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Environmental Expenditure Efficiency and its Determinants in Indonesia: A DEA - Tobit Model

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Abstract

This study aims to measure the efficiency of environmental expenditure by provincial governments in Indonesia and analyze the socio-economic and structural factors influencing it. Amid global climate challenges and fluctuations in national environmental budgets, evaluating fiscal performance has become essential for sustainable development. This research employs a quantitative approach covering thirty-four provinces over the period from 2020 to 2024. Efficiency is assessed using the Data Envelopment Analysis (DEA) method with an output-oriented Variable Returns to Scale (VRS) approach, where provincial governments are treated as Decision-Making Units (DMUs). The model utilizes environmental expenditure realization as the input, while the recycling rate, protected forest area, renewable energy production, and the Environmental Quality Index serve as outputs. Subsequently, a Tobit regression model is used to examine the determinants of efficiency, including Gross Regional Domestic Product (GRDP), population growth, industrialization level, and the Information and Communication Technology Development Index (ICTDI). The results indicate significant regional variations in efficiency, with only fourteen provinces achieving perfect efficiency scores, while the majority remain below the efficiency threshold. Second-stage analysis reveals that the industrialization level has a positive and significant effect on efficiency, reflecting better governance in developed regions. Conversely, the ICTDI shows a significant negative influence, indicating suboptimal technology integration in budget management. Economic capacity and population growth do not statistically explain efficiency variations. These findings suggest that the government should transition from an expenditure-based approach to performance-based budgeting by strengthening digital oversight systems and promoting green industrialization to ensure sustainable environmental quality improvement in Indonesia.

Introduction

The environment is a crucial instrument in sustainable development, demanding harmony between human activities and ecosystem preservation. Globally, challenges such as climate change, forest degradation, and pollution have driven governments in various countries, including Indonesia, to allocate substantial budgets for waste management, renewable energy, and emission reduction (Barrell et al., 2021). However, environmental conditions in Indonesia still face fundamental issues due to massive economic growth, where existing policies are often reactive and short-term, thus failing to provide significant and sustainable improvements in environmental quality (Sholeha & Suseno, 2025; Martínez Córdoba et al., 2025).

Current public policy realities reveal a gap between resource allocation and the achievement of environmental targets. This is evident in the sharp fluctuations between the budget and the

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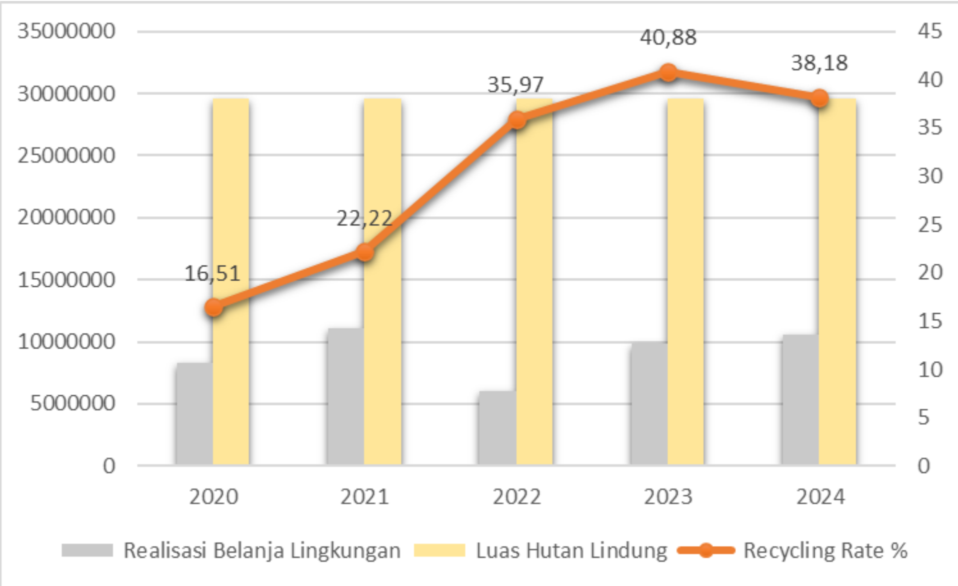
realization of environmental expenditure in Indonesia during the 2020-2024 period. Although the budget ceiling tended to remain stable in the range of IDR 12,000 - 13,000 billion, its realization was highly dynamic, increasing in 2021 (IDR 11,037 billion) but undergoing a sharp correction in 2022 (IDR 6,038 billion). This indicates that an increase in fiscal allocation does not always correlate linearly with the optimization of absorption and program implementation in the field.

Theoretically, government spending should transform from a mere "spending approach" into "performance-based expenditure" (Barrell et al., 2021). However, the data in Figure 1 shows that an increase in expenditure inputs has not fully yielded proportional outputs. For instance, the recycling rate, which rose to 40.88% in 2023, actually declined to 38.18% in 2024 despite increased spending. A similar trend is observed in the area of protected forests, which remains stagnant at approximately 20-30 million hectares, signifying that budget utilization efficiency remains a major challenge (Lacko et al., 2023).



Figur 1. Trends in Environmental Expenditure Realization, Protected Forest Area, and Recycling Rate (Sources: DJPK dan KLHK Indonesia)

On the other hand, the development of expenditure realization relative to renewable energy production and the Environmental Quality Index (EQI) in Figure 1 shows a gradual positive trend. Renewable energy production increased alongside the rise in expenditure from IDR 275.599 billion (2020) to IDR 343.891 billion (2024), followed by an increase in the EQI from 70.27 to 73.53. Nevertheless, the fluctuating results in other indicators reflect that policy effectiveness heavily depends on management efficiency and the precision of budget targeting (Wang, 2018; Gong & Wan, 2022).

Research concerning regional expenditure efficiency indicates that inter-regional efficiency levels still exhibit differences in performance achievements regarding the utilization of public budgets. While some regions have achieved optimal efficiency levels, the majority remain below the efficiency frontier, suggesting that government spending has not yet been fully capable of producing optimal development outputs (Suseno et al., 2022). These findings indicate that the magnitude of budget allocation does not always guarantee the efficiency of public expenditure management. Therefore, an analysis of environmental expenditure efficiency is essential to assess the extent to which local governments can optimize the use of fiscal resources to generate better environmental performance.

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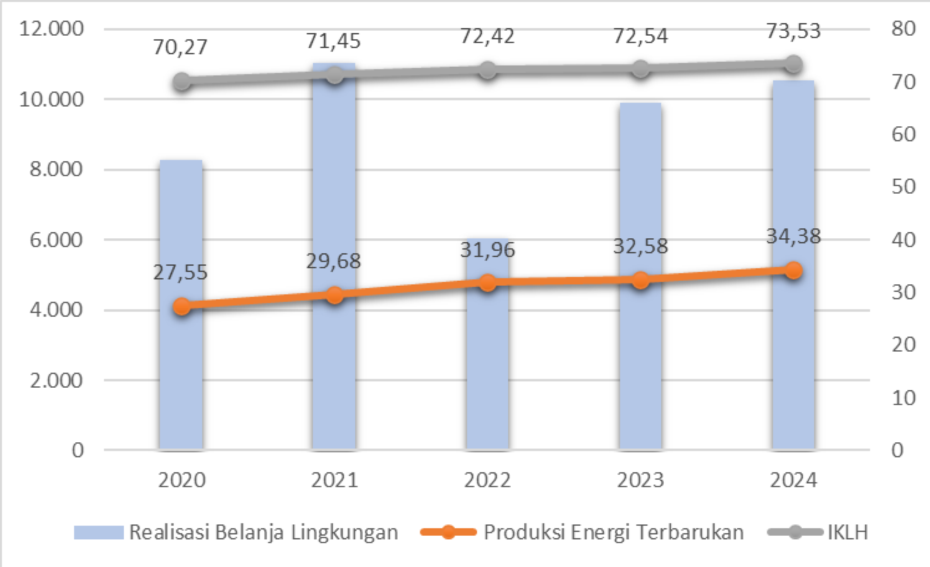

Figur 2. Trends in Environmental Expenditure Realization, Renewable Energy Production, and Environmental Quality Index/IKLH (Sources: BPS and KLHK Indonesian)

A number of studies suggest that the analysis of public expenditure efficiency needs to be complemented by an investigation into the factors influencing those efficiency levels. Several studies have found that economic characteristics, demographics, and regional technological developments can influence the efficiency of public budget management, including within the environmental sector (Moreno-Enguix & Bayona, 2017; Wang, 2018; Cheng et al., 2021). Consequently, this study not only measures the environmental expenditure efficiency of provincial governments in Indonesia using the Data Envelopment Analysis (DEA) approach but also analyzes the factors presumed to influence it namely, GRDP, population growth rate, industrialization level, and the Information and Communication Technology Development Index (ICTDI) to provide a more comprehensive understanding of the determinants of environmental expenditure efficiency in Indonesia.

This expenditure efficiency is also influenced by socio-economic and structural factors of the region. GRDP is considered a primary determinant reflecting the regional fiscal and technological capacity to manage budgets optimally (Wang, 2018; Xue et al., 2024). Population factors and industrialization levels also play a dual role; on one hand, they increase pollution pressure, but on the other, they provide efficiency potential through the adoption of eco-friendly technologies (Martínez Córdoba et al., 2025; Anggraini Rambe et al., 2024). Furthermore, in the digital era, the ICTDI has become a crucial new variable for enhancing transparency, digital data oversight, and green technology innovation.

This research is based on Farrell's (1957) efficiency theory, which states that technical efficiency is achieved when an entity can maximize output from available inputs (Coelli et al., 2005). In the context of the public sector, public finance theory emphasizes the government's role in allocating resources to address market failures in the provision of public goods, including the environment; thus, public spending must be managed optimally to produce maximum social benefits (Musgrave, 1959; Stiglitz & Rosengard, 2015). Furthermore, the Environmental Kuznets Curve (EKC) theory explains that an increase in GRDP at a certain stage can drive environmental quality improvement through strengthened fiscal capacity and more effective policies, thereby implying an increase in environmental expenditure efficiency (Grossman & Krueger, 1995; Dinda, 2004; Stern, 2004; Ahmad et al., 2024).

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Additionally, demographic transition theory explains that the population growth rate affects pressure on resources and the need for public spending, which ultimately can influence the efficiency level of local government spending (Notestein, 1945; Lee, 2003; Bloom et al., 2003; Birdsall, 1992; Liddle, 2014). Externality theory emphasizes that the level of industrialization potentially creates environmental impacts requiring fiscal intervention; therefore, efficient environmental expenditure management is vital in correcting both positive and negative externalities (Pigou, 1920; Wang, 2018; Zhou & Zhang, 2020). Finally, endogenous growth theory explains that technological development, represented by the ICTDI, can enhance institutional capacity and budget management effectiveness, contributing to increased environmental expenditure efficiency (Romer, 1986; Lucas, 1988; Wang, 2021).

Although various studies have examined government spending efficiency, research specifically analyzing environmental expenditure efficiency at the local government level in Indonesia remains relatively limited. Moreover, studies linking efficiency measurement with the analysis of its determinants are still scarce. Therefore, this study aims to analyze the environmental expenditure efficiency of provincial governments in Indonesia using the Data Envelopment Analysis (DEA) method and identify its influencing factors through the Tobit model, considering the variables of GRDP, population growth rate, industrialization level, and ICTDI (Wang, 2018; Moreno-Enguix & Bayona, 2017).

Given the importance of objectivity in measuring fiscal performance, this study utilizes the Data Envelopment Analysis (DEA) and Tobit methods to assess environmental expenditure efficiency and test the influence of GRDP, population growth, industrialization, and ICTDI. With a technological development perspective, this research, titled "Environmental Expenditure Efficiency and Its Determinants in Indonesia: A DEA - Tobit Model" is expected to contribute to the strengthening of adaptive and result-based fiscal policies in Indonesia.

Methods

This study adopts a quantitative approach aiming to measure the efficiency level of government environmental expenditure and analyze the socio-economic and structural factors influencing it. Efficiency measurement is conducted using the Data Envelopment Analysis (DEA) method, which compares environmental expenditure realization as the input against various environmental quality indicators as outputs. The research location covers thirty-three provinces, and the subjects of this study are the provincial governments in Indonesia, treated as Decision-Making Units (DMUs) in the efficiency analysis.

After obtaining the efficiency scores through the DEA method, the study proceeds with a Tobit regression model to identify the factors influencing these efficiency levels. This approach is utilized because DEA efficiency scores are censored, ranging between 0 and 1, which renders Ordinary Least Squares (OLS) regression inappropriate. Therefore, the Tobit model is considered more suitable for analyzing the relationship between efficiency scores and explanatory variables. This two-stage approach DEA in the first stage and Tobit regression in the second stage has been widely adopted in efficiency research to examine the determinants affecting the efficiency performance of a decision-making unit (Simar & Wilson, 2007).

To analyze the factors influencing environmental expenditure efficiency, the Tobit regression model is employed as the second stage of analysis. This model is utilized because the efficiency scores derived from the DEA method are bounded between 0 and 1, thus exhibiting censored characteristics. Through this approach, the Tobit model estimates the relationship between the environmental expenditure efficiency score as the dependent variable and several independent variables: GRDP, population growth rate, industrialization level, and the Information and

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Communication Technology Development Index (ICTDI). Consequently, this model aims to determine the factors responsible for the variations in environmental expenditure efficiency across provinces in Indonesia (Simar & Wilson, 2007; Banker & Natarajan, 2008; Hoff, 2007).

To provide clarity regarding the variables used in this study, it is necessary to elaborate on the operational definitions, measurement indicators, and data sources for each analyzed variable. This explanation is essential to ensure that the efficiency measurement process is conducted systematically and consistently within the analytical framework. In DEA-based research, the selection of input and output variables is a crucial aspect as it determines the model's ability to represent the relationship between resource utilization and performance achievement (Coelli et al., 2005; Farrell, 1957). Furthermore, research on environmental spending efficiency indicates that utilizing environmental performance indicators such as environmental quality, renewable energy, and waste management can reflect public policy outcomes more comprehensively (Moreno-Enguix & Bayona, 2017; Wang, 2018; Jialu et al., 2022). Therefore, the operational definitions, measurement indicators, units, and data sources in this study are presented systematically in the following table.

Research Variables and Operational Definitions in Analysis DEA

Table 1. Research Variables and Operational Definitions for DEA Analysis

Research Variable	Variable Type	Operational Definition	Indicator/Measurements	Unit	Data Source
Environmental Expenditure Realization	Variable Input (DEA)	Total provincial government expenditure realized for environmental protection and management activities within a single fiscal year.	Total realization of provincial government environmental expenditure	Billion Rupiah	Ministry of Finance (DJPK), BPS
Recycling Rate	Variable Output (DEA)	The percentage of waste successfully recycled from the total waste generated in a province	Waste recycling rate	Percent (%)	Ministry of Environment and Forestry (KLHK), SIPSN
Protected Forest Area	Variable Output (DEA)	The total area of forest designated and managed as protected forest in each province	Total area of protected forest zones	Hectare	Ministry of Environment and Forestry (KLHK)
Renewable Energy Production	Variable Output (DEA)	The amount of energy generated from renewable sources at the provincial level	Total renewable energy production derived from clean water sources	Gigawatt hour (Gwh)	BPS-Statistics Indonesia
Environmental Quality Index (EQI)	Variable Output (DEA)	An index value representing the environmental quality of a region in a given year as a result of environmental development policies and activities	Composite index of IKA, IKU, IKTL	Index (score IKLH)	Ministry of Environment and Forestry (KLHK)

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Determinants of Environmental Expenditure Efficiency

Table 2. Research Variables and Operational Definitions for Tobit Regression Analysis

Research Variable	Variable Type	Operational Definition	Indicator/Measurements	Unit	Data Source
Environmental Expenditure Efficiency	Variable Dependen (Y)	The level of ability of provincial governments to optimize environmental spending to produce environmental quality outputs	DEA result efficiency score	Ratio (0-1)	DEA Analysis Results
Gross Regional Domestic Product (GRDP)	Variable Independen (X1)	The gross value added generated by all economic activities in a province within one year	Real GRDP (at Constant Market Prices).	Billin Rupih	BPS-Statistics Indonesia
Population Growth Rate	Variable Independen (X2)	The percentage change in population size over a specific period, reflecting demographic pressure on the environment.	(Population year t – year t-1) / Population year t-1 × 100%	Percent (%)	BPS-Statistics Indonesia
Industrialization Level	Variable Independen (X3)	The intensity level of industrial activities within a province	Contribution of the industrial sector to total GRDP	Percent (%)	BPS-Statistics Indonesia
Information and Communication Technology Development Index (ICTDI)	Variable Independen (X4)	An index measuring the development and equity of access, usage, and skills in information and communication technology in a region.	ICT Development Index value	Index (0-10)	BPS-Statistics Indonesia

Based on the table, it can be observed that the research variables include input and output variables for the DEA model as well as explanatory variables used in the Tobit regression analysis. The structure of these variables is designed to illustrate the relationship between the utilization of regional government fiscal resources and the resulting environmental performance achievements. In public sector efficiency literature, a two-stage approach combining DEA and Tobit regression is widely utilized not only to measure relative efficiency but also to identify its influencing factors (Wang, 2018; Zhou & Zhang, 2020; Xue et al., 2024). Economic, demographic, and technological development variables such as GRDP, population growth, industrialization level, and information technology development are known to play a

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role in explaining efficiency variations across regions (Cheng et al., 2021; Lacko et al., 2023). Thus, the selection of these variables and data sources enables a comprehensive efficiency analysis and supports the testing of determinants for environmental expenditure efficiency at the provincial level in Indonesia.

The selection of variables in the Data Envelopment Analysis (DEA) model is based on the relationship between budget utilization and environmental performance outcomes. Environmental expenditure realization is used as the input variable, representing the fiscal resource allocation of local governments. Meanwhile, the recycling rate, protected forest area, renewable energy production, and the Environmental Quality Index (EQI) are used as output variables as they represent key aspects of environmental performance: waste management, natural resource conservation, clean energy, and overall environmental quality. This approach aligns with previous research utilizing multiple environmental indicators to assess the effectiveness of environmental policies more comprehensively (Moreno-Enguix & Bayona, 2017; Wang, 2018).

Data Collection Techniques

This study utilizes secondary data collected through the documentation method from various official and reliable sources. Data on environmental expenditure realization were obtained from the Directorate General of Fiscal Balance (DJPK), while environmental quality indicators—such as the recycling rate, protected forest area, and the Environmental Quality Index—were sourced from the Ministry of Environment and Forestry (KLHK). Additionally, data regarding renewable energy production, GRDP, population levels, and industrialization levels were sourced from BPS-Statistics Indonesia. All data were compiled into a provincial panel dataset covering the 2020–2024 period.

The collected data were subsequently selected and adjusted to ensure uniformity in units, regional coverage, and timeframes. This stage aims to ensure that the data can be processed consistently in both the efficiency analysis using the DEA method and the determinant analysis using the Tobit model. Consequently, the data utilized are representative of the actual conditions of environmental expenditure management in each province.

Data Analysis Techniques

This research employs a two-stage analysis approach to measure the efficiency level of environmental expenditure and analyze the factors influencing that efficiency across Indonesian provinces. This approach is widely used in public sector efficiency studies as it is capable of identifying efficiency performance while simultaneously explaining the determinants that drive efficiency variations among observed units.

Data Envelopment Analysis (DEA)

In the first stage, this study utilizes the Data Envelopment Analysis (DEA) method to measure the relative efficiency of each Decision-Making Unit (DMU), namely the provincial governments in Indonesia. DEA is a non-parametric method based on linear programming used to evaluate the relative efficiency of a unit by comparing the combination of inputs used and outputs produced (Farrell, 1957; Coelli et al., 2005). This method generates technical efficiency scores ranging from 0 to 1, where a value of 1 indicates that a DMU is efficient, while a value less than 1 suggests that the DMU has not yet optimized its available resources.

Data Envelopment Analysis (DEA) is employed in this study as a non-parametric frontier analysis technique widely recognized for evaluating the relative efficiency of decision-making units by incorporating multiple inputs and outputs (Banker et al., 1984; Coelli et al., 2005).

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This research specifically utilizes an output-oriented DEA model under the Variable Returns to Scale (VRS) assumption to measure environmental expenditure efficiency across provincial governments in Indonesia. This approach is adopted as the study aims to assess the extent to which local governments can maximize environmental performance given their existing levels of expenditure. Consequently, the model evaluates the potential for enhancing environmental outcomes without necessitating additional budgetary increases. Mathematically, the output-oriented dual DEA model used in this study is formulated as follows (Bajero et al., 2025):

Output-Oriented Dual DEA Model

$$\max \phi_i$$

subject to

$$\phi_i y_i - \sum_{j=1}^{n} \lambda_j y_j \leq 0$$

$$x_i - \sum_{j=1}^{n} \lambda_j x_j \geq 0$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \geq 0 \forall j = 1, \dots, n$$

Notation Key

ϕ_i: The output expansion factor or the technical efficiency score of the i-th province.

x_i: The input of the i-th province (environmental expenditure).

y_i: The output of the i-th province.

x_j: The input of the j-th peer (comparison) province.

y_j: The output of the j-th peer (comparison) province.

λ_j: The intensity weights of the peer province.

n: The number of decision-making units (provinces) analyzed.

The output-oriented DEA model is employed to evaluate the capacity of each province to enhance environmental performance while maintaining the same level of environmental expenditure. Provinces achieving the highest efficiency scores serve as benchmarks for other regions in optimizing the utilization of environmental budgets.

Tobit Regression Analysis

In the second stage, this study employs the Tobit regression model to analyze the factors influencing the environmental expenditure efficiency levels derived from the DEA results. The Tobit model is utilized because the dependent variable in this research the DEA efficiency score is a bounded variable ranging between 0 and 1. Consequently, the use of Ordinary Least Squares (OLS) regression would be inappropriate as it could produce predictions outside of these established bounds (Tobin, 1958).

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To examine the determinants of environmental expenditure efficiency, the second stage of the analysis applies a Tobit regression model, since the efficiency scores obtained from the DEA model are censored and limited within a specific range (Tobin, 1958; Chodakowska & Nazarko, 2017). The standard Tobit model for the latent, unobserved variable y_i^*, which depends linearly on the vector x_i, and the observed variable y_i, can be expressed as follows:

$$y_i = \begin{cases} y_i^* \text{if } y_i^* > 0 \\ 0 \text{if } y_i^* \leq 0 \end{cases}$$

where:

$$y_i^* = \beta x_i + \varepsilon_i; \varepsilon_i \sim n(0, \sigma^2)$$

Notation Key

y_i^*: The latent (unobserved) variable representing the potential efficiency score of the i-th province.

y_i: The observed DEA efficiency score.

x_i: The vector of independent variables affecting environmental expenditure efficiency.

β: The estimated parameters (coefficients).

ε_i: The normally distributed error component (stochastic error term).

i: The decision-making unit (province).

The Tobit model is utilized because DEA efficiency scores are censored, thereby violating the assumptions of Ordinary Least Squares (OLS) regression. Consequently, parameter estimation is conducted using the Maximum Likelihood Estimation (MLE) method to ensure consistent and unbiased results

Result and Discussion

Descriptive Results

The descriptive analysis in this study aims to provide a preliminary overview of the environmental expenditure efficiency levels among provincial governments in Indonesia. Efficiency is measured using the Data Envelopment Analysis (DEA) method, considering the relationship between environmental expenditure realization as the input variable and several environmental performance indicators as output variables namely, the recycling rate, protected forest area, renewable energy production, and the Environmental Quality Index (EQI). This approach is utilized to assess the extent to which local governments optimally utilize environmental budget allocations to generate environmental performance achievements.

The analysis of environmental expenditure efficiency for each province was conducted using the DEA method with an output-oriented Variable Returns to Scale (VRS) approach. This study employs one input variable, Environmental Expenditure Realization, and four output variables, including the Recycling Rate, Protected Forest Area, Renewable Energy Production, and the EQI. Utilizing the average data for the 2020-2024 period aims to provide a more stable performance overview, while the VRS approach was selected to accommodate differences in economies of scale and relative technical capabilities across regions in maximizing environmental outcomes.

The DEA results generate relative efficiency scores for each province, with values ranging from 0 to 1. An efficiency value approaching 1 indicates that a province is capable of optimally

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utilizing its environmental expenditure to produce the expected environmental outputs, while lower efficiency values suggest potential for improvement in environmental budget management. Thus, this analysis provides an overview of the variations in efficiency levels across provinces in managing environmental spending. A summary of these efficiency measurement results is presented in the following table.

Table 3. DEA Efficiency Scores of Environmental Expenditure

Province	**Environmental Shopping Efficiency Score**				
	2020	**2021**	**2022**	**2023**	**2024**
Aceh	0,92	0,93	0,97	0,95	0,97
North Sumatra	0,89	0,92	1	0,91	0,92
West Sumatra	0,91	0,92	0,99	0,96	0,9
Riau	0,83	0,87	0,91	0,85	0,9
Jambi	0,87	0,86	0,88	0,82	0,89
South Sumatra	0,87	0,85	0,92	0,86	0,9
Bengkulu	0,83	1	0,95	0,86	0,88
Lampung	0,82	0,83	0,83	0,84	0,79
Bangka Belitung Islands	0,9	0,89	0,88	0,87	0,76
Riau Islands	0,86	0,94	0,96	0,91	0,92
DKI Jakarta	0,67	0,69	0,69	0,69	0,71
West Java	0,92	0,85	0,91	0,86	0,93
Central Java	0,9	0,9	0,96	0,99	1
DI Yogyakarta	0,8	0,79	0,8	0,81	0,87
East Java	1	0,93	1	0,93	1
Banten	0,86	0,95	0,97	0,92	0,96
Bali	0,89	0,88	0,88	0,89	0,93
West Nusa Tenggara	0,85	0,86	0,86	0,86	0,88
East Nusa Tenggara	0,87	0,89	0,91	0,88	0,95
West Kalimantan	0,84	0,87	0,91	0,89	0,89
Central Kalimantan	0,89	0,92	0,95	0,9	0,9
South Kalimantan	0,83	0,97	0,88	0,96	0,93
East Kalimantan	0,94	0,92	0,93	0,92	0,93
North Sulawesi	0,87	0,87	0,87	0,89	0,94
Central Sulawesi	0,95	0,95	1	0,95	0,91
South Sulawesi	0,89	1	0,95	0,92	0,98
Southeast Sulawesi	0,89	0,89	0,93	0,94	0,96
Gorontalo	0,92	0,94	0,99	0,96	0,92
West Sulawesi	0,9	0,92	0,93	0,93	0,9
Maluku	0,93	0,95	0,94	0,94	0,96
North Maluku	0,91	0,95	0,95	0,96	0,99
West Papua	0,94	0,97	1	0,99	0,99
Papua	1	1	1	1	1

Based on the DEA results in the environmental expenditure efficiency table, it is evident that several provinces, such as Papua, DKI Jakarta, and East Kalimantan, achieved relatively high efficiency scores during several observation periods. In terms of time-series performance, some provinces exhibited relatively stable or increasing efficiency scores over time, while others experienced fluctuations. For instance, Papua demonstrated a high level of efficiency in several

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years because its relatively small environmental expenditure was capable of producing significant environmental outputs compared to other provinces. This may occur due to Papua's regional characteristics, which include extensive forest cover and relatively lower industrial pressure; thus, environmental indicators such as protected forest area and environmental quality tend to remain naturally superior. Conversely, several provinces with higher levels of economic development, such as West Java or East Java, may show lower efficiency scores due to high urbanization pressure, industrialization, and larger waste management volumes, meaning that the environmental spending incurred has not yet been fully optimized to produce significant environmental output improvements (Zhou et al., 2018; Song et al., 2019).

In a cross-sectional perspective, the efficiency table also reveals differences in efficiency levels across provinces, reflecting variations in institutional capacity, geographical conditions, and regional environmental policy priorities. Some provinces may not achieve a perfect efficiency score but show an increasing trend over time, indicating improvements in environmental expenditure management or enhanced regional environmental policy capacity. On the contrary, provinces experiencing a decline in efficiency scores may reflect inconsistencies in the implementation of environmental programs, shifts in budgeting priorities, or an imbalance between increased spending and environmental output achievements. Furthermore, discrepancies may exist between real-world conditions and DEA measurements, as this method measures relative efficiency based on inter-provincial comparisons; therefore, efficiency values can be influenced by data structure, regional characteristics, and differences in regional development capacities (Sueyoshi & Goto, 2012; Halkos & Petrou, 2019). Consequently, the interpretation of efficiency results should be understood not merely as a performance ranking, but as a preliminary indication of the potential for improving environmental expenditure management at the regional level.

Following the attainment of efficiency results through DEA, the next stage of this research is the Tobit regression analysis to identify the factors influencing these efficiency levels. Before the model estimation, descriptive statistics are presented to provide a general overview of the data characteristics for each research variable. A summary of these descriptive statistical results is presented in the following table.

Table 4. Descriptive Statistics

Variable	Mean	Std.dev.	Min	Max
EFFICIENCY	.906667	0.644236	0.67	1
InPDRB	12.0872	1.139886	10.24108	14.58146
Population Growth Rate	1.402727	5.147523	0.31	4.13
Industrialization Level	17.01885	11.80044	1.17	43.3
ICTDI	5.852364	0.706451	3.22	7.88

Descriptive statistics are employed to provide a general overview of the research variables' characteristics, including environmental expenditure efficiency (dependent variable) and Real GRDP, population growth rate, industrialization level, and ICTDI (independent variables). The analysis results show significant variations across provinces, reflecting differences in the economic and structural conditions of the regions during the observation period. The efficiency variable ranges from a maximum of 1.00 to a minimum of 0.67, with the average value still falling below the efficient frontier. Given that the efficiency variable is censored with an upper limit of 1.00, the data distribution is not entirely continuous but restricted to a specific interval. These data characteristics justify the selection of the Tobit regression model for the subsequent estimation stage. The Tobit model is deemed more appropriate than Ordinary Least Squares

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(OLS) for analyzing the influence of Real GRDP, population growth, industrialization, and ICTDI on environmental expenditure efficiency.

Table 5. Multicollinearity Test Results

	InPDRB	**LajuPe-k**	**Tingkat-i**	**IPTIK**
InPDRB	1.0000			
Population Growth Rate	-03356	1.0000		
Industrialization Level	0.4882	0.1171	1.0000	
ICTDI	0.3948	-0,3675	0.2331	1.0000

Table 6. Heteroscedasticity Test Results

Component	**Value**
Null Hypothesis (H0)	$\sigma(i)^2 = \sigma^2$ for all i
Chi-square (χ^2)	1.49
Degrees of Freedom (df)	5
Prob > χ^2	0.9141

Furthermore, the results of the classical assumption tests demonstrate that the model satisfies the requirements for estimation viability. The multicollinearity test indicates no strong correlation between independent variables, while the heteroscedasticity test shows constant residual variance. With these assumptions fulfilled, the Tobit regression model is considered valid for analyzing the impact of Real GRDP, population growth, industrialization, and ICTDI on environmental expenditure efficiency.

Tobit Model

Table 7. Tobit Model Results

Efisisnsi	**Dy/dx**	**Coefficient**	**Std.err.**	**Z**	**P>|z|**
LnGRDP	-0.020528	-0.027073	0.050888	-0.53	0.595
Population Growth Rate	0.059002	0.07785	0.103501	0.75	0.452
Industrialization Level	0.010961	0.014463	0.004522	3.20	0.001
ICTDI	-0.466674	-0.615756	0.709341	-7.65	0.000
_cons		1.267575	0.086324	17.87	0.000
/sigma_u		.0229841	0.031604	2.66	0.008
/sigma_e		.0534056	1.004413	16.90	0.000
rho		.1562728			

LR test of sigma_u=0: chibar2(01) = **15.79** Prob >= chibar2 = **0.000**

The Tobit model results indicate that the Industrialization Level has a positive and significant impact on environmental expenditure efficiency. This suggests that regions with higher levels of industrialization tend to possess superior economic, technological, and managerial capacities, enabling more efficient management of environmental budgets. Conversely, the Information and Communication Technology Development Index (ICTDI) exhibits a negative and significant influence on efficiency. This finding implies that advancements in information technology have not been optimally integrated into the management and oversight systems of environmental spending, thus failing to drive maximum efficiency improvements. These results align with previous studies stating that industrial economic structures and institutional readiness play a pivotal role in determining the efficiency of environmental policies and public expenditure management (Wang, 2018; Moreno-Enguix & Bayona, 2017; Zhou & Zhang, 2020).

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Meanwhile, GRDP and the Population Growth Rate do not show a significant influence on environmental expenditure efficiency. This indicates that differences in regional economic capacity and population growth dynamics do not directly determine the efficiency level of environmental budget management at the provincial level. In other words, environmental expenditure efficiency is more influenced by structural factors, institutional quality, and policy governance rather than purely by economic conditions and demographic pressures. This finding is consistent with several previous studies demonstrating that the scale of economic capacity or population size is not always the primary factor in determining the efficiency of public spending in the environmental sector (Jialu et al., 2022; Lacko et al., 2023; Cheng et al., 2021).

This discussion interprets the influence of economic and structural factors on environmental expenditure efficiency in Indonesia, as measured through the Data Envelopment Analysis (DEA) approach. The use of Tobit regression in this analysis is justified by the censored nature of DEA efficiency scores, aiming to avoid the estimation biases that might arise in an Ordinary Least Squares (OLS) model. The research findings reveal variations in influence and significance across variables, reflecting the distinct role of each factor in explaining regional efficiency levels. Systematically, this section elaborates on the meaning of the coefficients, the direction of influence, and the policy implications of each variable for environmental sustainability in Indonesia.

This discussion places empirical results within the framework of public efficiency theory and previous literature to explain why some variables are influential while others are not. From the perspective of Farrell's (1957) technical efficiency theory, efficiency is determined by the ability of regional governments to optimize inputs into outputs, rather than merely by the volume of resources possessed. The DEA results show that only a fraction of provinces reside on the efficient frontier, while the majority still experience inefficiency. This condition underscores that the primary issue is not the budget amount, but rather the quality of governance, managerial capacity, and the effectiveness of environmental policy implementation. These findings are consistent with Wang (2018), Barrell et al. (2021), and Xue et al. (2024), who state that environmental expenditure efficiency is heavily influenced by institutional capacity and the quality of regional fiscal management.

The most critical finding of this study lies in the variables that do not show significant influence: LnGRDP and the population growth rate. Theoretically, GRDP is often linked to the Environmental Kuznets Curve (EKC), which suggests that increasing income at a certain stage can improve environmental quality. However, the non-significance of LnGRDP indicates that regional economic capacity has not automatically translated into environmental budget management efficiency. This implies that economic growth is not yet fully integrated with environmental governance reforms. This finding aligns with Wang (2018), Jialu et al. (2022), and Sholeha & Suseno (2025), who emphasize that substantial economic capacity does not guarantee policy effectiveness without strong institutional support. Thus, the increase in GRDP in Indonesia reflects economic expansion more than an improvement in environmental expenditure management quality.

A similar pattern occurs with the population growth rate, which theoretically, based on Demographic Transition Theory (Notestein, 1945), could increase environmental pressure and the need for public spending. However, the results show that demographic dynamics do not directly influence environmental expenditure efficiency. This indicates that population pressure has not yet become a determinant in budget optimization, as efficiency is more dictated by planning mechanisms, oversight, and policy coordination. This finding is consistent

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with Jialu et al. (2022) and Hartono et al. (2023), who found that population size is not always a significant determinant of public spending efficiency. In other words, the efficiency problem in Indonesia lies not in the population size, but in how local governments manage available resources.

The industrialization level is proven to exert a positive and significant influence on environmental expenditure efficiency. This suggests that regions with higher industrial intensity tend to possess superior economic, technological, and institutional capacities to manage environmental budgets more efficiently. This finding can be theoretically framed through Pigou's (1920) positive externality theory, which posits that industrial activities do not merely generate environmental impacts but can also foster technological innovation, institutional capacity, and enhanced compliance with environmental regulations. Industrialization, when accompanied by technological modernization and robust regulatory enforcement, creates a more structured and measurable environmental management system, thereby driving the optimization of environmental spending. This result aligns with previous research highlighting that industrial transformation and technological innovation significantly improve the effectiveness and efficiency of environmental policies (Wang, 2018; Zhou & Zhang, 2020; Jialu et al., 2022).

From the perspective of endogenous growth theory (Romer, 1986; Lucas, 1988), technology can enhance productivity and efficiency only when supported by high-quality human capital, innovation, and policies capable of effectively integrating technology into institutional systems. In this study, however, the Information and Communication Technology Development Index (ICTDI) exhibits a negative and significant influence on environmental expenditure efficiency. This suggests that regional advancements in information and communication technology have yet to directly improve budget management efficiency, primarily due to suboptimal integration within the planning, budgeting, and oversight processes of environmental policies. This condition reflects a structural gap between technological development and the institutional capacity of local governments to implement digital-based policies. These findings align with prior research indicating that digitalization does not inherently improve public policy efficiency without the support of governance reforms and institutional capacity building (Moreno-Enguix & Bayona, 2017; Cheng et al., 2021; Lacko et al., 2023). Consequently, synchronizing technological integration with governance improvements is essential for ensuring that digital progress effectively drives environmental expenditure efficiency.

Overall, this discussion reaffirms that environmental expenditure efficiency in Indonesia is more influenced by the quality of economic structure and governance than by economic capacity or demographic pressure. The non-significant variables deliver a strong policy message: increasing economic growth and population dynamics do not automatically guarantee efficiency. Therefore, institutional reform, strengthening monitoring systems, and integrating performance-based policies are key factors in enhancing environmental expenditure efficiency in Indonesia.

The policy implications of these results emphasize that GRDP growth needs to be directed toward eco-friendly economic growth by strengthening the quality of performance-based spending. Controlling the population growth rate remains vital to reducing ecological pressure and maintaining regional fiscal efficiency. Furthermore, industrialization should be encouraged toward green industries oriented toward clean technology, while strengthening the ICTDI serves as a key strategy to increase transparency, budget management effectiveness, and environmental performance monitoring. Collectively, the synergy of economic, demographic,

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industrial, and digital transformation policies forms the essential foundation for supporting environmental sustainability in Indonesia.

Conclusion

Based on the Data Envelopment Analysis (DEA), the efficiency of environmental expenditure in Indonesia exhibits significant variation across provinces. While some regions have reached the efficient frontier in converting budgets into environmental outputs—such as recycling rates, protected forest areas, renewable energy, and the Environmental Quality Index (EQI)—the majority of provinces still operate under conditions of inefficiency, requiring substantial improvements in budget planning and management. The regression analysis confirms that economic capacity (GRDP) and a high-quality industrial structure exert a positive influence on efficiency, while the role of the ICTDI remains crucial in supporting transparency and the accuracy of program oversight. Overall, environmental expenditure efficiency is determined not merely by the magnitude of the budget, but by the synergy between economic capacity, demographic dynamics, industrialization, and technological advancement.

The policy implications of these findings emphasize that the government must transition from merely increasing budget allocations to strengthening the quality of budget management. Provinces with low efficiency scores should evaluate their output priorities and reinforce digital-based monitoring systems. Furthermore, the government needs to promote eco-friendly industrialization and optimize information technology to create more effective governance. Strategic measures, including managing population pressure and strengthening regional fiscal capacity, are essential to ensure sustainable environmental expenditure efficiency across Indonesia.

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