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Modelling the Effects of Road Network Connectivity Using SEM: Evidence from Aceh Province, Indonesia

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Abstract: Aceh Province is a critical case for freight and infrastructure studies due to its geographic isolation, post-disaster recovery context, and heavy dependence on roads for over 95% of commodity transport. Despite its rich agricultural output, limited multimodal infrastructure hampers efficient distribution. This study aims to (1) analyze the effect of road network connectivity on commodity transportation and regional development, and (2) develop a forecasting model to predict future commodity transportation needs in Aceh Province. The Structural Equation Modeling (SEM) was applied to analyze the relationships among Road Network Connectivity (RNC), Freight Transport (FT), and Regional Development (RD), using data from 400 respondents across 23 districts. The SEM results show all latent variables are interconnected. FT plays a strong mediating role, linking connectivity improvements to development benefits. The study also develops forecasting models for commodity generation and attraction based on population, expressed as $Y = 2.209\ X_1$ and $Y = 2.807\ X_1$. These models highlight population as a reliable predictor of freight demand and can be generalized to other regions with similar geographic and infrastructure constraints. This research introduces a novel SEM-based framework for freight analysis in Indonesia and offers policy insights for integrating road infrastructure planning with regional development strategies.

Keywords: Road network connectivity; Commodity flow forecasting; Regional development; Structural equation modeling; Latent variable analysis

1 Introduction

The development of a region is inseparable from an efficient transportation system and a well-connected road network. Transportation supports economic growth by balancing supply and demand and facilitating the smooth flow of goods and services [1]. Additionally, an integrated, well-connected system can establish relationships with other regions, attract investment, and create employment opportunities.

Aceh Province plays a strategic role in the Indonesian economy, particularly in trade and commodity distribution [2]. This excellence is both a source of pride and a responsibility. The province is renowned for its high-quality commodities, including coffee, palm oil, and spices. These commodities are crucial for meeting local and national demand [3–6]. Efficient connectivity is essential to ensure that these commodities can be marketed effectively.

The movement of goods in Aceh Province is dominated by road transportation, accounting for 95% of total goods movement in the region [7]. This finding indicates a strong reliance on land transport as the primary means of commodity distribution. Aceh Province is the northernmost province on Sumatra Island, and its only land border is with North Sumatra Province. Road transport between the two provinces accounts for 90% of outbound and inbound goods movement [8]. This underscores the importance of a well-maintained road network for smooth goods distribution.

Goods such as food, clothing, building materials, and industrial supplies travel from North Sumatra to Aceh via the eastern and western road corridors. Conversely, agricultural, plantation, and fishery products from Aceh are sent to North Sumatra along the same eastern and western corridors. Only a small portion of goods use the central corridor.

The distribution pattern highlights significant challenges in Aceh, where logistical activities rely on neighboring provinces due to poor internal road connectivity. Inadequate infrastructure reduces transportation efficiency, drives up commodity prices, and limits market availability. These issues underscore the importance of improving and maintaining road infrastructure to support economic activity and regional development.

A previous study examined freight transportation to assess the effect of RNC on delivery efficiency [9]. While that study confirmed a significant impact of connectivity on delivery efficiency, it did not consider the broader implications for regional economic development. Therefore, this study incorporates regional development as a key variable, which is essential for unlocking Aceh's economic potential.

The main objective of this research is to analyze the effects of road connectivity on freight transportation and regional economic development. The methodological approach is expected to produce a forecasting model that will assist Aceh in planning future commodity transportation. This model supports evidence-based planning and is designed to help government agencies and policymakers anticipate future transportation needs.

2 Literature Review

Transportation of goods is a crucial aspect of supply chain management in an increasingly globalized economy [10]. Transportation networks facilitate the movement of goods from suppliers to consumers; they include roads, railways, ports, airports, and other supporting infrastructure that links production locations to consumer markets.

After the 2004 tsunami, Aceh Province needed alternative routes because the main roads were damaged. Research by Saleh et al. [11] indicated that these routes played a significant role in transporting people and goods during the post-tsunami reconstruction. In the years since, continuous improvements to road infrastructure have significantly enhanced connectivity between Aceh's cities and rural areas, paving the way for the province's development.

According to Bryan et al. [12] and Cascetta and Pagliara [13], ports serve as marine transportation hubs and play an increasingly significant role in economic development by enhancing intermodal and multimodal transportation. They can facilitate the smooth movement of goods to regional and international markets when infrastructure is well-connected and in good condition. Reliable transportation increases trade benefits and reduces transportation costs and transit times.

Galambos et al. [14] emphasize that shifting freight from road to alternative modes such as rail and waterways is an important strategy for relieving pressure on the road network. This strategy is particularly relevant for Aceh Province, which faces infrastructure and regulatory challenges in optimizing maritime and rail transport to support more efficient and sustainable commodity distribution.

However, Pramoedya et al. [15] reveal that the government does not prioritize sea and rail freight due to inadequate infrastructure, insufficient facilities, and limited regulatory frameworks. Consequently, road transport remains the most efficient option for moving goods. Saleh et al. [16] report that 95% of freight transportation in Aceh Province relies on road transport.

Kulińska [17] states that developing logistics infrastructure is crucial for ensuring the smooth flow of goods and services, emphasizing its role in efficient logistics operations. This aligns with Shramenko et al. [18], who highlight that decision making in green logistics is significantly influenced by transportation infrastructure development, which serves as the foundation for the efficiency, sustainability, and effectiveness of the overall logistics system.

Soti et al. [19] identify key indicators for sustainable freight transportation: government subsidies, load factors, and noise pollution. Government subsidies help reduce operational costs and encourage the adoption of environmentally friendly technologies. Load factor, a measure of vehicle occupancy, improves logistics efficiency and profitability. Noise pollution, due to its impact on quality of life and public health, makes its reduction a priority in developing sustainable transportation. Managing these indicators affects not only the sustainability of transportation but also its efficiency and contribution to regional economic development.

Therefore, improving land transportation infrastructure is crucial for supporting economic growth and enhancing access, particularly for the region's road network connectivity. Wicaksono et al. [20] argue that rising economic activity across various sectors drives increased transportation demand, contributing to GDP growth. This view is supported by Liu [21], Chu and Liu [22], and Gao et al. [23], who report that freight transportation has a positive and significant effect on GDP. Thus, connectivity is a key element in Aceh's development strategy.

Wang et al. [24] examined the relationship between freight transportation and economic development by measuring changes in freight traffic turnover in 30 Chinese provinces from 1997 to 2017. They found an inverted U-shaped relationship between per capita goods traffic turnover and economic development, suggesting that transportation efficiency improves at higher development levels, reducing the need for larger transport volumes.

Lakshmanan [25] and Limão and Venables [26] also argue that good connectivity is vital for regional development and efficient goods distribution. Therefore, improving connectivity infrastructure is essential to stimulate development and enhance the efficiency of the goods distribution system.

Fithra et al. [9] analyzed the effect of road network connectivity on goods delivery in Aceh's northern zone. Because their focus was limited to this zone, the results cannot be generalized to the entire province or to areas with differing geographical or infrastructure conditions. The study considered variables such as road network connectivity and freight transportation, indicating that connectivity is significantly related to freight transportation. They found that improved road network connectivity strongly influences regional development activities, boosts community productivity and productive land use, and facilitates the establishment of economic zones.

Based on a comprehensive literature review, most prior studies have focused on isolated aspects, such as road network connectivity, commodity distribution, or their impacts on economic development, without integrating these dimensions into a unified analytical framework. Moreover, research on Aceh has generally been descriptive and geographically narrow, lacking a comprehensive quantitative approach.

This study bridges that gap by expanding the study area and using a quantitative method that integrates the three main variables. Using Structural Equation Modeling (SEM), this research also lays the groundwork for a logistics forecasting model based on population and commodity volumes. This model can be generalized and applied to other provinces with similarly challenging geography and infrastructure disparities.

Table 1 summarizes and compares key studies on freight transportation and regional development. Each study is classified by research focus, main findings, and its relevance to transportation planning and policy in Aceh. This table is a strategic reference for building research arguments and supporting an empirically grounded SEM framework tailored to the context.

Table 1. Summary and comparison of key studies literature

No.	Study/Author(s)	Research Focus	Main Findings	Relevance to Aceh
1	Saleh et al. [11]	Role of alternative roads after the tsunami	95% of freight relies on road transport; alternative inland roads are critical	Highlights the importance of remote inland connectors for Aceh's logistics recovery
2	Pramoedya et al. [15]	Agricultural commodity movement	Strong relationship between agricultural output and freight volume	Supports commodity-based freight forecasting for key Aceh products
3	Saleh et al. [16]	Reducing road maintenance costs via multimodal policy	Multimodal reduces costs from overdimensioned/overloaded trucks	Supports integration of road-sea transport modes to ease burden on Aceh's road network
4	Fitra et al. [9]	RNC and FT in northern Aceh	FT significantly mediates RNC-RD relationship	Forms theoretical basis for expanding SEM across the entire Aceh province
5	Archetti et al. [10]	Optimization in multimodal freight transport	Efficient mode choice based on network conditions	Guides mode selection between road and sea for Aceh's logistical challenges
6	Galambos et al. [14]	Urban freight sustainability initiatives	Policy, technology, and collaboration key to urban logistics efficiency	Relevant for Aceh's urban centers (e.g., Banda Aceh, Lhokseumawe)
7	Cascetta and Pagliara [13]	Public engagement in transport planning	DAD (Decide-Announce-Defend) limits stakeholder participation	Encourages inclusive planning for Aceh's logistics systems
8	Wicaksono et al. [20]	Transportation infrastructure and GDP	Fleet size and infrastructure strongly influence GDP	Empirical macro-level evidence supporting FT $\rightarrow$ RD hypothesis
9	Soti et al. [19]	Sustainable freight indicators	SEM result Key indicators: subsidy, load factor, infrastructre	Source for constructing latent variables in CFA (Confirmatory Factor Analysis)
10	Sreelekha et al. [27]	Road connectivity and spatial patterns	Highly connected roads foster spatial development	Theoretical basis for RNC variable in this study
11	Lakshmanan [25]	Economic impacts	Transport boosts agglomeration, innovation, and growth	Theoretical foundation for SEM-based economic linkage modeling
12	Limão and Venables [26]	Infrastructure, geography, and transport costs	Poor infrastructure increases costs	Explains why infrastructure is crucial for overcoming geographic isolation in Aceh

2.1 Concept of Freight Transportation System

The freight transportation system is crucial for ensuring the availability of goods for production and consumption across various locations; its objective is to optimize distribution and support economic growth. In this context, road freight transportation stands out as a primary mode, relying on extensive road infrastructure and diverse vehicle types [28].

The road network is the backbone of inland freight transportation, encompassing major highways, local roads, and supporting infrastructure such as bridges and tunnels. The quality of this network greatly affects the speed, safety, and cost of shipping goods; good roads enable fast, reliable delivery, while inadequate infrastructure leads to delays and higher expenses [29].

Vehicles used in road freight transportation vary widely, from small trucks to large tractor-trailers. Each type has different capacities and specifications, such as maximum carrying capacity and fuel efficiency, and is selected based on cargo type and travel distance. Specially outfitted vehicles may be employed for perishable or high-value goods to ensure shipment safety and reliability [30].

Logistics management for inland freight transportation encompasses planning, execution, and control of goods flow from origin to final destination. It involves inventory management, route optimization, and delivery scheduling. Effective communication among shippers, carriers, and receivers is crucial for a smooth logistics process [31].

To anticipate future freight transportation needs, it is essential to analyze freight movement patterns, specifically demand and supply dynamics, drawing on economic principles. By examining demand trends and excess supply, decision-makers can plan and manage freight transport with greater accuracy [32].

Economic models applied to freight movement analysis can forecast demand fluctuations and identify opportunities to improve transportation efficiency [33]. For example, understanding price elasticity of demand and shifting market conditions allows companies to adjust shipping strategies to maximize profits and operational efficiency. A road freight transportation system encompasses physical infrastructure and vehicles, logistics management, and economic analysis. Effective integration across these components is vital for achieving the system's primary objective: timely, efficient, and cost-effective goods availability to meet evolving market needs.

2.2 RNC

The road network is integral to a region's transportation infrastructure, connecting growth centers with surrounding areas. According to Indonesian Law No. 38 of 2004 [34] concerning roads, the road network is defined as a system that integrates various key points in a hierarchical order to deliver effective and efficient transportation services.

Sreelekha et al. [27] argue that the road network is a key factor in regional development, highlighting the importance of connectivity measures for evaluating the strength of relationships between road segments. In this context, connectivity refers to the network's ability to provide direct and continuous routes between destinations. Networks with many short links, optimized intersections, and few dead ends enable more efficient movement of goods and people.

Ferjani et al. [35] state that inadequate network infrastructure, such as a lack of multimodal terminals, can hinder the adoption of alternative transportation modes and reduce the efficiency of goods distribution. Developing road network connectivity is necessary to optimize transitions among land, water, and rail transport modes.

Suprayitno [36] emphasizes that connectivity quality is crucial for assessing how well nodes in a road network are linked. He suggests measuring this quality by comparing the existing network's performance against an ideal, albeit unattainable, standard. Similarly, Karkula [37] highlights that transportation networks link logistics subsystems involved in commodity movement. These networks connect production, storage, and consumption zones, consolidating separate subsystems and facilitating the exchange of goods.

Road network connectivity can enhance economic activity. Eshitera et al. [38] find that regions with higher road network density tend to exhibit stronger indicators of regional economic growth. Previous research shows that economic activity, as measured by nighttime luminosity, increases in areas where road infrastructure is well developed [39]. Moreover, urban luminosity data correlates most strongly with industrial-sector GDP [32].

This combined analytical approach enables policymakers and infrastructure planners to evaluate and improve existing road networks based on current conditions and future requirements. It also supports the development of more effective road-network policies that positively impact economic growth, community mobility, and access to essential services across regions.

2.2.1 The way road network connectivity impacts economic activity

Firstly, the presence and good condition of roads around freight origin sites can streamline freight transportation [40]. Agricultural, plantation, and farming commodities are usually supplied from rural areas, where roads may be absent or in poor condition due to financial and technical constraints [40].

Secondly, a connected road network can support an efficient supply chain. Developed transportation infrastructure accommodates high-capacity vehicles, decreasing unit transportation costs [41, 42]. High-capacity roads can be used by vehicles such as tractor-trailers and double-trailer trucks. In addition, road connectivity can reduce travel time [42], which affects unit costs such as driver, fuel, and asset expenses.

Moreover, connectivity enables the creation of strategic hubs [43]. These hubs collect freight from nearby locations and consolidate shipments from different origins. Connectivity also streamlines transportation routing [43], allowing multiple shippers to share the same trucks and call at several origin points. Efficient routing reduces empty runs, thereby lowering unit transportation costs.

Thirdly, road connectivity can link freight suppliers with more traders, enabling suppliers to expand their networks and set prices more freely [44].

Fourthly, tourism can develop due to improved road connectivity. Previous research finds that tourism sites, such as natural and historical attractions, have grown following enhanced network connectivity [45].

2.2.2 Regional development to enhance transportation connectivity in Aceh Province

Regional development in Aceh Province has shown significant progress in recent years despite ongoing challenges in connectivity, infrastructure, and economic distribution. As a province with a vast territory and diverse topography, Aceh has three main land transportation routes: the Northeast Coast, the West–South Coast, and the Central corridor. These routes connect inland areas such as Central Aceh, Bener Meriah, and Gayo Lues District. Most districts and cities in Aceh lie along these corridors, stretching from Banda Aceh to the border with North Sumatra Province.

The Government of Indonesia and the Aceh Provincial Government continue to enhance road networks by linking the West-South Coast corridor (Indian Ocean side) to the East Coast corridor (Strait of Malacca side) via the Central corridor. These three corridors play a vital role in supporting the movement of goods and passengers, although challenges such as damaged roads, narrow lanes, and frequent congestion persist [1].

According to data from the Ministry of Public Works and Housing (PUPR), the length of national roads in Aceh increased from 1,800km in 2014 to 2,100 km in 2023. However, the western and eastern cross-Sumatra routes still face obstacles that directly impact the regional economy, including high logistics costs due to long travel times.

The construction of the Banda Aceh–Sigli toll road has had a major impact on transportation efficiency in Aceh. This toll road significantly reduces travel time, enabling faster goods distribution and lowering logistics costs. This improvement strengthens the competitiveness of local products such as Gayo coffee, palm oil, and fishery products. In the future, integrating the toll road with other modes of transportation is expected to promote further inclusive and sustainable economic development [46].

The importance of transportation infrastructure in enhancing connectivity and reducing logistics costs in geographically isolated areas aligns with Rodrigue et al.'s theory [47]. This theory emphasizes that transportation infrastructure serves as a key catalyst for bridging economic and social distances in peripheral regions. Improvements to the national road network and construction of the Banda Aceh–Sigli toll road provide empirical evidence of how better accessibility accelerates the movement of goods and people, thereby supporting local economic growth.

In addition to road transportation, ferry services function as the primary mode connecting mainland Aceh to surrounding islands such as Weh Island (Sabang City), Simeulue Island (Simeulue District), and the Banyak Islands (Aceh Singkil District). Aceh has eleven ports of varying categories, reflecting the importance of maritime transportation in the region. Sub-regional maritime connections have developed through commercial shipping networks and traditional sea routes. Cargo loading and unloading occur at a few ports with limited facilities, such as Sabang, Malahayati, and Lhokseumawe. Major factories like PT Arun (natural gas), PT AAF, and PT PIM (fertilizer) operate dedicated ports to support export activities.

Infrastructure development in Aceh provides significant opportunities to drive economic growth and reduce dependence on North Sumatra Province. With the presence of the Arun Special Economic Zone and the development of Krueng Geukueh Port, Aceh has great potential to become an economic hub in ASEAN, particularly in anticipation of the opening of the Thailand Kra Canal. The relevance of Aceh's regional development can also be analyzed through development theories.

In the aviation sector, Aceh has eight well-managed airports. Sultan Iskandar Muda (SIM) International Airport, about 15 km from Banda Aceh, has a runway 3,000 m long and 45 m wide. In addition to serving as the main passenger hub, the airport plays a crucial role in freight transport, particularly for Aceh's key commodities. It has been upgraded to accommodate Hajj and Umrah flights and to enhance connectivity with other regions in Indonesia and neighboring countries. Smaller airports, such as Cut Nyak Dhien in Nagan Raya District and Maimun Saleh in Sabang City, have been developed to support logistics distribution and community mobility in remote areas [8].

Development in Aceh is also supported by the concept of social capital [48], which emphasizes the importance of community networks in sustaining infrastructure and resource management. Aceh's Islamic values and community solidarity serve as social capital that underpins successful regional development.

2.3 SEM

SEM is a statistical technique that directly analyzes the relationships between latent constructs and their indicators, among latent constructs themselves, and with measurement error [49]. In SEM, model identification falls into four categories [50]:

(1) Under-Identified: The number of parameters exceeds the available data points ($df < 0$), making the model unfit for analysis.

(2) Just-Identified: Parameters equal data points (df = 0); the model fits perfectly but cannot be statistically tested.

(3) Over-Identified: Parameters are fewer than data points ($df > 0$), allowing for model testing this is the ideal condition for SEM.

SEM requires an over-identified model to allow valid estimation and model testing. Under-identified models are avoided due to lack of analytical validity.

2.3.1 CFA

Each of the two types of variables used in SEM requires a distinct analysis. CFA assumes that observed variables are imperfect indicators of underlying latent constructs. Measurement (or factor) models focus on how observed variables represent latent constructs by capturing metrics of the latent variable through multiple indicators that correlate with its true values.

In CFA, the model is specified before analysis: the number of latent variables and their effects on observed variables are predetermined. Some direct effects can be fixed at zero or a constant, measurement errors may be correlated, and the covariances among latent variables can be freely estimated or constrained, requiring parameter identification. The adaptable CFA model effectively analyzes ordinal data, such as public perceptions. Research using CFA identifies the most influential indicators of each latent construct.

SEM's comprehensive framework models cause-and-effect relationships among latent constructs while simultaneously accounting for measurement error and observed indicators. The structural equation model is defined as:

$$h_t = Bh_t + Gx_t + z_t \tag{1}$$

The measurement model analyzes the relationships between observed indicators and their latent variables:

$$y_t = Lh_t + e_t \tag{2}$$

The structural model describes three types of relationships in a set of multivariate regression equations: among latent factors, among observed variables, and between factors and non-indicator observed variables. These relationships are expressed as linear regression equations for factor-dependent and continuously observed dependent variables.

2.3.2 Goodness of fit (GoF)

The GoF index in SEM requires adjusting each parameter estimated from observational data to standard reference values. It evaluates the feasibility of empirical models based on observed data. Model eligibility is determined by the standards set out in the index [51]. The index measures the fit between the hypothesized model and the collected data. It determines whether the model accurately represents the relationships observed in the data. GoF requirements are presented in Table 2.

Table 2. GoF indices and the recommended cut-off values in SEM analysis [52]

GoE Index	Variables	Recommended Values
RMSEA	The Root Means Square Error of Approximation	< 0.100
CFI	The Comparative Fit Index	> 0.900
GFI	The Adjusted GoF	> 0.900
AGFI	The Adjusted GoE Index	> 0.900

3 Methodology

This study employs two complementary methodological approaches to achieve the research objectives. The analysis adopts a quantitative research design that combines primary data (questionnaire-based surveys) with secondary data.

The first approach focuses on developing a predictive model of trip generation and attraction to investigate commodity flow patterns between regions. A multiple linear regression analysis was initially employed to assess the combined effects of population size (X_1) and gross regional domestic product (GRDP) (X_2) on the number of commodity trips (Y).

All variables were obtained from the Aceh Provincial Statistics Department, which provides population data and freight volume statistics across administrative regions. The selection of these variables is grounded in empirical evidence that indicates a strong correlation between population growth and freight-movement intensity, as highlighted in studies by Chun et al. [53], Lwin et al. [54], and Taena et al. [55]. Population size is used as a proxy for regional demand and consumption potential, while the number of trips represents ongoing logistics and distribution activities.

Table 3. Summary of total population and sample

No.	District/City	Population	Sample
1	Simeulue	92,865	7[3]
2	Aceh Singkil	126,514	10
3	South Aceh	232,414	18
4	Southeast Aceh	220,860	17
5	East Aceh	422,401	32
6	Central Aceh	215,576	16
7	West Aceh	198,736	15
8	Aceh Besar	405,535	31
9	Pidie	435,275	33
10	Birenen	436,418	33
11	North Aceh	602,793	46
12	Southwest Aceh	150,775	11
13	Gayo Lues	99,532	8
14	Aceh Tamiang	294,356	22
15	Nagan Raya	168,392	13
16	Aceh Jaya	93,159	7
17	Bener Meriah	161,342	12
18	Pidie Jaya	158,397	12
19	Banda Aceh	252,899	19
20	Sabang	41,197	3
21	Langsa	185,971	14
22	Lhokseumawe	188,713	14
23	Subulussalam	90,751	7
	Total	5,274,871	400

Table 4. Indicators of latent variable

Indicator	Description
Road Network Connectivity (RNC/X)	
RNC1	Road Structural Integrity
RNC2	Roadway Condition
RNC3	Road Maintenance
RNC4	Traffic Volume
RNC5	Traffic Speed Limit
RNC6	Vehicle Type
RNC7	Infrastructure
RNC8	Demand and supply
RNC9	Travel Safety
Regional Development (RD/Y_1)	
RD1	Economic Growth Aspect
RD2	Human Resource Development Aspect
RD3	Land Use Improvement Aspect
RD4	Environmental Protection Aspect
Freight Transportation (FT/Y_2)	
FT5	Regulation
FT6	Retribution
FT7	Insurance
FT8	Freight Business Operators
FT9	Truck Drivers
FT10	Freight Transportation Cost
FT11	Cargo Volume
FT12	Travel Distance
FT13	Travel Time
FT14	Timeliness
FT15	Type of Goods
FT16	Loading and Unloading System

Following the regression results, the final model was simplified to a linear regression model for predictive purposes. The rationale was to isolate population size as the primary predictor of freight flow volumes. Thus, the model offers a framework for understanding how demographic and economic indicators influence freight transportation dynamics across regions.

The second analytical model was developed using SEM. Its purpose is to examine relationships among road connectivity, freight transport, and regional development. A questionnaire-based survey using a five-point Likert scale was employed to capture respondents' perceptions of each indicator associated with the study variables.

Respondents were selected via stratified sampling using the Slovin equation, based on a total population of 5,274,871 in Aceh Province, Indonesia. The target population includes stakeholders in commodity movement across 23 districts and cities, such as logistics stakeholders, traders, and truck drivers. However, due to limited data on this specific group, the total population was used as an approximation for sampling (see Table 3).

Moreover, the SEM model consists of three latent constructs: Road Network Connectivity (X) as an exogenous latent variable, and Regional Development (Y_1) and Freight Transport (Y_2) as endogenous latent variables. These constructs are operationalized through multiple indicators derived from theoretical frameworks, operational definitions, national regulations, and prior empirical studies.

Relevant regulatory references include Ministry of Transportation Regulation No. 18/2021 [56], Government Regulation No. 79/2013 [57], and Ministry of Public Works and Housing Regulation No. 13/2024 [58]. In addition, indicators were informed by previous research conducted by Soti et al. [19], Wang et al. [24], and Fithra et al. [9]. The complete list of measurement indicators is provided in Table 4.

Finally, the model's validity and reliability are assessed using the GoF, which includes several conformity indices and cut-off values. These indices are calculated to evaluate the model's overall fit during the estimation process and to assess whether it meets requirements for the suitability test.

4 Result and Discussion

In this study, data analysis was conducted using the Statistical Package for the Social Sciences (SPSS) version 26.0 and Analysis of Moment Structures (AMOS) version 26.0. Descriptive statistics were employed to summarize the demographic characteristics of the respondents. Confirmatory Factor Analysis (CFA) was conducted to assess the measurement model's validity and reliability, while SEM was applied to examine the structural relationships among the latent constructs.

4.1 Movement Patterns

Based on the analysis of the questionnaire data, the percentage of commodity types transported from both Eastern Aceh Province and areas outside Aceh Province shows significant variation, while the agricultural sector is the most substantial contributor to commodity movements in the region, reflecting high production and distribution activities, as illustrated in Figure 1.

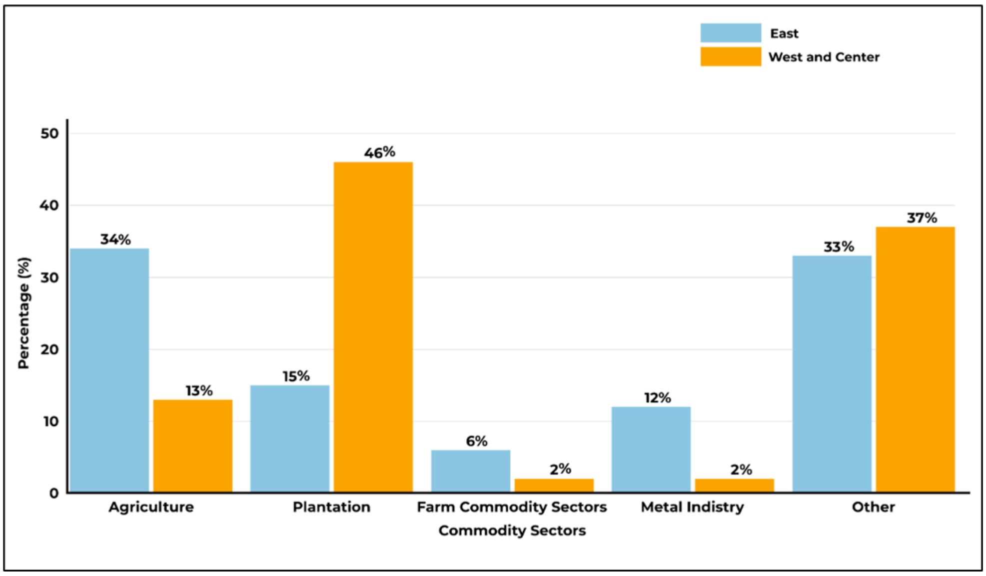

Figure 1. Distribution of commodities transported across regions in Aceh Province

Figure 2 illustrates the frequency of transit trip deliveries in the region. The majority of transit trips occur twice per week, an optimal frequency for many entrepreneurs because it allows them to efficiently meet market demand in terms of cost and time. On the other hand, the lowest frequency may reflect shipments of commodities with lower demand or longer routes.

Figure 3 shows that the highest percentage of commodity transporters operate with a capacity of more than 15 tons (77%). This figure indicates that most regional commodity transporters have large capacities, reflecting the high volume of goods transported on each trip. High capacity is associated with commodity delivery efficiency, as bulk transportation reduces trip frequency and operating costs.

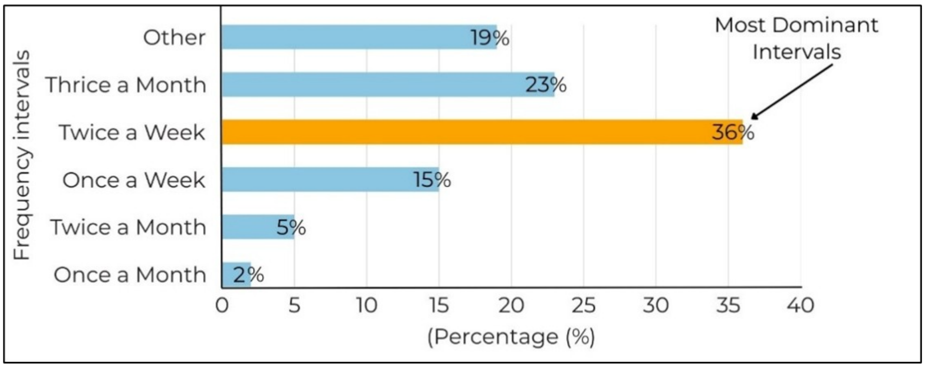

Figure 2. Transit trip frequency

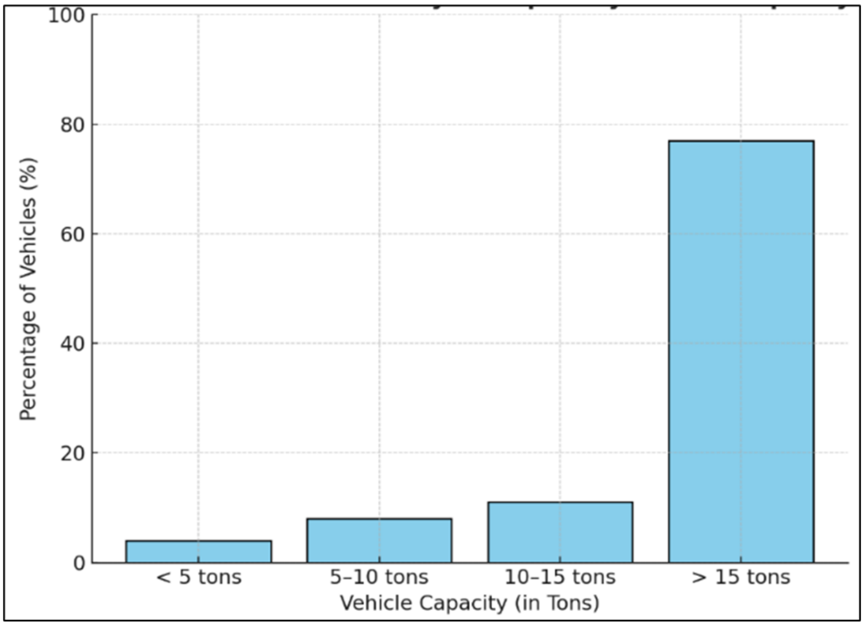

Figure 3. Trip capacity

This study depicts freight movement patterns based on a survey of people involved in freight transportation activities. The data are presented as desire lines, as shown in Figures 4 and 5, to facilitate understanding of freight movement patterns.

This approach was chosen because desire-line visualization allows direct observation and clearer comprehension of goods flows.

Figure 4 shows commodity transportation patterns originating in Aceh Province. The data reveal that most trips originate in Pidie District, with 33 trips recorded. Of these, 29 trips go to Medan; the remaining trips go to Simeulue District, Bireuen, Lhokseumawe, and East Aceh, each receiving one inbound trip. This indicates that Pidie District is the main trip generator in Aceh Province.

This is likely due to factors such as high commodity production in the area. In contrast, South Aceh District generates the fewest trips, with only one trip destined for Simeulue District. This low trip count may reflect limited production volume, inadequate transportation infrastructure, and low demand for commodities from that district.

Aceh Province's highest inbound commodity transportation originates from North Sumatra Province, as shown in Figure 5. There have been 125 trips; the details of the trip distribution are in Table 5.

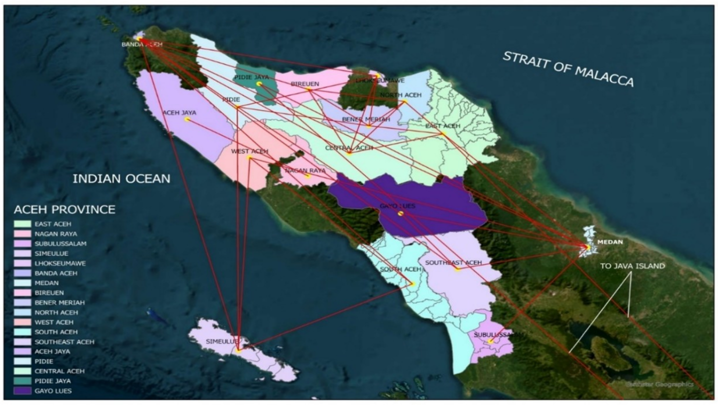

Figure 4. Desire line map of commodity movements from Aceh Province

Figure 5. Desire line map of commodity movements from North Sumatra

Table 5. Summary of total population and sample

Region	Inbound Trips	Explanation
Pidie Jaya	5	Indicates significant commodity transportation activity, though the number is smaller compared to other regions.
Pidie	28	Signifies its importance as one of the main destinations for commodities transported from North Sumatra.
Bireuen	27	One of the main destinations in Aceh Province after Pidie, with a relatively large volume of inbound trips.
Banda Aceh	5	As the provincial capital and economic centre, it has fewer inbound trips compared to other areas.
North Aceh	19	Indicates a sizable volume of commodities transported to this area.
East Aceh	17	Reflects active trade activity in the region.
Lhokseumawe	2	The small number of inbound trips, influenced by infrastructure factors and specific local demand.
Simeulue	9	Shows a steady demand for commodities on this island.
West Aceh	4	Indicates more limited commodity trade activity compared to other districts.
South Aceh	7	Reflects moderate commodity trade activity compared to other regions.
Subulussalam	2	Limited commodity trade activity, showing smaller inbound trip volumes compared to other regions.

4.2 Commodity Attraction and Demand Model

This section describes the research results based on data analysis using SPSS. Multiple linear regression analysis was used to examine the effects of population size (X_1) and gross regional domestic product (GRDP) (X_2) on goods attraction (Y). The following data were obtained from the analysis.

This study covers 23 districts and cities, which were grouped into 14 regions based on administrative divisions in Aceh Province and the surrounding province. Banda Aceh City, Sabang City, and Aceh Besar District were combined into one region. Langsa and East Aceh were combined into another region. Singkil and Subulussalam Districts were merged into a region centered on Subulussalam District. Southwest Aceh District currently produces no outbound freight transportation. This highlights the economic and goods production conditions in Southwest Aceh District. The results are shown in Table 6.

Table 6. Summary of total population and sample

N	Min	Max	Mean	Std.Deviation
		Number of trips		
S 14	1	28	9.29	9.48
A 14	1	29	7.57	8.37
		GRDP		
N 14	7,485.86	19,932,645.17	6,535,631.40	6,589,975.8
A 14	5,401.59	19,932,645.	5,516,543.55	6,818,4102
		Total population		
N 14	78,366	56,8807	316,234.64	168,951.92
A 14	78,366	568,807	291,908.57	177,094.96

Note: N (North Sumatra); A (Aceh)

The results of including two independent variables in the calculation and model calibration are presented in Table 7. These results indicate that only the total population variable (X_1) significantly affects the attraction of goods both from North Sumatra Province to Aceh Province and from Aceh Province to North Sumatra Province.

Table 7. Regression results

	Independent Variable	Coefficient	P-Value	R-Squared	t-Test
N	(X_1)	2.807	0.001	0.587	4.302
A	(X_1)	2.209	0.006	0.456	3.300

Note: N (North Sumatra); A (Aceh); X_1 (Total population)

The table shows the results of the regression model calibration. It indicates that only the total population variable (X_1) significantly affects goods attraction from North Sumatra Province to Aceh Province. Other variables included in the regression model do not have a significant effect. Thus, the regression equation formed from this analysis can be expressed as:

$$Y = 2.807X_1 \tag{3}$$

where,

X_1 = Population (in thousands);

Y = Number of commodity transport trips.

This equation predicts commodity attraction based on the total population value. The regression coefficient for the total population (X_1) is 2.807, which is positive. This means that for every unit increase in population, commodity attraction from North Sumatra Province to the region increases by 2.807 daily trips.

The significance of this relationship highlights population as a key driver of commodity transportation activities. Areas with larger populations tend to have higher commodity demand, which can influence transportation patterns. However, other variables, such as road conditions and income levels, may also act as supporting factors and warrant further analysis.

In addition, the regression equation for goods transported from Aceh Province to North Sumatra Province can be formulated as follows:

$$Y = 2.209X_1 \tag{4}$$

where,

X_1 = Population (in thousands);

Y = Number of commodity transport trips.

This equation predicts commodity generation based on total population. The regression coefficient for total population (X_1) is 2.209, meaning that for every unit increase in population, commodity generation from Aceh Province to North Sumatra Province increases by 2.209 daily trips. While population is an important factor, additional variables such as road infrastructure conditions, income levels, and local economic activity may also impact commodity generation.

The linear regression results demonstrating population's significant influence on commodity trip volumes reinforce the model's foundational premise. Regions with larger populations tend to generate higher volumes of commodity flows, both as origins and destinations. This relationship is reflected in the equations for Models 3 and 4, where the population coefficient may serve as a proxy for a region's economic strength in attracting logistics flows. These findings align with studies by Wang et al. [24] and Soti et al. [19], which emphasize population growth as a key driver of rising logistics demand in developing regions.

However, the analysis also indicates that population alone explains only part of the variance in trip volumes. Accordingly, this study expands its analytical scope by incorporating road network connectivity as a latent exogenous variable influencing both regional development and freight transport volume. This aspect will be elaborated further in Subsection 4.3.

4.3 SEM of Commodity Transportation

In the initial stage of path diagram modeling using the CFA approach, it was found that most indicators did not meet the recommended GoF criteria, indicating that the model did not adequately fit the collected data. Consequently, model modifications were undertaken based on the highest Modification Indices (MI) values.

These modifications involved the removal of indicators with low factor loadings and adjustments to the relationships between latent variables and error terms to enhance model fit. The results of the model fit evaluation after modification are presented in Figure 6.

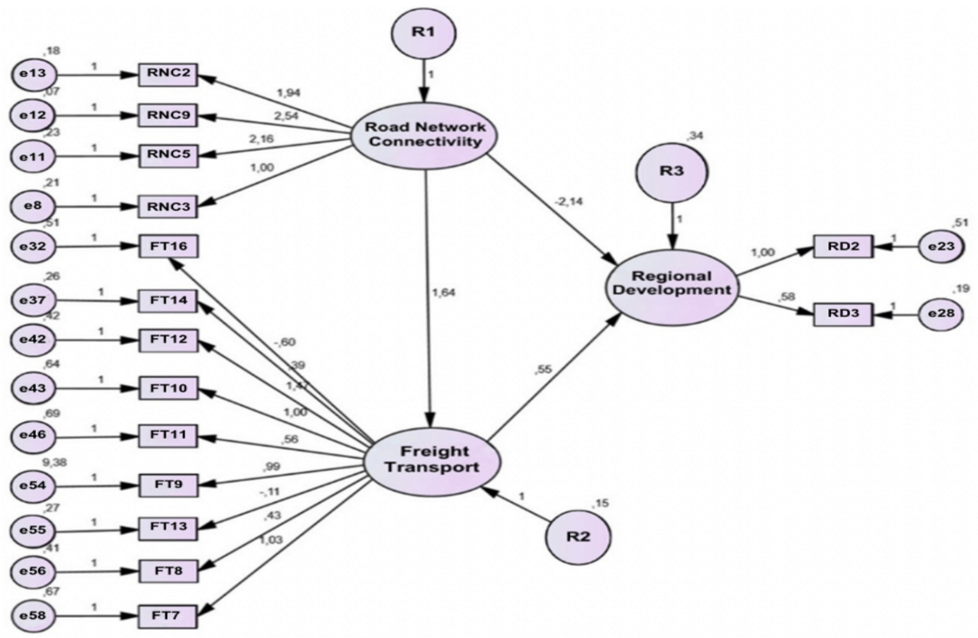

Figure 6. Results of coding with CFA

As shown in Table 8, most indicators used to assess the GoF met the recommended thresholds from the literature, reflecting a substantial improvement in model fit compared to the initial, unmodified model.

Table 8. Regression results

No.	Criteria	Results	Terms	Evaluation
1	GFI (Goodness of Fit)	0.927	> 0.900	Good fit
2	AGFI (Adjust Goodness of Fit Index)	0.900	> 0.900	Good fit
3	CFI (Comparative Fit Index)	0.864	> 0.900	Marginal fit
4	RMSEA (Root Mean Square Error of Approximation)	0.058	< 0.100	Good fit

Based on Table 8, the calculated GoF test values indicate that the model fits well following adjustments to its specification. However, the CFI value of 0.864 suggests a marginal fit, though it still provides valuable insights into the data structure used in the analysis.

Based on Figure 7, the model illustrates how all latent variables are interconnected. Notably, there is a positive relationship between RNC and Freight Transport (FT), underscoring the influence of road infrastructure on the efficiency of freight movement. It shows that transportation infrastructure facilitates the mobility of goods and opens up new areas for trade. This finding aligns with previous research by Fithra et al. [9], which emphasized that road network connectivity significantly contributes to the success of freight transport activities.

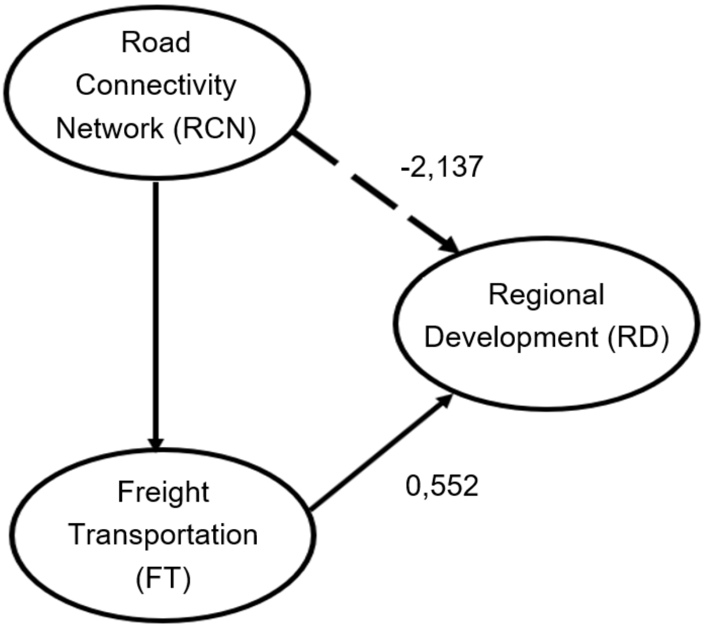

Figure 7. Results of coding with CFA

There is a significant negative correlation (-2.137) between Road Network Connectivity and Regional Development. This finding is somewhat contradictory to several previous studies, such as Eshitera et al. [38], which state that a well-developed road network promotes regional economic growth. Regions with higher road network density tend to exhibit better development indicators. In addition, road development has also been associated with increased nighttime luminosity as an indicator of economic activity [39], which is closely correlated with industrial-sector GDP [32].

This negative result may be attributed to several factors. First, respondents may not directly perceive the benefits of the road network, such as increased income, improved access to services, or local economic growth. Second, there may be disparities in development between regions, with eastern Aceh Province more developed than its western and southern parts, since respondents tend to use routes in the eastern region that are superior in geometry and infrastructure. A similar pattern is observed in Sreelekha et al. [27], who highlight how road network connectivity shapes spatial structure and contributes to regional disparities, as is also evident in Aceh.

Furthermore, the existing road network is not yet fully integrated with economic activity centers and is not supported by equitable development distribution policies, resulting in impacts that do not yet reflect the region's full potential.

Theoretically, improved road connectivity should strengthen economic activity by increasing accessibility, reducing logistics costs, and expanding market reach. Therefore, this finding suggests that respondents may not fully appreciate the strategic role of road connectivity, despite Aceh's heavy reliance on road infrastructure to support regional development. This underscores the need to raise awareness among stakeholders about the critical importance of road infrastructure in promoting sustainable regional growth.

5 Policy and Infrastructure Development Implication

The research findings have implications for policy and infrastructure development. Firstly, the pavement conditions of the roads connecting freight origins and destinations should be good. Based on these research findings, the majority of commodities from Aceh Province are agricultural, plantation, and farm products. The origins of such commodities are typically in the rural areas. The roads in rural areas should be properly paved. As a result, the commodities can be hauled properly from the origin sites. The district and city governments usually fund the local roads. City and district governments should budget funds to maintain roads that serve as initial access routes to these commodity sites. This recommendation directly aligns with previous research [39].

Based on these findings, South Aceh District is the smallest receiver of outbound freight from North Sumatra in Aceh Province. Road conditions between North Sumatra and South Aceh District are typically poor; as a result, transportation costs along this corridor may be high. This is typically due to fuel costs, travel time, and limited fleet capacity. Better road conditions might increase freight transport by reducing these costs.

Secondly, road obstacles between freight transport origin and destination points should be eliminated. For example, on-street parking on primary and collector roads should be removed. Vehicles should use designated parking lots or pockets off the main thoroughfares. Likewise, street vendors must be regulated so traffic can run smoothly.

Thirdly, roadway equipment on routes connecting freight origins and destinations must be properly provided. For example, street lighting and safety equipment should be of sufficient quality. Such equipment can smooth the movement of freight vehicles as they merge with passenger traffic.

Fourthly, hubs should be built near primary roads with direct access to high-capacity routes so that freight can be moved by high-capacity vehicles such as tractor-trailers. These hubs collect cargo from origin points, which is usually carried there by small trucks over local or collector roads. Their existence can reduce freight transport costs through economies of scale. This idea is relevant to previous research [42]; the higher a fleet's capacity, the lower its transportation cost per freight unit [40].

Fifthly, inter-hub corridors should be developed so transporters can consolidate freight from multiple hubs. This idea is also supported by previous research [42]. Trucks can combine loads from several hubs en route to the same destination, reducing empty runs and lowering costs.

Sixthly, the government should upgrade underused freight corridors. For example, the central road corridor of Aceh Province should be improved. Upgrading this corridor would allow freight producers to reach more traders and expand their networks. This idea is relevant to previous research [43].

Seventhly, the government should upgrade roads near potential tourist sites. Previous studies show that road development near tourism locations stimulates tourism and, in turn, boosts economic activity [44]. Such economic activity may further stimulate freight transport in the region.

6 Conclusions

This study emphasizes the influence of road network connectivity in shaping freight transportation patterns and regional development. The agricultural sector emerged as the dominant contributor to commodity movements in the region. The regression analysis further explains that population is a significant determinant of attraction and demand. Densely populated areas tend to become centers for goods distribution and consumption.

Next, the SEM analysis reveals complex relationships among the variables. The model confirmed a positive relationship between RNC and FT, supporting the idea that connected roads enhance freight transport efficiency and flow.

Meanwhile, a negative relationship was observed between RNC and RD. This finding reflects potential biases in respondents' perceptions or contextual limitations. Thus, infrastructure improvements must be aligned with strategic planning that addresses regional disparities and promotes inclusive development.

By integrating SEM and freight forecasting techniques, this research provides a novel empirical framework that links infrastructure quality, logistics performance, and regional growth dynamics. The developed population-based forecasting models offer practical tools for anticipating commodity movement needs, especially in regions where road-based logistics prevail.

However, the study location was limited to Aceh Province, which restricts the generalizability of the findings to other regions with different characteristics. Future research should consider longitudinal approaches, include broader indicators (e.g., accessibility, costs, and socioeconomic data), and conduct comparative studies across regions.

A concrete next step is to conduct longitudinal studies that monitor how improvements in road connectivity affect freight volumes and regional indicators over time. Such time-series data would enable causal inference and dynamic calibration of the SEM models. Additionally, adapting the forecasting models into decision-support systems integrated with GIS would enhance their practical utility in policymaking in other underdeveloped logistics regions.

Author Contributions

Conceptualization, S.M.S., Y.D., and M.I.; Methodology, Y.D. and M.I.; Software, A.D.; Validation, S.M.S., Y.D., and A.D.; Formal analysis, M.I.; Investigation, A.D.; Resources, S.M.S., Y.D., and M.I.; Data curation, Y.D. and A.D.; Writing-original draft preparation, S.M.S. and F.M.; Writing-review and editing, S.M.S., M.A., K.Z., and F.M.; Visualization, F.M.; Supervision, S.M.S.; Project administration, F.M.; and Funding acquisition, S.M.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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