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Value Engineering Based on Ecological-Visual Dual Function in Toll Road Landscape Planning: Empirical Evidence of Life Cycle Cost Efficiency of the Dumai–Rantauprapat Section

Nasrul Fanani[1]*, Suryawan Murtiadi[2] , Dwi Dinariana[3]
Institut Sains dan Teknologi Nasional, Jakarta, Indonesia
*Corresponding Author: fanani.nasrul@gmail.com

ABSTRACT

This study evaluates landscape planning for Package 1 of the Dumai–Rantauprapat Toll Road (STA 0+000–27+000), comprising 15 plant species with an initial budget of IDR 8,261,901,154. Plant selection must balance ecological functions, including soil protection, visual quality, and long-term costs. The objectives are to identify major cost contributors, establish plant-selection priorities, and estimate potential life-cycle savings. Using a case study and ex-ante evaluation, the study combines Value Engineering, Pareto analysis, the Value Index, and Analytic Hierarchy Process (AHP) assessments by three experts. Life Cycle Cost Analysis (LCCA) covers 40 years at an 8% discount rate. Data were drawn from cost budget documents and modeled plant-replacement scenarios. Pareto analysis shows that Dew Grass accounts for 63.38% of the landscape budget, while three principal aesthetic plants represent 87.60% of costs within the aesthetic group. AHP assigns the highest priority to ecological function (29.46%), followed by visual function (20.26%), with a combined consistency ratio of 0.0376. A proposed combination of Bahia Grass, Yellow Fire, Akalipa, and Alamanda yields an estimated life-cycle cost of IDR 56,816,365,772, compared with IDR 59,608,395,120 for the original design. The modeled difference is IDR 2,792,029,348, equivalent to potential savings of 4.68%. These savings are projections rather than realized financial outcomes, and the ecological and visual performance of replacement species remains unverified in the field. The study offers an integrated framework for prioritizing landscape expenditure, comparing plant alternatives, and planning maintenance over the operational lifespan of toll roads. Future field assessments should validate plant survival, maintenance needs, and aesthetic performance.

Keywords: *Value Engineering, Highway Landscape, Ecological Function, Visual Function, Life Cycle Cost Analysis.*

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INTRODUCTION

The construction of the Trans-Sumatra Toll Road is one of the government's efforts to streamline transportation, expedite the delivery of goods, and strengthen interregional economic ties. This project requires not only a sturdy road but also proper landscape planning to preserve the environment along the route. In June 2025, the Ministry of Public Works reported that the Dumai–Rantauprapat Toll Road section was still in the planning stage. This situation provides an opportunity to evaluate the design before construction begins, when changes can still be made without incurring additional costs for demolition or repairs. According to the Cost Estimate (RAB) document for the STA 0+000–27+000 section, landscaping work includes 15 plant species with a total budget of Rp8,261,901,154. One of the largest components is Dew Grass, with a budget of Rp5,236,038,878. The magnitude of these costs indicates that the selection of plant species needs to be evaluated systematically. Such an evaluation should not be limited to comparing initial prices but must also consider the plants' functions and maintenance costs over the toll road's operational lifespan.

The landscape along a highway plays a broader role than simply beautifying the environment. Plants can help cover the soil surface, reduce erosion, support slope stability, and create a pleasant view for road users. [1] demonstrated through a physical experiment that vetiver vegetation is capable of reducing soil loss caused by rainwater runoff under the tested conditions. Meanwhile, [2], through a review of 50 studies, found that visual conditions along roads are related to driver attention, fatigue, and behavior. However, these effects depend on the characteristics of the observed environment. These two findings indicate that highway vegetation serves two important functions: an ecological

function to support environmental conditions and a visual function to shape the quality of the landscape. Therefore, reducing landscaping costs without considering these two functions may result in a cheaper design, but one that is not necessarily in line with technical and environmental requirements.

Research on vegetation shows that plant success depends heavily on their characteristics and the conditions of the planting site. [3] discuss the use of vetiver grass as one approach to improving the resilience of road infrastructure. [4] demonstrate that the root characteristics of vetiver grass influence water-soil interactions on slopes during rainfall. Furthermore, [5] found that a plant's ability to stabilize road slopes varies depending on the plant species, root properties, and slope conditions. These three studies collectively support the conclusion that vegetation selection cannot be based solely on price or appearance. However, these studies primarily describe the technical capabilities of plants under specific conditions. Their results cannot be directly applied to confirm that replacement plants along the Dumai–Rantauprapat section possess the same capabilities. Differences in soil, rainfall, slope gradient, and maintenance requirements must still be taken into account.

In addition to ecological benefits, long-term costs play a crucial role in determining vegetation alternatives. Kurth et al. [6] explain that nature-based infrastructure management must consider the entire lifecycle of the infrastructure, not just the initial construction costs. [7] found that the assessment of green infrastructure still faces discrepancies in methods, scopes of analysis, and the indicators used, making it difficult to directly compare results across studies. These findings are reinforced by [8], who demonstrated that options with lower costs do not necessarily result in better environmental outcomes. [9] also found that assessments of the economic benefits of nature-based solutions often rely on different cost assumptions, discount rates, and analysis periods. Collectively, these studies highlight the importance of linking the functional capacity of plants to costs over their entire service life. However, applying this to the selection of vegetation for highway landscapes still requires an approach tailored to the specific conditions and needs of each project.

One approach that can be used is Value Engineering (VE), a method for finding ways to fulfill required functions more cost-effectively. In VE, the best option is not always the one with the lowest purchase price, but rather the option that can fulfill the required functions at a justifiable cost. To help determine the level of importance of various functions, VE can be combined with the Analytic Hierarchy Process (AHP). [10] explain that AHP can help establish decision priorities based on the comparison of several criteria, but the consistency of the assessments must be verified to ensure the reliability of the weighting results. AHP weights must also be distinguished from the performance scores of each alternative. A high weight assigned to an ecological function indicates that the criterion is considered important; it does not prove that a particular plant species possesses high ecological capability. Therefore, the use of AHP in landscape planning must be supported by an assessment of plant function and suitability. Furthermore, Life Cycle Cost Analysis (LCCA) is used to compare initial costs with estimated costs that will arise during the period of use.

Based on the previous studies reviewed, there are several interrelated limitations. Research on slope vegetation provides evidence regarding the ability of roots and plants to protect the soil, but has not directly linked this to visual priorities and the life-cycle costs of highway landscapes [2], [11], [12]. Studies on the visual environment of roads explain the relationship between scenery and the driver's experience, but do not specifically determine plant combinations based on construction and maintenance costs [13]. Meanwhile, research on green infrastructure and life-cycle costs highlights the importance of long-term economic evaluation, but still faces limitations in consistently integrating environmental function metrics with costs [8], [11], [14]. The research gap lies in the limited evaluation of highway landscape planning that simultaneously identifies high-cost components, sets priorities for ecological and visual functions, and compares the life-cycle costs of alternative plantings within a single decision-making framework. This gap is particularly important to address on the Dumai–Rantauprapat section because decisions regarding plant species can be evaluated before physical construction begins.

The novelty of this study lies in the application of a Value Engineering framework based on two functions—ecological and visual linked to a 40-year landscape cost evaluation during the highway planning phase. 's research combines Pareto analysis to prioritize high-cost tasks, the Value Index as an initial indicator for cost comparison, and AHP to determine the weights of six criteria covering ecological function, visual function, construction costs, maintenance costs, regulatory compliance, and ease of implementation. Furthermore, LCCA was used to estimate the cost differences between the initial design and several alternative plant combinations. The main distinction of this study lies not in the creation of a new method, but in the integration of these methods to support landscape planning decisions for a single toll road section. This approach also distinguishes verifiable cost calculations from the ecological and visual capabilities of plants, which still require field testing.

Based on these gaps and novel aspects, this study has three objectives. First, to identify the plant species that contribute the most to costs among 15 landscape work items using Pareto analysis and the Value Index. Second, to determine the importance levels of six plant selection criteria using AHP and to identify vegetation alternatives that need to be evaluated based on their ecological and visual functions and application requirements. Third, to estimate

the life-cycle costs and potential savings of alternative plant combinations compared to the initial design using LCCA over a 40-year period at a base discount rate of 8%. This study is expected to provide a more quantifiable basis for decision-making for project owners, planners, and toll road operators in setting budget evaluation priorities and comparing design alternatives. In practical terms, the research framework can be used to support improvements in landscape specifications and long-term cost control, while still requiring an assessment of ecological, technical, and visual suitability before plant alternatives are implemented in the field.

MATERIALS AND METHODS

This study employs an applied case study approach with ex-ante evaluation using the Value Engineering (VE) method to assess cost efficiency and the fulfillment of ecological and visual functions in highway landscape planning. The subject of the study is the landscape work for Package 1 of the Dumai–Rantauprapat Highway Project, from STA 0+000 to STA 27+000. Quantitative analysis was used to identify cost concentrations, calculate value indices, determine criterion weights, and estimate life-cycle costs. Expert assessment was used to evaluate ecological and visual functions, as well as the feasibility of vegetation implementation.

The research data were sourced from the Cost Estimate (RAB) for the landscaping project, which included 15 plant species with a total cost of Rp8,261,901,154, planning documents, and the assessment results of three experts reported in the study. These data served as the basis for identifying high-cost components and developing vegetation alternatives. The life-cycle cost analysis uses a 40-year horizon and a base discount rate of 8%. The base price year, data collection period, maintenance cost details, as well as the experts' identities and qualifications must be obtained from the original research documents.

Phase 1: Budget Analysis and Pareto Analysis

The first phase aims to identify the types of landscaping work that account for the largest share of costs so that they can be prioritized in the value engineering analysis [15]. The data used consists of the cost values of 15 types of plants grouped into five functional categories: slope stability, aesthetics, shade, boundary, and conservation [16].

The Pareto analysis was conducted at two levels. The first level compared the magnitude of costs across functional categories relative to the total landscape budget. The second level ranked the costs of each plant species within a category to identify the most dominant items. Priorities were identified using a cumulative Pareto approach, with an 80% threshold serving as an initial guideline for selecting high-cost items, rather than as the sole basis for determining that a plant has low functional value [5], [9].

The percentage contribution of each item's cost to the total budget is calculated using Equation (1).

$$P_i = \frac{C_i}{C_{total}} \times 100\% \quad (1)$$

Notes:
(P_i) = percentage of the cost of the (i)-th item.
(C_i) = cost of item (i) (IDR).
(C_total) = total cost of the landscaping project (IDR).
To determine the cumulative cost contribution in descending order from highest to lowest, Equation (2) is used.

$$K_k = \frac{\sum_{i=1}^{k} C_{(i)}}{\sum_{i=1}^{n} C_i} \times 100\% \quad (2)$$

Notes:
(K_k) = percentage of cumulative cost up to the (k)-th item.
(C_(i)) = cost of the item sorted from largest to smallest.
(n) = the number of items in the group being analyzed.

Step 2: Analysis of the Function and Value Index

The second stage aims to identify the basic and additional functions of each plant species before evaluating the costs incurred. The functional analysis is conducted based on the technical and environmental objectives of the plants, taking into account the vegetation's ability to protect the soil surface, support slope stability, enhance visual quality, provide shade, define space, and support environmental conservation [7], [17].

The Value Index (VI) is calculated by comparing the functional value (worth) to the actual costs listed in the Bill of Quantities (BoQ), using Equation (3).

$$VI_i = \frac{W_i}{C_i} \quad (3)$$

Notes:
VI_i = value index of the i-th item.
W_i = the reference cost used as the worth (IDR).
C_i = cost of item i (IDR).

Stage 3: Development and Screening of Vegetation Alternatives
The third stage aims to develop plant alternatives that can replace high-cost components without compromising the ecological, visual, and highway safety requirements. The development of alternatives is based on plant species identified as priorities in the Pareto and Value Index analyses, taking into account growth characteristics, environmental suitability, seedling availability, and maintenance requirements [4], [13], [18].

Plant selection is based on the function of vegetation in the roadside landscape, as stipulated in Ministry of Public Works Regulation No. 05/PRT/M/2012. In addition, replacement plants must be suitable for local environmental conditions, particularly rainfall, soil characteristics, slope gradients, and maintenance requirements throughout the service life of the toll road [19], [20].

Table 1. Analyzed Candidate Replacement Plants

Group	Original Plant	Alternative Candidates
Slope Stability	Dew Grass	Bahia Grass
Tree Aesthetics	White Tabebuya	Yellow Fire
Shrub Aesthetics	Red Shoots	Akalipa
Ornamental Plant Aesthetics	Bougainvillea	Alamanda

Step 4: Weighting Criteria Using the Analytic Hierarchy Process (AHP)
The weighting process used six criteria: ecological function (C1), visual function (C2), construction cost efficiency (C3), maintenance cost efficiency (C4), regulatory compliance (C5), and ease of implementation (C6). Weighting is performed through pairwise comparisons using the Saaty scale of 1–9 [12], [21]. A value of 1 indicates that the two criteria are equally important, while values of 3, 5, 7, and 9 indicate increasing levels of importance. Values of 2, 4, 6, and 8 are used as intermediate values, while their inverses are used to indicate opposite preferences.

$$a_{ij}^{G} = \left(\prod_{h=1}^{m} a_{ij}^{(h)} \right)^{1/m} \tag{4}$$

Stage 5: Assessment and Ranking of Vegetation Alternatives
The fifth stage aims to compare the performance of each vegetation alternative based on six criteria that have been weighted using the AHP method. The evaluation is conducted on candidates that meet the mandatory requirements in the screening stage, so that low-cost alternatives that do not fulfill the technical requirements can still be excluded from the selection process [3], [22].

The performance of each alternative can be assessed using the ecological and visual indicators described in the functional analysis stage, and then combined with an assessment of costs, regulatory compliance, and ease of implementation. For an evaluation design using a 1–5 scale, a score of 1 indicates very poor performance and a score of 5 indicates very good performance. Scores must have consistent definitions and evidence bases for all alternatives.

$$S_a = \sum_{j=1}^{6} w_j \, r_{aj} \tag{5}$$

Stage 6: Life Cycle Cost Analysis (LCCA)
The sixth phase aims to compare the long-term costs between the initial vegetation design and alternative designs using the Life Cycle Cost Analysis (LCCA) method. The analysis was conducted to estimate cost savings over the service life, taking into account initial costs, maintenance, plant replacement, and other operational costs [1], [23].

The analysis period was set at 40 years with a base discount rate of 8%, in accordance with the parameters reported in the study. The discount rate is used to convert future expenditures into present value. In practice, the use of constant prices requires a real discount rate, while the use of nominal prices requires a consistent nominal discount rate.

$$LCC = C_0 + \sum_{t=1}^{T} \frac{M_t + P_t + R_t + O_t}{(1+r)^t} - \frac{V_T}{(1+r)^T} \tag{6}$$

Step 7: Sensitivity Analysis

The seventh stage aims to test the stability of cost savings against changes in key assumptions in the LCCA calculation. This analysis is necessary because the estimated costs over a 40-year period can be affected by changes in the discount rate and plant maintenance expenses [2], [24].

The sensitivity analysis was designed using four discount rates—4%, 6%, 8%, and 10%—and five maintenance cost change scenarios: −20%, −10%, 0%, +10%, and +20% relative to the baseline assumptions. Maintenance costs under each scenario were calculated using [25]:

$$M_t' = (1 + \delta)M_t \tag{7}$$

The difference in life-cycle costs between the baseline and alternative conditions is recalculated for each scenario using:

$$\Delta\mathrm{LCC}(\mathrm{r}, \delta) = \mathrm{LCC_e}(\mathrm{r}, \delta) - \mathrm{LCC_a}(\mathrm{r}, \delta) \tag{8}$$

The efficiency percentage for each scenario is calculated using:

$$\mathrm{E}(\mathrm{r}, \delta) = \frac{\Delta\mathrm{LCC}(\mathrm{r}, \delta)}{\mathrm{LCC_e}(\mathrm{r}, \delta)} \times 100\% \tag{9}$$

RESULTS

Existing Conditions and Cost Concentration

The Bill of Quantities (BoQ) document covers 15 types of plants with a total initial cost of Rp8,261,901,154. The slope stability category accounts for approximately 63.59% of the budget, primarily consisting of Dew Grass at Rp5,236,038,878—or 63.38% of the total cost—covering an area of 129,817 m^2. The unit cost can be calculated as Rp5,236,038,878 / 129,817 m^2 = Rp40,334/m^2. This figure demonstrates the significant impact of Rumput Embun's cost on the budget but does not prove the inefficiency of the unit price without comparing productivity, installation methods, and the equivalence of slope functions. The three main ornamental plants (White Tabebuya, Red Shoots, and Bougainvillea) have a combined cost of Rp1,195,017,064, or approximately 14.46% of the total landscape cost.

Table 1. Cost concentration by landscape function category

Function Categories	Portion of the Cost	Key Findings
Slope Stability	±63.6%	Dominated by Dew Grass (63.38%)
Aesthetics	±17%	Three dominant types account for 87.60% of the aesthetics category (14.46% of the total budget)
Shade	±12%	Mahogany identified as a problematic item
Barriers	±5%	Relatively small cost contribution
Conservation	±3%	Small savings potential

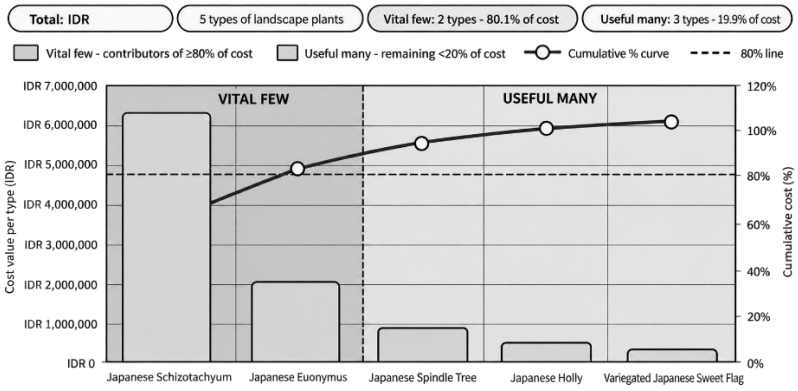


Figure 1. Level 1 Pareto Results Graph

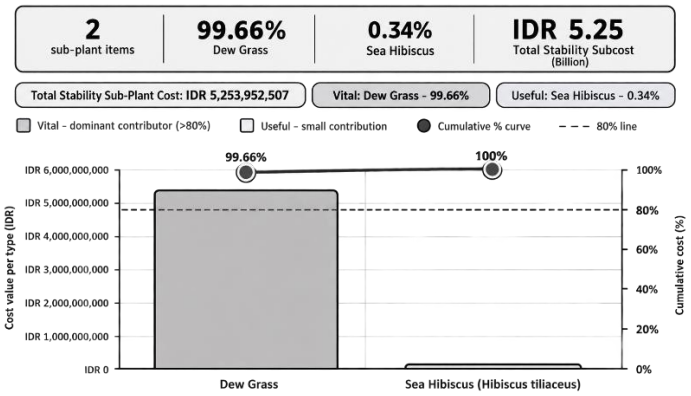


Figure 2. Pareto Yield Chart: Level 2 Crop Stability

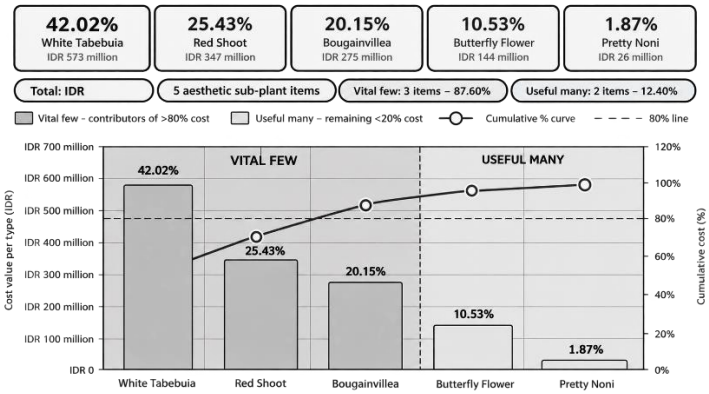


Figure 3. Level 2 Pareto Results Graph for Aesthetic Plants

Value Index and Low Value

The value-to-cost ratio indicators in Tables 2 and 3 indicate that components with large budgets require more in-depth evaluation. White Tabebuya has the lowest VI in the aesthetics group, namely 25,514,706 / 573,189,806 = 0.0445 (rounded to 0.045). Rumput Embun has a VI of 17,913,629 / 5,236,038,878 = 0.003421 (rounded to 0.0034). These low values are primarily due to the fact that the "worth" used is the cost of the cheapest comparable item, not the function score from the test results. Therefore, the "poor value" label should be interpreted as a priority for examining cost and function, not as a definitive judgment that the plant fails to perform its ecological or visual functions.

Table 2. Cost-to-Worth Analysis Results for Aesthetic Plant Types

No.	Plants	Cost (IDR)	Worth (IDR)	VI
1	Beautiful Violin	25,514,706	25,514,706	1,000
2	Butterfly Flowers	143,705,569	25,514,706	0.178
3	Bogenvil	274,912,746	25,514,706	0.093
4	Red shoots	346,914,512	25,514,706	0.074
5	White Tabebuya	573,189,806	25,514,706	0.045

Table 3. Cost-to-Value Analysis of Stabilization Plant Types

No.	Plants	Cost (IDR)	Value (IDR)	VI
1	Sea Waru	17,913,629	17,913,629	1,000
2	Dew Grass	5,236,038,878	17,913,629	0.0034

Weight of Evaluation Criteria

Table 4 shows that the ecological function (K1) has the highest weight, at 29.46%, followed by regulatory compliance (K5) at 20.30% and the visual function (K2) at 20.26%. The combined weight of ecological and visual functions is 49.72%, higher than the combined weight of construction and maintenance cost efficiency (22.72%). The reported combined CR of 0.0376 falls below the general practice threshold of 0.10; however, without the three original matrices and the CR per expert, the consistency of each evaluator cannot yet be re-tested. The sum of the two-decimal-place weight figures in the table results in 100.01% due to rounding. The high ecological weight may reflect the priority given to slope and environmental protection in decision-making.

Table 4. Weights of AHP outcome evaluation criteria (CR = 0.0376)

Criteria	Code	Weight	Ratings
Fulfillment of Ecological Functions	K1	29.46%	1
Regulatory Compliance	K5	20.30%	2
Visual Function Performance	K2	20.26%	3
Construction Cost Efficiency	K3	11.49%	4
Maintenance Cost Efficiency	K4	11.23%	5
Ease of Implementation	K6	7.27%	6

Life cycle costs and selected combinations

Based on the LCCA figures presented for a 40-year horizon and a base discount rate of 8%, the cost of the initial design model is Rp59,608,395,120, while the selected combination is estimated at Rp56,816,365,772. The difference between the two is Rp2,792,029,348, or 4.68395% (rounded to 4.68%) of the initial design cost. The largest proportion of savings within each category comes from Akalipa (43.99%), while the largest nominal savings come from replacing Rumput Embun with Bahia Grass (Rp1,330,603,048).

Table 5. Recapitulation of 40-Year LCC Savings by Category

Categories	Existing → Selected	Savings (IDR)	Efficiency
Stability	Dew Grass → Bahia Grass	1,330,603,048	2.54%
Tree Aesthetics	White Tabebuya → Yellow Fire	533,718,995	14.80%
Aesthetics Shrub	Red Shoots → Akalipa	602,212,040	43.99%
Estetika (Bogenvil)	Bogenvil → Alamanda	325,495,265	15.06%
TOTAL	**Optimal Combination**	2,792,029,348	**4.68%**

Table 6 shows four vegetation composition scenarios. The reported optimal combination (Bahia Grass, Yellow Fire, Akalipa, and Alamanda) has the most favorable model cost difference, namely 4.68% compared to the initial conditions. Based on the rounded percentage, the savings for Combination III amount to 3.11% × Rp59,608,395,120 ≈ Rp1.85 billion, not Rp1.85 million as shown in the original table; the exact amount requires the LCC of the scenario without rounding. For Combination II, the relative cost figure of −130.79% could mean a cost more than twice that of the initial design.

Table 6. Comparison of vegetation combination schemes (LCC over 40 years)

Scheme	Composition	Efficiency vs. Existing
Combination I	Vetiver + Bungur + Peacock + Alamanda	−0.03% (more expensive)
Combination II	Indigofera + Flamboyant + Hibiscus + Red Cambodian	−130.79% (much more expensive)
Combination III	Bahia Grass + Yellow Fire + Akalipa + Cana	+3.11% (estimated savings ≈Rp1.85 billion)
Optimal Combination	Bahia Grass + Yellow Fire + Akalipa + Alamanda	+4.68% (savings of Rp2.79 billion)

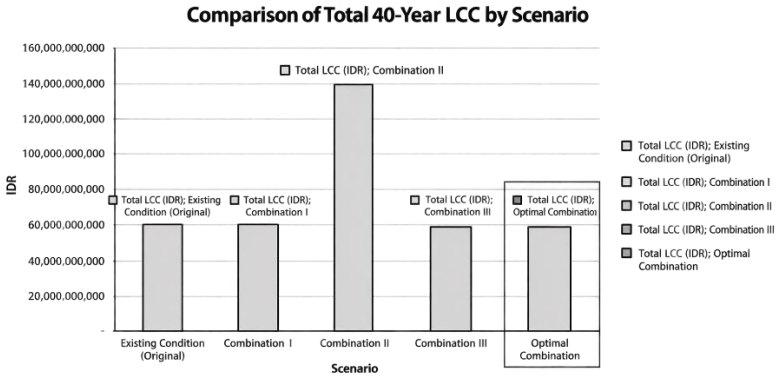


Figure 5. Comparison of 40-year life-cycle cost models: baseline, Combinations I, II, III, and the optimal combination.

DISCUSSION

Landscape Cost Concentration and Value Engineering Priorities

The results show that landscape costs in the Dumai–Rantauprapat Toll Road Project are concentrated in a few plant types. Of the total landscape budget of IDR 8,261,901,154, Dew Grass accounts for IDR 5,236,038,878, representing 63.38% of the total cost. Additionally, White Tabebuya, Red Shoots, and Bougainvillea account for 87.60% of the costs within the aesthetic plant category. These findings suggest that evaluating a small number of high-cost plant items could offer greater opportunities for cost savings than reviewing all plant types equally. However, a high cost does not necessarily indicate poor functional value, as costs also depend on planting area, quantity, site conditions, and technical requirements.

These findings are consistent with [21], who reported that plant selection and planting design play important roles in the ecological, aesthetic, and social performance of landscapes. Their findings support the need to evaluate plants based on their functions rather than their appearance alone. The present study extends this approach by applying Pareto analysis to identify plant types that require priority cost evaluation. The Value Index results for Dew Grass (0.0034) and White Tabebuya (0.045) indicate significant differences between their actual costs and the reference costs used in the analysis. However, since the value indices were based on the lowest-cost items within each category, these indices should be interpreted as preliminary cost indicators rather than direct measures of plant performance.

Belaire et al. (2023) [24] provide further evidence that landscape design can support ecological benefits while reducing water use and maintenance needs. Their findings build upon the present study by demonstrating that plant value should also account for the benefits provided throughout the plant's service life. Therefore, expensive plants should not automatically be replaced if they provide important ecological or technical functions. Replacement should only be considered when a lower-cost alternative can meet the same functional requirements. In this study, Pareto analysis and the Value Index are useful for identifying cost priorities, while the final selection of replacement plants still requires evidence of functional performance.

Ecological Functions and Plant Suitability for Slope Stability

The AHP results show that ecological function received the highest weight at 29.46%. This finding indicates that the experts considered environmental performance an important factor in landscape planning, particularly for soil protection and slope stability. This consideration is important because roadside plants must not only enhance the landscape's appearance but also survive and perform their functions under local soil and rainfall conditions.

This finding is supported by Prasetyaningtiyas et al. (2024) [22], who found that grass root characteristics influence soil-water interactions and slope stability during rainfall. Their study demonstrated that root length, surface area, and branching patterns can affect soil reinforcement under the tested conditions. Similarly, Keybondori et al. (2025) [23] reported that roadside slope stability depends on plant species and the mechanical properties of their roots. These studies underscore the importance of ecological performance when selecting vegetation for slope protection.

However, Keybondori et al. (2025) [23] also demonstrated that some native plants with relatively shallow roots can provide effective soil reinforcement due to their dense root systems. This finding expands our understanding of slope protection by showing that root depth alone does not determine a plant's effectiveness. It is particularly relevant to the proposed replacement of Dew Grass with Bahia Grass in the present study. The LCCA results indicate that this replacement could reduce life-cycle costs by IDR 1,330,603,048, or 2.54%, within the stability category. However, these savings do not prove that Bahia Grass provides the same level of slope protection as Dew Grass. Further assessment of root development, ground coverage, erosion resistance, and adaptation to local soil conditions is

required. Therefore, the proposed replacement offers a potential economic benefit, but its technical suitability must still be confirmed.

Ecological and Visual Functions in Plant Selection

The AHP results show that ecological and visual functions received weights of 29.46% and 20.26%, respectively. Together, these criteria account for 49.72% of the total weight, exceeding the combined weight of construction and maintenance cost efficiency (22.72%). This result indicates that the experts placed greater importance on environmental and visual performance than on direct cost considerations. However, AHP weights represent the importance of evaluation criteria, not the actual ecological or visual performance of individual plants.

This finding is consistent with Belaire et al. (2023) [24], who identified a positive relationship between landscape visual quality and pollinator diversity. Their study also showed that landscapes with high visual quality could have relatively low water requirements. These results support the argument that ecological and visual functions do not always conflict. Fernandes et al. (2025) [21] further expanded on this argument through a systematic review of 127 publications, demonstrating that planting design should integrate ecological, aesthetic, and management objectives. Collectively, these studies support the use of multiple criteria in landscape planning, as applied through the six AHP criteria in the present study.

Nevertheless, ecological benefits may vary among different groups of organisms. Brown et al. (2024) [27] found that replacing roadside vegetation with native understory plants increased bee abundance and species richness but did not provide clear evidence of an increase in bird populations. This finding indicates that improvements in vegetation do not necessarily benefit all animal groups equally. Fernandes et al. (2026) [25] also found that introducing patches of native vegetation along roads increased plant diversity and habitat variation without compromising road safety under the conditions studied. These findings suggest that vegetation changes can enhance ecological performance, but the benefits depend on plant composition, local environmental conditions, and the specific organisms being assessed.

In the present study, Dew Grass accounts for 63.38% of landscape costs. However, this cost share does not prove that Dew Grass occupies the same percentage of the planted area or that the landscape has low biodiversity. Additional information on planted area, species composition, and ecological conditions is needed before drawing such conclusions.

From a visual perspective, Anciaes (2023) [26] reported that roadside visual environments can have varying effects on driver comfort, attention, and behavior. Some visual features may enhance the driving experience, while others may distract drivers. This finding contradicts the assumption that greater variation in plant colors and shapes always improves road conditions. Therefore, the selection of Yellow Fire, Akalipa, and Alamanda should involve an assessment of visual continuity, planting location, sight distance, and road safety requirements. Since the present study did not measure driver attention or accident rates, potential safety benefits should not be presented as confirmed outcomes.

Life Cycle Cost Efficiency and Long-Term Cost Uncertainty

The LCCA results show that the estimated 40-year life cycle cost of the existing landscape design is IDR 59,608,395,120. The selected combination of Bahia Grass, Yellow Fire, Akalipa, and Alamanda has an estimated cost of IDR 56,816,365,772. The difference represents a potential savings of IDR 2,792,029,348, equivalent to 4.68% of the existing design cost. Although this percentage is relatively modest, the monetary savings are substantial. The largest monetary saving comes from replacing Dew Grass with Bahia Grass (IDR 1,330,603,048), while the highest percentage saving occurs when Red Shoots is replaced with Akalipa (43.99% within its category).

These findings are consistent with Jalilzadehazhari (2026) [29], who emphasized the importance of considering construction, operation, maintenance, and other costs throughout the service life of nature-based infrastructure. The study explained that focusing solely on initial investment costs may result in an incomplete assessment of long-term economic performance. Similarly, Oluk et al. (2026) [28], through a systematic review of 128 studies on green infrastructure, emphasized the importance of evaluating life cycle costs alongside environmental performance. These findings support the use of LCCA in the present study because decisions regarding plant replacement can affect maintenance expenses over many years.

However, Oluk et al. (2026) [28] also found that alternatives with lower economic costs do not always result in lower environmental impacts. This finding offers a contrasting perspective on the use of cost efficiency as the primary basis for selecting landscape alternatives. In the present study, the combination of Bahia Grass, Yellow Fire, Akalipa, and Alamanda has the lowest estimated life cycle cost among the evaluated scenarios. Nevertheless, this result does not prove that the combination provides the best ecological or visual performance. The final decision requires evidence that the selected plants meet the necessary requirements for slope protection, climate adaptation, and ecological safety.

Jalilzadehazhari (2026) [29] also highlighted that differences in discount rates, analysis periods, and included cost components can alter the economic outcomes of nature-based solutions. This finding is important because the present study employs an 8% discount rate and a 40-year analysis period. Although the estimated savings amount to 4.68%, the robustness of this result under varying maintenance costs and discount rates has not been fully established using the project's annual cost data. Therefore, a sensitivity analysis is required to determine whether the selected combination remains economically viable when the original assumptions change. Until the annual cost data become available, the reported savings should be treated as model-based estimates rather than actual project savings.

Differences in Previous Findings on Vegetation Maintenance and Biodiversity

An important consideration in plant selection is the relationship between maintenance costs and ecological benefits. Plants that require frequent pruning, watering, or replacement may increase long-term operating costs. However, reducing maintenance activities does not always yield the same ecological outcomes across different locations. Therefore, maintenance efficiency should be evaluated in conjunction with plant growth requirements and local environmental conditions.

Hu and Lima (2024) [30], in a review of 92 studies, found that high mowing intensity was generally associated with lower plant diversity in urban green spaces. Similarly, Horstmann et al. (2024) [32] found that roadside areas mowed in late summer had higher flower density, which was associated with greater wild bee abundance and species richness. These findings underscore the importance of incorporating maintenance practices into landscape planning. Under suitable conditions, less frequent mowing may reduce maintenance costs while supporting insects that depend on roadside vegetation.

In contrast, Bakker et al. (2026) [31] conducted a three-year field study on ten roadside grasslands in the Netherlands and found that mowing twice a year, at the appropriate times, resulted in higher plant diversity in highly productive grasslands. In less productive grasslands, changes in mowing frequency did not yield clear biodiversity benefits. These findings differ from the general pattern reported by Hu and Lima (2024) [30]. This discrepancy suggests that maintenance frequency should be tailored to local site conditions rather than determined by a single general rule. Plant species, growth rates, climate, and soil conditions can influence the most suitable maintenance schedule.

These findings have practical implications for the Dumai–Rantauprapat Toll Road Project. The proposed replacement of Dew Grass, White Tabebuya, Red Shoots, and Bougainvillea should not be evaluated solely based on estimated maintenance savings. The assessment should also consider watering requirements, pruning frequency, plant survival rates, replacement needs, and potential impacts on drainage and driver visibility. Horstmann et al. (2024) [32] also reported that high traffic intensity could reduce the abundance and diversity of bees and butterflies along roadsides. This finding indicates that the ecological benefits of roadside vegetation may depend on traffic and environmental conditions. Therefore, the lowest-cost maintenance strategy may not yield the best ecological outcomes in every location.

RESEARCH CONTRIBUTIONS, PRACTICAL IMPLICATIONS, AND LIMITATIONS

The findings demonstrate that Value Engineering can support more systematic cost evaluation and landscape design decisions in toll road projects. Key results include the high cost concentration of Dew Grass (63.38%), the dominant AHP weight assigned to ecological function (29.46%), and the estimated life-cycle cost savings of IDR 2.79 billion (4.68%). Compared to previous studies, the main contribution of this research is the integration of cost prioritization, the weighting of ecological and visual criteria, and life-cycle cost comparisons within a single toll road landscape planning case. This approach complements earlier studies that primarily examined plant engineering characteristics, visual quality, or green infrastructure costs separately [21], [22], [28].

In practical terms, the results can help project owners, planners, and toll road operators identify landscape components that require priority evaluation. High-cost items can be reviewed through functional assessment, comparison of plant specifications, and long-term maintenance planning. Alternatives with lower estimated costs can be considered when they meet ecological, visual, technical, and safety requirements. This approach is consistent with Jalilzadehazhari (2026) [29], who emphasized the importance of long-term economic evaluation and performance monitoring in the management of nature-based infrastructure.

This study has several limitations. First, it focuses on a single toll road section, so the results may differ in other locations with different soil conditions, rainfall, plant prices, and maintenance requirements. Second, the AHP assessment involved three experts, but the individual comparison matrices and performance scores for all plant-alternatives have not been fully presented. Third, the LCCA results are based on assumptions covering a 40-year period, while detailed annual cost data are not yet available to conduct a complete sensitivity analysis. Fourth, the

ecological and visual performance of the proposed replacement plants has not been verified through field measurements.

CONCLUSION

This study shows that the application of the Value Engineering (VE) method can help identify cost priorities and estimate savings in the landscape planning for Package 1 of the Dumai–Rantauprapat Toll Road. Based on the first objective, a Pareto analysis of 15 plant species with a total budget of Rp8,261,901,154 showed that Rumput Embun accounted for the largest share of costs at 63.38%, while the three main aesthetic plants accounted for 87.60% of the aesthetic group's costs. Based on the second objective, the Analytic Hierarchy Process (AHP) weighting showed that the ecological function had the highest level of importance at 29.46%, followed by the visual function at 20.26%; thus, these two functions are key considerations in plant selection. Based on the third objective, a 40-year Life Cycle Cost Analysis (LCCA) with a discount rate of 8% shows that the combination of Bahia Grass, Yellow Fire, Akalipa, and Alamanda has an estimated cost of Rp56,816,365,772, which is lower than the initial design cost of Rp59,608,395,120, with a potential savings of Rp2,792,029,348 or 4.68%. These findings indicate that integrating cost analysis, ecological functions, and visual functions can help planners prioritize tasks and select more economical landscape alternatives. However, these savings are still based on model calculations, while the ecological and visual capabilities of the replacement plants have not yet been proven through field testing. Therefore, this study provides a basis for toll road managers to evaluate budgets and plant alternatives in a more measured manner, while still requiring technical testing, plant growth monitoring, and maintenance cost assessments before the design is implemented.

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CONFLICT OF INTEREST

The authors declare that they have no financial, personal, or professional conflicts of interest that could have influenced the research findings or conclusions.

DATA AVAILABILITY STATEMENT

The data used in this study include the project Cost Budget Plan (RAB), expert assessments, and Life Cycle Cost Analysis (LCCA) calculations. The main findings are presented in the article. The original project documents are subject to data ownership and access restrictions. Access to supporting data requires permission from the relevant data owner.

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DECLARATION OF AI TOOL USAGE

No AI tools were used for field data collection.

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