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Ecological Pressure and Biodiversity Conservation in Protected Areas: MDS Approach on Road Development in TN Babul, Indonesia

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ABSTRACT

Infrastructure development within protected areas has become a critical concern in biodiversity conservation, particularly in ecologically sensitive regions like Bantimurung Bulusaraung National Park (TN Babul), Indonesia. This study aims to evaluate the ecological, social, economic, institutional, and infrastructural sustainability of the Maros–Watampone road corridor that crosses TN Babul. Using a qualitative descriptive design, the research employed the Multidimensional Scaling (MDS) method supported by leverage and Monte Carlo analysis. Data were gathered from key stakeholders through purposive sampling and analyzed based on sustainability attributes across five dimensions. The findings reveal that environmental, institutional, and infrastructure dimensions scored in the "less sustainable" category, indicating high ecological risk and governance gaps. In contrast, economic and social dimensions were moderately sustainable, reflecting emerging opportunities for inclusive growth. Sensitive attributes influencing sustainability include habitat fragmentation, road design, governance coordination, and community participation. The study concludes that balancing development with conservation requires integrated, multi-stakeholder strategies and targeted interventions that address the most vulnerable sustainability dimensions.

Keywords: Protected Area; Sustainable Development; Ecological Impact; Road Infrastructure; Multidimensional Scaling (MDS); TN Babul; Stakeholder Analysis; Conservation Strategy

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1. Introduction

Biodiversity conservation and ecosystem integrity are fundamental pillars for maintaining environmental sustainability [1,2]. Healthy ecosystems are essential for addressing climate crises, ensuring ecological stability, and sustaining vital ecosystem services [3]. Protected areas such as national parks serve as the last refuge for rare species and support activities such as research, education, and ecotourism [4,5]. As one of the world's mega biodiversity countries, Indonesia bears a significant responsibility to protect its biological wealth through the establishment of conservation areas. One of the critical sites is the Bantimurung Bulusaraung National Park (TN Babul) in South Sulawesi.

TN Babul is renowned for its unique tropical karst ecosystems and high levels of biodiversity. This area is a natural habitat for numerous endemic species, including distinctive butterflies and rare primates such as Tarsius fuscus. Beyond its ecological value, the park also holds considerable cultural and geological significance. Its uniqueness has attracted the attention of researchers, tourists, and policymakers from various backgrounds. However, the area is currently under significant pressure due to national infrastructure development [6,7]. One project with the potential to disrupt TN Babul's ecosystem is the upgrading of the Maros–Watampone National Road. This approximately 11-km stretch of road, which passes through the conservation area, is a vital segment of the Trans-Sulawesi route. Although the road has existed for decades, it now faces issues such as damage, misalignment, and increased risk of traffic accidents. The government plans to widen and improve this road to enhance regional connectivity and economic growth. However, this infrastructure upgrade also poses ecological impacts that require thorough assessment.

Road development within conservation areas can lead to habitat fragmentation, disrupt wildlife movement, and increase human activity. Global studies have shown that roads are often a primary driver of environmental degradation in protected areas [8,9]. In ecologically sensitive tropical areas like TN Babul, the risks are even higher due to their ecological vulnerability. Roads may also provide access to previously remote areas, encouraging illegal activities such as encroachment and poaching. Therefore, infrastructure projects in such areas demand comprehensive scientific evaluation. Unfortunately, most road impact studies in Indonesia remain descriptive and lack quantitative approaches based on ecological and spatial data. Environmental Impact Assessments (EIAs or AMDAL in Indonesian) often fail to fully capture the complexity of interactions between development and conservation. Analytical methods that integrate multiple dimensions of ecological pressure and stakeholder perceptions are urgently needed [10,11]. One relevant method is Multidimensional Scaling (MDS), which allows for the identification of key pressures and prioritized mitigation strategies. MDS also provides visual representations of the relative positions of various factors in multidimensional space.

The application of MDS in this context offers advantages, as it can combine quantitative and qualitative data from multiple sources. This method enables mapping of stakeholder perceptions regarding impact severity, importance, and feasibility of management strategies. By involving various actors such as park authorities, local communities, academics, and policymakers, the analysis becomes more inclusive and representative. The results of MDS can be used to formulate more contextual and implementable mitigation strategies [12,13]. This approach is essential for addressing the complex conflict between development and conservation.

The primary issue in the road upgrading project in TN Babul is the imbalance between economic development interests and environmental conservation. Direct impacts such as deforestation and soil erosion are often followed by indirect consequences such as encroachment, poaching, and habitat degradation. In the long term, these conditions may threaten species survival and disrupt the park's ecological functions. Therefore, infrastructure development must consider existing ecological values. MDS-based research enables the identification of management scenarios that best align with sustainability. In the context of TN Babul, several alternatives have been proposed, such as elevated roads, dedicated lanes, and buffer zones. However, the feasibility and effectiveness of these strategies have not been scientifically evaluated based on local conditions. Using the MDS approach, it is possible to assess which strategies are most effective and acceptable to stakeholders. Moreover, this analysis can identify the most urgent pressures to address. The results are expected to provide an empirical foundation for more environmentally conscious planning. This study aims to prioritize and formulate conservation-based mitigation strategies. The primary focus of the study is the Maros–Watampone road segment that traverses the national park. Through this approach, the research seeks to generate solutions that balance development and conservation needs. The use of MDS is expected to simplify the complexity of the issue into easily interpretable visual forms. This is crucial for supporting data-driven decision-making.

2. Literature Review

2.1. Global Perspectives on Road Development and Conservation Trade-Offs and Basic Concept of Sustainable Development

Road development within conservation areas has posed sustainability challenges worldwide. For instance, the Pan Borneo Highway in Malaysia has been criticized for bisecting critical orangutan habitats [14]. Similarly, road expansion in the Amazon basin has accelerated deforestation and illegal logging, threatening vast tracts of tropical rainforest [15]. In Africa, studies on road intrusion into protected savannahs reveal increased human–wildlife conflict and biodiversity loss, particularly among large mammals [16]. These examples underscore the global urgency of adopting integrated conservation infrastructure planning. Such comparisons highlight the importance of incorporating ecological design principles—such as wildlife corridors, green road infrastructure, and zoning restrictions—into road development. Moreover, robust environmental governance and inter-agency coordination are critical to ensuring that infrastructure projects near biodiversity hotspots do not undermine conservation goals.

Sustainable development, as defined by the World Commission on Environment and Development [17], is a normative approach that emphasizes a balance among three main pillars: economic, social, and environmental (**Figure 1**). This approach aims to ensure the well-being of both current and future generations. Criticism of conventional development models—which are often exploitative and non-inclusive—has led to the emergence of this idea as a fairer and more sustainable alternative. In line with this thinking, Solihuddin et al. [18], argues that sustainable development is a synthesis of environmentally friendly economic growth, social justice, and adaptive and collaborative governance. Consequently, these dimensions serve as the foundation for measuring development success at both local and global levels and have evolved into various international initiatives such as Agenda 21, the Millennium Development Goals (MDGs), and more recently, the Sustainable Development Goals (SDGs).

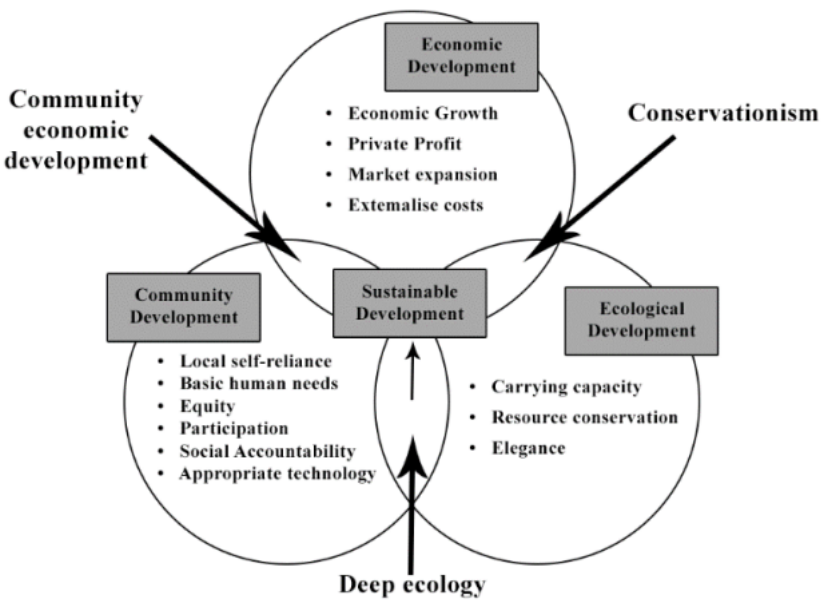

Figure 1. Grand Theory: Sustainable Development Theory [19].

2.2. Ecological Pillar of Sustainable Development

The ecological dimension of sustainable development emphasizes the importance of preserving ecosystem functions in the long term. From this perspective, the environment is not merely viewed as a resource to be exploited but also as a life-supporting system with both intrinsic and economic value. According to Cerveny [20] and Tabata [21], introduced the concept of environmental carrying capacity as one of the indicators of ecological sustainability, which can be assessed through water and air quality, as well as biodiversity. According to Auad and Fath [22], further asserted that ecological sustainability must ensure that development does not cause structural damage to existing ecosystems. Therefore, infrastructure projects in conservation areas must consider their impacts on the preservation of natural habitats and the ecosystem's resilience.

2.3. Social Pillar: Justice, Participation, and Empowerment

The social dimension of sustainable development focuses on social inclusion, active community participation, and the equitable distribution of development benefits. According to Cerveny [20], posits that sustainable development should not only aim to increase income but also to expand individual capabilities. In this regard, local community involvement in the planning, implementation, and evaluation of policies is crucial, particularly in areas vulnerable to ecosystem changes [21]. Such active participation can strengthen a sense of ownership over policies and foster successful project implementation. In conservation areas, social sustainability must take into account community perceptions, local needs, and potential social conflicts that may arise from unequal benefit distribution.

2.4. Economic Pillar: Efficient Growth and Environmental Valuation

Within the sustainable development framework, the economic dimension does not only emphasize short-term growth but also focuses on the efficient use of resources and the internalization of environmental costs in decision-making processes. According to Tabata [21] state that valuing ecosystem services is a vital tool for measuring the losses caused by environmental degradation. Techniques such as Willingness to Pay (WTP), Contingent Valuation, and Cost of Illness (COI) allow the conversion of ecological values into monetary units that can be utilized in economic analysis. Thus, development decisions can be made more rationally, data-driven, and fairly, while also being more responsive to the negative externalities resulting from environmentally unfriendly projects.

2.5. Institutional Pillar: Governance and Policy

The success of sustainable development heavily depends on adaptive and participatory institutional structures. Rizal et al. [1] and Chaluluddin et al. [23], emphasized that effective management of common-pool resources requires transparent institutional systems capable of responding to social and ecological dynamics. In conservation areas, multi-actor management—encompassing government, communities, academia, and the private sector—is key to ensuring long-term sustainability [24]. Institutional capacity deficiencies can hinder the effective implementation of policies and increase the likelihood of conflict among stakeholders with competing interests. Therefore, institutional analysis must be an integral part of sustainability assessments, especially for projects involving multiple stakeholders.

2.6. Infrastructure Pillar: Accessibility and Ecological Risk

Infrastructure development has a significant impact on both the environment and social welfare. Gugule dan Mesra [25], identified that road construction can trigger habitat fragmentation, land-use change, and increased access to previously protected areas. Therefore, infrastructure within the context of sustainable development must be designed with attention to ecological impact mitigation principles, such as green infrastructure and mitigation-based design [26]. In conservation areas, infrastructure—particularly roads—must consider wildlife corridors, habitat quality, and indirect effects such as encroachment or pollution. Synergy between social, ecological, and institutional dimensions is essential to ensure that infrastructure development does not harm existing ecosystems.

2.7. MDS Integration in Sustainability Analysis

To comprehensively analyze sustainability, quantitative approaches such as Multidimensional Scaling (MDS) can be employed to illustrate relationships among pressure dimensions and strategies within a multidimensional space. Pitcher and Preikshot [12], demonstrated that MDS can simplify data complexity by visualizing relationships among variables, thus facilitating the understanding of interactions between sustainability dimensions. This approach has been applied in sustainability studies of coastal areas, conservation zones, and rural development. The advantage of MDS lies in its ability to integrate both qualitative and quantitative data while incorporating stakeholder perceptions—an aspect that is highly relevant for projects involving multiple actors with divergent interests, such as road construction in Babul National Park.

3. Research Method

3.1. Research Location

This research was conducted in the Bantimurung Bulusaraung National Park Area, located in Maros Regency, South Sulawesi Province (**Figure 2**). The focus of the location is an approximately 11 km stretch of national road that passes through the national park area, which serves as a major transportation corridor and also has high interaction between human activities and the park's ecosystem [27]. The research was carried out between June 2024 and February 2025, with field data collection conducted gradually according to the availability of informants, weather conditions, and conservation area entry permits.

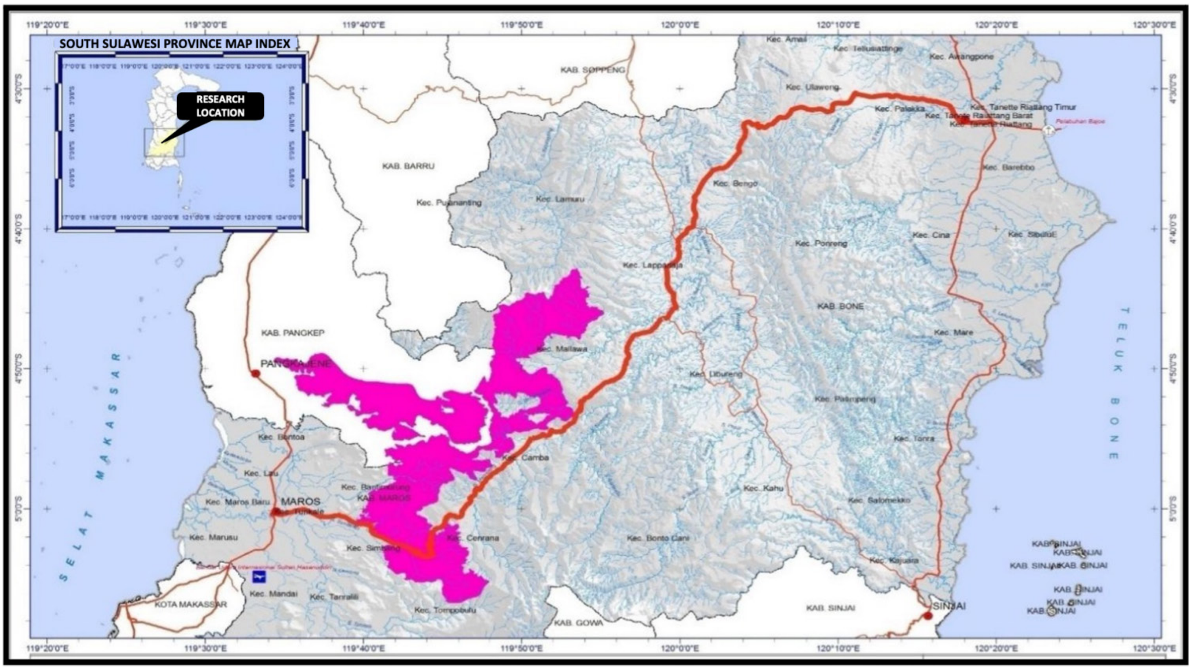

Figure 2. Research Location.

3.2. Research Design

Research design in this study is descriptive quantitative research using the Multidimensional Scaling (MDS) approach to evaluate the sustainability of the management of the national road area that passes through Bantimurung Bulusaraung National Park (**Figure 3**). The study identifies stakeholders' perceptions and assessments of sustainability from various established dimensions. Primary data were collected through the distribution of questionnaires and interviews with key informants selected through purposive sampling, including individuals who have strategic roles or knowledge in the management of the area, such as park managers, local government officials, community leaders, and NGOs. Secondary data were obtained from planning documents, policies, and relevant previous studies.

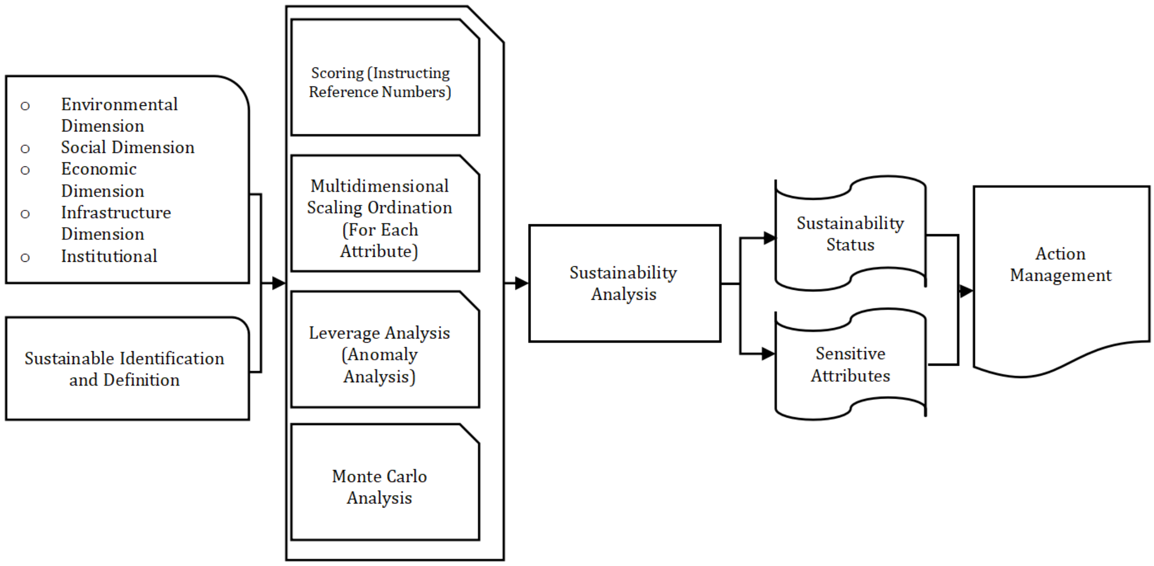

Figure 3. Research Design.

3.3. Research Dimensions and Attribute

The data in the sustainability analysis of community-based ecotourism management comes from the environmental, social, economic, infrastructure, and institutional dimensions (**Table 1**).

Table 1. The Operational Definitions of Each Attribute.

Dimension	Attribute	Source
Environment	Number of species of flora and fauna after development	Cerveny [20], Tabataba [21], Auad and Fath [22]
	Area of remaining natural vegetation cover	
	Habitat fragmentation level	
	Presence of endemic or protected species	
	Water and soil quality (chemical and biological indicators)	
Social	Changes in community access to the park area	Cerveny [20], Tabataba [21]
	Community participation in biodiversity conservation	
	Human-wildlife conflict due to development	
	Community perception of the road development impact	
	Changes in conservation knowledge/education in the community	
Economy	Community income from ecotourism activities post-development	Solihuddin [18], Auad and Fath [22]
	Potential economic value of impacted species	
	Environmental rehabilitation costs due to road development	
	Economic loss due to disruption of ecosystem services	
	Changes in local livelihoods	
Institutional	Effectiveness of development monitoring on ecological impacts	Rizal et al. [1], Chaliluddin [23], Purwanti et al. [24]
	Coordination between agencies in mitigating road impacts	
	Availability of wildlife corridor policies	
	Community involvement in road development planning	
	Availability of biodiversity monitoring systems based on data	
Infrastructure	Distance and distribution of roads relative to sensitive habitats	Gugule and Mesra [25], Efani et al. [26]
	Availability of wildlife corridors or crossing paths	
	Environmentally friendly road design (green road infrastructure)	
	Drainage systems that do not pollute the surrounding environment	
	Distance of roads from core conservation areas	
	Noise and vibration levels due to vehicles	

3.4. Research Analysis

To determine the current condition and sustainability level of the conservation area, as well as to formulate future scenarios, a sustainability analysis is conducted using the rapid appraisal method with the Rap-Mad analysis. The sustainability analysis utilizes Multidimensional Scaling (MDS), leverage analysis, Monte Carlo analysis, and the determination of stress values and coefficient of determination (R^2).

This study specifically employed the Multidimensional Scaling (MDS) approach due to its strength in capturing stakeholder perceptions and evaluating complex, multidimensional sustainability attributes. Unlike Geographic Information System (GIS)-based models, which offer spatially explicit analyses such as habitat suitability or corridor mapping, MDS focuses on relational patterns among variables and perceptions without relying on spatial data. The choice to exclude GIS was deliberate, as the primary aim was to assess ecological pressure and sustainability status through stakeholder-based prioritization rather than spatial modeling. While GIS-based approaches can complement spatial planning and infrastructure alignment, MDS offers a more participatory and perception-driven method suitable for rapid appraisal of ecological trade-offs in data-limited environments. Nonetheless, future research could integrate MDS with GIS to enhance both perceptual and spatial dimensions of analysis, particularly for mapping fragmentation risks and visualizing policy scenarios.

The selection of MDS in the Rapfish analysis is based on the fact that it yields more stable results compared to other multivariate analysis methods, such as factor analysis and Multi-Attribute Utility Theory (MAUT) [12]. The Rapfish ordination analysis using the MDS method in this study follows several stages (**Figure 4**), namely:

a) The stage of determining diving tourism management attributes, which includes five dimensions: environmental, social, economic, infrastructure, and institutional dimensions.
b) The stage of scoring each attribute on an ordinal scale based on the sustainability criteria of each dimension. Attribute scoring is carried out through a review of previous research findings and interviews with key informants.
c) The stage of conducting Rapfish ordination analysis using the MDS method with the Rap-Mad Excel software to determine the ordination and stress values using the ALSCAL algorithm.
d) The formulation of the sustainability index and current ecotourism sustainability status based on eight dimensions (environmental, social, economic, infrastructure, institutional, conservation, technological, and regulatory dimensions) which serve as sustainability indicators.

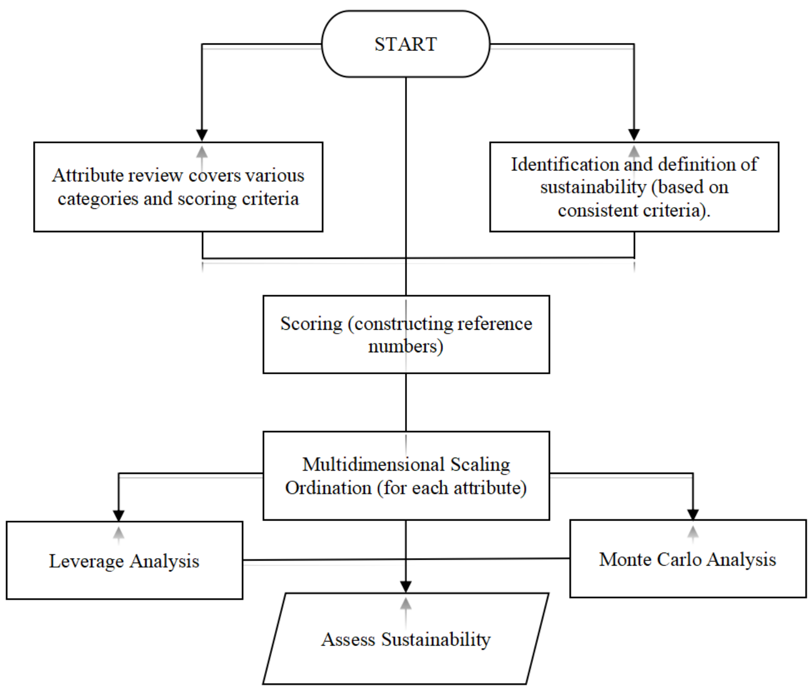

Figure 4. Data Analysis.

Figure 5 presents the fundamental formula of the Multidimensional Scaling (MDS) approach, which is used to map objects into a multidimensional space based on their levels of similarity or dissimilarity. Leverage analysis is conducted to identify the most sensitive attributes. The results of the leverage analysis are expressed as a percentage (%) change in the Root Mean Square (RMS) of each attribute when omitted from the ordination. Attributes with higher percentages are the most sensitive and have the greatest influence on sustainability. The greater the RMS change, the more sensitive the attribute is in contributing to the improvement of the sustainability status. Furthermore, the sustainability index value of each dimension can be visualized using a kite diagram. The score values represent the sustainability index of each dimension (**Table 2**).

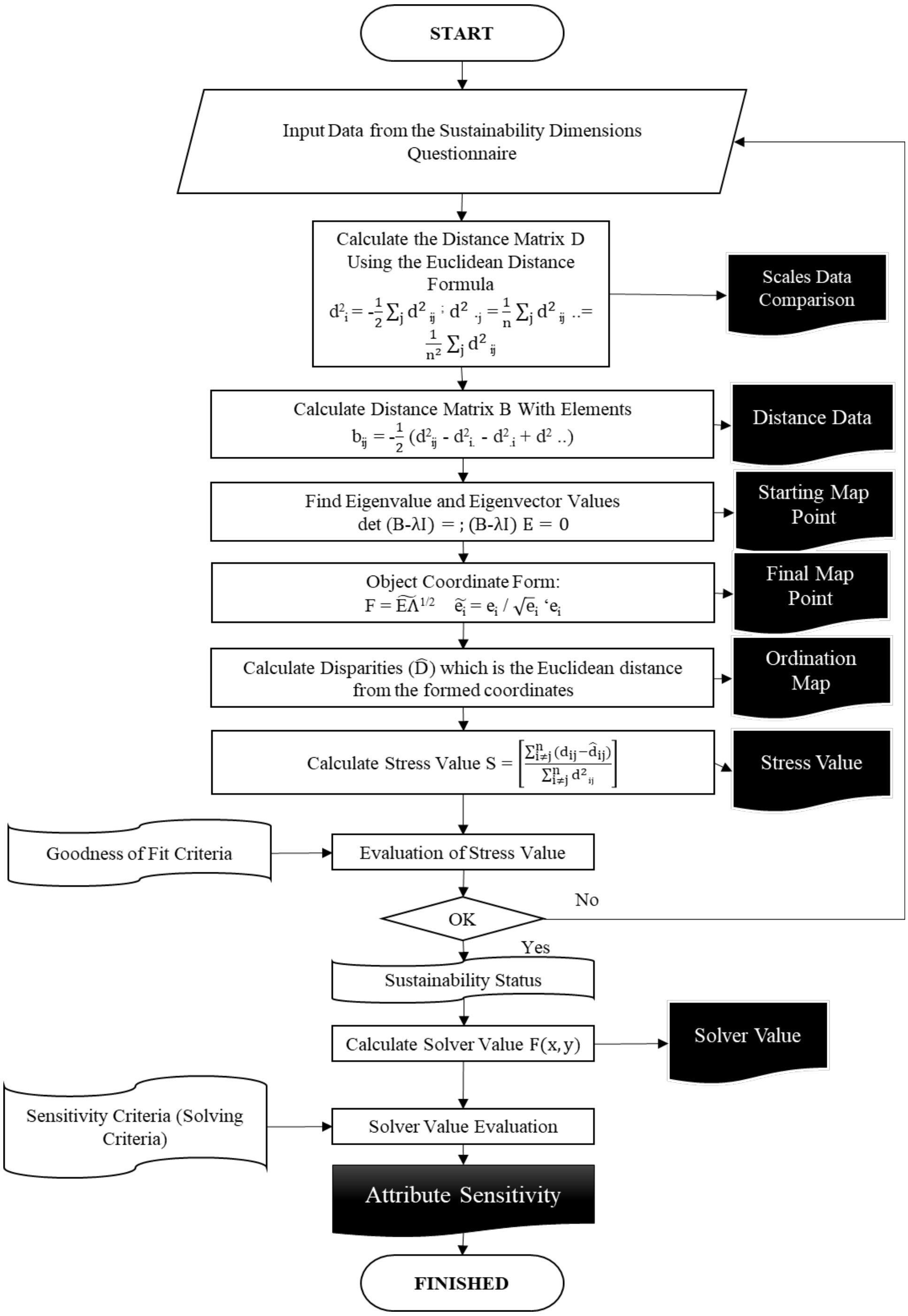

Figure 5. Formula of MDS.

Table 2. Sustainability Status Index [12].

Sustainability Index	Status	Description
0–25	Poor	Not Sustainable
26–50	Low	Less Sustainable
51–75	Fair	Moderately Sustainable
76–100	Good	Highly Sustainable

4. Result and Discussion

4.1. Validation Test (R-Square and Stress Value)

Stress values and the coefficient of determination (R^2) serve as measurement scales for data validity, indicating whether additional modifications are necessary to ensure that the variables used accurately represent the properties of the compared objects. A coefficient of determination approaching 1 (100%) signifies that the analyzed attributes can reliably represent the objects under comparison. Conversely, a low stress value indicates that the proposed model closely fits the observational data, confirming its validity [28]. In this study, each sustainability dimension exhibited an R^2 value near 1 (100%) and a stress value below 0.25 [29]. These results demonstrate a high degree of concordance between the MDS model and the observed data (**Table 3**).

Table 3. Sustainability Status Index.

Sustainablity Dimensions	Parameter	
	R^2 (%)	Stress Value
Environment	93.01	0.17
Social	92.78	0.15
Economic	93.21	0.16
Institutional	92.05	0.16
Infrastructure	92.90	0.17

4.2. Monte Carlo Test

The Monte Carlo test is an innovative approach in the world of statistics that utilizes simulation by using random numbers to understand and test mathematical models or complex situations. Monte Carlo simulations are used in sustainability analysis to test the stability and resilience of model results to variations or uncertainties in data inputs. The following are the results of the monte carlo test (**Figure 6**).

Monte Carlo analysis aims to evaluate the influence of error on the estimation process of sustainability ordination values [30]. In the context of sustainability analyses—such as Multidimensional Scaling (MDS) or other methods used to understand data relationships—Monte Carlo analysis can help estimate the extent to which errors in the measurement or estimation processes may affect the final results.

The values shown in **Table 4** indicate Rapfish scores and Monte Carlo simulation results of less than 5%. This is generally interpreted as a strong outcome, suggesting that the system or model analyzed exhibits a high level of sustainability or efficiency. Additionally, the Monte Carlo simulations reveal no significant differences, meaning the results can be considered consistent and reliable within the context of this study. Furthermore, the discrepancy between the ordination analysis and the Monte Carlo simulation across all five dimensions is under 5%. This demonstrates that the ordination technique used effectively manages random errors and thus reinforces the robustness and interpretability of the analysis.

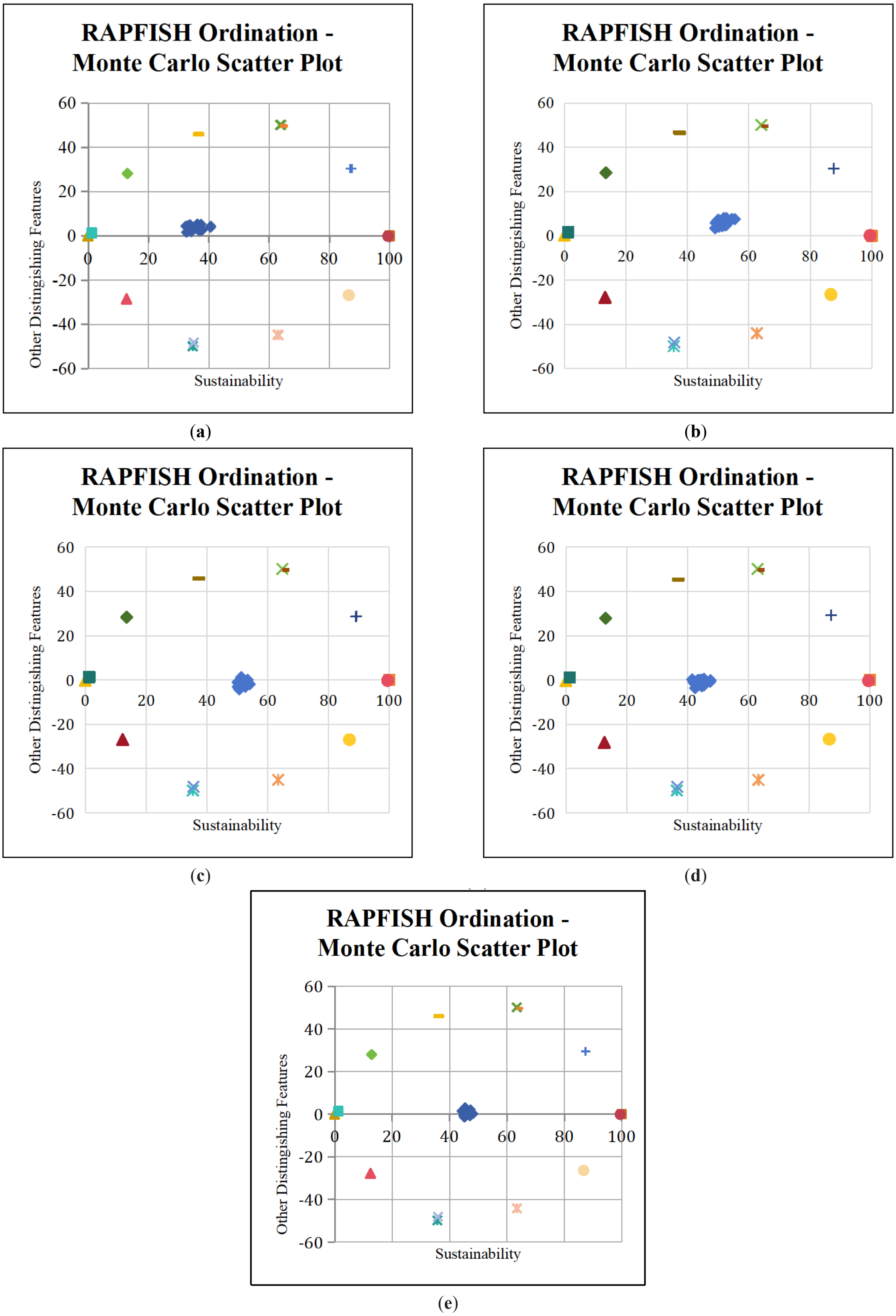

Figure 6. Monte Carlo Ordinations. (**a**) Environment; (**b**) Social; (**c**) Economy; (**d**) Institutional; (**e**) Infrastructure.

Table 4. Monte Carlo Test.

Sustainability Dimensions	Sustainability Index		Difference (%)	Status
	Score Rapfish	Monte Carlo		
Environment	36.42	36.36	0.06	Less Sustainable
Social	52.14	51.52	0.62	Moderately Sustainable
Economic	52.21	51.66	0.55	Moderately Sustainable
Institutional	44.24	44.12	0.12	Less Sustainable
Infrastructure	46.49	46.13	1.69	Less Sustainable
Average		46.30		Moderately Sustainable

4.3. Flagship Species under Threat: *Macaca maura* and the Impact of Road Development in TN Babul

Bantimurung Bulusaraung National Park (TN Babul) is a critical biodiversity hotspot in Sulawesi, Indonesia, characterized by tropical karst ecosystems and a rich array of endemic species. Among its most ecologically and conservation-significant fauna is the Sulawesi Black Macaque (*Macaca maura*), a flagship primate species that plays a vital role in forest regeneration through seed dispersal and ecological interaction. This study places particular focus on *Macaca maura*, as it represents one of the most directly affected species by the Maros–Watampone road development that cuts across the park's conservation zone. *Macaca maura* is highly sensitive to habitat fragmentation, edge effects, and increased human activity—factors that are intensified by road construction and expansion. The widening of the national road has not only reduced contiguous forest habitat but also severed traditional movement corridors critical for foraging, social cohesion, and reproduction. Increased noise, vehicle traffic, and encroachment have forced *Macaca maura* troops to migrate toward the park's periphery, often resulting in conflict with nearby human settlements. Such interactions elevate the risks of crop raiding, poaching, and capture for illegal trade, threatening both the population viability and the species' ecological role.

Beyond *Macaca maura*, TN Babul is home to several other protected and endemic species—including *Rhyticeros cassidix* (the Sulawesi hornbill), *Tarsius fuscus*, and over 140 species of butterflies—yet *M. maura* remains the most visibly impacted due to its wide-ranging behavior and terrestrial tendencies. Road-induced habitat fragmentation reduces genetic flow between subpopulations, leading to increased inbreeding and greater vulnerability to disease and environmental change. Without intervention, the long-term survival of this species is at serious risk. In response to these threats, urgent conservation measures are required. These include the construction of wildlife overpasses or arboreal bridges, reforestation of buffer zones, and ecological zoning regulations to minimize further disturbance. Community-based conservation initiatives—such as participatory monitoring and local stewardship programs—should also be expanded to promote coexistence and reduce human–wildlife conflict. Regular population monitoring using camera traps, acoustic sensors, and GIS-based tracking will be essential for detecting early signs of population decline and informing adaptive management strategies.

Positioning *Macaca maura* as an ecological indicator species allows for a deeper understanding of the broader impacts of infrastructure development on TN Babul's biodiversity. Protecting this primate is not only a moral imperative but also a practical pathway to sustaining the park's ecological integrity. Therefore, aligning conservation actions with the spatial needs and behavioral ecology of *Macaca maura* should be a central strategy in reconciling development with long-term ecosystem sustainability.

4.4. Sustainability Status

Overall, the sustainability index analysis reveals uneven performance across dimensions, reflecting the varied challenges in achieving holistic sustainable development (**Figure 7**). The Environmental dimension emerges as the weakest, with the lowest score and a status of "Less Sustainable". The infrastructure dimension also falls below the "Moderately Sustainable" threshold, indicating it does not yet support sustainability principles. Meanwhile, the Institutional dimension highlights weak governance coordination, suboptimal community involvement, and inadequate monitoring systems. In contrast, the Economic dimension fares relatively better, achieving a status of "Moderately Sustainable," although challenges remain in internalizing environmental costs within economic activities. Finally, the social dimension also registers as "Moderately Sustainable", demonstrating relatively positive outcomes in community participation and increased conservation awareness. Collectively, these results suggest that sustainability efforts have established an initial foundation—particularly in social and economic aspects—but that environmental, infrastructure, and institutional dimensions still demand serious attention and priority interventions. An integrated, cross-dimensional approach is essential to advance development towards an adaptive, resilient, and truly sustainable social-ecological system.

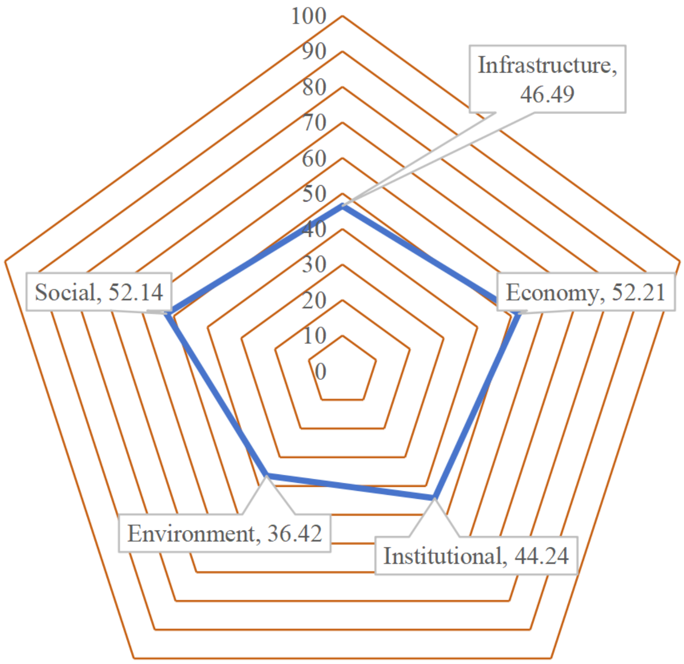

Figure 7. Kite Diagram: Sustainability Ordinations.

Environmental Dimension

The Environmental dimension stands out as the most vulnerable within the sustainability framework, with a Rapfish score of 36.42—well below the "Moderately Sustainable" threshold. This result reflects systemic failures to maintain and restore ecosystem functions after interventions, underscoring an urgent need for remedial action. The low overall score indicates that anthropogenic pressures and inadequate restoration capacity have eroded ecological resilience in Bantimurung Bulusaraung National Park. Declines in post-development flora and fauna populations serve as primary indicators of restoration failure: many native species have not returned to baseline levels, and some key species are showing alarming downward trends [31]. This loss of biodiversity not only diminishes intrinsic value but also weakens ecosystem services—such as pollination, natural pest control, and nutrient cycling—reducing overall ecosystem productivity. The crisis in natural vegetation cover exacerbates these problems, as both primary and secondary forests have suffered significant degradation. Shrinking green cover accelerates soil erosion, increases sedimentation in waterways, and diminishes the land's capacity to sequester carbon [32,33]. These impacts extend beyond the local scale, contributing to global climate vulnerability by releasing stored organic carbon from soils and vegetation. Habitat fragmentation further breaks continuous ecosystems into isolated patches, hindering wildlife migration, foraging, and breeding. High fragmentation creates "island effects", intensifying inbreeding and reducing genetic diversity, which makes populations more susceptible to disease and environmental change. Weak ecosystem connectivity risks the collapse of interdependent ecological networks [34]. Declining populations of endemic and protected species highlight weaknesses in policy enforcement: although regulations exist, field surveillance is often sporadic and habitat protection is underfunded. Consequently, some species found only within the study area face extensive threats and even local extinction. Water and soil quality issues add complexity: road construction has likely contaminated water sources, affecting communities that depend on them for daily needs, increasing disease risk, and undermining local food security.

Social Dimension

With a Rapfish score of 52.14, the social dimension also falls into "Moderately Sustainable". Although community participation and conservation awareness provide a relatively strong foundation, gaps remain that must be filled to ensure equitable benefits. Community engagement in conservation planning—evidenced by high attendance at village meetings and tree-planting events—often stalls afterward due to a lack of follow-through and clear incentives. Without feedback mechanisms or recognition for conservation champions, initial enthusiasm wanes before long-term goals are achieved. Human–wildlife conflicts persist: despite a quantitative decline in wildlife incursions, fear and resistance to habitat restoration endure. The absence of integrated risk mitigation systems leads some residents to take damaging preventive measures, such as setting traps or encroaching directly on wildlife habitats. Perceptions of road impacts vary: some welcome new economic opportunities, while others remain unaware of long-term ecological risks, such as noise, dust, and loss of green spaces [17,18]. This information gap calls for more inclusive communication strategies that address health and cultural values. Conservation education shows promise—training modules and field visits have improved basic understanding of ecosystem cycles and biodiversity's importance—but integration into local curricula and ongoing evaluation remain limited.

Economic Dimension

Scoring 52.21—within the "Moderately Sustainable" range but still far from the optimal target (>75)—the Economic dimension reflects both local strengths and structural weaknesses. The economic value of impacted species remains under-realized, as habitat disruption from road upgrades has reduced wildlife populations and diminished the park's appeal. Significant environmental rehabilitation costs—reforesting, wetland restoration, and wildlife corridor reconstruction—place a heavy financial burden on the local government's limited budget, diverting funds from other social welfare programs. Ecosystem service losses (carbon sequestration, clean water provision, microclimate regulation) are not adequately internalized in economic models, since their nonmarket values are often overlooked [18,22]. As a result, infrastructure decisions and land-use changes rarely account for these externalities, perpetuating ecosystem degradation without fair compensation to affected communities. On a positive note, road improvements have increased visitor access, boosting local ecotourism income and diversifying livelihoods.

Institutional Dimension

Currently rated "Less Sustainable" (score 44.24), the Institutional dimension is hampered by weak ecological oversight, overlapping authorities, inconsistent wildlife corridor policies, limited community involvement, and reliance on manual reporting rather than real-time data systems. To improve sustainability scoring, standardized SOPs should unify operational procedures across agencies to ensure regular, measurable, and non-duplicative field patrols. A collaborative digital platform (web/mobile) would enable "one-stop" data coordination and rapid response to environmental incidents. Co-management arrangements—granting local communities shared authority in monitoring and resource management—can enhance ownership and regulatory compliance [1,23,24]. Although corridor policies exist on paper, local implementation is sporadic: protection zones often lack clearly marked boundaries, allowing infrastructure to traverse key corridors without adequate safeguards. Local bylaws must mandate wildlife crossing structures and impose strict penalties on violators. Current biodiversity monitoring relies on periodic, manual data collection, leading to delays and potential bias. An integrated online platform, coupled with technical training for field officers in digital tools, would facilitate continuous monitoring of biodiversity trends, environmental quality, and incident reporting.

Infrastructure Dimension

The Infrastructure dimension scores 46.49 "Less

Sustainable"—indicating that the physical and technical structures supporting conservation are inadequate to protect ecosystem functions and wildlife safety. Wildlife corridors and crossing structures are scarce; most roads are built without regard for animal migration routes, forcing wildlife to cross busy surfaces. Eco-friendly road design features—elevated overpasses, underpasses, permeable materials—are not widely adopted. Conventional asphalt and impervious construction disrupt local hydrology by preventing natural water infiltration. Drainage systems remain basic open channels that discharge runoff directly into nearby water bodies, failing to filter pollutants and degrading aquatic habitats [25,26]. Proximity of roads to core conservation zones undermines buffer functions: many paths skirt or penetrate protected boundaries, bringing noise, air pollution, and human disturbance into the park's most sensitive areas. Collectively, these deficiencies reduce the core area's capacity to serve as an effective ecological buffer.

4.5. Sensitivity of Sustainability Dimension Attributes

Leverage value is the degree of influence of an attribute on the overall sustainability index, an attribute that has a high leverage value means that it has a large impact in determining the level of sustainability on a dimension (environmental, economic, social, infrastructure, or institutional) [29]. Leverage values are obtained through sensitivity analysis conducted in the Rapfish method, where each attribute is tested to see the extent to which its changes can significantly affect the sustainability index. **Table 5** presents strategies for boosting each dimension's sustainability score by directly targeting its sensitive attributes:

Table 5. Sensitive Attributes.

No	Sustainability Dimensions	Sensitive Attributes
1	Environment	• Number of flora and fauna species after development (6.17) • Level of habitat fragmentation (2.40) • Presence of endemic or protected species (2.15) • Area of remaining natural vegetation cover (2.13)
2	Social	• Human–wildlife conflict resulting from development (10.13) • Community perception of road development impacts (7.69) • Community participation in biodiversity conservation (4.4) • Changes in conservation knowledge/education among the community (2.29)
2	Economic	• Environmental rehabilitation costs due to road development (4.85) • Economic losses from disrupted ecosystem services (2.89) • Changes in local community livelihoods (2.30) • ?Potential economic value of impacted species (1.90)
4	Institutional	• Availability of wildlife corridor policies (7.21) • Effectiveness of development monitoring on ecological impacts (4.64) • Community involvement in road development planning (4.46) • Availability of data-driven biodiversity monitoring systems (0.38)
5	Infrastructure	• Environmentally friendly road design (green road infrastructure) (3.85) • Drainage systems that do not pollute the surrounding environment (1.23) • Availability of wildlife corridors or crossing structures (1.03) • Distance of the road to core conservation areas (0.62)

The sensitive attributes in the environmental dimension are: number of flora and fauna species post-development; remaining natural vegetation cover; habitat fragmentation level; and presence of endemic species. To improve this dimension's sustainability score, a focused reforestation program should be implemented—planting native species in critically degraded areas to expand green cover, accumulate carbon stocks, and restore wildlife habitat. Next, habitat connectivity can be enhanced by constructing ecological corridors (e.g., wildlife overpasses and vegetated arboreal bridges) to reduce fragmentation, facilitate endemic species migration, and maintain gene flow among isolated populations. Protection of highly vulnerable species must be strengthened through more frequent, scheduled field patrols and rigorous enforcement of anti-poaching and illegal-trade laws; these measures will help restore population numbers and prevent local extinctions [35–37]. Finally, pollutant control is essential for water and soil quality: installing biofilters and bioswales in drainage channels will remove heavy metals, sediments, and excess nutrients before runoff enters aquatic ecosystems and agricultural soils, thus returning physicochemical parameters to safe thresholds and supporting natural regeneration. Zhang et al. [38], by combining these four targeted interventions, each sensitive attribute is specifically addressed, moving the Environmental dimension toward the "Sustainable" category.

Although scoring "Moderately Sustainable," the social dimension still has gaps to fill. Its sensitive attributes include community participation in biodiversity conservation; human–wildlife conflict; community perceptions of road impacts; and changes in conservation knowledge. Participation can be enhanced through a Conservation Champion scheme—formal recognition for individuals or groups that consistently contribute to preservation—motivating attendance at meetings, support for planting projects, and reporting of violations. To mitigate human–wildlife conflicts, installing living fences, deterrent systems (e.g., motion-activated lights and sound devices), and wildlife escape routes will reduce property damage and animal attacks, while compensation schemes build trust and cooperation among affected residents [39]. Because perceptions of road impacts often overlook long-term ecological risks, inclusive outreach—using local media, village theater, and digital platforms—should clearly communicate the consequences of dust, noise, and habitat loss, as well as the benefits of mitigation measures like wildlife underpasses. Finally, sustaining gains in conservation knowledge requires ongoing education: integrating conservation modules into primary and secondary school curricula, offering adult workshops (e.g., on building simple biofilters), and conducting regular ecological literacy assessments will ensure measurable improvements [40]. By combining recognition, technical mitigation, strategic communication, and systemic education, the social dimension can become a robust pillar of inclusive, long-term sustainability.

With a Rapfish score of 52.21 ("Moderately Sustainable"), the Economic dimension remains constrained by the imbalance between short-term gains and long-term environmental costs. Its four sensitive attributes are: potential economic value of impacted species; rehabilitation costs; economic losses from disrupted ecosystem services; and local livelihood changes. To raise its sustainability score, government-led green economic incentives (e.g., subsidies or tax breaks) should directly support conservation communities, alleviating rehabilitation costs so that ecosystem restoration becomes an economic opportunity rather than a burden [41]. Such schemes will foster green entrepreneurship, increasing local incomes and reducing pressure on natural resources. Diversifying livelihoods—through ecotourism training, sustainable agroforestry, and craft production—shifts dependence away from extractive practices, reduces ecosystem service losses, and engages communities in maintaining the environmental quality that underpins their products' appeal. Market-access partnerships can link small producers to national and global distribution networks under internationally recognized eco-certification standards, maximizing the economic value of impacted species, boosting profit margins, and reinvesting in conservation [42]. The synergy of certification, market access, and fiscal incentives can propel the local economy toward truly sustainable models.

Currently rated "Less Sustainable," the Institutional dimension is hampered by low ecological oversight effectiveness, overlapping mandates, inconsistent corridor policy implementation, limited community engagement, and reliance on manual reporting. To improve its score, standardize SOPs across all agencies so that field patrols are routine, measurable, and non-duplicative. Develop a collaborative web/mobile platform to provide a "one-stop" hub for data sharing and real-time response to environmental incidents. Implement co-management with local communities—granting them shared authority in designing and conducting monitoring—to increase ownership and regulatory compliance [23,43]. Although corridor policies exist, local enforcement is sporadic; county and municipal regulations must mandate wildlife crossings and impose firm penalties for non-compliance. Transitioning from manual logs to an integrated digital monitoring system, supported by field-officer training in data collection tools, will enable timely, unbiased tracking of biodiversity trends, environmental quality, and incident reports.

The infrastructure dimension remains "Less Sustainable," constrained by scarce wildlife crossings, conventional road designs that ignore ecology, pollutant-carrying drainage systems, and roads' proximity to core conservation zones. To increase its Rapfish score, implement Green Road Design: redesign road segments with dedicated wildlife underpasses and overpasses, controlled elevations, and permeable materials to facilitate fauna movement and preserve natural hydrological cycles. Complement this with buffer zones and vegetated swales along road shoulders—planting riparian vegetation and installing bioswales to trap sediments, heavy metals, and excess nutrients before runoff reaches water bodies [44,45]. Finally, spatially realign road networks to minimize direct impacts on core ecosystems and strengthen buffer functions. By integrating these three approaches, the infrastructure network can transform into a green corridor that supports ecosystem sustainability while ensuring wildlife safety and environmental quality.

5. Conclusions

This study's Multidimensional Scaling (MDS)–based sustainability assessment of the Maros–Watampone road corridor through Bantimurung Bulusaraung National Park reveals significant disparities among five key dimensions. Environmental, infrastructure, and institutional dimensions scored in the "Less Sustainable" category, underscoring critical deficits in ecosystem integrity, green infrastructure design, and governance capacity. In contrast, economic and social dimensions achieved "Moderately Sustainable" status, owing to nascent green economic incentives and strong community engagement. These findings highlight that piecemeal intervention are insufficient: only an integrated strategy—combining targeted ecological restoration (e.g., reforestation and wildlife corridors), adoption of green-road design, standardized multi-stakeholder governance protocols, and continued social-economic incentivization—will drive the system toward true sustainability. The study carries several practical implications. First, conservation managers and transport planners must prioritize sensitive attributes—identified via leverage analysis—to optimize resource allocation and policy action. Second, embedding co-management frameworks and digital monitoring platforms can strengthen institutional resilience and data-driven decision making. Third, market-based mechanisms (e.g., ecotourism certification, green subsidies) should be scaled to internalize environmental costs and diversify livelihoods. These findings carry several policy implications. First, infrastructure development within protected areas must adopt binding ecological design standards, including mandatory wildlife corridors and green road elements. Second, national environmental regulations should mandate comprehensive biodiversity offset strategies for infrastructure projects intersecting conservation zones. Third, multi-agency coordination should be institutionalized through policy mechanisms that incentivize joint monitoring and enforcement. Lastly, spatial planning laws should integrate conservation priorities to prevent ecological fragmentation. By aligning infrastructure planning with biodiversity objectives, policymakers can minimize trade-offs between development and ecological resilience. However, this research has limitations: its reliance on stakeholder perceptions may introduce subjectivity, and the temporal scope (June 2024–February 2025) constrains long-term trend analysis. Furthermore, the single-site focus limits generalizability to other conservation landscapes. Future studies should incorporate longitudinal ecological monitoring, expand to multi-site comparisons, and integrate high-resolution spatial data to validate and refine the MDS model.

Author Contributions

Conceptualization, S.A. and H.R.; methodology, S.A and R.T.; software, S.A.; validation, S.A., H.R., and G.C.; formal analysis, S.A. and R.T.; investigation, S.A.; resources, S.A.; data curation, S.A.; writing—original draft preparation, S.A.; writing—review and editing, S.A., H., and G.C.; visualization, S.A. and R.T.; supervision, H.R. and G.C.; project administration, H.N.; funding acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Universitas Brawijaya, Indonesia.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions of the respondents.

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Conflicts of Interest

The authors declare no conflict of interest.

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