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Statistical Analysis of Factors Influencing Green Cost Performance in Indonesian Toll Road Projects Based on the Greenroads Framework

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Abstract

Background: Road transport contributes approximately 69% of global inland transport greenhouse gas (GHG) emissions, making compliance with green infrastructure standards increasingly critical. However, no evidence-based model of green cost performance has yet been developed for Indonesian toll road projects.
Objective: This study examined the statistical factors influencing green cost performance in Indonesian toll road projects implementing the Greenroads sustainability framework.
Method: A quantitative survey of 80 toll road industry professionals investigated the effects of three independent variables Key Success Factors (X1), Greenroads implementation (X2), and Value Engineering application (X3) on Green Cost Performance (Y). Data were analyzed using IBM SPSS Statistics Version 21 through reliability (Cronbach's alpha), validity (Pearson correlation), normality (Kolmogorov–Smirnov), and multiple linear regression analyses. All 93 sub-indicators were found to be valid and reliable.
Results: The Durbin–Watson statistic (DW = 2.153) indicated no autocorrelation, while tolerance values > 0.10 and variance inflation factor (VIF) values < 10.0 confirmed the absence of multicollinearity. The regression equation, $Y = 3.591 + 0.135X1 + 0.125X2 + 0.160X3$, identified Value Engineering (X3) as the strongest predictor ($t = 7.490$), followed by Greenroads implementation (X2; $t = 6.898$) and Key Success Factors (X1; $t = 5.394$). The overall model was statistically significant ($F = 47.329$, $p < .05$), with $R^2 = 0.734$, indicating that the three independent variables jointly explained 73.4% of the variance in green cost performance.
Conclusion: The findings provide a measurable and replicable decision-making framework for cost-sustainable infrastructure development, with direct implications for policies promoting mandatory green financing.

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INTRODUCTION

Toll road infrastructure constitutes a critical component of national transportation networks, enabling the efficient movement of people and goods across economic corridors. Indonesia's sustained expansion of toll roads under the National Strategic Projects program reflects the government's recognition of infrastructure as a driver of economic growth and regional connectivity, contributing to the Sustainable Development Goals (SDGs), particularly SDG 8, SDG 9, SDG 11, and SDG 13 (Ikhsan & Gunawan, 2025; Nations., 2015).

This growth occurs, however, against a backdrop of mounting environmental pressure. The transportation sector accounts for approximately 23% of global annual greenhouse gas (GHG) emissions, of which inland transport contributes 72%, with road transport alone responsible for 69% of that figure (UNECE., 2024). Road and highway construction consumes up to 50% of global natural resources and 40% of global energy (Muench & Anderson, 2009), and the cumulative carbon footprint of the construction sector is projected to exceed the annual carbon budget consistent with the Paris Agreement's 1.5°C and 2°C targets within the coming decades (Li et al., 2025). Beyond emissions, transportation infrastructure has been identified as a major driver of global biodiversity loss, with impacts on surrounding ecosystems extending up to 5 km from road corridors and disproportionately affecting the Global South (Zhou et al., 2026).

The Greenroads™ Rating System, developed at the University of Washington and subsequently applied to 33 certified roadway projects worth more than USD 2 billion, provides a quantitative framework for evaluating and certifying the sustainability performance of road infrastructure (Muench & Anderson, 2009; Zokaei Ashtiani & Muench, 2024, 2022). Adopting such frameworks, however, frequently increases project costs through higher procurement costs for environmentally friendly materials, investments in low-emission equipment and monitoring technologies, and more complex environmental management requirements, including pollution prevention, stormwater management, and habitat conservation (Azam et al., 2024; Oreto, Russo, et al., 2024). Value Engineering (VE) offers a complementary, function-based methodology for systematically eliminating unnecessary costs without compromising performance or sustainability objectives, with documented savings of 5–25% in infrastructure projects (Berawi, 2023; International., 2015; Rahmat et al., 2023).

In the Indonesian context, cost escalation is already a well-documented challenge independent of any sustainability requirement. Change orders alone have been shown to explain more than 94% of the variation in cost overruns in national toll road projects, with technical design changes representing the strongest single driver (Sasmito & Amin, 2026). Layering green compliance requirements onto this already cost-sensitive environment compounds the challenges that project managers, contractors, and government agencies face in balancing sustainability standards with cost efficiency (Djalante et al., 2020; Sutikno et al., 2025b). A separate comparative evaluation of six Indonesian toll roads under the national Green Toll Road Indonesia (GTRI) standard found that non-certified roads exhibit weaker regulatory enforcement and less consistent standard operating procedures than certified roads (Ikhsan & Gunawan, 2025). This evidence, however, speaks to implementation gaps rather than to the statistical drivers of cost outcomes after green measures have been adopted the specific problem addressed in this study.

Despite the importance of this topic, few studies have simultaneously examined Key Success Factors (KSFs), Greenroads implementation, and Value Engineering application as statistical determinants of green cost performance in the Indonesian toll road context using multiple regression analysis. This study addresses these gaps by developing and validating a multiple linear regression model that provides actionable insights for project managers, contractors, and policymakers seeking to optimize cost performance while achieving sustainability targets derived from the Greenroads framework.

Three strands of prior research bear directly on this problem, yet each stops short of addressing it. Ikhsan and Gunawan (2025) compared green policy implementation across six Indonesian toll roads using the GTRI standard and identified regulatory and procedural gaps between certified and non-certified roads, but assessed compliance qualitatively without quantifying its relationship with cost outcomes. Sutikno, Hardjomuljadi, and Wiyanto (2025a) integrated Value Engineering and life-cycle cost analysis with the GREENSHIP Rating System to develop a statistically validated cost-effectiveness model, demonstrating that VE can be empirically associated with green cost performance. Their model, however, was developed for building construction and has not been extended to linear infrastructure such as toll roads. Tran and Yang (2020) compared material and energy efficiency criteria across several international sustainable roadway rating systems and identified measurable cost-reduction potential, but their analysis was conducted at the criterion level rather than through an integrated statistical model incorporating organizational success factors and Value Engineering (Yang et al., 2026). Collectively, green policy compliance, rating-system-based cost modeling, and Value Engineering integration have each been examined independently; however, no previous study has operationalized the Greenroads framework as a quantitative variable alongside Key Success Factors and Value Engineering within a single regression model calibrated to the Indonesian toll road context.

The Greenroads™ Rating System, developed at the University of Washington and applied to 33 certified roadway construction projects with a combined value exceeding USD 2 billion, has demonstrated its viability as a practical and measurable tool for quantifying sustainable best practices in road infrastructure (Zokaei Ashtiani & Muench, 2024). Collectively, these conditions establish that integrating green principles into toll road infrastructure is no longer optional but has become an environmental and economic imperative requiring a structured, evidence-based measurement framework.

Failure to adopt green principles in road infrastructure development carries severe and long-term environmental consequences. Transportation infrastructure has been identified as one of the principal drivers of global biodiversity loss and habitat degradation, with impacts including toxic pollution, noise, light pollution, and microclimatic changes extending far beyond the physical footprint of the infrastructure itself. A landmark global study found that transportation infrastructure impacts extend up to 5 km from road corridors, contributing to 4.26 million km^2 of forest loss, equivalent to 10.7% of the global forest extent in 2020, with the Global South accounting for 54.8% of the most severe degradation between 2000 and 2020 (Zhou et al., 2026).

Beyond direct ecological damage, road construction and maintenance generate substantial indirect carbon emissions that are often overlooked, including emissions associated with traffic congestion during lane closures and longer detour routes used to avoid maintenance zones challenges that remain largely unaddressed in the current literature . In the Indonesian context, a comparative study of six toll roads confirmed that non-certified roads continue to face weak regulatory frameworks, limited human resources, and the absence of sustainable standard operating procedures, resulting in uneven environmental performance across the national toll road network (Ikhsan & Gunawan, 2025). The absence of a mandatory, measurable green compliance standard therefore does not merely represent a missed opportunity; it actively perpetuates environmental degradation at both local and global scales.

Addressing the environmental impacts of road infrastructure requires the establishment of comprehensive, integrated green policy frameworks spanning the entire project life cycle. Research by Ametepey, Aigbavboa, and Thwala (2023) notes that developing countries struggle to incorporate sustainability requirements into highway projects because of inconsistent interpretations and the absence of unified guidelines . In Indonesia, the Ministry of Public Works and Housing (*Kementerian Pekerjaan Umum dan Perumahan Rakyat* [PUPR]) Circular Letter No. 04/SE/M/2018 established initial green road rating guidelines. However, Ikhsan and Gunawan (2025) recommend a more integrated approach encompassing regulatory alignment, education, stakeholder collaboration, and green financing mechanisms.

Building upon this recommendation, this study proposes that the Indonesian government establish mandatory green compliance requirements within the *Kerjasama Pemerintah dan Badan Usaha* (KPBU; Public–Private Partnership [PPP]) scheme, whereby financing approval from both the banking sector and the Minister of Public Works cannot be granted without demonstrated compliance with a recognized green road rating system such as Greenroads. Such a policy instrument would transform green compliance from a voluntary practice into a mandatory financial prerequisite, fundamentally reshaping the investment landscape for sustainable toll road development in Indonesia.

In developed economies, the absence of green compliance in road and building infrastructure is already producing measurable financial and regulatory consequences. The European Union has established the Emissions Trading System 2 (EU ETS2), a carbon pricing mechanism that extends cap-and-trade obligations to CO_2 emissions from fuel combustion in road transport, buildings, and small industrial emitters not covered under the original EU ETS. The system is scheduled to become fully operational in 2028. EU ETS2 places compliance obligations on fuel suppliers to monitor and surrender carbon allowances, with the associated costs expected to be passed on to end users through higher transportation and energy prices. Complementing this framework, 23 European countries have implemented national carbon taxes on emissions, ranging from less than €1 per metric ton in Ukraine to more than €100 per metric ton in Sweden, Liechtenstein, and Switzerland. Furthermore, the Carbon Border Adjustment Mechanism (CBAM), which entered its transitional phase in October 2023 and will impose full charges beginning in 2026, extends carbon pricing pressures to trading partners of the European Union, including developing countries whose production processes do not meet established carbon standards.

According to the State and Trends of Carbon Pricing 2024 report published by the World Bank, global carbon pricing revenues exceeded USD 100 billion for the first time in 2023, signaling an accelerating global transition toward mandatory carbon cost internalization across all sectors, including transportation.

Against this global backdrop, the need for a measurable, evidence-based framework for evaluating green cost performance in toll road infrastructure becomes increasingly evident. The Greenroads™ Rating System, originally developed at the University of Washington (Muench & Anderson, 2009) and subsequently applied to more than 33 certified roadway projects valued at over USD 2 billion (Zokaei Ashtiani & Muench, 2024), provides precisely such a framework. However, its application as a quantitative operational variable within a multiple linear regression model of toll road cost performance, particularly in the Indonesian context, has not previously been documented in the published literature. This study addresses this gap by developing and validating a multiple linear regression model that quantifies the influence of Key Success Factors (X1), Greenroads implementation (X2), and Value Engineering application (X3) on Green Cost Performance (Y) in Indonesian toll road projects. The findings are intended to provide project managers, contractors, and policymakers with a replicable, empirically grounded basis for prioritizing cost-optimization interventions and for developing mandatory green compliance mechanisms within project financing frameworks.

METHOD

This study employed a quantitative research design using a structured questionnaire survey to collect primary data from toll road construction professionals in Indonesia. The research variables were operationalized as: (X1) Key Success Factor of Toll Road Projects with 25 sub-indicators; (X2) Greenroads Implementation with 31 sub-indicators across six categories; (X3) Value Engineering Application with 25 sub-indicators; and (Y) Green Cost Performance with 12 sub-indicators. In total, 93 research sub-indicators were developed and expert-validated through iterative literature synthesis.

The research was conducted through three sequential stages. The first stage identified the research variables through a systematic review of the Greenroads™ Rating System manual and relevant international journals, covering technical, managerial, and environmental factors influencing cost performance in green toll road construction. The second stage comprised instrument development and expert validation, in which the identified sub-indicators were tabulated and reviewed for content relevance to the Indonesian toll road context. The third stage consisted of statistical modeling of the validated survey data prior to multiple linear regression analysis.

The Jakarta–Cikampek II Selatan Toll Road, a National Strategic Project extending approximately 64 km and serving as an alternative corridor to relieve congestion on the existing Jakarta–Cikampek and Cipularang toll roads, served as the contextual reference, ensuring that respondents evaluated the indicators against the realities of a large-scale green toll road project.

The study population consisted of professionals directly involved in the Jakarta–Cikampek II Selatan Toll Road Package IIB project, including client, contractor, consultant, and project management personnel engaged in its planning, design, and construction activities. The minimum sample size was determined using Cochran's (1977) formula: $n0 = Z^2 \times P \times (1-P) / \varepsilon^2$, and $n = n0 / (1 + (n0-1) / N)$, where $Z = 1.96$, $P = 0.50$, $\varepsilon = 0.05$, and $N = 93$, yielding a minimum of 80 respondents. From 100 questionnaires distributed (March 2-27, 2026), 80 were returned and usable (80% return rate). The instrument used a six-point Likert scale (1 = Strongly Disagree to 6 = Strongly Agree), deliberately excluding the neutral midpoint to reduce central tendency bias.

The questionnaire was structured in two parts: the first captured the respondent profile, including educational background, professional role, work experience, and project experience, while the second contained the 93 closed-ended statements representing the research sub-indicators. Each statement was formulated from indicators reported by earlier researchers and tabulated systematically before assembly into the final instrument, which was then reviewed and approved by subject-matter experts to confirm clarity, content relevance, and alignment with the Greenroads framework and Value Engineering practice.

The six-point scale followed the expected–unexpected answer principle, in which a score of 1 represents the response most contrary to the expected condition and 6 represents the ideal condition. The questionnaire was distributed through combined online and direct approaches targeting project managers, contractors, planning consultants, and field supervisors. Returned responses were tabulated in a structured spreadsheet and transferred to SPSS version 21, with careful verification at each step to ensure the accuracy and integrity of the dataset.

Data analysis was conducted in five sequential stages: (1) Reliability Testing using Cronbach's Alpha ($\alpha > 0.600$ threshold); (2) Validity Testing using Pearson Correlation (r > r-table = 0.220; df = 78, n = 80, $\alpha = 0.05$); (3) Normality Testing using Kolmogorov-Smirnov (Asymp. Sig. > 0.05) and Box Plot outlier analysis; (4) Classical Assumption Tests including Durbin-Watson autocorrelation test (acceptable range: dU < DW < 4-dU) and multicollinearity test (Tolerance > 0.10, VIF < 10.00); and (5) Multiple Linear Regression $Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3$, tested through partial t-tests and simultaneous F-tests. All analyses were conducted using SPSS version 21.

This study involved four research variables: Key Success Factors (X1), Greenroads Implementation (X2), and Value Engineering application (X3) as independent variables, and Green Cost Performance (Y) as the dependent variable. The general research hypothesis (H) states that X1, X2, and X3 influence Y, both partially and simultaneously. This hypothesis was tested through partial t-tests, to determine whether X1, X2, and X3 each exert a significant partial effect on Y, and a simultaneous F-test, to determine whether X1, X2, and X3 jointly exert a significant effect on Y. The decision criteria were established as follows: the hypothesis is supported for a given variable if t-count exceeds t-table (1.992; df = 76) with Sig. < 0.05 in the partial test, and supported simultaneously if F-count exceeds F-table (2.725; df1 = 3, df2 = 76) with Sig. < 0.05 in the simultaneous test.

RESULTS AND DISCUSSION

Result

Respondent Profile

The 80 respondents represented a diverse cross-section of the Indonesian toll road construction industry. Educational background: S1 (56.25%), D3 (22.50%), SMA/SMK (15.00%), S2 (6.25%). Professional roles included supervision consultants/construction management (31.25%), site engineers (12.50%), directors/owner representatives (6.25%), and other professionals (45.00%). Work experience in the toll road sector: <5 years (50.00%), 5-10 years (31.25%), >10 years (18.75%). Project experience: toll roads (50%), national/arterial roads (25%), bridges/flyovers (15%), and building/structure projects (10%). Most respondents (75%) possessed direct experience in linear infrastructure relevant to toll road construction.

Reliability and Validity Testing

Reliability testing confirmed high internal consistency for all 93 sub-indicators. As shown in Table 1, the overall Cronbach's Alpha for each construct ranged from 0.753 (Y) to 0.947 (X2), all exceeding the 0.600 threshold. Validity testing confirmed all 93 sub-indicators as valid, with Pearson r values ranging from 0.448 (X2_23) to 0.727 (Y_07 and X3_02), all exceeding the r-table = 0.220. All Sig.(2-tailed) values equaled 0.000, well below the 0.050 threshold, confirming convergent validity across all measurement instruments.

Table 1

Summary of reliability test results (Cronbach's alpha)

Variable	No. of Items	Alpha Range	Result
X1 – Key Success Factor	25	0.942	Reliable
X2 – Greenroads Implementation	31	0.947	Reliable
X3 – Value Engineering	25	0.920	Reliable
Y – Green Cost Performance	12	0.753	Reliable

Normality Testing

Box Plot analyses showed that data were approximately normally distributed for all variables. Variable X1 exhibited one mild outlier (respondent 14, value ≈82.00) identified by a circle marker, within tolerable limits. Variables X2, X3, and Y showed no outliers. The

Kolmogorov-Smirnov test confirmed normality for all variables (Table 2). All Asymp. Sig.(2-tailed) values equaled 0.200, substantially exceeding the 0.05 threshold, confirming suitability for parametric regression analysis.

Table 2
Kolmogorov-Smirnov normality test result

Variable	N	Mean	Std. Dev.	Asymp. Sig.
X1 – Key Success Factor	80	114.350	9.424	0.200
X2 – Greenroads Implementation	80	139.538	11.871	0.200
X3 – Value Engineering	80	106.088	7.661	0.200
Y – Green Cost Performance	80	51.250	3.219	0.200

Classical Assumption Tests

The Durbin-Watson (DW) test yielded DW = 2.153 (Table 3). With n = 80 and k = 3, the critical bounds are dL = 1.560 and dU = 1.715, giving the acceptable range 1.715 < 2.153 < 2.285. Since DW falls within this range, the model is confirmed free of autocorrelation. R^2 = 0.734 indicates that 73.4% of green cost performance variability is explained by the three independent variables.

Table 3
Model summary and Durbin-Watson test

Model	R	R Square	Adj. R Square	Std. Error	DW
1	0.857	0.734	0.723	1.690	2.153

Multicollinearity testing (Table 4) showed Tolerance values of 0.798 (X1), 0.632 (X2), and 0.704 (X3), all exceeding 0.100; VIF values were 1.253, 1.583, and 1.421, all well below 10.00, confirming absence of multicollinearity in the regression model.

Table 4
Multicollinearity test results (collinearity statistics)

Variable	Tolerance	VIF
X1 – Key Success Factor	0.798	1.253
X2 – Greenroads Implementation	0.632	1.583
X3 – Value Engineering	0.704	1.421

Multiple Linear Regression Analysis

The t-test results (Table 5) confirmed statistically significant partial effects of all three independent variables on Y (Green Cost Performance) at α = 5% (t-table = 1.992, df = 76). Value Engineering (X3) registered the highest t-value (7.490), followed by Greenroads Implementation (X2, t = 6.898) and Key Success Factors (X1, t = 5.394). All p-values equaled 0.001 < 0.050. The resulting regression equation is:

$$Y = 3.591 + 0.135\ X1 + 0.125\ X2 + 0.160\ X3$$

Table 5
Partial t-test results (coefficients)

Variable	B	Std. Error	Beta	t	Sig.
(Constant)	3.591	4.399		0.816	0.417
X1 – Key Success Factor	0.135	0.025	0.375	5.394	0.001
X2 – Greenroads Implementation	0.125	0.018	0.461	6.898	0.001
X3 – Value Engineering	0.160	0.021	0.497	7.490	0.001

The simultaneous F-test (Table 6) yielded F = 47.329 (F-table = 2.725, df1 = 3, df2 = 76, α = 5%), with Sig. = 0.000 < 0.050, confirming that X1, X2, and X3 jointly exert significant simultaneous effects on Y.

Table 6

Simultaneous F-Test results (ANOVA)

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	394.679	3	131.560	47.329	0.000
Residual	211.308	76	2.780		
Total	605.988	79			

Mean Ranking Analysis

Analysis of mean scores across 93 sub-indicators (Table 7) revealed that the top-ranked indicators are dominated by sub-factors from X3 (Value Engineering). The top three sub-indicators are: Y_03 (Stability of project cost against design changes, Mean = 5.025), Y_01 (Optimization of green toll road design cost, Mean = 4.950), and Y_10 (Cost efficiency of stormwater management, Mean = 4.875). Of the 25 sub- indicators, 19 (76%) belong to X3 (Value Engineering), interspersed with five Y (Green Cost Performance) sub-indicators (ranks 1–3, 8, and 14) and one X2 (Greenroads Implementation) sub-indicator (rank 19, X2_14), confirming the central, though not exclusive, role of Value Engineering in practitioners' perception of green TABLE 7. Top 10 sub-indicators by mean score

Table 7

Top 10 sub-indicators by mean score

Rank	Code	Sub-Indicator Description	Mean	Group
1	Y_03	Stability of cost against design changes	5.025	Y
2	Y_01	Optimization of green toll road design cost	4.950	Y
3	Y_10	Cost efficiency of stormwater management	4.875	Y
4	X3_22	Simplification of construction process	4.850	X3
5	X3_18	Procurement-stage VE of materials	4.838	X3
6	X3_04	Identification of low-value functions	4.825	X3
7	X3_06	Innovation in construction methods	4.813	X3
8	Y_07	Energy cost efficiency of road lighting	4.813	Y
9	X3_08	Evaluation of risk and technical feasibility	4.800	X3
10	X3_19	Cost-benefit sensitivity analysis	4.775	X3
11	X3_25	Digital technology-based VE implementation (e-VE)	4.7750	X3
12	X3_02	Collection of cost and technical data	4.7625	X3
13	X3_05	Development of design alternatives	4.7500	X3
14	Y_02	Reduction of rework costs	4.7375	Y
15	X3_07	Cost–function comparison analysis	4.7250	X3
16	X3_16	Reduction of construction waste	4.7250	X3
17	X3_09	Preparation of VE recommendations	4.7125	X3
18	X3_15	Life-cycle cost value analysis	4.7125	X3
19	X2_14	Increasing project value index	4.7125	X2
20	X3_13	Documentation and reporting of VE study results	4.6875	X3
21	X3_14	Involvement of multidisciplinary experts in VE workshops	4.6875	X3
22	X3_24	Cost benchmarking against similar projects	4.6875	X3
23	X3_01	Identification of the project's primary function	4.6750	X3
24	X3_10	Implementation of VE results in the project	4.6750	X3
25	X3_11	Achievement of cost savings	4.6750	X3

Discussion

The regression results establish a robust quantitative basis for understanding the multi-factor determinants of green cost performance in Indonesian toll road projects. The dominance of Value Engineering (X3, $\beta = 0.497$, $t = 7.490$) as the most influential variable is consistent with findings by Sutikno, Hardjomuljadi, and Wiyanto (2025a) and Sutikno, Husin, and Magdalena (2025b), who similarly demonstrated VE as the primary mechanism for cost efficiency in green infrastructure (Sutikno et al., 2022). The strong influence of X3 is further reinforced by the mean ranking analysis, which placed 21 of the top 25 sub-indicators in the X3 group, particularly those related to function identification, FAST diagram application, and cost-function ratio assessment.

The significant contribution of Greenroads Implementation (X2, β = 0.461, t = 6.898) confirms that adopting the Greenroads rating framework is significantly and positively associated with cost performance, contrary to the common industry perception that green standards necessarily increase project costs. This finding aligns with Tran and Yang (2020), who demonstrated that material and energy efficiency criteria generate measurable cost reductions when systematically implemented (Yang et al., 2026). Specific Greenroads criteria that ranked highly include Ecological Connectivity, Water Conservation, Recycled Material Content, and Energy Efficiency, all of which have documented cost-reduction potential (Medina et al., 2023; Oreto, Veropalumbo, et al., 2024).

Key Success Factors (X1, β = 0.375, t = 5.394) contribute significantly to green cost performance. The relatively lower beta coefficient for X1 compared to X3 suggests that the technical and analytical capacity to implement VE systematically has greater direct leverage on cost outcomes than organizational success factors alone. This is practically significant: even when toll road projects meet standard organizational success criteria, the presence of a structured VE methodology constitutes a critical determinant of whether green construction costs are optimized or merely managed conventionally (31, 32).

The $R^2 = 0.734$ indicates that 73.4% of the variance in green cost performance is explained by the three variables collectively. The remaining 26.6% likely reflects project-specific factors not captured in this model, such as contractor experience with specific green technologies, regional material availability, and site-specific geotechnical complexities, which represent directions for future research.

It is important to note that the regression findings in this study establish statistical association, not a direct causal mechanism linking Value Engineering or Greenroads adoption to financing approval outcomes. The recommendation for incorporating Greenroads compliance into PPP (KPBU) financing evaluation is therefore proposed as a policy implication grounded in the demonstrated cost-saving potential (specifically, the Bronze-level Greenroads scenario yielding a cost reduction of IDR 160.19 billion (6.67% of the total project budget)) rather than as a proven causal outcome of the regression model itself. This recommendation aligns with the broader objective of KPBU financing schemes, which prioritize project bankability and long-term cost efficiency, but its formal integration into financing approval criteria would require additional validation through case-based or longitudinal studies across multiple toll road projects before being adopted as a mandatory policy instrument. We present this recommendation as an evidence-informed starting point for policymakers rather than a definitive causal claim.

CONCLUSION

This study developed and validated a multiple linear regression model to examine the effects of Key Success Factors (X1), Greenroads Implementation (X2), and Value Engineering Application (X3) on Green Cost Performance (Y) in Indonesian toll road projects. The results confirm that all three variables are statistically significant and positively associated with green cost performance, with Value Engineering Application emerging as the most influential factor (β = 0.497), followed by Greenroads Implementation (β = 0.461) and Key Success Factors (β = 0.375). Together, these three variables explain 73.4% of the variance in green cost performance ($R^2 = 0.734$, $Y = 3.591 + 0.135X_1 + 0.125X_2 + 0.160X_3$), indicating that the systematic application of VE methodology combined with Greenroads-based sustainability practices provides toll road stakeholders with a practical, evidence-based pathway to optimize cost efficiency without compromising sustainability outcomes.

The primary contribution of this research lies in the pioneering integration of the Greenroads rating framework as a quantitative operational variable within a statistical regression model for Indonesian toll road projects, an approach not previously documented in existing literature, thereby bridging the gap between green rating systems and empirical cost management research. This study is nonetheless limited by its cross-sectional survey design, which establishes statistical association rather than causal relationships, and by its focus on a single toll road project (Jakarta–Cikampek II Selatan), which may constrain generalizability across projects of different scale or regional context. Future research should therefore apply Structural Equation Modeling (SEM) to establish causal pathways and mediation effects, and extend the analysis through field implementation data across multiple toll road projects to validate and refine the model under varying project scales and conditions.

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AUTHOR CONTRIBUTION STATEMENT

Abdullah Ahmad Badawi: Conceptualization, methodology, investigation, data collection, formal analysis, data interpretation, writing – original draft preparation, and manuscript revision. Albert Eddy Husin: Supervision, validation, methodology review, interpretation of findings, writing – review and editing, and final approval of the manuscript. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work, ensuring the accuracy and integrity of the research. v

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