



ISSN: 2617-6548

URL: www.ijirss.com



A revisiting regional development efficiency in west sumatra: A dea–bootstrap analysis of infrastructure and human capital quality

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Abstract

This study evaluates how effectively regional inputs—local government expenditures, bank credit, domestic investment, and foreign direct investment—are transformed into economic outputs (GRDP, inverse unemployment rate, and inverse Gini ratio) across West Sumatra's districts and cities for the period 2022–2024. We employ a two-stage quantitative approach. First, Data Envelopment Analysis (DEA) with an input-oriented Variable Returns to Scale (VRS) model measures the relative efficiency of 19 decision-making units (districts/cities) observed over three years (57 observations). Second, Structural Equation Modeling-Partial Least Squares (SEM-PLS) is applied to test the influence of physical infrastructure (road density, water supply capacity, electricity customers, fuel stations) and human capital quality (Human Development Index/HDI) on the DEA efficiency scores. The DEA results reveal significant efficiency disparities, with average efficiency at 88.4%, suggesting potential input savings of 11.6%. Physical infrastructure exhibits a significant negative effect on efficiency ($\beta = -0.350$; $p < 0.001$), while HDI shows a positive but statistically insignificant effect ($\beta = 0.094$; $p = 0.399$). The model explains 12.4% of the variance in efficiency scores ($R^2 = 0.124$). The findings reveal a paradox: increasing infrastructure investment does not necessarily enhance efficiency unless supported by institutional and managerial capacity. Human capital improvements have not yet been fully absorbed by local labor markets. Institutional quality, absorptive capacity, and implementation effectiveness are critical moderators. Local governments should: (1) prioritize institutional strengthening and procurement transparency alongside infrastructure investment; (2) adopt context-sensitive, demand-driven infrastructure projects rather than large-scale expansions where absorptive capacity is low; and (3) align human capital policies with local labor-market needs through vocational training and firm-education linkages to ensure HDI gains translate into productive efficiency.

Keywords: Absorptive capacity, Data envelopment analysis, Efficiency, Human development index, Physical infrastructure.

DOI: 10.53894/ijirss.v9i4.11490

Funding: This study received no specific financial support.

History: Received: 26 January 2026 / **Revised:** 14 March 2026 / **Accepted:** 19 March 2026 / **Published:** 10 April 2026

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Competing Interests: The authors declare that they have no competing interests.

Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Acknowledgments: The authors express their sincere appreciation to Universitas Negeri Padang whose support contributed to the completion of this study.

Publisher: Innovative Research Publishing

1. Introduction

1.1. Research Background

Efficient use of public and private resources has become a pressing concern for sustainable regional development [1, 2]. Despite high growth potential, many Indonesian regions, including West Sumatra, lag behind national averages in productivity and equity, suggesting that inputs are not being fully converted into social gains [3, 4]. Indeed, recent studies document large disparities in local spending efficiency: in Indonesia's lagging districts, expenditure productivity has declined even as poverty and infrastructure gaps persist [3, 5, 6]. Similarly, DEA-based analyses in other developing contexts show that regions with better infrastructure and human capital tend to achieve faster growth and poverty reduction [4]. However, most existing work focuses on individual outcomes (e.g. GDP or health) or on narrow inputs [2] and few studies link government spending together with financial flows (bank credit, domestic and foreign investment) to multi-dimensional performance indicators such as regional GDP, inequality and employment.

In West Sumatra specifically, the simultaneous effects of budget outlays, credit availability and investment on growth and equity have not been examined, nor has the role of infrastructure and human capital in shaping these efficiencies. This gap is critical: as studies in Asia note, improving access to finance (e.g. via credit bureaus) strongly boosts firm-level job growth [7] while foreign investment can reduce income inequality especially where human capital is strong [8]. By neglecting how local governments and markets transform inputs into outcomes, prior research leaves unanswered whether West Sumatra's subnational units are using resources effectively. Addressing this is urgent given Indonesia's decentralization and recent central initiatives to promote inclusive growth; lagging regions require targeted policies to catch up. In short, understanding the efficiency of resource-to-outcome conversion in West Sumatra is novel and urgent, as it can reveal bottlenecks in public spending, credit distribution and investment that are hindering growth, equality and job creation.

1.2. Research Questions

- a. How efficient are West Sumatran districts in converting local government spending, bank credit, and domestic/foreign investment into economic outputs (GRDP), equitable outcomes (inverse Gini), and employment? This question extends prior DEA studies of spending efficiency [9] by including multiple input flows (finance and investment) and output measures beyond GDP.
- b. What explains differences in this efficiency across districts? In particular, do infrastructure quality and human capital (HDI) drive the spatial variation in efficiency scores? This follows findings that socio-economic factors (e.g. literacy, urban density) significantly influence regional spending efficiency [3].
- c. Do districts with strong institutions or higher income per capita exhibit systematically higher efficiency? For example, evidence from Sumatra shows that provinces with higher GRDP per capita and density had significantly higher spending efficiency [9] we ask if similar patterns hold in West Sumatra when broader inputs are considered.

1.3. Objectives

- a. Measure transformation efficiency. Use output-oriented Data Envelopment Analysis (DEA) to quantify how effectively each of the 19 districts turns inputs (per capita government operating/capital expenditures, local bank credit, and domestic/foreign investment inflows) into outputs (GRDP, inverse of unemployment, and the inverse of the Gini index as an equality proxy). By computing these efficiency scores (2022–2024), we will identify which districts lie on the “best-practice” frontier and which have shortfalls, building on approaches used for Vietnamese and Indonesian local governments [9, 10].
- b. Test determinants of efficiency. Apply SEM PLS to relate each district's DEA score to external factors, focusing on physical infrastructure (e.g. road density, electricity access) and human capital (HDI components). This will reveal whether and how infrastructure and education amplify the impact of inputs on outputs. For instance, cross-country evidence suggests that FDI's inequality-reducing impact is stronger in regions with more human capital; our analysis will test analogous synergies at the district level.
- c. Assess multi-output performance. By including inverse Gini and unemployment as outputs (Gini and Unemployment is inherently a negative economic indicator), the study explicitly connects resource use to social outcomes, following

the Sustainable Development Goals. We will evaluate whether districts that generate more GDP per unit input also achieve better equity and job growth, or whether trade-offs exist.

- d. Provide policy guidance. The combined analysis of efficiency and its drivers aims to inform public managers which bottlenecks (e.g. inadequate roads or skills) are most critical. Given that improved credit access significantly raises SME employment growth [7] the study will also comment on financial policies needed to support efficient local development.

1.4. Research Urgency

This research makes several novel contributions. First, it is, to our knowledge, the first district-level analysis in Indonesia that jointly assesses the efficiency of transforming public spending, bank credit and investment into growth, equality, and jobs. Prior studies have measured local fiscal efficiency in Sumatra or Vietnam [9, 10] but rarely with such a broad set of inputs and outputs. Second, by incorporating the inverse Gini ratio and unemployment, we link fiscal/intermediation efficiency to equity and labor outcomes; for example, studies in Asia find that FDI can help reduce inequality especially where human capital is high [6, 8] a nuance we will explore regionally. Third, our use of bootstrap regression to isolate infrastructure and HDI effects on efficiency extends the literature on non-discretionary factors, resonating with findings that literacy and urbanization raise spending efficiency [3]. Finally, the analysis has direct policy implications: identifying underperforming districts and their constraints. As Sugiyarto, et al. [3] emphasize, targeted interventions in infrastructure and socio-economic capacity are crucial for lagging regions. Similarly, Ayyagari, et al. [7] note that credit-market reforms foster job growth. Our results will thus inform West Sumatra's authorities and Indonesia's national planners how best to allocate budgets, attract investment, and build human capital so as to maximize development returns on scarce resources.

2. Literature Review

2.1. Efficiency

Efficient use of limited resources is fundamental to sustainable regional development. In practice, efficiency in regional development means maximizing outputs (economic growth, employment) while also advancing equity and social inclusion [11, 12]. The Data Envelopment Analysis (DEA) framework provides a common method to gauge how well decision-making units (regions or governments) convert multiple inputs into desired outputs. This approach has been widely applied to development contexts (e.g. human development indices) to benchmark relative performance [13]. In addition, human capital theory emphasizes that the quality of education, skills and health ("high-end talent") in a population is a core determinant of productivity and growth [14, 15]. Thus, improving workforce skills and education expands productive capacity, while robust infrastructure (roads, power, telecom) reduces transaction costs and connects markets – both factors that underlie regional efficiency and inclusive growth [16, 17].

Empirical studies of Indonesian regions highlight large efficiency gaps. Using DEA, Prasetyo, et al. [18] find that outside Java most provinces underperform, whereas Jakarta, Yogyakarta and West Java lead in spending efficiency. In particular, they report that larger population, higher government accountability, stronger democracy, more universities, and greater local investment correlate positively with local government efficiency, while sheer area size has a negative effect. Similarly, Sugiyarto, et al. [3] observe that lagging districts (e.g. in eastern Indonesia) tend to have lower expenditure efficiency. Their analysis shows that socio-economic factors such as urbanization, population density and literacy rates all improve efficiency, whereas dependence on central government grants tends to reduce it. In the banking sector, Andani, et al. [19] apply DEA to Indonesia's regional development banks (BPDs) and find that on average BPDs still operate below full efficiency in converting deposits and costs into loans and income. These findings underscore that institutional capacity, fiscal resources and human capital together shape regional efficiency outcomes.

2.2. Infrastructure

A broad macroeconomic literature confirms that physical infrastructure typically boosts economic efficiency. Infrastructure services (roads, highways, airports, communications, energy) reduce trade and transaction costs and enhance mobility, which in turn raises productivity and growth. For example, Arif, et al. [17] estimate Total Factor Productivity (TFP) across Asian manufacturing sectors and show that lagged infrastructure capital – especially telecommunications and power supply – significantly accelerates industrial productivity, whereas road networks matter most for low-tech, labor-intensive sectors. Likewise, a recent review by Pokharel, et al. [16] concludes that transport investments make regions more attractive to economic activity: improved highways and transit networks stimulate new investment and trade, thereby fostering higher regional GDP and urban growth. At the country level, Ruvalcaba [20] analyze Mexico's states and find that regions with more road and airport infrastructure *and* a better-educated workforce tend to grow faster; in fact, their regression results indicate that state-level transportation infrastructure and education each significantly facilitate GDP growth. (These studies also note that infrastructure is most effective when combined with complementary factors like institutions and innovation capacity.) In short, abundant high-quality infrastructure generally underpins greater production efficiency, although its impact can vary with context and absorptive capacity.

2.3. Human Capital

Human capital is similarly pivotal for regional efficiency. Education and skill levels raise labor productivity and innovation, leading to better conversion of inputs into outputs. For instance, Annabi [14] model Canada's growth and find that higher government spending on tertiary education expands skills and knowledge, generating "sustainable productivity gains" when human-capital externalities are accounted for. In the context of regions, Zhang, et al. [15] stress that "high-end

talent” – i.e. technically skilled, innovative workers – has become “the most valuable capital” and a main factor of economic growth. They note that talent development is directly linked to a region’s capacity for innovation and competitiveness; in other words, provinces with larger and higher-quality skilled workforces achieve much higher development efficiency. Empirical evidence from China and elsewhere confirms that provinces or regions with better education, health and human-capital indicators systematically outperform less-educated regions on productivity measures. In summary, the literature implies that regions with stronger human capital endowments will tend to exhibit higher efficiency in generating economic output from inputs [14].

2.4. Research Hypotheses

In light of this evidence, the present study posits that the variation in regional development efficiency in West Sumatra can be explained primarily by (1) the quality of physical infrastructure and (2) the quality of human capital (HDI). Specifically:

H₁: Higher-quality physical infrastructure leads to a higher regional development efficiency score in West Sumatra. In other words, better roads, power supply and telecom networks improve accessibility and reduce costs, thereby raising how efficiently local governments translate spending and investments into economic output.

H₂: Higher human capital quality (as measured by the Human Development Index) leads to a higher regional development efficiency score in West Sumatra. More educated, skilled and healthy populations enhance labor productivity and the “absorptive capacity” of a region, increasing the efficiency with which public and private inputs are converted into growth.

These hypotheses reflect the consensus that physical capital and human capital are key drivers of regional performance. The proposed analysis will first measure each West Sumatra district’s development efficiency using DEA, and then test how variations in infrastructure and HDI predict those efficiency scores.

2.5. Conceptual Framework

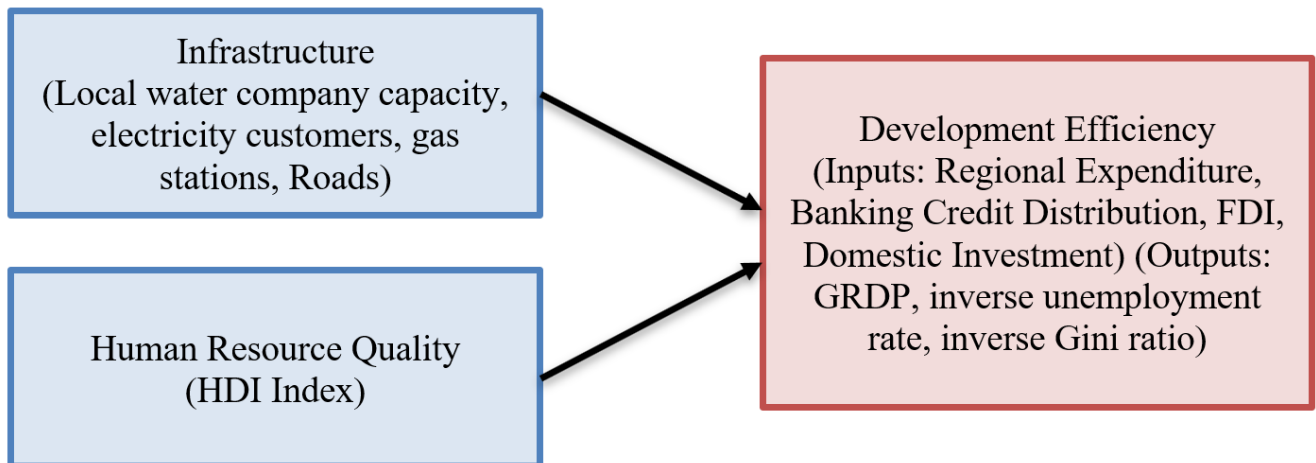


Figure 1.
Conceptual Framework

Figure 1 Explains the position of the conceptual framework which places regional development efficiency as the dependent variable. The inputs consist of regional expenditure realization, bank credit distribution, as well as domestic investment (PMDN) and foreign direct investment (PMA). The outputs are represented by Gross Regional Domestic Product (GRDP), the inverse of the unemployment and Gini ratio. The determinants of efficiency are focused on two primary independent variables: physical infrastructure and human resource quality.

3. Methods

3.1. Research Design and Analytical Strategy

This study adopts a quantitative, two-stage nonparametric design to evaluate how effectively subnational units in West Sumatra convert development inputs into socio-economic outcomes. In stage one we estimate relative efficiency scores for each district/city (the Decision-Making Units, DMUs) using Data Envelopment Analysis (DEA). In stage two we investigate the statistical determinants of those DEA scores by applying SEM-PLS. SEM-PLS is employed because it is well suited for models with complex causal structures, latent constructs, and relatively small samples, which characterize subnational-level empirical settings. In addition, SEM-PLS does not impose strict distributional assumptions and remains robust under non-normal data conditions, making it appropriate for DEA-derived efficiency scores.

3.2. Population, Sample, and Panel Structure

The population comprises all administrative districts and cities in the Province of West Sumatra. The empirical sample is a census of these units (19 DMUs) observed for three consecutive years (2022–2024), yielding a short panel of 57

observations. Because DEA evaluates relative performance across comparable DMUs, a census approach ensures full coverage and maximizes cross-unit comparability for the provincial case study.

3.3. Data Sources and Variable Definitions

All variables derive from authoritative secondary sources: Statistics Indonesia (BPS), Bank Indonesia publications and regional fiscal reports (local government financial statements, SEKDA), and official regional human development reports.

- a. Stage-one (DEA) inputs — annual realizations of: (a) local government expenditures (operating + capital), (b) bank credit disbursement (working capital, investment, consumption credit aggregated at district level), (c) domestic private investment (PMDN), and (d) foreign direct investment (PMA).
- b. Stage-one (DEA) outputs — annual: (a) Gross Regional Domestic Product (GRDP, nominal or real as specified), (b) employment level (total employment or employment per capita), and (c) inverse Gini ratio (i.e., $1/\text{Gini}$ or transformed Gini so that higher values indicate more equality).
- c. Stage-two determinants comprise: (i) physical infrastructure (road density (km/km²), water supply capacity (m³/day per 1,000 residents), electricity customers per 1,000 population, and number of fuel stations), and (ii) human capital quality (HDI and its subindices: education and health). All determinant variables are measured at the district level for the corresponding year.

3.4. DEA Model Specification

We implement an input-oriented DEA model under variable returns to scale (VRS) (the BCC specification). The input orientation is appropriate for a policy context where public managers and financiers seek to minimize resource use (fiscal, credit, investment) while achieving desired outputs. VRS is chosen because districts operate at different scales and local production processes are unlikely to satisfy constant returns to scale across heterogeneous subnational units. Standard DEA scores range from 0 to 1 (or 0%–100%), where 1 indicates that a DMU is on the efficient frontier. For sensitivity analysis we also compute alternative specifications (output-oriented, CRS/CCR) to verify the robustness of ranking and inference. Use of VRS as the primary specification is consistent with regional DEA practice [21].

Because frontier estimators are sensitive to extreme observations, we adopt an explicit outlier detection and treatment protocol prior to DEA estimation. Steps include: (1) univariate screening (Winsorizing at selected percentiles for extreme measurement errors), (2) multivariate detection using DEA-specific methods (e.g., super-efficiency scores and forward-search approaches), and (3) application of robust frontier techniques (order- α frontier or other robust DEA extensions) where indicated. We will report any excluded or adjusted DMUs and present sensitivity results with and without the adjustments. Recent nonparametric and DEA literature on outlier detection guides this procedure [22].

3.5. Structural Equation Modeling – Partial Least Squares (SEM–PLS)

To investigate the determinants of regional development efficiency, this study applies Structural Equation Modeling using the Partial Least Squares approach (SEM–PLS) as the second-stage analytical technique. PLS–SEM is widely accepted as a variance-based SEM approach suitable for complex causal modeling involving latent constructs with fewer distributional assumptions and smaller sample sizes compared to covariance-based SEM methods [23].

In this framework, the DEA efficiency score obtained in the first stage is treated as an endogenous latent construct, representing overall regional development efficiency. Two key exogenous latent constructs—Physical Infrastructure and Human Capital Quality—are modeled as determinants of efficiency. Each latent construct is operationalized using multiple observed indicators, allowing SEM–PLS to explicitly account for measurement error and to capture the multidimensional nature of development inputs.

3.6. Measurement Model Specification

The measurement model follows a reflective specification, consistent with the conceptualization of infrastructure capacity and human capital as underlying latent traits manifested through observable indicators. Specifically:

- Physical Infrastructure is measured using road density, water supply capacity, electricity access (number of customers), and fuel station availability.
- Human Capital Quality is measured using the Human Development Index (HDI) and its core components (education, health, and income dimensions where applicable).
- Regional Development Efficiency is measured using the DEA efficiency score as a single-indicator latent construct, a practice commonly adopted in two-stage DEA–SEM studies when efficiency is conceptually treated as a holistic performance outcome.

3.7. Justification of SEM–PLS in a DEA-Based Framework

The integration of DEA and SEM–PLS is increasingly adopted in regional and public-sector efficiency studies because it enables researchers to move beyond purely technical efficiency measurement toward theory-driven causal explanation. DEA identifies performance differentials, while SEM–PLS allows these differentials to be systematically linked to structural and institutional factors within a coherent latent-variable framework. This approach is particularly advantageous when efficiency is influenced by multidimensional and policy-relevant constructs such as infrastructure systems and human capital accumulation. Recent methodological reviews emphasize that PLS–SEM is appropriate for models with reflective

and formative indicators and when predictive explanation of latent constructs is prioritized, particularly in social sciences and applied research [23-25].

SEM–PLS estimation is conducted using specialized software such as SmartPLS or equivalent R-based packages. All procedures follow contemporary reporting standards for PLS-SEM, including transparent disclosure of algorithm settings, bootstrapping parameters, and validity thresholds. By combining nonparametric DEA with SEM–PLS, this study offers a robust two-stage framework that integrates efficiency benchmarking with latent-variable causal analysis. The approach is particularly appropriate for subnational development studies characterized by small samples, multidimensional policy constructs, and non-normal data distributions.

4. Results, Analysis, and Discussion

4.1. Descriptive Statistics

A descriptive analysis was conducted on 19 regencies/cities in West Sumatra over the period 2022–2024, yielding a total of 57 observations. The results are presented in Table 1.

Table 1.
Descriptive Statistics of Dependent Variables.

Variable/ Dimension	Mean	Median	Min	Max	Standard Deviation	Excess Kurtosis	Skewness
Road Length (km)	1,139.00	1,161.00	106.00	2,712.00	719.00	0.369	0.565
Water supply Capacity (m ³ /day)	378.00	270.00	0.00	1,725.00	365.00	2.404	6.165
Electricity Customers (per 1,000 pop)	88.06	71.86	18.59	355.05	66.00	2.621	7.747
Number of Gas Stations	7.83	7.00	2.00	29.00	5.80	2.366	6.688
HDI Index	70.31	73.67	64.83	84.38	17.77	-3.080	8.700

Table 1 presents descriptive statistics—including mean, median, minimum, maximum, standard deviation, skewness, and kurtosis—for the output variables employed in the DEA model and key infrastructure indicators. This table provides an overview of the data distribution and variability across regions prior to frontier efficiency estimation.

4.2. Regional Development Efficiency Scores

The input variables consist of realized regional expenditure, bank credit distribution (encompassing working capital credit, investment credit, and consumption credit), Domestic Investment (PMDN), and Foreign Direct Investment (PMA). Meanwhile, the output variables are Gross Regional Domestic Product (GRDP), the inverse of the Gini ratio, and the inverse of the unemployment rate.

Table 2.
Relative Regional Development Efficiency Scores of Regencies/Cities in West Sumatra.

District/City	2022	2023	2024	Average (2022–2024)	Status
Agam	100.0%	100.0%	100.0%	100.0%	Efficient
Bukittinggi	93.0%	96.6%	90.2%	93.3%	Inefficient
Dharmasraya	93.1%	98.4%	86.9%	92.8%	Inefficient
Kepulauan Mentawai	100.0%	94.9%	100.0%	98.3%	Inefficient
Lima Puluh Kota	100.0%	100.0%	100.0%	100.0%	Efficient
Padang	100.0%	100.0%	100.0%	100.0%	Efficient
Padang Panjang	100.0%	100.0%	93.9%	98.0%	Inefficient
Padang Pariaman	100.0%	97.7%	100.0%	99.2%	Inefficient
Pariaman	100.0%	98.4%	91.1%	96.5%	Inefficient
Pasaman	76.1%	74.4%	71.8%	74.1%	Inefficient
Pasaman Barat	100.0%	98.5%	100.0%	99.5%	Inefficient
Payakumbuh	90.0%	87.6%	85.5%	87.7%	Inefficient
Pesisir Selatan	60.1%	60.6%	55.6%	58.8%	Inefficient
Sawahlunto	97.3%	100.0%	99.9%	99.1%	Inefficient
Sijunjung	86.8%	80.4%	82.8%	83.3%	Inefficient
Solok (Kabupaten)	94.6%	89.7%	91.3%	91.9%	Inefficient
Solok (Kota)	94.7%	93.6%	99.4%	95.9%	Inefficient
Solok Selatan	84.8%	75.6%	100.0%	86.8%	Inefficient
Tanah Datar	87.6%	82.5%	76.2%	82.1%	Inefficient
Average (All Regions)	90.5%	89.2%	88.4%	88.4%	–

Table 2 reports the relative development efficiency scores generated using the input-oriented DEA model with variable returns to scale (VRS). The scores identify regencies and cities operating on the efficiency frontier as well as those exhibiting input inefficiencies, thereby indicating potential opportunities for resource optimization.

4.3. Model Test Results

Table 3.
Model Test Results

Criteria	Saturated Model	Estimated Model
SRMR	0.069	0.069
d_ ULS	0.099	0.099
d_ G	0.077	0.077
Chi-Square	23.359	23.359
NFI	0.883	0.883

Table 3 reports model diagnostics (SRMR=0.069; d_ ULS=0.099; d_ G=0.077), indicating acceptable fit for SEM-PLS. These indicators are used to assess the adequacy of both the measurement and structural models prior to hypothesis testing, confirming that the model meets acceptable empirical thresholds.

The model demonstrates an approximately acceptable fit, as indicated by the SRMR ($0.069 < 0.080$) and the relatively small discrepancy values (d_ ULS / d_ G). Consequently, we can proceed to the subsequent tests.

A Data Envelopment Analysis (DEA) model using an input-oriented Variable Returns to Scale (VRS) approach was employed to measure the Regional Development Efficiency scores. The results reveal a considerable disparity among the regencies/cities. The areas consistently achieving full Development Efficiency scores (100%) are Padang City, Padang Panjang City, and Lima Puluh Kota Regency. In contrast, the areas with the lowest scores are Pesisir Selatan (55.6% in 2024) and Pasaman (71.8% in 2024). The average Development Efficiency score across all regions is 88.4%, indicating a potential input savings of approximately 11.6% to produce the same level of output.

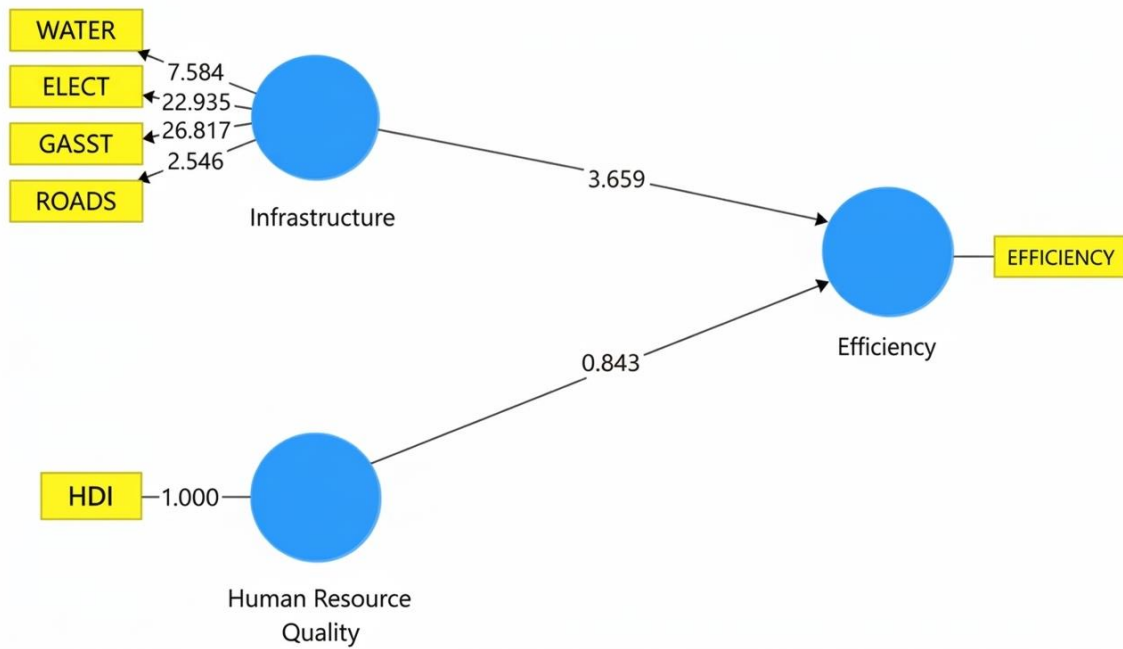


Figure 2.
PLS-SEM Inner Model (Bootstrapping).

Figure 2 illustrates the structural (inner) model of the PLS-SEM analysis, depicting the hypothesized causal relationships between physical infrastructure, human capital, and regional development efficiency. Bootstrapped path coefficients and significance levels are displayed to facilitate interpretation of the strength and statistical relevance of the proposed relationships.

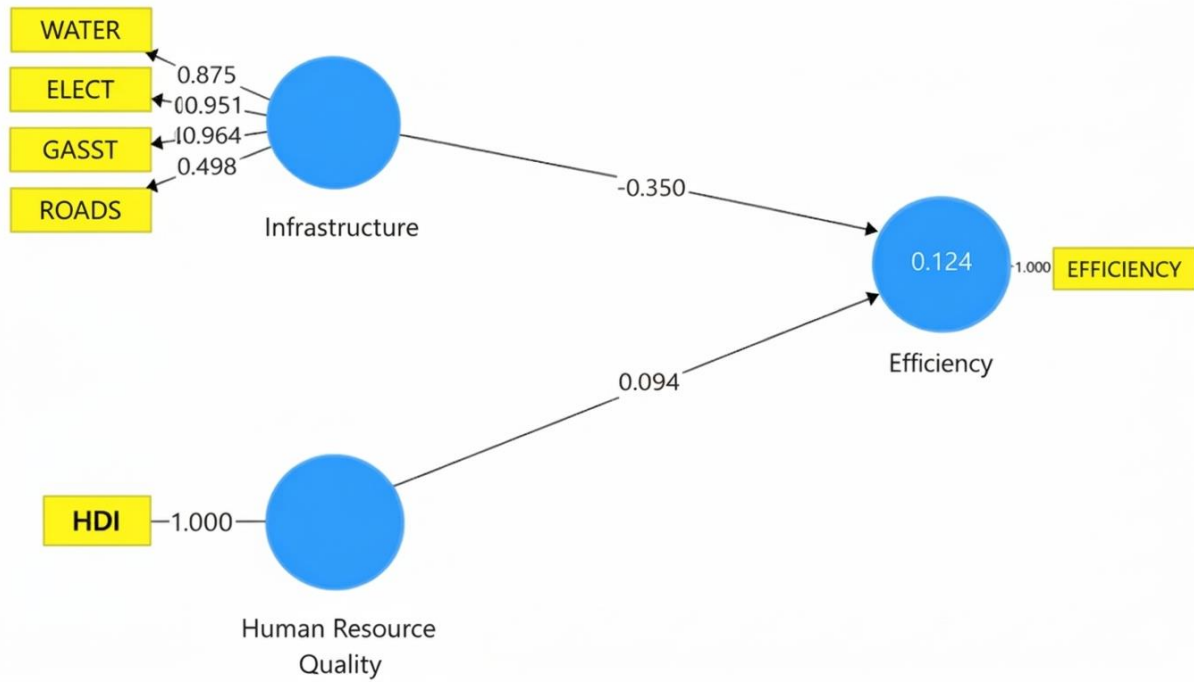


Figure 3. PLS-SEM Outer Model (Algorithm).

Figure 3 presents the measurement (outer) model estimated using the PLS algorithm, including indicator loadings for each latent construct. This figure demonstrates the convergent validity and reliability of the measurement model, confirming that the selected indicators appropriately represent their respective constructs.

Table 4. Total Effects for Hypothesis Testing.

Variable	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (O/STDEV)	P Values
Infrastructure -> Dev. Efficiency	-0.350	0.364	0.096	3.659	0.000
Human Resource Quality -> Dev. Efficiency	0.094	0.093	0.112	0.843	0.399

Table 4 reports the total effects of the latent constructs on regional development efficiency, including estimated coefficients, bootstrapped standard errors, t-statistics, and p-values. This table enables direct evaluation of the magnitude, direction, and statistical significance of the hypothesized effects.

4.4. Hypothesis Testing

Hypothesis testing was conducted using bootstrap regression with the DEA Development Efficiency score as the dependent variable. The results indicate:

- Physical infrastructure has a significant negative effect on the Development Efficiency score (coefficient = -0.350; $p < 0.001$).
- Human Resource Quality (HDI) has a positive but non-significant effect on the Development Efficiency score (coefficient = 0.094; $p = 0.399$).

To reinforce the hypothesis testing, the R-Square values for infrastructure and human resource quality were examined as their total effect within the proposed Development Efficiency model.

Table 5. Total Effect Hypothesis Testing (Model Summary).

	R Square	R Square Adjusted
Development Efficiency	0.124	0.092

Table 5 provides a summary of key model evaluation metrics, including R^2 , adjusted R^2 , and related explanatory measures for the endogenous construct. This summary facilitates assessment of the model’s explanatory capacity and clarifies the extent to which physical infrastructure and human capital jointly account for variation in regional development efficiency. The model explains 12.4% of the variance in Development Efficiency ($R^2 = 0.124$), which is consistent with similar studies emphasizing the existence of other external and institutional determinants beyond the variables examined in this research [26].

A relatively low R^2 value does not imply methodological inadequacy in DEA-based efficiency studies. Efficiency scores are relative, bounded measures (ranging between 0 and 1) and are inherently influenced by a wide range of unobserved institutional, managerial, and contextual factors. Consequently, the limited explanatory power of observable variables is a well-documented characteristic of efficiency modeling. Rather than signaling model weakness, a low R^2 highlights the presence of additional institutional and governance-related determinants that merit further empirical exploration in future research.

4.5. Discussion of Empirical Findings

The empirical analysis yields a counter-intuitive but robust result: higher measured allocations to physical infrastructure are associated with lower regional development efficiency scores in West Sumatra (DEA scores), while human capital (HDI) shows a positive but statistically non-significant relationship with efficiency. This pattern persists across a range of sensitivity checks (alternative DEA orientations and specification tests) and is therefore not plausibly due to a single modeling choice.

4.5.1. The Negative Infrastructure–Efficiency Relationship

Several logically coherent mechanisms can explain why larger infrastructure allocations may coincide with lower measured efficiency at the district level.

4.5.1.1. Institutional Quality and Governance Condition the Returns to Infrastructure.

Infrastructure is not a neutral, self-executing input: its capacity to raise economic output depends critically on the quality of local governance (planning, procurement, maintenance, and complementary public services). Empirical work in regional economics finds that the economic returns to transport and other public capital are significantly **conditioned** by government quality; in weak institutional settings, large projects (e.g., motorways) often yield lower returns than smaller, more targeted investments because of misallocation, poor contracting, or weak maintenance regimes. This interaction government quality and infrastructure explains why regions with similar infrastructure stocks can display very different outcomes [27].

4.5.1.2. Absorptive Capacity and Complementary System Constraints.

Infrastructure delivers benefits only when users (firms, households, local administrations) can absorb and exploit additional capacity. The absorptive-capacity literature (recently extended to national and subnational settings) shows that infrastructure's growth dividend depends on coexisting capacities: specialized skills, financial intermediation, business environment and public-policy effectiveness. In contexts where these complementary capacities are limited, additional infrastructure may remain underutilized or even impose maintenance and fiscal burdens that reduce net efficiency. This mechanism is consistent with findings across LMICs that emphasize the systemic nature of productive capacity [28].

4.5.1.3. Non-Linear (Threshold) Effects and Crowding/Misallocation.

Several studies document nonlinear effects of infrastructure: below a threshold, new infrastructure can have weak or even negative net effects (e.g., by crowding out private investment, creating duplication, or generating unproductive 'white elephants'); above the threshold (and if used effectively) the marginal returns can become positive. Thus, where infrastructure expansion is rapid but the region has not crossed utilization or quality thresholds, measured economic efficiency may decline. Such threshold/nonlinear dynamics provide a natural explanation for the observed negative coefficient in the West Sumatran context [29].

4.5.1.4. Sectoral And Project-Level Heterogeneity (Energy, Transport, Etc.).

Detailed DEA and project-level studies reveal that the efficiency of infrastructure investments varies by sector and by local industrial structure. For instance, analyses of energy-infrastructure investments have found that increased project efficiency does not automatically translate into higher regional GDP unless matched by appropriate industrial linkages and management capacity. In sum, sectoral heterogeneity and mismatches between the type/scale of infrastructure and local economic structure can reduce aggregate conversion of inputs into outputs [30].

4.5.1.5. Procurement, Cost-Overruns, And Fiscal Burden (Implementation Failures).

Practical implementation failures—procurement irregularities, cost overruns, delays, and maintenance neglect—are common channels through which infrastructure spending becomes inefficient. These governance and procurement problems both reduce the effective service delivered per unit of spending and increase ongoing fiscal liabilities, thereby lowering observed DEA efficiency. While country- and region-level manifestations differ, cross-country evidence and procurement reviews document systematic losses when procurement transparency and contracting capacity are weak [31].

Together, these mechanisms show that more infrastructure spending is not isomorphic with higher development efficiency: the institutional and absorptive context, project choice and scale, and implementation quality are decisive moderators.

4.5.2. Human Capital (HDI) is Positive but Statistically Non-Significant

The positive (but statistically weak) effect of HDI on efficiency aligns with the theoretical expectation that better-educated and healthier populations should elevate productivity. However, three plausible empirical reasons explain the lack of significance in this sample:

4.5.2.1. Measurement and Relevance (Quality Vs Quantity)

The aggregate HDI captures broad welfare improvements (enrolment and life expectancy) but may not reflect market-relevant skills that firms require to utilize infrastructure and financial resources effectively. If HDI improvements reflect expanded basic education without concurrent gains in vocational skills or tertiary quality, the effect on production efficiency can be muted. Recent micro- and regional studies in middle-income contexts highlight that *skill composition* and alignment with local demand matter more than headline education indicators [32].

4.5.2.2. Temporal Lags and Long-Run Maturation.

Human-capital investments typically affect productivity with lags: schooling cohorts must enter the labor market, and health/education gains must translate into usable skills and innovation capacity. A three-year panel (2022–2024) may be too short to detect statistically significant HDI effects on DEA efficiency, especially where educational reforms and skill upgrading take several years to materialize in firm-level productivity. The literature advises caution when interpreting short-horizon correlations between broad human-capital indices and regional outputs [29].

4.5.2.3. Institutional Mediation and Skill-Matching Failures.

Even where HDI is high, institutional weaknesses (labor market rigidities, weak firm-education linkages) can prevent human capital from translating into productivity and innovation. Studies show that in many developing-country regions, higher education enrollment coincides with skill-mismatch problems and weak industry-academia linkages, reducing the measurable impact of human capital on economic efficiency. This helps explain why HDI's coefficient is positive in direction but fails to reach statistical significance [32].

The findings mirror a growing consensus in regional and development economics: Infrastructure and human capital are necessary but not sufficient for efficient development outcomes. They must be embedded in a system of good governance, institutional capacity, appropriate project selection, and labor-market relevance. Studies of European regions demonstrate that government quality conditions infrastructure returns (i.e., poor governance reduces returns) — a pattern that appears to replicate at subnational levels in developing countries as well. Similarly, cross-country analyses of absorptive capacities stress the complementarity of infrastructure, finance, specialized human capital and policy capacity for growth; absent these, infrastructure may underperform or become counterproductive. These multidimensional perspectives align closely with our empirical pattern in West Sumatra [33].

5. Conclusion and Implication

5.1. Conclusion

This study reveals that the efficiency of regional development across the regencies/cities of West Sumatra during the 2022–2024 period demonstrates significant disparities. While several regions, such as Padang City, Padang Panjang City, and Lima Puluh Kota Regency, achieved full efficiency, others, notably Pesisir Selatan and Pasaman, recorded low efficiency scores. An analysis of efficiency determinants using bootstrap regression indicates that physical infrastructure exerts a significant negative influence on efficiency scores, whereas human resource quality (as measured by the HDI) exhibits a positive yet statistically insignificant effect. These findings suggest that infrastructure development, if not supported by adequate institutional capacity, may potentially reduce efficiency. Furthermore, improvements in human resource quality have not yet been fully absorbed or leveraged by the local labor market.

5.2. Theoretical Implications

5.2.1. Refining Endogenous Growth and Production Efficiency Theory.

Classic endogenous growth models emphasize infrastructure and human capital as core drivers of productivity. Our empirical evidence suggests these drivers are context-dependent: their effectiveness is moderated by absorptive and institutional capacities. This finding argues for integrating *institutional and absorptive capacity variables* into frameworks that model public capital and human capital effects at the regional scale — i.e., moving from simple factor endowments to *systems models* where complementarities and thresholds matter.

5.2.2. Contribution To DEA and Policy-Oriented Efficiency Literature.

Methodologically, the combination of DEA benchmarking with latent-variable causal analysis (SEM–PLS) highlights that technical efficiency scores are appropriate for identifying performance shortfalls, but causal interpretation requires modeling latent systemic factors (infrastructure quality, institutional capacity, human capital composition). Practically, the study contributes to the literature by showing that higher physical inputs (spending) can correlate with lower frontier performance when system-level moderators are weak: a cautionary result for policy narratives that equate spending volume with development success.

5.3. Policy Implications

- a. Prioritize institutional strengthening and procurement transparency alongside infrastructure investment; improving governance raises the returns to capital and reduces waste.
- b. Adopt targeted, context-sensitive infrastructure choices, favoring smaller, maintenance-oriented or demand-driven projects where absorptive capacity is low, and scaling up new infrastructure only when utilization thresholds are achievable.
- c. Align human-capital policies with local labor-market needs (vocational training, apprenticeship, firm-education linkages) to ensure HDI gains translate into usable skills that improve conversion of inputs into outputs.

5.4. Limitations and Avenues for Future Research

While the present study controls extensively for alternative specifications and performs robustness checks, causal identification at subnational level remains challenging. Future work should: (i) incorporate direct measures of institutional quality and procurement performance at district level; (ii) extend the time horizon to capture lagged human capital effects; and (iii) exploit quasi-experimental variation (e.g., exogenous funding shocks, program roll-outs) to better isolate causal effects of infrastructure investments.

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