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Research Article

Segment-Based Landslide Susceptibility Modeling Using Frequency Ratio and LSI in a Tropical Road Corridor

Widianto Eka Pramana[a*)]; Rahma Anisa[2,b)]

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Abstract

Landslides pose a significant threat to transportation infrastructure in tropical mountainous regions, particularly in countries with complex geological and climatic conditions such as Indonesia. This study develops a spatially segmented landslide susceptibility model along the 64.11 km Bengkunat Sanggi corridor, a critical segment of the West Sumatra National Road in Lampung Province. The modeling approach integrates the Frequency Ratio (FR) method and Landslide Susceptibility Index (LSI), employing seven geospatial and geotechnical parameters: slope, elevation, lithology, land cover, rainfall intensity, proximity to drainage networks, and landslide occurrence history. A total of 350 road segments were delineated to enhance the resolution of risk mapping and allow localized analysis. Each parameter was statistically analyzed to determine its influence on landslide occurrence, and the resulting FR values were summed to compute LSI scores for individual segments. The final susceptibility map classified road segments into four risk categories: low, moderate, high, and very high. The findings reveal that slope steepness, proximity to drainage, moderate elevation, and historical landslides contribute most significantly to hazard levels. This study is among the first to apply FR LSI in a segment-based framework tailored for tropical road corridors. The model achieved a high predictive performance, with an Area Under the Curve (AUC) value of 0.947, indicating robust classification accuracy. This research contributes a data-driven methodology for targeted landslide risk mitigation along critical transportation corridors and offers a transferable framework for hazard management in similar geoclimatic settings.

Keywords: *Landslide; Susceptibility; Segment Based; Tropical Infrastructure*

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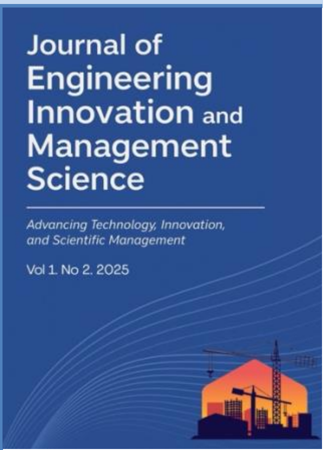

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INTRODUCTION

Landslides are among the most pervasive and destructive natural hazards that severely affect both human lives and critical infrastructure, particularly in tropical countries characterized by steep topography, high rainfall intensity, and complex geological formations (Arrisaldi et al., 2025; Zainal et al., 2024). In these settings, the stability of hillslopes is continuously challenged by seasonal climatic dynamics, hydrological changes, and anthropogenic pressures (Hirye et al., 2023; Nguyen et al., 2024). Roads and highways traversing such regions are especially vulnerable, as even minor slope failures can lead to road closures, traffic disruption, casualties, and considerable economic losses (Nseka et al., 2021). Moreover, transportation corridors are also exposed to additional environmental pressures such as noise pollution from motor vehicle traffic, which further highlights the need for comprehensive infrastructure risk assessments (Ardianti et al., 2024). In developing countries like Indonesia, where mountainous terrain intersects with poorly maintained infrastructure, the impact of landslides is further magnified by limited monitoring systems and reactive rather than preventive engineering responses (Bhandari et al., 2024; Murdawati et al., 2024).

The Bengkunat Sanggi corridor, located in Lampung Province on the western coast of Sumatra, exemplifies a critical transportation route that is persistently exposed to landslide hazards (Bacha et al., 2018; Ortiz-Giraldo et al., 2023). Spanning approximately 64.11 kilometers, this segment of the West Sumatra National Road serves as a vital link between districts, traversing diverse landforms, including steep hills, forested national parks, small-scale agricultural zones, and densely inhabited settlements (Andespa et al., 2020; Putri et al., 2022). Historical records and field surveys indicate that this route experiences recurrent landslides, especially during the rainy season, disrupting logistics, isolating communities, and increasing the cost of infrastructure rehabilitation (Hasan et al., 2024; Paswan & Shrivastava, 2023; Ramadhani et al., 2024). Despite the strategic role of this road in regional mobility and economic activity, there has been little effort to develop a spatially explicit model that captures localized landslide susceptibility patterns (Froude & Petley, 2018; Gunadi et al., 2017). Related environmental assessments, such as studies on road-induced noise pollution, emphasize that infrastructure corridors require multi-dimensional evaluations beyond conventional hazard mapping (Ardianti et al., 2024). The absence of such models hampers the ability of decision-makers and engineers to allocate resources effectively, design slope protection structures, and implement timely disaster mitigation strategies (Sugandhi et al., 2023; Wahyu et al., 2023).

Although various studies have implemented statistical and hybrid approaches for landslide susceptibility mapping using Frequency Ratio (FR), Landslide Susceptibility Index (LSI), and combinations with other models such as Shannon's Entropy, AHP, or machine learning techniques (Di Napoli et al., 2020; Sifa et al., 2020), most of these applications are conducted at regional or watershed scales, focusing on continuous spatial surfaces rather than linear infrastructures. Furthermore, while several studies have evaluated model performance using ROC–AUC metrics, few have applied these methods to segment-based analyses along critical road corridors, where hazard conditions can vary sharply over short distances and where detailed, location-specific information is essential for infrastructure maintenance. Current literature lacks models that integrate detailed segment-level spatial data with historical landslide records, particularly in tropical environments with complex terrain and dynamic rainfall patterns (Genene & Meten, 2021; Magar & Bhandari, 2025). This creates a critical gap in developing operationally relevant, high-resolution landslide susceptibility models tailored for road infrastructure planning in geohazard-prone regions.

Addressing this gap, the present study emphasizes that most previous landslide susceptibility assessments have been conducted at regional or watershed scales, which often overlook localized variations along transportation corridors. To overcome this limitation, the study proposes a segment based landslide susceptibility modeling framework for the Bengkunat Sanggi corridor by employing the FR–LSI approach. The road was divided into 350 analytical units to capture fine-scale variability in hazard conditions. Seven key parameters slope gradient, elevation, lithology, land cover, rainfall intensity, distance to drainage, and history of landslide events were extracted and quantified using geospatial techniques. By calculating FR values and aggregating them into LSI scores for each segment, the study generates a susceptibility map with high spatial specificity. The model's predictive power is validated using Receiver Operating Characteristic (ROC) curve analysis, with Area Under the Curve (AUC) as the performance metric. Ultimately, the study contributes a practical and transferable methodology for infrastructure-focused landslide risk assessment in tropical environments, offering valuable support for disaster risk management and transportation planning.

METHODS

Study Area

This research was conducted along the Bengkunat–Sanggi corridor, a 64.11-kilometer section of the West Sumatra National Road located in Lampung Province, Indonesia. The route traverses steep and geologically unstable terrain within the Bukit Barisan mountain range, cutting across the districts of Pesisir Barat and Tanggamus. The region is characterized by high rainfall, diverse land cover including natural forest, plantations, and settlements and a history of recurring slope failures, making it suitable for landslide susceptibility assessment.

Data Sources and Preparation

The study integrated spatial and non-spatial data acquired from various sources. Landslide event locations from 2023 to 2024 were obtained through field surveys and reports issued by the Ministry of Public Works and Meteorological Agency. The elevation and slope were derived from a 30 meter resolution Digital Elevation Model (DEM). Geological data, including lithology, were taken from regional geological maps. Land cover classification was extracted from recent satellite imagery, and rainfall data were obtained from provincial climatological records. Hydrological features, including streams and rivers, were used to determine drainage proximity. All spatial datasets were standardized to UTM Zone 48S and processed using Geographic Information Systems (GIS) to ensure spatial consistency.

Road Segmentation Approach

To enhance spatial resolution and allow localized analysis, the road was divided into 350 segments. The segmentation length varied depending on terrain complexity: 100 meters for steep and high risk areas, 300 meters for moderate slopes, and 500 meters for relatively flat terrain. This segmentation design supports both statistical robustness and practical applicability for infrastructure maintenance units.

Selection of Conditioning Factors

Seven parameters known to influence landslide occurrence were selected: slope gradient, elevation, lithology, land cover, rainfall intensity, distance to drainage, and landslide history. Each factor was discretized into classes based on natural intervals or domain specific standards. These classifications enabled statistical comparison between factor classes and landslide events.

Table 1. Selection of parameters and scoring factors

No	Parameters	Engineering Rationale	Supporting Studies	Reason for Proportional Scoring	Scoring (%)
1	Slope	Slope angle is directly proportional to soil shear stress	Bjerrum (1973) demonstrated that a 15° increase in slope increases the risk of landslides by 300% in cohesive materials.	Slope gradient is the most dominant factor in slope stability.	20
2	Height	Slope height affects overburden pressure	Pressures >100 kPa in soft clay cause uncontrolled consolidation (Terzaghi, 1943).	Overburden pressure ($\sigma = \gamma H$) is directly proportional to elevation.	15
3	Drainage Conditions	Poor drainage increases pore water pressure (u), reducing effective shear strength	A FHWA study (2018) showed that 82% of road landslides were triggered by damaged drainage.	Poor drainage increases pore pressure (u), reducing effective shear strength.	15
4	Landslide History	Recurrent landslides indicate unstable geological conditions (principle of "historical precedence" Varnes, 1984)	Areas with a history of landslides have a fivefold higher risk (Gupta & Joshi, 1990).	Landslide history shows residual shear zones with residual friction angles ($\varphi_r < 10°$).	20
5	Rainfall	Rainfall >100 mm/day causes infiltration of saturated water	The BMKG (Meteorology, Climatology, and Geophysics Agency) sets 100 mm/day as the landslide alert limit (BMKG Regulation No. 4/2022).	Rainfall is an external trigger, not an intrinsic cause. Its effect is not linear.	10
6	Rock Type	Low-cohesive materials are susceptible to liquefaction when saturated with water (Seed & Idriss, 1971).	-	Intrinsic parameters are relatively stable, except for changes in water content.	10

7	Land Cover	Plant roots increase apparent cohesion (c' = c + c_root) up to 20 kPa	Sidle & Ochiai (2006) study: Vegetation reduces landslides by 40-80%.	Vegetation reduces erosion and increases apparent cohesion.	10
					100

Frequency Ratio Analysis

The Frequency Ratio (FR) method was used to assess the relationship between landslide occurrences and each class of conditioning factors. The FR value for each class was calculated using the formula:

$$\mathrm{Fri} = \frac{(NL,i/Nl)}{(Ni/N)} \quad \text{......} \quad (1)$$

Where:
Fri = Frequency Ratio for Class i
NLi = Number of landslide segments in class i
NL = Total number of segments with landslide
Ni = Total number of segments in class i
N = Total number of segments

An FR value greater than 1 indicates that a class is more susceptible to landslides than average, while a value below 1 suggests lower susceptibility.

Relative Frequency (RF)

RF is a normalization of the FR value, which indicates the relative contribution of a class to the overall vulnerability:

$$\mathrm{RF} = \frac{FR_i}{\sum FR} \quad \text{......} \quad (2)$$

The RF value helps compare the weights of contributions between parameters proportionally.

Computation of Landslide Susceptibility Index (LSI)

After calculating the FR for all classes, each road segment was assigned a Landslide Susceptibility Index (LSI) by summing the FR values of the classes to which the segment belongs:

$$\mathrm{LSIj} = \Sigma i = 1^{n}\ \mathrm{FR}_{ij} \quad \text{......} \quad (3)$$

Where:
LSIj = Susceptibility index of segment j
FRij = Frequency ratio of the ith parameter class in segment j
n = Number pf parameters (7 in this study)

The resulting LSI scores were used to classify segments into four susceptibility zones—low, moderate, high, and very high—using the Natural Breaks (Jenks) method to ensure data-driven thresholds.

Model validation using ROC-AUC

To evaluate the predictive performance of the FR-LSI model, a receiver operating characteristic (ROC) curve wa constructed. The Area Under the Curve (AUC) was calculated as a measure of model accuracy in distinguishing landslide-prone from stable segments. The TPR (True Positive Rate) and FPR (False Positive Rate) were calculated as:

$$\text{TPR} = \frac{TP}{TP+FN,}\ ;\ \text{FPR} = \frac{FP}{FP+TN} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where:
TP = Correctly predicted landslide segments
FN = Landslide segments not identified by the model
FP = Non landslide segments wrongly predicted as susceptible
TN = Correctly predicted stable segments

AUC can be calculated practically via rank-sum (Mann–Whitney)

$$\text{AUC} = \frac{\sum rank_{+} - \frac{n_{+}(n_{+}+1)}{2}}{n_{+}n_{-}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Where:
$\sum rank_+$ = Total number of positive segment ratings
n_+ = Number of landslide segments
n_- = Non-landslide segments

An AUC score approaching 1 indicates excellent predictive capability. In this study, the model achieved an AUC of 0.947, reflecting high reliability and practical relevance for risk-informed infrastructure planning.

RESULT AND DISCUSSIONS

Influence of Conditioning Parameters Based on Frequency Ratio

To determine the influence of geotechnical parameters on landslide risk on the Bengkunat-Sanggi national road, an analysis was conducted using the Frequency Ratio (FR) and Relative Frequency (RF) methods. This method is used to assess the relationship between the distribution of landslide points and the condition of each parameter that affects slope stability, such as slope, elevation, sediment conditions, landslide layers, rainfall, rock type, and land cover. Each parameter is classified into several categories with a certain score range, then the FR and RF values are calculated for each category based on the proportion of landslide events to existing conditions.

Table 2. Results of Frequency Ratio and Relative Frequency analysis

No	Paramater	Category	Assessment Criteria	FR	RF
1	Slope	Low	• <30°: 5-9	0.508	0.105
		Moderate	• 30-45°: 10-14	1.046	0.216
		High	• 45-50°: 15-19	1.498	0.309
		Very High	• >50°: 20	1.797	0.371
2	Height	Low	• <3m: 5-6	0.000	0.000
		Moderate	• 3-6m: 7-9	0.494	0.206
		High	• 6-10m: 10-14	0.851	0.354
		Very High	• >10m: 15	1.059	0.440
3	Drainage Conditions	Low	• Good (functional): 0-3	0.347	0.087
		Moderate	• Fair (damage <50%): 4-8	0.686	0.172
		High	• Poor (clogged): 9-14	1.230	0.308
		Very High	• None: 15	1.734	0.434
4	Landslide History	Low	• None: 5	0.936	0.167
		Moderate	• 1x: 10	1.872	0.333
		High	• 2x: 15	2.807	0.500
		Very High	• ≥2x: 20	0.000	0.000
5	Rainfall	Low	• <100mm: 3-4	0.000	0.000
		Moderate	• 100-200mm: 5-6	0.000	0.000
		High	• 200-300mm: 7-9	0.907	0.474
		Very High	• >300mm: 10	1.008	0.526
6	Rock Type	Low	• Hard rock: 0-3	0.000	0.000
		Moderate	• Grainy rock: 4-6	0.674	0.194
		High	• Clay and silt: 7-9	1.164	0.334
		Very High	• Loose rock: 10	1.644	0.472
7	Land Cover	Low	• Dense forest: 0-3	0.628	0.186
		Moderate	• Settlements: 4-6	1.047	0.310
		High	• Shrubland/plantations: 7-9	1.699	0.504
		Very High	• Open land: 10	0.000	0.000

The analysis results show that topographic factors have a significant influence on landslide susceptibility. The slope inclination shows a clear trend, where the steeper the slope, the higher the FR value, with the >50° category reaching an FR of 1.797 and an RF of 0.371. A similar pattern is observed with elevation, where elevations >10 m show the highest FR of 1.059 and RF of 0.440. Drainage conditions also play an important role, as segments with poor to non-functional drainage have an FR of 1.734 and an RF of 0.434, while good drainage shows the lowest values. Meanwhile, landslide history is the dominant indicator, as segments experiencing landslides more than twice show the highest FR of 2.807 and RF of 0.500, making event history a key predictive parameter.

Climate factors and geological conditions also contribute to vulnerability. Monthly rainfall >300 mm indicates an FR of 1.008 with an RF of 0.526, signifying a high contribution of rainfall as a landslide trigger. From a geological perspective, hard rocks are not associated with landslides (FR=0), while clay-silt to loose rocks show an FR of 1.644 with an RF of 0.274, confirming the vulnerability of weak materials to weathering and water saturation. From a land use perspective, segments with dense forest cover are more stable (FR 0.628), while shrub and plantation areas have the highest FR of 1.699 and RF of 0.500, indicating that land use change from natural forest to other uses increases the risk of landslides. Thus, the combination of steep slopes, high elevation, poor drainage, soft rock, high rainfall, and open land cover are the dominant factors causing landslides on the research road section.

Landslide Susceptibility Classification Based on LSI

To synthesize the collective influence of all parameters, the FR values for each contributing factor class were aggregated to compute a Landslide Susceptibility Index (LSI) for each of the 350 segmented road units. These LSI values were then grouped into four susceptibility categories using the Natural Breaks (Jenks) classification method. The results are presented in Table 2.

Table 3. Landslide Susceptibility Zonation by Segment

Susceptibility Class	LSI Range	Number Segments	Percentage (%)
Low	< 6.0	52	15
Moderate	6.0 – 8.0	221	63
High	8.1 – 10.5	77	22
Very High	> 10.5	0	0

A majority of segments (63%) were categorized under moderate susceptibility, reflecting widespread but non critical exposure to landslide-inducing conditions. These segments typically correspond to areas with gentle to moderate slopes, stable vegetation, and reasonably effective drainage. The high-risk category encompassed 22% of the corridor, predominantly located in steep sections with poor land cover and close proximity to drainage lines. The complete absence of segments in the very high category may indicate that while hazards are distributed along the corridor, conditions rarely reach the extreme thresholds associated with massive or catastrophic slope failures. The spatial distribution of these classes is particularly informative for infrastructure managers. High-risk segments are often clustered near bends, elevation changes, and deforested slopes, which are commonly overlooked in coarse-scale hazard mapping. The detailed segment-based zonation thus offers an operational advantage in targeting localized mitigation efforts.

Model Validation and Predictive Performance

The predictive performance of the FR LSI model was evaluated using Receiver Operating Characteristic (ROC) curve analysis. The resulting Area Under the Curve (AUC) value was 0.947, indicating excellent discriminatory power. This confirms that the model is capable of accurately differentiating between susceptible and non-susceptible segments, validating the effectiveness of both the selected parameters and the segment-based analytical approach.

The AUC score aligns well with best practices in landslide modeling, where values above 0.90 are considered indicative of high model robustness. The inclusion of real world landslide occurrences in the model calibration process enhances its reliability, as it ensures that the susceptibility mapping reflects actual terrain behavior rather than purely theoretical assumptions. Moreover, the segment based structure of the model provides additional interpretability. Unlike raster-based models that may dilute hazard intensity over large grid cells, the segment focused method retains the operational scale relevant to road infrastructure, enabling clear identification of critical zones that require engineering attention.

Interpretive Insights and Practical Implications

The findings confirm that terrain morphology, especially slope steepness and hydrological connectivity, are the dominant forces influencing landslide risk along tropical mountain roads. This is consistent with established geomorphological research and validates the prioritization of slope-related parameters in susceptibility modeling. The influence of historical landslide occurrence is particularly notable, reinforcing the importance of including past hazard data in planning scenarios.

While lithological and vegetation factors exert moderate influence, their interaction with primary variables such as slope and water flow pathways should not be overlooked. For instance, weathered rock formations may become critical failure zones when combined with steep terrain and high rainfall. Similarly, vegetation loss due to human activity may accelerate slope degradation even in otherwise low risk geological contexts. From a practical standpoint, the susceptibility zoning output is highly applicable for prioritizing interventions such as slope reinforcement, improved drainage, and early warning system placement. The model offers a replicable and data driven framework for road authorities to implement proactive landslide risk reduction strategies. Additionally, its methodology can be extended to other infrastructure corridors across tropical regions with similar geotechnical profiles.

Discussion

The results of this study underscore the dominant role of terrain-related variables particularly slope gradient, proximity to drainage, and elevation in influencing landslide susceptibility along linear infrastructure in tropical mountainous regions. The strong predictive contribution of historical landslide occurrence further highlights the persistence of geomechanical instability in previously failed slopes, which tend to retain structural weaknesses. While lithology and land cover showed relatively moderate associations, their interaction with hydrological and morphological stressors can intensify slope vulnerability under specific conditions. The high AUC score obtained from model validation confirms the robustness of the FR LSI framework and supports its application in road segment based risk analysis. Unlike pixel-based susceptibility models that often generalize spatial hazard patterns, the segmented approach used in this study provides operational level insights that are directly applicable to infrastructure planning, maintenance prioritization, and site-specific mitigation. These findings emphasize the importance of integrating empirical hazard records with spatially explicit models to support proactive decision-making, particularly in regions where transportation corridors traverse complex terrain and are exposed to recurring geohazards.

Implication

The findings of this study have important practical and methodological implications for infrastructure resilience and geohazard management in tropical mountainous regions. By adopting a segment based susceptibility modeling approach, this research offers a framework that aligns more closely with the operational realities of road maintenance and disaster mitigation planning. The ability to pinpoint specific high risk segments along a transport corridor enables targeted allocation of resources for slope stabilization, drainage improvement, and early warning system deployment. Moreover, the model's strong predictive performance reinforces the value of integrating empirical landslide inventories with spatially disaggregated risk assessments. This approach not only enhances the precision of susceptibility zoning but also provides a scalable method that can be adapted to other critical infrastructure networks facing similar environmental challenges. Consequently, the study contributes to the broader agenda of climate-resilient infrastructure planning by offering data-driven tools to support proactive, localized interventions in areas vulnerable to slope failure.

Limitation and Suggestion for Further Research

While the segment-based FR LSI model developed in this study demonstrated high predictive accuracy and practical utility, several limitations should be acknowledged. The analysis relied primarily on static spatial datasets and did not incorporate temporal dynamics such as seasonal rainfall variation, land-use change, or soil moisture fluctuations, which may significantly influence landslide initiation. Additionally, the resolution of certain input data particularly rainfall and lithological maps was relatively coarse and may not fully capture local heterogeneity within each segment. Field validation of susceptibility classifications was limited to the availability of recorded landslide points, which may omit undocumented or minor slope failures. Therefore, future research is encouraged to integrate time-series remote sensing data, higher-resolution geotechnical surveys, and physically based modeling techniques to enhance the model's temporal responsiveness and geomechanical representation. Expanding the methodology to include machine learning approaches and real-time monitoring systems could also offer promising pathways for developing adaptive, data-rich early warning frameworks suited for dynamic infrastructure environments.

CONCLUSION

This study successfully developed and validated a segment-based landslide susceptibility model for a critical national road corridor in Lampung Province, Indonesia, by integrating the Frequency Ratio (FR) method and Landslide Susceptibility Index (LSI) within a geospatial framework. By analyzing seven key conditioning factors including slope, elevation, lithology, land cover, rainfall intensity, drainage proximity, and landslide history the model provided high-resolution susceptibility scores for 350 road segments, offering spatially explicit insights into landslide risk distribution. The results demonstrated that slope steepness, prior landslide events, and proximity to drainage channels were the most influential variables, with the model achieving excellent predictive performance (AUC = 0.947). The classification of susceptibility zones revealed that 22% of segments fall into high-risk categories, highlighting the need for focused mitigation measures. Unlike conventional regional-scale assessments, the segment based approach proved effective for supporting localized risk reduction strategies and infrastructure resilience planning. Overall, the study contributes a scalable, data-driven methodology that can be adapted to similar geohazard-prone transport corridors, reinforcing the importance of integrating empirical hazard data with targeted spatial analysis in the pursuit of sustainable and disaster-resilient infrastructure systems.

AUTHORS INFORMATION

Corresponding Authors

Widianto Eka Pramana – Civil Engineering Program/Engineering Faculty, Universitas Tanjungpura (Indonesia)
Email: widiantosp@civil.untan.ac.id

Authors

Rahma Anisa – Geodesy Engineering Program/Engineering Faculty, Universitas Lampung (Indonesia)
Email: rahma.anisa@eng.unila.ac.id

AUTHORS CONTIBUTIONS STATEMENT

All authors contributed substantially to the conception and design of the study, as well as to the analysis and interpretation of the data. led the conceptualization of the research framework, coordinated field data collection, and prepared the initial manuscript draft. was responsible for developing the methodology, conducting statistical analyses, and interpreting the findings in the context of existing literature. contributed to the acquisition of project documentation, facilitated stakeholder engagement, and provided critical revisions to enhance the intellectual content. All authors participated in refining the manuscript, approved the final version for submission, and agree to be accountable for all aspects of the work, ensuring the integrity and accuracy of the reported results.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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