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Factors Influencing Pedestrian Movement in Banda Aceh: The Role of Urban Density, Land Use, and Connectivity

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ABSTRACT: High urbanization in Indonesia created significant mobility challenges, particularly due to the intensive use of motorized vehicles that led to congestion and environmental degradation. This study aimed to analyze the factors influencing pedestrian volume in Banda Aceh as an alternative solution to promote active mobility. The analysis was conducted using the Structural Equation Modeling–Partial Least Squares (SEM-PLS) method with three main variables—land use mix, density, and connectivity—measured across 44 grids of 800×800 meters within the city. The findings showed that density had a significant positive effect on pedestrian volume (path coefficient = 0.425; p-value = 0.007), while land use mix and connectivity did not demonstrate significant effects. The proposed model explained 27.2% of the variation in walking mobility. These results highlighted the importance of urban density in encouraging walking activity and suggested that compact urban development could be an effective strategy to promote active mobility in Indonesian cities.

KEYWORDS: Pedestrian volume; land use mix; density; connectivity; SEM

1. Introduction

Cities in Indonesia experienced rapid growth characterized by urbanization, land conversion, and diversification of spatial functions. This phenomenon led to increased intensity of urban activities, making mobility one of the key challenges of urban life. Cities that relied heavily on private motorized vehicles often faced traffic congestion and environmental degradation [1]. Recent studies in Southeast Asia confirmed this trend, showing that motorization rates in Indonesian cities increased significantly since the early 2000s, particularly in medium-sized urban centers where public transport infrastructure remained underdeveloped [2, 3]. Therefore, urban areas increasingly adopted the concept of active mobility, particularly walking, which is more efficient in terms of space and resource use and environmentally friendly.

To encourage people to walk rather than rely on private vehicles for daily needs, cities needed to provide a pedestrian-friendly ecosystem. The 5D framework—Density, Diversity, Distance to Transit, Destination Accessibility, and Design—has been widely recognized as a basis for creating walkable environments [4, 5]. Among these dimensions, density, diversity, and accessibility were the most frequently examined factors associated with walking mobility [6, 7].

A recent review of walkability studies published between 2021 and 2022 showed that built-environment factors such as land-use mix, street connectivity, and density remained the most consistent elements influencing how people chose to walk in different urban settings [8]. In Asian cities, studies increasingly employed integrated approaches combining GIS-based built-environment measures with space syntax metrics to understand pedestrian patterns, reflecting an evolving methodological sophistication in the region [9].

However, research findings remained inconsistent. Some studies reported that land-use mix (LUM) positively correlated with pedestrian volume [10, 11]. In contrast, studies conducted in cities such as Seoul and Jakarta, representing East and Southeast Asian contexts, found that the relationship tended to follow a bell-shaped curve, indicating that higher LUM did not always translate into greater walking activity [12, 13]. These inconsistencies suggested that LUM should not be understood as a standalone factor but rather analyzed in conjunction with other dimensions such as density and connectivity.

This study aimed to examine the factors influencing pedestrian mobility—specifically land-use diversity, density, and connectivity—using Structural Equation Modeling (SEM) in Banda Aceh, a medium-sized Indonesian city characterized by moderate density and a mix of urban functions. Empirical research on pedestrian mobility determinants in medium-sized Indonesian cities remained very limited, which may lead to findings that differ from those observed in large metropolitan areas such as Jakarta. This created a significant research gap that this study sought to address. Moreover, Banda Aceh offered a relevant context, as the city continued to rely heavily on private vehicles while walking had yet to be fully developed and integrated as a practical mode of daily mobility.

Building upon this gap, the present study empirically examined how land-use mix, density, and connectivity influenced pedestrian volume in Banda Aceh. Through the application of Structural Equation Modeling–Partial Least Squares (SEM-PLS), the analysis aimed to determine whether the established 5D framework remained valid in this context or required contextual adjustment. Specifically, the study investigated (1) which built-environment factors most strongly determined walking activity, and (2) to what extent land-use diversity, density, and street connectivity jointly explained variations in pedestrian volume.

2. Materials and Methods

This study employed a quantitative approach using Structural Equation Modeling–Partial Least Squares (SEM-PLS) to assess the direction and magnitude of the influence of land-use mix (LUM), density, and connectivity on pedestrian volume in Banda Aceh. SEM-PLS was chosen because it allows for the simultaneous analysis of relationships between latent variables by testing both the outer model, which evaluates the validity and reliability of indicators, and the inner model, which estimates causal relationships between constructs. The indicators used to represent each variable are summarized in Table 1. The LUM variable was measured using the entropy index, which reflects the variation and proportion of land uses within an area. A higher entropy index indicates greater diversity of land-use functions, thereby creating shorter travel distances for pedestrians [18]. In addition, LUM was represented by the ratio of residential to non-residential areas, capturing the spatial balance of land functions. A balanced proportion between residential areas as origins and non-residential areas as destinations enables daily needs to be met within walking distance [15].

Table 1. Variables and indicators.

Variable	Indicator (Code)	Definition	Formula/ Data Collection	Source
Pedestrian Volume (endogenous variable)		Number of pedestrians observed in a certain area during 11:00–12:00 local time (Monday–Thursday)	Direct field survey using manual counting method	
A. Land Use Mix (LUM)	Entropy Index (A1)	Degree of diversity in land use	$EI = -\frac{\sum_{j=1}^{k} Pj\ In\ Pj}{In\ k}$ (Eq. 1)	[14]
	Residential – Nonresidential Ratio (A2)	Comparison of residential land area to non-residential land area	$RNRR = 1 - \left\lvert\frac{Res_i - NonRes_i}{Res_i + NonRes_i}\right\rvert$ (Eq. 2)	[15]
B. Density	Building Density (B1)	Ratio of building floor area to total land area	$Bdens = \frac{Building\ Floor\ Area}{Area}$ (Eq. 3)	[15]
	Population Density (B2)	Ratio of population to total land area	$Pdens = \frac{Total\ population}{Area}$ (Eq. 4)	[15]
	Number of Bus Stops (B3)	Number of Trans Koetaradja bus stops in a given area	GIS mapping and secondary data from local transport agency	[14]
C. Connectivity	Number of Intersections (C1)	Number of intersections within a given area	GIS network analysis	[16]
	Number of Cul-de-Sacs (C2)	Number of dead-end roads in a given area	GIS network analysis	[17]
	Street Network Density (C3)	Ratio of total street length to land area	$Rdens = \frac{Street\ Length}{Area}$ (Eq. 5)	[15]

The density variable was represented by building density, population density, and the number of public transport stops in a given area. Areas with high building density formed a more compact urban structure, where functional activities tended to be located closer together [19]. High population density indicated greater potential for walking trips, as it reflected the concentration of origins of pedestrian movement [18]. Density was also reflected in the availability of public transport stops, as the presence of bus stops in certain areas signaled a high demand for movement [20].

The connectivity variable was measured by the number of intersections. A higher number of intersections provided more route options, acting as shortcuts to reach destinations more efficiently [16]. To ensure effective route options, each connected road at an intersection needed to be integrated into the broader street network and not terminate as a dead end; therefore, the number of cul-de-sacs and street network density were also considered important indicators [16, 17]. All of these variables were analyzed to determine their influence on pedestrian volume. The conceptual model of relationships between the variables tested using SEM-PLS is presented in Figure 1.

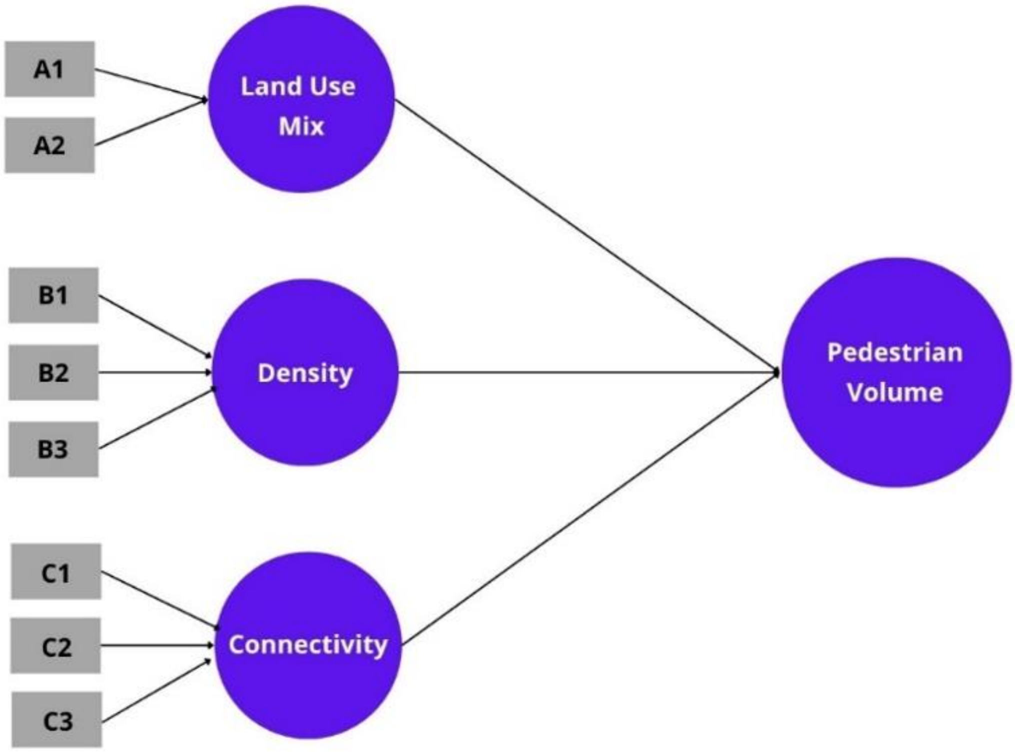

Figure 1. Initial SEM model.

Each indicator was analyzed based on a grid size of 800 × 800 meters. The grid size was determined with reference to the average walking distance of urban residents worldwide, which generally ranged between 400 and 800 meters [21]. However, in the local context, Althoff et al. [22] noted that the walking capacity of Indonesian residents was below the global average, making 400 meters a more representative distance. Therefore, an 800-meter grid was applied to represent a 400-meter radius from the grid center, allowing each unit to capture the potential influence of the surrounding environment on walking decisions.

The 44 grids were distributed across all districts of Banda Aceh in a structured yet random manner to ensure proportional spatial coverage. The grid centers were placed along collector and local roads, as these street types were most relevant to pedestrian activities. Consequently, some grids slightly overlapped. However, this did not affect the results, as each grid was analyzed as an isolated observation unit. Minor overlaps did not lead to identical outcomes because land-use compositions and built-environment characteristics varied even between adjacent grids.

Banda Aceh was selected as the study area because it exhibited diverse land-use characteristics, particularly in the city center, as well as spatial dynamics shaped by the post-2004 tsunami, which significantly altered land use in coastal areas. This variation in land use formed the basis for constructing 44 uniform observation grids, as illustrated in Figure 2. These grids were then used to calculate spatial indicators of land use mix (LUM), density, and connectivity, which were subsequently analyzed using SEM to test their relationships with pedestrian volume.

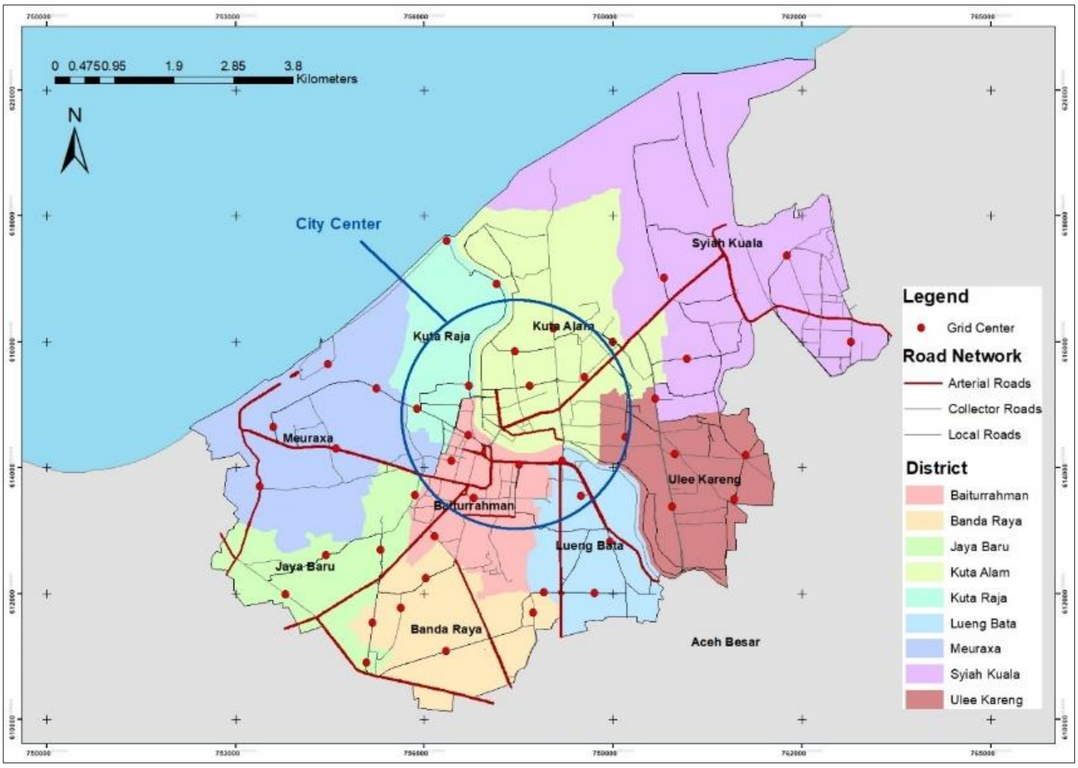

Figure 2. Distribution of observation points used as the centers of the analysis grids.

3. Results and Discussion

3.1. Land use characteristics and indicator variations.

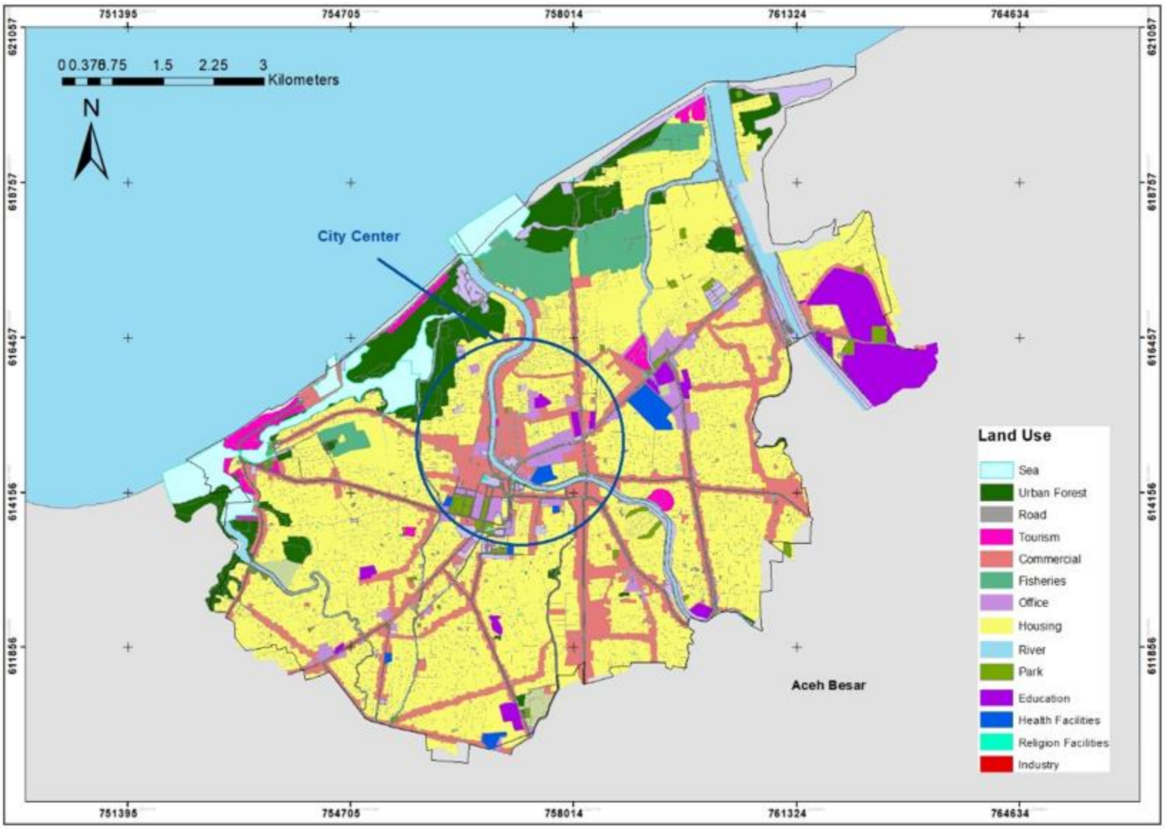

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Figure 3. Land Use Map of Banda Aceh City [23]
Source: Banda Aceh City Government, 2021 [23]

The land-use map (Figure 3) illustrates the spatial variation of land uses in Banda Aceh. However, this study focuses on nine land-use categories including industry, health, sports, tourism, education, religious facilities, offices and commercial areas, residential areas, and parks [23]. These nine categories were selected because they are considered the most relevant to urban activities that influence walking mobility. The map shows that land use patterns in the city center are more diverse, including offices and commercial areas, education, and residential uses with relatively balanced proportions. In contrast, the peripheral areas tend to be more homogeneous, dominated by residential land and open spaces. Based on the pedestrian volume survey, the highest concentration of pedestrians was recorded in the city center. This suggests that the central area functions as a zone of high visitation intensity due to the wide range of activities available within its mixed-use environment.

Indicator analysis was conducted on 44 uniform grids, each measuring 800 × 800 meters, distributed across Banda Aceh. All indicators representing the variables of land use mix (LUM), density, and connectivity were analyzed at the grid level, allowing spatial variations between areas to be systematically compared. The spatial distribution of grids with the highest and lowest values for each indicator is illustrated in Figure 4.

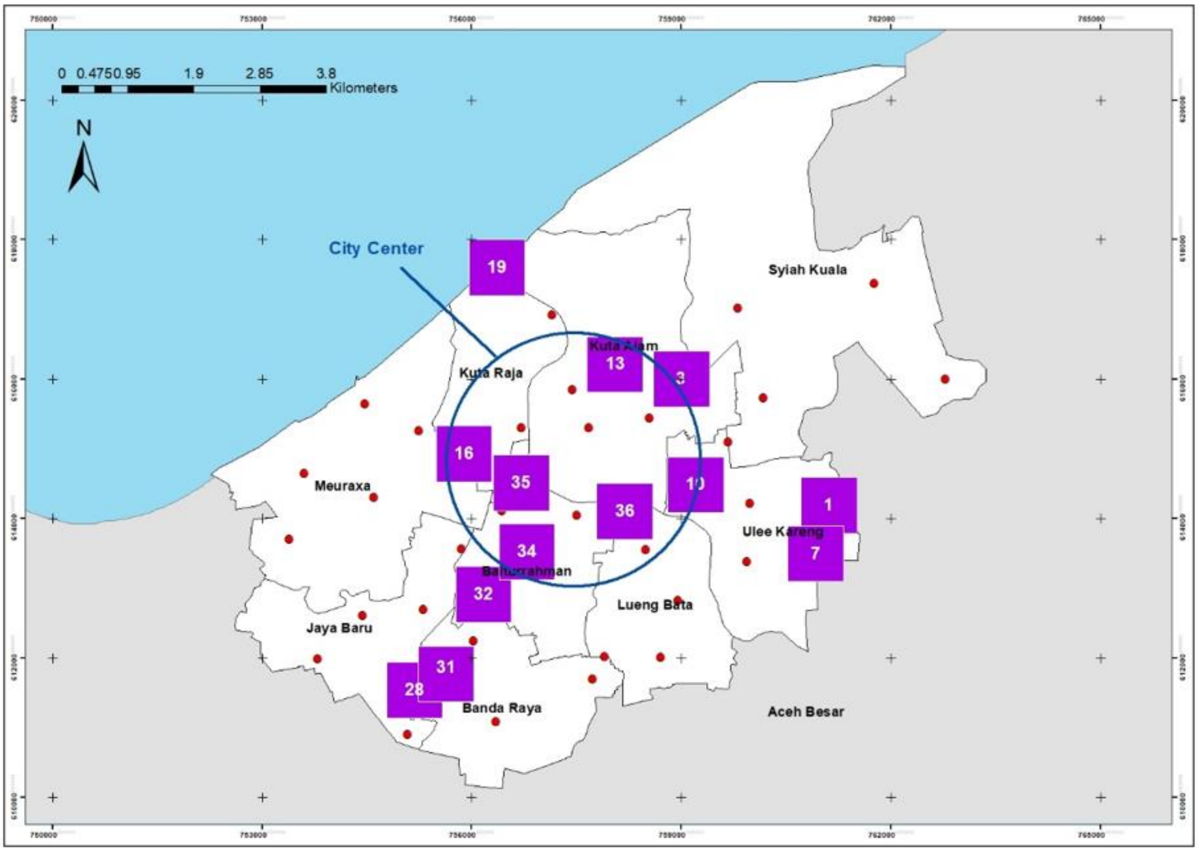

Figure 4. Spatial distribution of highest and lowest grid values for each indicator.

Based on the Figure 5, for the LUM variable, the highest EI value is found in grid 3, which is still part of the city center area, while the lowest EI value is observed in grid 7, located in the suburban area dominated by residential land use (see Figure 4). Meanwhile, the highest residential-to-non-residential ratio is found in grid 1, indicating that this area has a balance between residential and non-residential land uses. This also suggests that although grid 3 has a more diverse land-use composition, the proportion of residential land is not greater than that of other land uses.

In terms of density, the area with the highest building density is located in grid 32. Interestingly, the area with the largest population is not found in grid 32 but in grid 13. The non-linear relationship between building density and population density indicates that buildings in grid 32 are predominantly used for non-residential purposes. Meanwhile, the area with the highest number of bus stops is found in grid 21. Finally, in terms of connectivity, the area with the largest number of road intersections is located in grid 16, while the area with the highest number of cul-de-sacs is found in grid 1. Meanwhile, the area with the highest road network density is identified in grid 36.

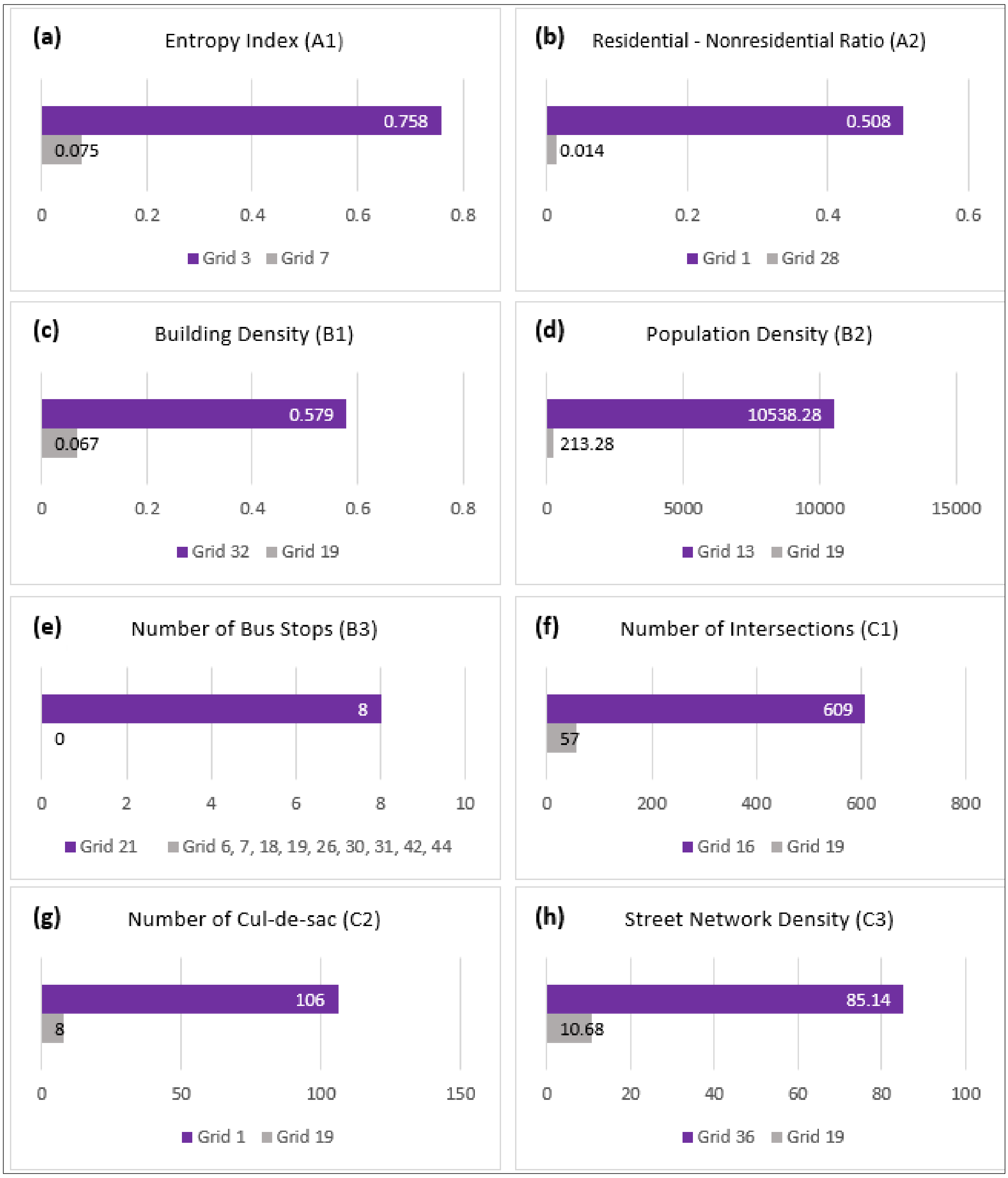

Figure 5. Graph of highest and lowest values across indicators: Entropy index (a), Residential – nonresidential ratio (b), Building density (c), Population density (d), Number of bus stops (e), Number of intersections (f), Number of cul-de-sacs (g), and Street network density (h)

Table 2 summarizes the descriptive statistics of all indicators across the 44 observation grids. The entropy index (A1) and residential–nonresidential ratio (A2) show moderate variation, indicating that land-use diversity in Banda Aceh is relatively balanced but more pronounced in central districts than in suburban areas. Density indicators (B1–B3) exhibit greater dispersion, reflecting the concentration of built-up areas, high population density, and the limited yet uneven distribution of public transport stops in the city center. Connectivity indicators (C1–C3) also vary considerably, with higher intersection and street network densities found in mixed-use urban zones, while peripheral grids tend to contain more cul-de-sacs and less connected street patterns. These results quantitatively support the spatial patterns shown in Figures 3–5, confirming that Banda Aceh's central areas possess a denser and more compact urban structure compared to the outer zones. The significance and direction of the relationship of each indicator in shaping its respective variable, as well as the interrelationships among variables in influencing pedestrian volume, will be presented through the outer model and inner model of the SEM-PLS analysis.

Table 2. Descriptive statistics of spatial indicators across 44 grids in Banda Aceh.

Variable	Indicator (Code)	Mean	SD	Min	Max
Pedestrian Volume		10.72	9.78	0	52
Land Use Mix	A1	0.34	0.13	0.09	0.75
	A2	0.45	0.27	0.01	0.97
Density	B1	0.32	0.12	0.07	0.58
	B2	5860.63	2333.41	213.28	10538.28
	B3	2.68	2.04	0	8
Connectivity	C1	122.04	37.68	19	199
	C2	48.43	25.11	8	112
	C3	43.55	15.61	10.68	85.14

3.2. Evaluation of the measurement model (outer model).

In this study, the constructs are specified as formative measurement models, meaning that each indicator contributes to forming the construct (variable). Accordingly, the statistical validation process differs from reflective models, where reliability (Cronbach's alpha or composite reliability) and convergent validity (AVE, Fornell–Larcker) are typically evaluated. In formative models, the assessment focuses instead on three key aspects: (1) multicollinearity among indicators, tested through variance inflation factor (VIF) values, (2) significance of indicator contribution, measured by the p-values of the outer weights, and (3) indicator relevance, examined through the outer loadings between indicators and their constructs [24].

As shown in Table 3, all indicators recorded VIF values below the threshold of 5, confirming the absence of multicollinearity and indicating that each indicator contributes unique information to its construct. Indicators with non-significant outer weights were retained if they exhibited conceptual relevance and acceptable loading values (>0.5), consistent with common formative-model practice in PLS-SEM applications.

Table 3. VIF test results.

Indicators	Code	VIF
Entropy index	A1	2.904
Residential – nonresidential ratio	A2	2.904
Building density	B1	2.101
Population density	B2	2.075
Number of bus stops	B3	1.019
Number of intersections	C1	3.464
Number of cul-de-sacs	C2	1.093
Road network density	C3	1.000

To ensure methodological consistency, the evaluation procedure followed the decision-making framework proposed by Hair et al [24]. The process begins by assessing the significance of each indicator's outer weight. When the weight is significant, the indicator is retained and interpreted based on its relative importance. If the weight is not significant, the indicator's loading is then examined: indicators with loadings ≥ 0.5 are retained for their theoretical relevance, while those with both non-significant weights and low loadings (< 0.5) are considered for removal. This systematic approach ensures that each indicator retained in the model contributes meaningfully either statistically or conceptually to the construct being measured. Furthermore, indicators that do not meet statistical thresholds may still be retained when they capture a unique and theoretically essential aspect of the construct, as removing them could compromise the model's content validity [24].

Table 4 presents the results of the outer weight and outer loading tests, which assess the relative contribution and strength of each indicator in forming its respective construct. The findings show that most indicators, except for building density and population density, have non-significant outer weights ($p > 0.05$). However, because the model is specified as formative, the evaluation does not rely solely on weight significance but also considers the direct contribution of each indicator through its outer loading, which should exceed the threshold value of 0.5. As indicated in Table 3, only two indicators—population density and road network density—do not meet the loading criterion, suggesting that these variables contribute less strongly to their constructs compared to other indicators.

Table 4. Outer weight dan outer loading test results.

Indicators	Code	Outer Weight (P-values)	Outer Loading
Entropy index	A1	0.264	0.981
Residential – nonresidential ratio	A2	0.623	0.908
Building density	B1	0.000	0.626
Population density	B2	0.022	-0.010
Number of bus stops	B3	0.089	0.500
Number of intersections	C1	0.159	0.883
Number of cul-de-sacs	C2	0.520	0.581
Road network density	C3	0.371	-0.111

In the measurement model above, it is evident that the road network density indicator does not meet either the outer weight or outer loading criteria. Empirically, this implies that the road network density indicator does not provide either a direct or relative contribution in forming the connectivity construct in Banda Aceh. Nevertheless, this indicator may still be retained in the model due to its strong conceptual foundation, particularly in representing urban mobility.

3.3. Evaluation of the structural model (inner model).

Following the evaluation of the measurement model, it is necessary to proceed with the evaluation of the structural relationships between endogenous and exogenous variables (inner model). The inner model is assessed by examining the path coefficients along with the coefficient of determination (R^2), as illustrated in the following figure.

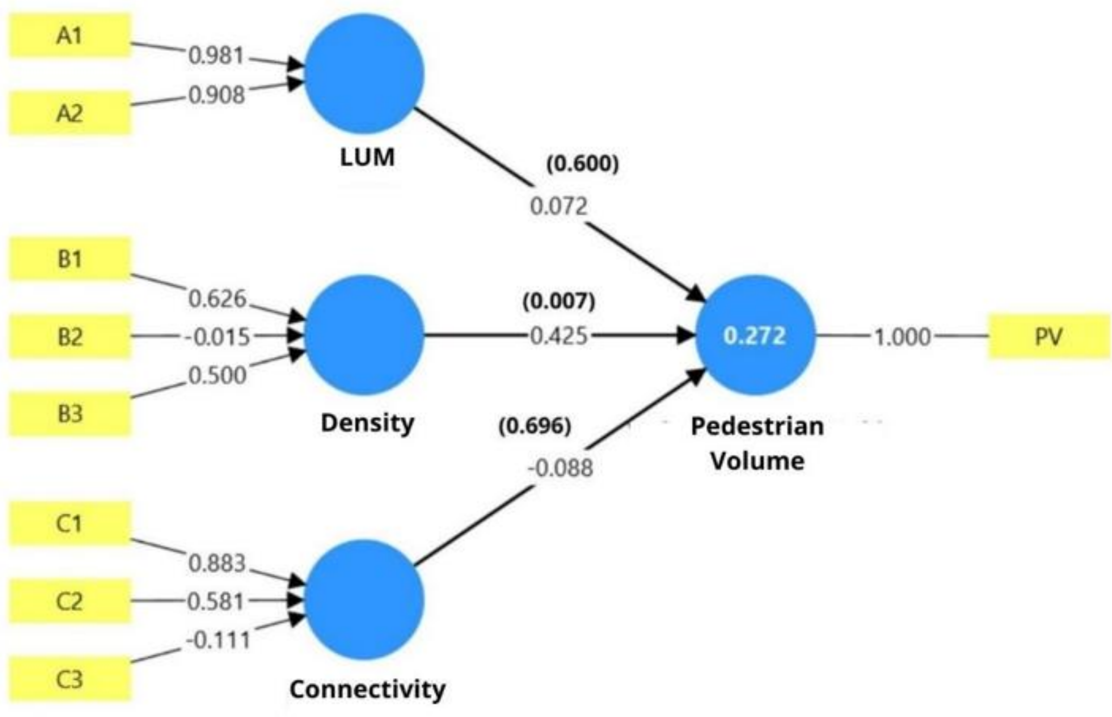

Figure 6. SEM-PLS test results.

The SEM-PLS results shown in Figure 6 indicated that among the three variables tested, only density was found to have a statistically significant effect on pedestrian volume (path coefficient = 0.425; p = 0.007 < 0.05). This finding reinforced the dominant role of urban density in shaping walking activity, as denser environments typically provided shorter distances between origins and destinations and a greater concentration of public transport stops, allowing activity zones to overlap and strengthen pedestrian flows. This result was consistent with previous studies indicating that high-density areas tended to generate more pedestrians due to reduced travel distances and enhanced perceptions of safety arising from increased social interaction [26, 27]. From a theoretical standpoint, this relationship also aligned with the principles of Critical Mass Theory, which emphasized the minimum number of people and functional diversity required to sustain continuous pedestrian activity and commercial vibrancy [28], particularly in medium-sized cities with developing public transport systems and emerging walkability.

In contrast, LUM had a positive but insignificant influence on walking propensity (path coefficient = 0.072; p = 0.600). This underscored that the variety of land uses alone could not enhance walking in the absence of adequate density or destination attractiveness. This result was consistent with [29], who argued that the measurement of land-use mix should also account for the attractiveness value of each land-use type. In other words, even though an area might exhibit high land-use diversity, it did not necessarily generate higher pedestrian volumes, as each land use contributed differently to walkability depending on its function and spatial weight. In the case of Banda Aceh, the insignificant relationship between LUM and pedestrian activity could also be attributed to the city’s organic urban growth pattern and the incomplete implementation of spatial planning policies [13]. Consequently, the potential influence of LUM was likely constrained by contextual factors such as high private-vehicle dependency, traffic congestion, and the uneven distribution and quality of pedestrian infrastructure across urban areas.

The connectivity variable showed a similar pattern. It exhibited a weak and slightly negative association with pedestrian volume (path coefficient = −0.088; p = 0.696). Although the road-network-density indicator did not reach statistical significance, it was retained due to its theoretical relevance and contextual appropriateness. Conceptually, road network density reflected the compactness and permeability of the street system, determining route alternatives and accessibility as core attributes of urban connectivity that were expected to enhance walkability [30]. However, the weak influence of this variable in the context of Banda Aceh was likely driven by a strong dependence on private vehicles. In many Indonesian cities, including Banda Aceh, private vehicle ownership was not merely a means of transportation but also a symbol of social status [31], which consequently reduced the preference for walking. Ivanescu [32] emphasized that local cultural norms and travel habits played a decisive role in shaping mode choice, often outweighing spatial or infrastructural design factors. As a result, good road connectivity might paradoxically reinforce motorized mobility rather than pedestrian activity, as high traffic volumes and vehicular dominance often acted as barriers to pedestrian movement [33].

The low explanatory power of the model (R^2 = 27.2%) underlined that while spatial form in general, and density in particular, played a meaningful role, many other determinants of walking behavior fell outside this model. For example, sidewalk quality, microclimatic comfort, safety perceptions, and aesthetic attractiveness of streetscapes were all factors potentially relevant to decisions to walk, which were not covered here. Pedestrians were shown to be quite sensitive to both thermal comfort and perceived safety, factors that might act as deterrents to walking in tropical cities when heat exposure or traffic conflicts occurred [34]. Consequently, further research would need to incorporate these perceptual and socio-cultural dimensions to develop a more holistic understanding of walkability within Indonesian contexts.

From a planning perspective, these findings underlined several policy implications. First, compact-development strategies that maintained and intensified density in central areas should be prioritized to create a pedestrian critical mass. Second, land-use diversity policies needed to go beyond entropy-based targets and focus on destination attractiveness through active ground-floor uses, informal commerce, and mixed-use corridors. Third, efforts to improve connectivity had to be paralleled by the provision of pedestrian-oriented infrastructure continuous sidewalks, street shading, traffic-calming measures, and safe crossings to transform dense yet motorized networks into truly walkable environments. By aligning spatial planning, urban design, and mobility management, Banda Aceh and other medium-sized cities could translate their density potential into sustainable, pedestrian-friendly urban systems.

4. Conclusions

This study found that density was the most influential factor affecting walking mobility in Banda Aceh, while the other two factors included in the model, namely land-use mix and connectivity, did not have significant effects. This suggested that walking mobility in the context of a medium-sized city, as represented by Banda Aceh, was primarily determined by building density, population density, and the availability of public transport stops. The SEM-PLS model applied in this research was able to explain 27.2% of the variation in walking mobility in Banda Aceh. In other words, a substantial number of additional factors still needed to be examined in relation to walking mobility. These may include the availability and quality of pedestrian infrastructure, thermal comfort, neighborhood safety, as well as psychological and cultural influences within the local community. It was expected that such factors, together with density as the key finding of this study, could serve as important considerations in planning cities for comprehensive sustainable mobility.

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Author Contribution

Ghaffari Naufal was responsible for conceptualization, methodology, data collection, data analysis, and writing of the original draft. Yori Herwangi contributed to reviewing and editing the manuscript, provided supervision, and gave feedback on both substance and writing.

Competing Interest

The authors declare that they have no known financial, personal, or professional competing interests that could have appeared to influence the work reported in this paper.

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