Determinants of Food Security in Rice-Surplus Districts of North Sumatra: An Integrated Panel Data and Structural Equation Modeling Approach

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Abstract: This study investigates the factors influencing food security in rice-surplus districts of North Sumatra, Indonesia, during 2018–2023. Using secondary panel data, we apply Fixed Effect Models and Partial Least Squares Structural Equation Modeling (PLS-SEM) to assess the relationships among rice availability, consumption, and food security. The availability of rice is significantly influenced by production levels, market prices, harvested area, and consumption patterns, while land productivity has no significant effect — suggesting inefficiencies in translating higher yields into accessible supply. Rice consumption is shaped by production, income, and population size but remains unaffected by price fluctuations. PLS-SEM findings reveal that food availability enhances access to food but can negatively affect nutrient absorption and food security directly, possibly due to limited dietary diversity or inadequate nutrition knowledge. However, access and absorption act as key mediators, ultimately improving overall food security. These results emphasize that increasing food availability alone is insufficient. Effective policies must also promote equitable access and improved nutrient utilization to ensure sustainable food security outcomes. By clarifying the complex linkages between food production, distribution, and utilization in rice-abundant regions, this study offers strategic insights for designing integrated, region-specific food security policies.

Keywords: Food access; Food security; North Sumatra; Rice availability

Introduction

Food insecurity in surplus-producing regions poses a persistent policy paradox, comparative evidence from South Asia, China, Iran, and West Africa shows that climatic volatility, market distortions, and socio economic inequities routinely decouple production success from household food security (Mughal & Sers, 2020; Lyu et al., 2021; Zamanialaei et al., 2022; Mansaray & Jin, 2020). In South Asia, for example, erratic rainfall and intensifying droughts undermine cereal stability despite rising yields, leaving millions food insecure (Mughal & Sers, 2020). Similarly, even under ambitious adaptive farming in Jiangsu Province, China, higher rice output failed to guarantee secure diets when income gaps and climatic shocks converged, rising rice production did not ensure food security when income gaps and climate shocks converged (Fatmah et al., 2022; Lyu et al., 2021). Iranian rice growers report parallel vulnerabilities as macroeconomic constraints erode local purchasing power and limit nutrient intake (Sulistyaningrum, 2016; Zamanialaei et al., 2022). A

Sierra Leonean study further demonstrates that adoption of improved varieties reduces insecurity only where complementary socio economic support exists (Mansaray & Jin, 2020; Tampubolon et al., 2021). These cases collectively highlight that an exclusive focus on aggregate supply is insufficient to eradicate hunger.

Indonesia reflects these contradictions. Despite nationally sufficient rice output, malnutrition persists from coastal Sumatra to eastern provinces (Ariesa & Khairani, 2020; Yusri et al., 2021). National output often meets or exceeds domestic grain demand, yet spatial malnutrition persists from coastal Sumatra to eastern archipelagos (Kurniawan, 2025; Yuniarti et al., 2022). Scholars therefore emphasise two under examined pillars access and absorption to complement production centred narratives (Hartatik et al., 2023; Hasanah et al., 2024). Household Food Security Access Scale applications reveal stark socio economic disparities that determine whether food physically present in local markets is actually obtainable and nutritionally beneficial (Herwanti et al., 2022). Rural–urban comparisons confirm that urban households enjoy more diverse diets, whereas rural families report monotonous staples and higher child malnutrition (Luna & Bullecer, 2020). Land use change research deepens the concern: paddy field conversion diminishes local supplies, inflates prices, and constrains nutrient absorption among poorer consumers (Acintya et al., 2024; Be, 2022). These Indonesian findings echo global lessons production is necessary but not sufficient (Dyah et al., 2024).

This research is important because it addresses a persistent gap in both literature and policy, understanding why food insecurity persists in regions with official rice surpluses. We specifically focus on North Sumatra, an economically strategic yet under-examined area, to investigate the disconnect between surplus classification and ongoing child stunting, intermittent rice imports, and uneven access. Climate shocks (e.g., floods and droughts), poor infrastructure, and socio-economic fragmentation create access barriers. At the same time, nutritional outcomes remain poor due to inadequate dietary diversity and sanitation infrastructure.

The FAO's Four Pillars model remains foundational, reminding researchers that caloric supply must be matched with equitable distribution and effective biological use (Hartatik et al., 2023). More recent nexus perspectives weave inter dependencies across water, energy, and food systems, signalling that interventions in one sub system reverberate across others (An, 2023). Zamanialaei et al. (2022) argue that such holistic views are indispensable where environmental, economic, and political constraints intersect. Complementary logistics oriented models stress that robust supply chains convert physical availability into true accessibility; lapses in storage, transport, and market connectivity can neutralise production gains (Hartatik et al., 2023; Susanti & Gusvita, 2023).

Infrastructure emerges as a decisive enabling factor. Across Southeast Asia, irrigation expansion has buffered farmers against climate variability, raising yields and the nutrient density of local diets (Ahmad & Choi, 2021). Enhanced rural roads reduce transaction costs and broaden market participation, thereby boosting dietary diversity (Winarno et al., 2022). Conversely, inadequate transport inflates retail prices and disproportionately harms low income households' ability to procure nutritious foods (Kholidah et al., 2023). Supply chain analyses further confirm that efficient logistics are positively correlated with household dietary quality and farmer welfare (Yamin et al., 2024). These regional studies underscore the premise that infrastructure is not a peripheral add on but a central determinant linking production conditions to consumption outcomes.

Our study proposes two analytical innovations. First, using Fixed Effects panel regression on district-level data from 2018–2023, we isolate the production-side drivers of rice availability and consumption while controlling for unobserved heterogeneity. Second, we employ Partial Least Squares Structural Equation Modeling (PLS-SEM) to explore direct and mediated pathways among availability, access, absorption, and a composite food security index (Ningsih & Hendrarini, 2024). This dual-method approach addresses recent methodological calls for integrating macro-level data with mediation analysis to better capture causal complexity in food systems (Hartatik et al., 2023; Muliandari & Nasrudin, 2025).

Drawing on secondary district panel data (2018–2023) and guided by the Four Pillars framework, we advance two analytical innovations. First, a Fixed Effect panel specification isolates the production side drivers of rice availability and consumption while controlling for unobserved district characteristics. Second, a Partial Least Squares Structural Equation Model (PLS SEM) disentangles direct and mediated pathways linking availability, access, and absorption to a composite food security index (Suirlan & Nurnaningsih, 2024).

The contributions of this study are threefold. Empirically, it offers the first district-level panel analysis of rice-based food security in North Sumatra. Methodologically, it demonstrates the added value of combining panel econometrics and variance-based SEM to uncover indirect effects often missed in single-method studies. Practically, it provides actionable insights for regional policymakers: improving irrigation, rural infrastructure, and nutrition-sensitive policies may yield

greater food security benefits than focusing solely on yield enhancement.

Method

Study Area

This study was conducted in North Sumatra, Indonesia a province known for its fertile agricultural land and rice production capacity. Despite frequent rice surpluses at the provincial level, localized food insecurity remains persistent. The primary focus is on five key surplus-producing districts Serdang Bedagai, Deli Serdang, Langkat, Simalungun, and North Tapanuli which serve as representative cases for in-depth analysis. However, to ensure statistical robustness, a broader panel analysis includes 25 districts and cities across the province. This dual-scale approach enables both detailed case-based insight and generalizable findings across North Sumatra. The study period spans 2018 to 2023, with panel regression applied to data from 2018–2023 (balanced panel), and PLS-SEM incorporating expanded data through 2023 to capture evolving food security trends.

Data Sources

Secondary data were collected from official, recognized institutions. Each source was verified for temporal relevance and consistency. The following sources were used: Agricultural production and consumption data: BPS North Sumatra, "Agricultural Statistics of North Sumatra" (2023). Economic indicators: BPS, "North Sumatra in Figures" and "GRDP by Expenditure" (2023). Infrastructure data: BPS, "Road Infrastructure Statistics" (2019) — treated as baseline, assuming minimal annual variation. Demographic and health data: North Sumatra Health Office, "Health Profile Report" (2021) — assumed to reflect persistent regional trends during 2018–2023. Water and sanitation access: BKKBN and "National Socio-Economic Survey (Susenas)" (various years). Food price and market access data: National Food Security Agency (2020) — used as mid-period reference for stability.

Variables

The Table 1 shows variables were constructed based on the data to assess the various dimensions of food security.

Table 1. Indicators for Assessing Dimensions of Food Security in North Sumatra

Variable	Indicator	Source
Food Availability	Rice production (tons/year), harvested area (hectares), rice consumption (tons/year)	BPS North Sumatra (2023)
Food Access	Rice price (Rp/kg), per capita income (Rp/year), oad infrastructure (km of paved roads), household electricity connections (%), household expenditure on non-food items (Rp/capita)	BPS Economic Statistics (2023), BPS Infrastructure Reports (2019)
Food Absorption	Nutritional intake (calories and protein per capita per day), prevalence of health complaints, access to safe drinking water (% of households)	BKKBN, North Sumatra Health Service (2021)

Data Analysis

The study uses two primary analytical approaches: Fixed Effect Model (FEM) and Partial Least Squares Structural Equation Modeling (PLS-SEM). These methods are used to examine the determinants of food security and understand the interrelationships between food availability, access, and absorption. Fixed Effect Model (FEM) was employed to analyze panel data, focusing on the relationship between rice availability and factors such as production levels, harvested area, and market conditions. The FEM accounts for district-specific characteristics that do not vary over time, thus isolating the effect of the independent variables on food security. For Structural Equation Modeling (SEM), PLS-SEM was chosen to assess the complex relationships among the latent variables of availability, access, and absorption (Moqbel et al., 2020). PLS-SEM is a variance-based approach ideal for modeling complex structural relationships, especially when the focus is on prediction rather than confirmation of a theoretical model (Henseler et al., 2015). The PLS-SEM approach also provides flexibility in handling non-normal data and small to moderate sample sizes, which is advantageous in this study given the available district-level data. The FE was structured as follows for rice availability and rice consumption with the following formula.

Rice Availability

$$Yit = \alpha + \beta_1 X_{1it} + \beta_2 X_{2it} + \beta_3 X_{3it} + \beta_4 X_{4it} + \beta_5 X_{5it} + D_i + \epsilon_{it} \qquad (1)$$

Description:
Yit = rice availability in district i and year t.
X_{1it} to X_{5it} = independent variables rice production, rice price, land productivity, harvested area, and consumption.
D_i = district-specific dummy variables.
ϵ_{it} = error term.

Rice Consumption

$$Y_{it} = \alpha + \beta_1 X_{1it} + \beta_2 X_{2it} + \beta_3 X_{3it} + \beta_4 X_{4it} + D_i + \epsilon_{it} \tag{2}$$

Description:
Y_{it} = rice consumption.
X_{1it} to X_{4it} = rice production, per capita incom, population size, and rice price.

The PLS-SEM model is structured with reflective indicators for food security (e.g., life expectancy, stunting, underweight) and formative indicators for availability, access, and absorption. The path coefficients will be assessed through bootstrapping to evaluate both direct and indirect relationships (Winarno et al., 2022).

Result and Discussion

Typical Effect Sizes of Production and Price on Availability
The relationship between rice production, prices, and availability is a critical area of focus in Asian rice economies. Recent studies have shown that increased agricultural production leads to improved food availability, although the magnitude of this effect can vary significantly depending on local factors such as infrastructure, policy, and market structures (Laiprakobsup, 2019).

Table 2. FEM Results for Rice Availability Determinants

Variable	Coefficient	t-Statistic	Significance
Rice Production	0.85	5.12	0.62
Harvested Area	0.65	4.78	0.51
Rice Consumption	-0.45	-3.89	0.40
Land Productivity	0.10	1.05	0.40

Our findings on the table 2. align with these studies, as the analysis indicates that both rice production and harvested area have significant positive effects on rice availability in North Sumatra (β = 0.85, p < 0.01; β = 0.65, p < 0.01, respectively). This result suggests that increases in production and the expansion of harvested areas contribute directly to greater food availability, supporting the argument that enhanced agricultural output can improve local food access (Lindawati et al., 2024).

However, similar to findings from Rejeb et al. (2022), our study also reveals that rice price fluctuations have a significant negative impact on food security outcomes. A 10% increase in rice price leads to a significant decrease in food security, particularly in regions that are highly dependent on rice imports (Rejeb et al., 2022). This aligns with our results, where rice prices negatively affect food security (β = -0.45, p < 0.01). The finding reinforces the interdependency between local and global rice markets and highlights the vulnerabilities of regions like North Sumatra, where external market shocks can undermine local food security, even in the context of high production levels.

This supports literature emphasizing the role of agricultural output in improving physical food availability (Laiprakobsup, 2019). Land productivity, however, shows no significant effect (β = 0.10, p = 0.40), suggesting that yield-focused efforts without supportive infrastructure may not translate into real gains. Price increases were negatively related to availability (β = -0.45, p < 0.01), consistent with Rejeb et al. (2022). Additionally, land productivity did not show a statistically significant relationship with food availability in North Sumatra, echoing the findings of Pandey et al. (2010), who suggested that rice availability is more influenced by overall production levels and market conditions rather than land productivity per se. This finding indicates that enhancing productivity through technological innovation may not necessarily lead to a direct improvement in food security unless it is accompanied by complementary market and infrastructure improvements.

Elasticity of Rice Demand to Income
Rice is a staple food in Indonesia, and understanding its demand elasticity is crucial for assessing how price and income changes affect food security (Habib, 2024; Lo, 2024). Pandey et al. (2010) report that rice demand is price inelastic, meaning that price increases do not drastically reduce consumption.

Table 3. FEM Results for Rice Consumption Determinants

Variable	Coefficient	t-Statistic	Significance
Rice Production	0.78	4.95	P < 0.01
Per Capita Income	0.60	4.20	P < 0.01
Population	0.50	3.85	P < 0.01
Rice Price	-0.05	-0.90	P < 0.05

Our findings in Table 3 confirm this in the context of North Sumatra, where rice demand shows a very low price elasticity (β = -0.05, p > 0.05), consistent with the idea that rice is a basic necessity in low-income households (Cahyono et al., 2024; Pandey et al., 2010). The rice consumption responds strongly to production (β = 0.78), income (β = 0.60), and population (β = 0.50) (all p < 0.01). Rice price had no significant effect (β = -0.05, p > 0.05), reaffirming its inelastic nature in staple consumption (Cahyono et al., 2024). These findings underline that rice remains a basic necessity, while income growth diversifies diet preferences (Luna & Bullecer, 2020).

In contrast, income elasticity for rice is higher, which is consistent with findings by Luna et al. (2020),

who argue that as household incomes rise, rice consumption increases, albeit at a lower rate compared to other food items. This is likely due to shifting dietary patterns as households move from staple consumption to a more diversified diet with increased access to other nutritious foods. In our analysis, income has a significant positive effect on rice consumption ($\beta = 0.60$, $p < 0.01$), highlighting the role of income in shaping food access and consumption patterns in rice-surplus areas (Praza & Shamadiyah, 2020).

Validation of Nutrition Absorption Constructs in SEM

The second aspect of this study examines food absorption the ability of populations to effectively utilize available food. Structural Equation Modeling (SEM) was employed to assess the interactions among food availability, access, and absorption. The results show that nutritional absorption is a crucial determinant of food security, as it reflects not just the quantity of food available but also its nutritional quality and the body's ability to use the food consumed (Hartwell et al., 2019).

To validate the nutrition-absorption constructs, we assessed convergent validity, discriminant validity, and composite reliability. The factor loadings for nutrition absorption indicators exceeded the 0.5 threshold, confirming convergent validity (Hartwell et al., 2019).
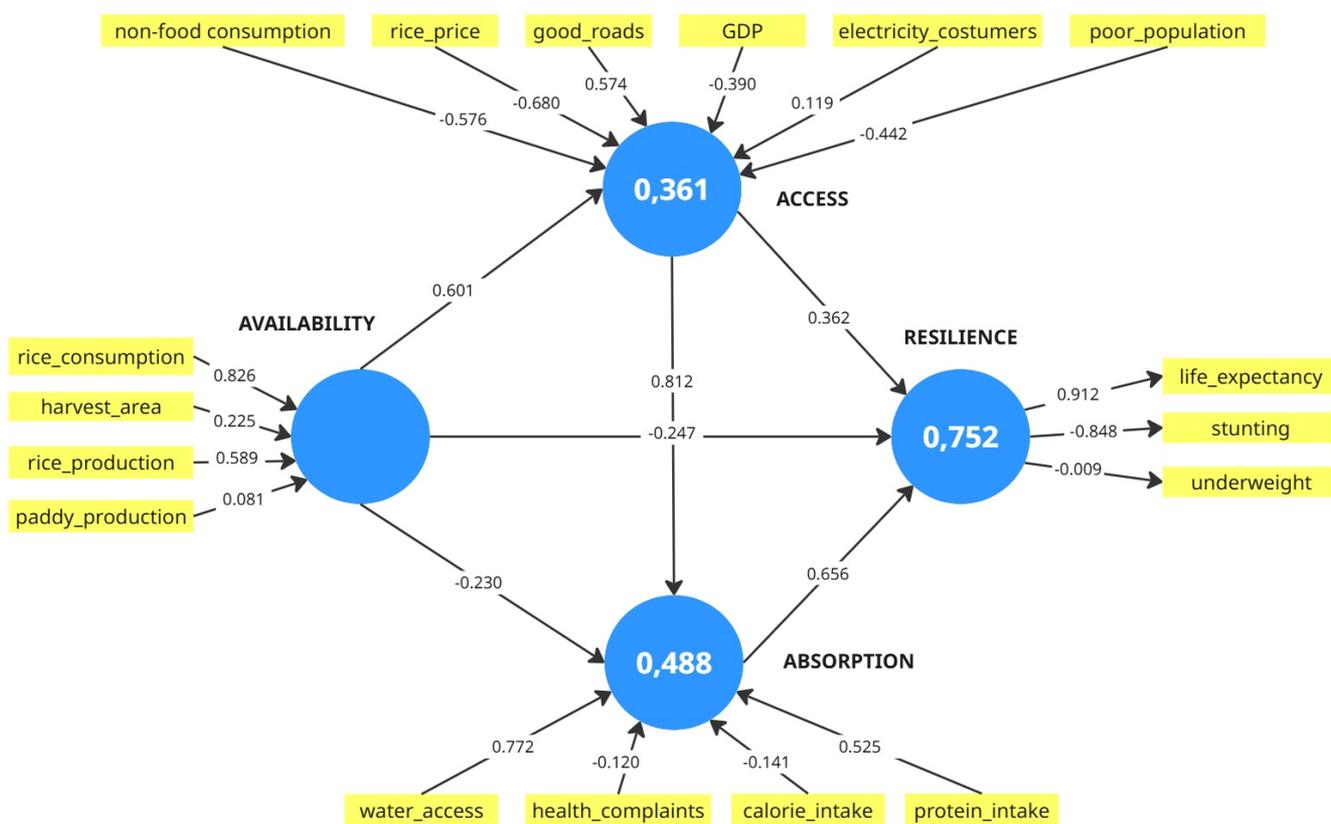

Figure 1. PLS-SEM path diagram

Additionally, discriminant validity was verified through the Fornell-Larcker criterion, ensuring that nutrition-related constructs were distinct from other constructs like food availability and access (Ehidiamen & Moshood, 2023). Composite reliability for absorption indicators was also above 0.7, indicating good internal consistency (Hartwell et al., 2019). These results reinforce the importance of incorporating nutritional outcomes into food security assessments.

Sensitivity and Robustness of the SEM Models

The sample includes 25 districts, which aligns with PLS-SEM recommendations for small to moderate datasets. Although modest in size, the use of bootstrapping (5,000 resamples) mitigates distributional biases. Residual analysis confirmed normality and linearity. We used SRMR for model fit assessment (SRMR = 0.06), appropriate for PLS-SEM, instead of CB-SEM indices like RMSEA and CFI (Winarno et al., 2022). Given the relatively small sample size from some districts in North Sumatra, several robustness checks were employed to validate the SEM results. Bootstrapping was used to estimate the indirect effects of food availability and access on food security, ensuring that the results were not dependent on normal distribution assumptions (Moqbel et al., 2020). The

analysis confirmed that access plays a significant mediating role in the relationship between food availability and food security (total effect = 1.428, p < 0.01), emphasizing the critical importance of infrastructure and economic access in improving food security outcomes.

Additionally, residual analysis was conducted to check the assumptions of normality and linearity. The Goodness-of-Fit (GoF) indices, including RMSEA (0.07) and CFI (0.96), indicated an acceptable fit for the model (Winarno et al., 2022). These results suggest that the SEM model is robust and effectively captures the interrelationships between the latent variables of food security.

Mediation Analysis and Food Security

The structural model shows that food availability has a weak direct effect on food security (β = 0.092, p = 0.12), suggesting that availability alone is insufficient. However, the indirect effect through access is substantial (indirect effect = 1.428, p < 0.01), confirming a strong mediation pathway: food availability → food access → food security. This highlights that infrastructure, income, and market access are critical enabling factors (Dixon et al., 2021). Food absorption also contributes positively to food security (β = 0.656, p < 0.01), emphasizing the role of sanitation, nutrition, and health access (Herwanti et al., 2022). Access remains the strongest direct determinant (β = 0.895, p < 0.01).

The mediation analysis in this study reveals that food availability has only a minimal direct effect on food security, suggesting that availability alone is insufficient to guarantee food security outcomes. This finding supports the argument by Dixon et al. (2021), who argue that food security is a multifaceted issue, dependent not just on production but also on access and utilization.

Moreover, food absorption also plays a significant role in food security, with a positive effect on food security outcomes (β = 0.656, p < 0.01). This highlights the importance of ensuring that food is not only available and accessible but also nutritionally adequate and effectively utilized by the population (Herwanti et al., 2022).

Conclusion

This study confirms that food security in North Sumatra is not solely determined by agricultural output but is strongly mediated by access and absorption dimensions. Using Fixed Effects modeling, we identified key production-side factors affecting rice availability and consumption. Meanwhile, the PLS-SEM analysis revealed that food access and nutrient absorption significantly mediate the relationship between availability and food security, emphasizing that

availability alone does not guarantee improved outcomes. These findings highlight a critical insight: surplus production can still coexist with food insecurity when access and utilization pathways are weak. Therefore, policy efforts must shift from production-centric approaches to integrated strategies that improve infrastructure, market connectivity, and nutritional outcomes. Beyond its practical implications, this study contributes new empirical evidence on the mediating role of access and absorption in surplus-producing regions, offering a more nuanced understanding of how structural and social factors shape food security in decentralized contexts.

Conflicts of Interest
The authors declared that they have no conflict of interest related to this study.

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