score	Priority Rank
Technical guidelines should be revised and clarified	4.31	1
EMP performance should be considered in project tender evaluation	4.15	2
Independent EMP monitoring body is needed	4.08	3
Community participation in EMP monitoring should be strengthened	4.02	4
Incentives for contractors complying with EMP should be implemented	3.88	5

Note: EMP = environmental management plan.

As shown in Table 5, stakeholders prioritized revisions to technical guidelines and the integration of EMP performance in project tender evaluations as top policy actions. These results suggest a strong demand for clearer regulatory frameworks and accountability mechanisms in infrastructure procurement. The establishment of independent EMP monitoring bodies and the strengthening of community participation were also viewed as essential to improving transparency and environmental compliance. These stakeholder preferences indicate a shift toward more performance-oriented and participatory models of environmental governance in toll road construction.

4.5 Proposed performance indicator model (AHP-LCA framework)

To respond to the gaps identified through both the AHP and stakeholder perception analysis, a structured performance indicator model was developed, as presented in Figure 6. This model aims to evaluate the effectiveness of EMP implementation in sustainable toll road construction projects, particularly in environmentally sensitive areas such as Riau Province.

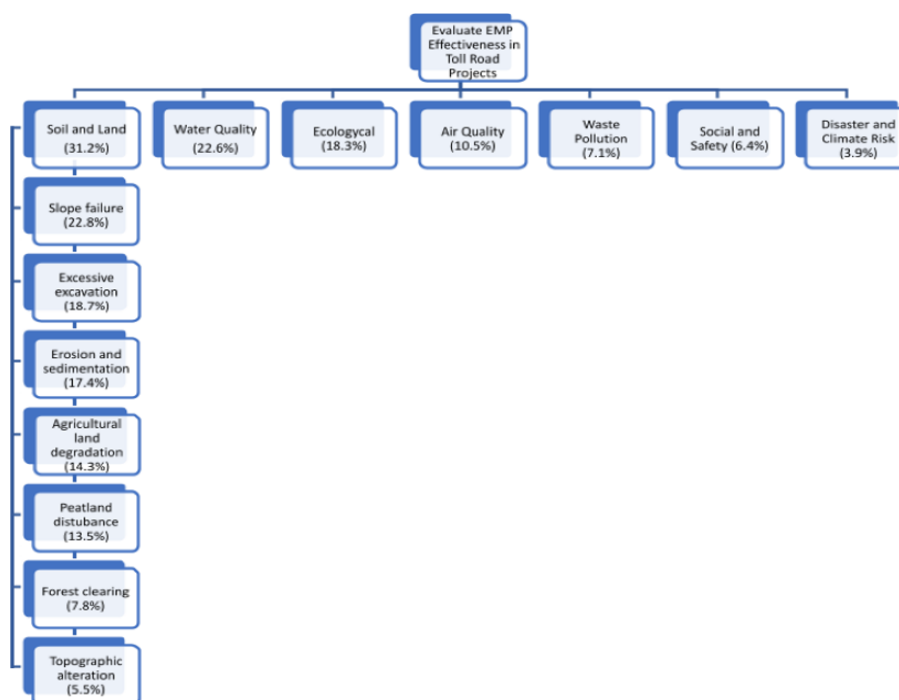


Figure 6. Performance indicator model for environmental management plan (EMP) in sustainable toll road construction (AHP-LCA framework)

The model begins with a top-level objective: to assess EMP effectiveness through a combination of stakeholder priorities and environmental impact data. This objective is elaborated through seven main environmental aspects: Soil and Land (31.2%), Water Quality (22.6%), Ecology (18.3%), Air Quality (10.5%), Waste and Pollution (7.1%), Social and Safety (6.4%), and Disaster and Climate Risk (3.9%), derived from the AHP results.

The highest-ranked aspect, Soil and Land, is further decomposed into seven sub-indicators: slope failure (22.8%), excessive excavation/fill (18.4%), erosion and sedimentation (17.4%), peatland disturbance (16.6%), agricultural land degradation (11.9%), sediment runoff (7.2%), and topsoil stripping (5.4%). These reflect shared concerns among stakeholders about land stability, drainage, and ecological degradation caused by construction activities in peatland regions.

This hierarchical model is grounded in a hybrid AHP-LCA methodology. AHP captures structured expert judgments and stakeholder values, while LCA validates these priorities through empirical data, particularly regarding GHG emissions and land use impacts during the construction phase. The synergy of these approaches enhances both the practical relevance and scientific robustness of the model. The complete structure of this proposed model is presented in Figure 6.

This integrative framework serves several key functions: assisting project owners and contractors in targeting mitigation priorities; supporting environmental regulators in aligning monitoring protocols with real environmental risks; enabling performance-based audits by environmental consultants; and translating broad EMP commitments into specific, actionable metrics. Its modular design also allows for replicability in other large-scale infrastructure projects across tropical regions. As emphasized, models that embed multi-criteria stakeholder input and life cycle-based environmental validation offer stronger pathways for integrating sustainability into infrastructure governance [14, 23]. Furthermore, Hosny et al. [27] affirmed that structured indicator models are essential for ensuring transparency, traceability, and enforcement in environmental management across diverse project phases.

To operationalize this model and ensure its usability in real-world EMP monitoring, the following stepwise procedure is proposed. First, stakeholder judgments are collected using structured pairwise comparisons to generate weighted environmental priorities (AHP stage). Second, these priorities are cross-validated with LCA data on material use, emissions, and land disturbance (LCA stage). Third, the validated indicators are embedded into EMP monitoring protocols, allowing project owners and regulators to track compliance using measurable benchmarks. Finally, feedback from monitoring results can be used to refine EMP measures and inform future policy revisions. This iterative cycle ensures that the model functions not only as an evaluation tool but also as a continuous learning mechanism for sustainable infrastructure governance.

4.6 Discussion

The findings of this study underscore the critical need to prioritize environmental risks in toll road construction projects, particularly those located in ecologically fragile regions such as the peatlands of Riau Province. The AHP revealed that Soil and Land was the highest-ranked

environmental aspect, receiving 31.2% of the total stakeholder-derived weight. This reflects widespread concern over slope instability, erosion, and peatland degradation, issues commonly triggered by large-scale earthworks and drainage modification. These findings are consistent with previous research by Hoxha et al. [11], who identified land disturbance as a dominant source of ecological degradation in tropical highway construction. Liu et al. [20] further emphasized that even minimal peatland disturbance can initiate subsidence, heighten fire risk, and release large quantities of stored carbon.

The prominence of Water Quality and Ecology as second and third-ranked aspects reinforces findings from recent studies. Previous studies [2, 3] documented the adverse effects of infrastructure development in hydrologically sensitive and biodiverse landscapes, including sedimentation, drain blockage, and habitat fragmentation. The sub-indicators prioritized in this study, such as sediment runoff, biodiversity loss, and disrupted drainage, mirror patterns observed in toll road projects across Sumatra, Borneo, and Papua, supporting the ecological relevance of the AHP outputs.

The LCA findings provided quantitative validation of these priorities. Construction activities, including earthworks, material transport, and asphalt paving, were estimated to emit approximately 2,450 tons of CO₂e/km. This aligns with the conclusions [18, 19], who found that over 70% of infrastructure-related emissions occur during the construction phase. Additionally, the significant emissions linked to peat oxidation support previous assessments by the references [3, 17], confirming the environmental cost of peatland conversion during road construction.

Insights from stakeholder perception analysis further highlighted implementation gaps in EMP execution. Despite the availability of formal EMP documents, only 41% of respondents believed that mitigation measures were implemented as planned. This discrepancy between environmental planning and field execution echoes the findings of the references [4, 5], who identified enforcement gaps and technical capacity constraints as recurring problems. Weak legal sanctions, underqualified environmental staff, and the absence of standardized performance indicators continue to hinder effective EMP monitoring, trends also noted in other Indonesian provinces such as Aceh [10].

To address these challenges, several policy recommendations emerged. Stakeholders expressed strong support for the establishment of independent EMP monitoring bodies, integration of performance-based indicators into national infrastructure databases, and the use of EMP scores as criteria in contractor selection and evaluation. These measures align with international best practices that advocate for third-party audits, real-time environmental monitoring, and public access to environmental performance data [6, 15]. Additionally, participatory environmental governance, as promoted by previous studies [7, 23], is seen as key to building public trust, improving compliance, and enhancing the legitimacy of EMP enforcement.

This study contributes to the growing literature on integrated and indicator-based environmental management frameworks in infrastructure development. The proposed AHP-LCA model demonstrates how stakeholder preferences and empirical environmental data can be systematically combined to develop a transparent, replicable, and evidence-driven monitoring tool. The case of the Pekanbaru-Dumai Toll Road thus offers a scalable reference for future projects across

tropical peatland regions, where environmental vulnerability demands adaptive, performance-based, and accountable management strategies.

Beyond the case study, these findings have broader policy implications. The integration of AHP-LCA into EMP evaluation provides a replicable framework that can be mainstreamed into Indonesia's national AMDAL system and linked to performance-based procurement. By embedding hybrid indicators into project tendering and monitoring requirements, policymakers can incentivize contractors to adopt more sustainable construction practices. Moreover, the model can serve as a foundation for green infrastructure financing, where verified EMP performance becomes a prerequisite for accessing climate funds or sustainability-linked loans. In a regional context, the framework is transferable to other tropical peatland landscapes across Southeast Asia, offering a scalable decision-support tool for balancing infrastructure expansion with ecological resilience.

5. CONCLUSIONS

This study developed an integrated performance indicator model to evaluate the effectiveness of EMPs in toll road construction, using the Pekanbaru-Dumai Toll Road in Riau Province as a representative case. By combining the AHP and LCA, the model offers a stakeholder-informed and data-driven framework for environmental performance monitoring in large-scale infrastructure projects. AHP results identified Soil and Land as the highest-priority environmental aspect, followed by Water Quality and Ecology. These stakeholder-derived priorities were substantiated by LCA, which showed that earthworks, material transport, and asphalt paving were the primary contributors to GHG emissions and land degradation.

In parallel, stakeholder perception analysis revealed substantial gaps in EMP implementation. Only 41% of respondents believed that EMP measures were effectively applied in the field. Weak enforcement, limited technical capacity, and the absence of performance-based monitoring were cited as critical barriers. These findings highlight a persistent disconnect between environmental planning and execution, underscoring the need for stronger institutional coordination and greater transparency in EMP enforcement.

Based on these insights, the study proposes several key recommendations. First, indicator-based frameworks should be institutionalized by integrating the AHP-derived model into EMP planning, documentation, and evaluation protocols. Second, LCA should be incorporated during early project planning to identify impact hotspots and inform mitigation strategies. Third, coordination among key agencies, including the Ministry of Public Works and Housing (PUPR), Ministry of Environment and Forestry (KLHK), and Regional Environmental Offices (DLHK) must be enhanced to ensure consistent oversight and enforcement.

Additionally, the establishment of independent environmental audit bodies is recommended to strengthen objectivity and accountability. EMP performance should be formally embedded in contractor selection, project progress reviews, and final handover assessments to drive continuous improvement and regulatory compliance. The proposed AHP-LCA framework is adaptable and scalable, providing a structured tool for sustainable infrastructure management in other ecologically sensitive regions.

This study contributes to the advancement of performance-based environmental evaluation by demonstrating how AHP and LCA can be synergistically applied to produce a robust and practical EMP monitoring framework. Future research should focus on field validation of indicators, integration with digital monitoring systems, and alignment with national sustainability goals to ensure long-term environmental resilience in infrastructure development.

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