The 2nd ASEAN School of Business Network International Conference 2025
www.aseansbn.org August 7-8, 2025 Negeri Sembilan, Malaysia

Revisiting the EKC Hypothesis in Indonesia: The Role of Economic Growth, Coal Production, and Renewable Energy in Carbon Emissions

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ABSTRACT

The Environmental Kuznets Curve (EKC) hypothesis suggests an inverted U-shaped relationship between economic growth and carbon emission. This study revisits the EKC hypothesis in Indonesia by examining the dynamic interplay among economic growth, coal production, and renewable energy consumption. Using time-series data from the World Development Bank and Our World in Data from 1991-2021, the study applies a quadratic linear regression model based on the Ordinary Least Squares (OLS) method to assess whether Indonesia exhibits the characteristic EKC pattern. Furthermore, the role of renewable energy in mitigating environmental degradation is explored. The findings confirm the existence of an EKC pattern in Indonesia, with carbon emissions initially rising alongside GDP growth but declining as income reaches higher levels. The estimated turning point occurs at an average GDP per capita of approximately USD 7,256. However, renewable energy consumption does not yet show a statistically significant effect on emissions reduction, which may be attributed to its relatively small share in the national energy mix. This study highlights the unique context of Indonesia, a major emerging economy with high fossil fuel dependency and underdeveloped renewable energy infrastructure. It offers novel insights by integrating coal production and renewable energy as core factors affecting emissions trajectories.

Keywords: Environmental Kuznets Curve, Economic Growth, Renewable Energy, Carbon Emissions, Coal Production

DOI: https://doi.org/10.64458/asbnic.v2.94

INTRODUCTION

The global effort to mitigate climate change has intensified the need for sustainable development strategies, especially in emerging economies (Sachs, 2015; Falcone, 2023; Jakob et al., 2020). Indonesia, as the largest carbon emitter in Southeast Asia, is currently facing a pressing dual challenge, maintaining economic growth while addressing the adverse effects of climate change (World Bank, 2023). The country's economic expansion has been heavily reliant on fossil fuels, particularly coal, which has resulted in elevated carbon emissions and environmental degradation (Fatah, 2008; Jupesta et al., 2011; Massagony et al., 2025). Despite commitments made through the Paris Agreement and the introduction

of a national energy transition roadmap, Indonesia's shift towards renewable energy sources remains relatively slow and fragmented (Sugiawan & Managi, 2016).

Despite the abundance of renewable energy resources such as solar, wind, and geothermal, Indonesia's energy system is still largely dependent on non-renewable sources due to policy inertia, infrastructural constraints, and the entrenched interests of fossil fuel industries (Jupesta et al., 2011; Pambudi et al., 2023). These structural issues, coupled with a projected rise in energy demand driven by population growth and industrialization, amplify the urgency of adopting a well-structured and evidence-based transition strategy (Sasana et al., 2022).

Indonesia's rapidly growing economy and continued dependence on coal provide a unique empirical setting to test the EKC hypothesis under conditions of high fossil fuel reliance. The study's originality lies in incorporating renewable energy as a moderating factor, offering practical policy implications for Indonesia's Just Energy Transition. In this context, the Environmental Kuznets Curve (EKC) hypothesis offers a compelling lens to explore this dynamic. The EKC posits that there is a non-linear, inverted U-shaped relationship between economic growth and environmental degradation. It posits that environmental degradation initially increases with economic growth, but after reaching a certain income level, referred to as the turning point, it begins to decline due to improved technologies, environmental awareness, and stricter regulations (Grossman & Krueger, 1995). Although widely validated in developed economies, the EKC's validity in emerging economies like Indonesia is still under debate (Leal & Marques, 2022). The EKC remains contentious when applied to developing countries, where institutional quality, energy dependency, and governance capacity often differ significantly from high-income economies (Stern, 2004; Leal & Marques, 2022).

Some studies have confirmed the existence of an EKC pattern in Indonesia (Massagony & Budiono, 2022), while others argue that emissions continue to increase alongside economic growth, indicating the absence of a meaningful turning point (Prasetyanto & Sari, 2021). Moreover, most studies focus solely on the statistical validation of EKC without linking the findings to managerial or policy implications for energy transition in Indonesia's industrial sectors.

Indonesia's potential for renewable energy development is substantial, yet the realization of this potential is hindered by financial, technical, and political barriers (Pambudi et al., 2023). A lack of strategic integration between economic planning and environmental sustainability goals further undermines the country's capacity to achieve net-zero emissions (Fu et al., 2021; Raihan et al., 2023). The current policy landscape does not sufficiently incentivize industrial actors to invest in green technologies, nor does it offer a long-term vision for transitioning energy-intensive sectors such as manufacturing, mining, and transportation (Wang et al., 2024; Kiran et al., 2024; Carfora et al., 2018).

This study aims to bridge that gap by providing empirical evidence on the validity of the EKC hypothesis in Indonesia and investigating the mediating role of renewable energy and coal dependency. This study seeks to determine whether Indonesia has reached (or is approaching) the EKC turning point. It also aims to generate policy-relevant insights that support strategic energy transition planning, particularly in managing the trade-off between economic competitiveness and environmental performance. Findings from this research are expected to offer valuable implications for decision-makers in government and industry, guiding investment priorities, regulatory reforms, and sustainability strategies in the era of green transformation.

LITERATURE REVIEW

The Environmental Kuznets Curve (EKC) hypothesis has been widely examined in environmental economics to understand the relationship between economic growth and environmental degradation. First introduced by Grossman and Krueger (1995), who identified an inverted-U shaped relationship hypothesized by Kuznets (1955), the EKC proposes an inverted U-shaped curve in which environmental degradation rises in the early stages of economic development but declines once a specific income

threshold is reached. Most Research showed that certain type of emission follows an inverted U-shaped as income grows at the beginning of EKC argument ((Dai et al., 2022; De Bruyn et al., 1998).

Despite its theoretical appeal, empirical evidence on the EKC remains inconclusive, particularly in developing countries (Simbi et al., 2024). Stern (2004) and Leal and Marques (2022) emphasize that outcomes vary significantly depending on model specification, data coverage, and country-specific institutional dynamics. In emerging economies like Indonesia, where environmental regulations are relatively weak and fossil fuel reliance remains high, the presence of a definitive EKC turning point is still under debate. Some studies affirm the existence of the EKC pattern in Indonesia (Massagony & Budiono, 2022; Prasetyanto & Sari, 2021), while others report ongoing increases in emissions despite economic growth (no identifiable turning point), reflecting the challenges of decoupling growth from environmental harm (Sasana et al., 2022).

To address these inconsistencies, recent literature has proposed an expansion of the EKC framework by incorporating additional explanatory variables. Among these, renewable energy consumption and coal dependency have received increasing attention. Several scholars argue that renewable energy not only contributes directly to emission reduction but may also accelerate the onset of the EKC turning point, particularly in economies with high energy intensity (Bekhet & Othman, 2018; Raihan et al., 2023). Conversely, continued dependence on coal has been associated with delayed or even negate the expected downward slope of the curve (Fu et al., 2021; Kartal et al., 2024).

While prior studies often model renewable energy as a direct predictor of emissions, this study posits that its role may be more accurately conceptualized as a moderating factor. In the Indonesian context, where fossil fuels still dominate the energy mix, renewable energy is unlikely to directly determine emission levels in isolation. Instead, it is expected to function by dampening the environmental impact of fossil fuel consumption. This aligns with studies suggesting that renewable energy serves as a buffering mechanism that weakens the emission intensity of energy-intensive economies (Fu et al., 2021; Raihan et al., 2023; Teklie & Yağmur, 2024). Rather than serving solely as an independent driver of emissions reduction, renewable energy may strategically moderate the adverse environmental effects of coal use. This study thus extends the EKC framework by examining the interaction between coal production and renewable energy consumption in shaping Indonesia's carbon emissions trajectory.

In parallel, there remains a significant gap in the literature regarding the managerial and policy relevance of EKC findings. Existing studies have primarily focused on macroeconomic indicators and statistical validation, without exploring how these insights can inform corporate energy management or policy frameworks, leaving a significant gap in managerial and strategic perspectives (Carfora et al., 2018). Integrating these practical considerations is essential, particularly in economies where the industrial sector plays a major role in GDP and carbon emissions.

Given these research gaps, this study proposes a more contextualized empirical validation of the EKC hypothesis in Indonesia by including renewable energy and coal production as key explanatory variables. The goal is not only to test the theoretical shape of the EKC but also to offer insights that are relevant for both policy formulation and industrial energy management. Based on this review, the study formulates the following hypotheses:

H_1: *Coal production is positively associated with CO_2 emissions.*

H_2: *There is an inverted U-shaped relationship between GDP per capita and CO_2 emissions in Indonesia, consistent with the EKC hypothesis.*

H_3: *Renewable energy consumption weakens the positive relationship between coal production and CO_2 emissions.*

Method

This study employs a quantitative approach using annual time-series data for Indonesia from 1991 to 2021. The end point of 2021 was selected because the most recent data on renewable energy consumption, is only available up to that year. The data were obtained from the World Bank and Our World in Data. The primary variables are:

1. CO_2 emissions (metric tons per capita) as dependent variable, representing the level of environmental degradation.
2. GDP per capita (in USD) as independent variable, to capture the level of economic growth.
3. Squared GDP per capita to test the non-linear (inverted U-shaped) relationship as proposed by the EKC hypothesis.
4. Coal production (primary energy in terawatt-hour/TWh) as independent variable, as a proxy for fossil fuel reliance and carbon-intensive economic activity.
5. Renewable energy consumption (percentage of total final energy consumption) as moderator variable, to assess whether the shift toward cleaner energy sources weakens the environmental impact of coal usage.

To control for other macroeconomic and structural determinants of CO_2 emissions, the following variables are included:

6. Total population, as population size is closely linked to consumption and energy demand.
7. Industrial structure (share of the tertiary industry sector in GDP), capturing the degree of economic structural transformation toward less carbon-intensive sectors.
8. Net foreign direct investment (FDI), measured as a percentage of GDP, as a proxy for external capital inflow that may influence industrial growth and energy use.

The study formulates two econometric models to estimate the hypothesized relationships:

Model 1 - EKC Baseline Model

This model tests the conventional EKC framework by examining the non-linear effect of GDP on CO_2 emissions while controlling for coal usage and other structural variables.

$$\mathrm{CO_2} = \alpha + \beta_1 \mathrm{GDP} + \beta_2 \mathrm{GDP}^2 + \beta_3 \mathrm{Coal} + \beta_4 \mathrm{Population} + \beta_5 \mathrm{Industry} + \beta_6 \mathrm{FDI} + \epsilon$$

Model 2 - Moderation by Renewable Energy

In Model 2, the interaction term is included to assess whether renewable energy consumption moderates the effect of coal production on emissions. A significant negative coefficient for this interaction would suggest that renewable energy dampens the environmental impact of fossil fuel use.

$$\mathrm{CO_2} = \alpha + \beta_1 \mathrm{GDP} + \beta_2 \mathrm{GDP}^2 + \beta_3 \mathrm{Coal} + \beta_4 \mathrm{RE} + \beta_5 (\mathrm{Coal} \times \mathrm{RE}) + \beta_6 \mathrm{Population} + \beta_7 \mathrm{Industry} + \beta_8 \mathrm{FDI} + \epsilon$$

Where:
CO_2: carbon emissions per capita
GDP: gross domestic product per capita
GDP^2: squared GDP per capita (to capture non-linear effect)
Coal: coal production (in million tons)
RE: renewable energy consumption (% of total energy)
Coal × RE: interaction term for moderation effect
Population: total population
Industry: industry value added (% of GDP)
FDI: foreign direct investment (% of GDP)

To identify the turning point, the level of income at which CO_2 emissions begin to decline, we apply the standard EKC formula:

$$\textbf{Turning Point (log GDP)} = -\frac{\beta_1}{2 \cdot \beta_2}$$

To address potential heteroskedasticity and improve model stability, natural logarithm (LN) transformation was applied to all variables. This transformation helps reduce data skewness, scale down large magnitudes, and stabilize the variance across observations. All models will be estimated using the Ordinary Least Squares (OLS) method, which is appropriate for analyzing time-series data when the goal is to assess linear and non-linear relationships among variables. This approach allows the study to examine the magnitude and direction of the relationship between economic growth, fossil fuel use, and environmental degradation.

RESULTS

Table 1 summarizes the key characteristics of the variables used in this study. All variables have been log-transformed to reduce skewness and make the data more suitable for regression analysis. The average CO_2 emissions per capita is 5.9 metric tons per year, ranging from 5.16 to 6.46. This level is consistent with upper-middle-income countries and reflects Indonesia's ongoing industrial development and reliance on fossil fuels. Coal production indicating stable yet persistently high dependence on coal as a primary energy source in the national energy mix. The average foreign direct investment inflow is 4.3% of GDP, although the standard deviation of 2.4 suggest significant fluctuations in foreign capital, possibly reflecting shifts in political risk or regulatory changes. Renewable energy contributes an average of 3.6% to total final energy consumption, highlighting the marginal role of renewables in the national energy. The population variable reflects Indonesia's large and growing demographic, which is closely linked to energy demand and emissions (Xuan, 2024; Rahman et al., 2024). Meanwhile, INDUS captures the share of the service sector in GDP and helps explain structural changes in the economy. Overall, these statistics depict an economy with rising carbon intensity, a heavy reliance on coal, and underutilized renewable energy potential, characteristics that are central to this study's investigation of the EKC hypothesis in Indonesia.

Table 1. Description of Variables

Variable	Obs	Mean	Median	Max	Min	Std. Dev	Skewness	JB p-value
CO2	31	5.9	5.95	6.46	5.16	0.37	-0.37	0.44
COAL	31	1.68	1.71	1.82	1.46	0.91	-0.94	0.09
FDI	31	4.35	6.02	9.39	-2.6	2.39	-5.29	0.0
GDP	31	8.76	8.72	9.35	8.02	0.42	-0.02	0.33
INDUS	31	2.57	2.56	2.68	2.45	0.82	-0.06	0.21
POP	31	1.92	1.93	1.94	1.9	0.12	-0.2	0.38
RE	31	3.65	3.73	4.08	2.99	0.31	-0.57	0.32

Table 2. Correlation Matrix of Variables

Variable	CO^2	GDP	FDI	COAL	INDUS	POP	RE
CO^2	1.000						
GDP	0.974	1.000					
FDI	-0.107	-0.165	1.000				
COAL	0.086	0.047	0.203	1.000			
INDUS	0.933	0.980	-0.206	-0.031	1.000		

Variable	CO^2	GDP	FDI	COAL	INDUS	POP	RE
POP	0.992	0.984	-0.109	0.066	0.945	1.000	
RE	-0.939	-0.958	0.102	-0.115	-0.908	-0.955	1.000

Prior to regression estimation, classical assumption tests were conducted to verify the validity of the OLS approach. These include normality, heteroscedasticity, autocorrelation, and multicollinearity diagnostics. The results are presented in Table 3.

Table 3. Results of Classical Assumption Tests

Test	Method Used	Test Statistic / p-value	Interpretation
Normality Test	Jarque-Bera	p = 0.821	Residuals are normally distributed
Heteroskedasticity Test	Breusch-Pagan-Godfrey	p = 0.437	No evidence of heteroskedasticity
Autocorrelation Test	Breusch-Godfrey LM	p = 0.337	No serial correlation detected
Multicollinearity Test	VIF (see Table 4)	All VIF < 5 (except POP)	No serious multicollinearity (acceptable range)

Table 4. Variance Inflation Factor (VIF) Values

Variable	VIF	Interpretation
COAL	1.283	No multicollinearity
FDI	1.196	No multicollinearity
GDP	2.983	No multicollinearity
INDUS	1.005	No multicollinearity
POP	6.035	*Moderate multicollinearity*
TRADE	4.298	Acceptable
RE	3.451	Acceptable

The findings from Model 1 confirm the presence of an Environmental Kuznets Curve (EKC) pattern in Indonesia. This is evidenced by the statistically significant positive coefficient of GDP and a negative coefficient of GDP squared. This finding approved EKC hypothesis and strengthening the relationship between CO_2 and carbon emission in Indonesia (Rokhmawati et al, 2024). These results support the inverted U-shaped relationship between economic growth and CO_2 emissions, suggesting that at lower levels of income, economic development tends to exacerbate environmental degradation, but beyond a certain threshold, further growth leads to environmental improvement (Simbi et al., 2024; Hasan et al., 2023).

Based on the regression results from Model 1 and applying the standard EKC formula, the estimated turning point for GDP per capita is approximately USD 7,256 (PPP), indicating the income level at which CO_2 emissions begin to decline as economic growth continues. As Indonesia's current income level is approaching this critical point, there are signs that the country may be transitioning into the post-turning phase of the EKC. Nevertheless, whether this transition results in a sustained decline in emissions will largely depend on the consistency of structural reforms, advancements in clean energy technology, and the effectiveness of environmental governance.

However, coal production is not a significant determinant of CO_2 emissions in either Model 1 or Model 2. This finding suggests that coal output alone does not directly explain variation in national carbon emissions within the observed period. A plausible explanation for this result is that Indonesia exports a significant portion of its coal, meaning that production volume does not equate to domestic

consumption. Therefore, the domestic emission load may not align proportionally with production figures. This finding was supporting that energy usage negatively impacts environmental quality (Wijhetunga et al., 2024).

Furthermore, Model 2 reveals the interaction term between coal production and renewable energy consumption (Coal × RE) is insignificant, suggesting that renewable energy does not moderate the impact of coal on CO_2 emissions. This finding may be attributed to three key factors: first, the share of renewable energy in Indonesia's total energy mix remains relatively small, limiting its ability to generate a measurable systemic effect on national emission levels; second, the absence of strong regulatory or market-based incentives reduces the motivation for industries to transition away from coal, thereby weakening the practical influence of renewable energy adoption on emission outcomes; and third, the potential of renewable natural resources such as geothermal and wind energy that have not been maximized.

The split-sample analysis further supports the results obtained in the interaction model, confirming that the relationship between coal production and CO_2 emissions is insignificant, regardless of the renewable energy consumption level. This implies that, within the Indonesian context, renewable energy has not yet reached a critical threshold where it could moderate the environmental impact of fossil fuel use. Both sub-samples, representing low and high levels of renewable energy, show insignificant results for coal production, suggesting that other structural or policy factors may play a more pivotal role in shaping emission outcomes. Together, these findings highlight a persistent structural challenge in Indonesia's energy transition efforts, while macroeconomic growth dynamics support EKC theory, the dominance of coal and marginal role of renewables continue to hinder meaningful emission reductions.

Table 5. Baseline Regression Results

Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
GDP	3.5415***	5.4806***	5.1007***	-17.2512*	4.9724
	(0.0059)	(0.0020)	(0.0050)	(0.0751)	(0.3579)
GDP^2	-0.1919***	-0.3186***	-0.2999***	0.8372*	-0.2760
	(0.0036)	(0.0021)	(0.0044)	0.0993	(0.4041)
COAL	0.0057	0.0035	-0.1150	0.0032	0.0056
	(0.5589)	(0.7081)	(0.3856)	(0.8351)	(0.4981)
POP	2.6727***	2.4656***	2.5259***	7.0233**	2.7326***
	(0.0000)	(0.0001)	(0.0001)	(0.0132)	(0.0002)
INDUS	-0.0420	0.0233	0.0321	0.5922**	-0.0311
	(0.5443)	(0.7598)	(0.6780)	(0.0247)	(0.6275)
FDI	-4.8888	-1.2333	-1.8111	0.0264	-1.3333
	(0.8895)	(0.7181)	(0.6780)	(0.3328)	(0.5744)
RE		-0.2983*	-0.8652		
		(0.0921)	(0.3703)		
COAL X RE			0.0321		
			(0.1920)		
Cons	-60.816***	-64.6324***	-62.0443***	-57.8053	-68.3156**

Variable	(1)	(2)	(3)	(4)	(5)
	(0.0000)	(0.0000)	(0.0000)	(0.2997)	(0.0324)
No. Obs	31	31	31	17	17
R2 Overall	0.9899	0.9911	0.9914	0.9660	0.9943

p-value in parentheses
*p<0.10, ** p< 0.05, *** p<0.01

Discussion

The finding of this study supports the inverted U-shaped relationship between economic growth and CO_2 emissions, suggesting that at lower levels of income, economic development tends to exacerbate environmental degradation, but beyond a certain threshold, further growth leads to environmental improvement. Environment pollution rises with the GDP per capita and falls as GDP per capita reaches a certain threshold, and there are different turning points for different pollutants (Dai et al., 2022). On the other hand, in African lower income countries, early economic growth may reduce emissions, but continued development may lead to increased environmental stress. It was in accordance with the experiences of the countries around the world. In the beginning of development process, the focus was generally on economic growth, while at higher level of growth, attention begins to be paid to environment issue (Dai et al., 2022; Simbi, 2024).

This study highlighted coal production alone did not contribute to carbon emission. Furthermore, renewable energy does not significantly moderate the impact of coal on CO_2 emissions. The reason was because: first, the share of renewable energy in Indonesia's total energy mix remains relatively small and constant (Rokhmawati et al., 2024), limiting its ability to generate a measurable systemic effect on national emission levels. Second, the absence of strong regulatory or market-based incentives reduces the motivation for industries to transition away from coal, thereby weakening the practical influence of renewable energy adoption on emission outcomes.

Data shows there are shifting in energy consumption. In 2016, the proportion of fuel oil for electricity generation was 6.5% and become 2.7% in 2022. Oil fuel was replaced by coal, which show in 2016 the proportion of coal used was 55% and increased to 67% in 2022 (Ministry of Energy and Mineral Resources, 2023). Indonesian government was initiated carbon tax that will be implemented in 2025 after several years of delay. Based on Rokhmawati et al. (2024) simulation, Indonesia's carbon emission peak was expected in 2040 and under the carbon tax, carbon emission can be reduced by improving energy structures, adjusting industrial structures to green business, and emphasizing fixed asset investment more environmentally friendly. Third, the potential of renewable natural resources such as geothermal and wind energy that have not been maximized. The utilization of the renewable energy can replace country's dependency on coal and reduce Carbone emission. Table 4 Show the potency of renewable energy in Indonesia.

Table 4. Potency of Renewable Energy in Indonesia

Type of energy	Potency (MW)	Installed Capacity (MW)	Utilization (%)
Geothermal	29.544	2.438,5	4,9
Water	75.091	4.826,7	6,4
Mini and macro hydro	18.385	197.4	1
Solar	207.898	78.5	0,04
Wind	60.647	3,4	0,01
Bioenergy	32.654	1.671	5,1
Sea	17.898	0,3	0,002

Source: IESR (2017)

CONCLUSION

This study revisited the Environmental Kuznets Curve (EKC) hypothesis in the context of Indonesia by analyzing the relationship between economic growth, coal production, renewable energy consumption, and CO_2 emissions using time-series data from 1991 to 2021. The empirical findings yield several key insights. First, the EKC hypothesis is strongly supported in the case of Indonesia. This suggests that after a certain income threshold, further economic growth may contribute to environmental improvements, likely due to structural changes and adoption of cleaner technologies. Second, population emerges as the most dominant factor influencing CO_2 emissions, underscoring the demographic pressures on energy demand and environmental sustainability. As Indonesia's population continues to grow, managing its environmental impact becomes increasingly crucial. Third, coal production does not show a significant relationship with CO_2 emissions, indicating that production volume may not reflect domestic coal consumption patterns. This could be due to Indonesia's high coal export levels or the fact that other emission sources such as transportation and manufacturing, may play a more substantial role in driving national emissions. Lastly, the moderating effect of renewable energy on the relationship between coal production and emissions is not statistically significant.

This may be attributed to two main factors:

(1) The current share of renewable energy in Indonesia's total energy consumption remains too low to generate measurable systemic impacts, and
(2) There is still a lack of strong policy or market-based incentives for industries to transition from fossil fuels to renewable sources.

Overall, while Indonesia may be on a trajectory aligned with the EKC hypothesis, the findings also underscore the urgent need to scale up renewable energy deployment and create effective policy mechanisms to reduce dependency on coal and other high-emission sources. These efforts are critical to achieving long-term environmental sustainability without compromising economic growth.

Recommendations

This result carries important policy implications. It suggests that proactive environmental regulation and increased investment in green technologies are crucial at this income stage to reinforce the downward trend in emissions. Additionally, while economic growth can lead to improved environmental outcomes after the turning point, the role of complementary factors such as institutional quality, renewable energy adoption, and energy efficiency remains essential to ensure sustainable development. For the government and policy maker, our recommendations are, first to establish a unified vision and mission for carbon emission reduction. Second, strengthen regulatory and enforcement mechanisms. Third, enhance inter-ministerial and industrial collaboration. Fourth, promote environmental literacy and public awareness.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support from Pusat Pengembangan Manajemen (Center for Development of Management Studies), Jurusan Manajemen, Fakultas Bisnis dan Ekonomika Universitas Islam Indonesia for providing a research grant to this study.

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