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Mitigating Agricultural Methane Emissions through Policy Reform: Long-Run Evidence from Indonesia's Climate-Aligned Transition

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ABSTRACT: Agricultural methane (CH_4) emissions remain a critical yet under-addressed component of global climate mitigation, particularly in tropical economies. This study investigates the long- and short-run drivers of CH_4 emissions from Indonesia's agricultural sector between 1970 and 2022, focusing on three major sources: rice cultivation, enteric fermentation, and manure management. Using a dynamic econometric framework—including Autoregressive Distributed Lag (ARDL), Dynamic Ordinary Least Squares (DOLS), and Newey–West estimators—we quantify source-specific impacts and evaluate structural changes following post-2008 climate policy reforms. Results confirm rice cultivation as the dominant long-run contributor, where a 1% increase in CH_4 from paddy fields corresponds to a 0.72% rise in total agricultural methane emissions. Enteric fermentation and manure management also show significant effects, though to a lesser extent. A post-2008 policy dummy indicates a structural shift in emission dynamics, reflecting Indonesia's transition toward climate-aligned agriculture through REDD+ and the National Action Plan for GHG Reduction (RAN-GRK). Short-run dynamics reveal corrective adjustments after emission shocks, highlighting system responsiveness to policy and environmental changes. The study underscores both the potential and the limitations of national mitigation efforts in reshaping long-term emission trends. Findings suggest that methane mitigation strategies—such as alternate wetting and drying (AWD) in rice farming and improved feed quality for livestock—can reduce emissions without compromising productivity. This study offers novel empirical insights for policymakers and climate practitioners seeking to integrate food security, sustainability, and low-emission agricultural development in emerging economies.

Keywords*:* Agricultural Methane Emissions, Rice Cultivation, Enteric Fermentation, Manure Management, Climate Policy

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INTRODUCTION

Methane (CH_4) is a potent greenhouse gas with a global warming potential 84–87 times greater than CO_2 over a 20-year horizon, despite its lower atmospheric concentration (Wu et al., 2023). Its relatively short atmospheric lifetime makes it a high-leverage target for near-term climate stabilization. Projections suggest that global methane emissions may reach 380 million tons annually by 2030—an 8% increase from 2020 levels (Tatsumi, 2023). Agriculture is the largest anthropogenic source of CH_4, primarily through rice cultivation, enteric fermentation, and manure management. These emissions are especially concentrated in tropical economies with intensive rice and livestock systems, yet the sector remains underexplored in long-term dynamic modeling—particularly in rapidly developing economies like Indonesia. Reducing CH_4 from agriculture is therefore critical not only for global climate goals but also as a pathway for sustainable land use and food system transformation.

Indonesia plays a pivotal role in the global methane landscape, particularly due to its dominance in rice cultivation and livestock production. Traditional paddy farming practices, which rely on continuous flooding, create anaerobic conditions ideal for methanogenesis, making rice fields a major source of CH_4 emissions (Wu et al., 2023). Enteric fermentation from ruminants, especially in smallholder systems with low feed efficiency and limited manure management, adds to the sector's emission burden (Amriana et al., 2024). At the same time, agriculture is central to Indonesia's food security agenda, which must serve a population projected to surpass 300 million by 2040. Balancing this dual imperative—productivity and sustainability—presents a core challenge for agricultural development. As a leading rice producer in the Global South, Indonesia's experience offers transferable lessons for other methane-intensive agricultural economies.

Despite the sector's importance, there remains a persistent empirical gap in understanding how specific agricultural sources—such as rice cultivation, enteric fermentation, and manure management—contribute to Indonesia's total CH_4 emissions over time. While these emission pathways have been widely acknowledged in the literature (Amriana et al., 2024; Gu et al., 2022), most existing studies rely on static or cross-sectional approaches, which generalize emission patterns without capturing the distinct temporal dynamics of each source. As a result, the short- and long-run effects of disaggregated CH_4 sources remain insufficiently quantified through rigorous time-series methods. This methodological limitation is particularly problematic when evaluating the influence of climate-responsive policies, as static models fail to reflect dynamic structural shifts (Ito et al., 2023; Tatsumi, 2023). Moreover, empirical assessments of national mitigation frameworks—such as REDD+ and the National Action Plan for Greenhouse Gas Reduction (RAN-GRK)—are still limited, with few studies quantifying their structural impact across Indonesia's diverse agroecological landscapes (Lakshani et al., 2023; Zhou et al., 2024). These gaps collectively constrain the development of context-specific and policy-responsive mitigation strategies.

Addressing these research gaps, this study introduces a dynamic time-series framework to disentangle the short- and long-run effects of key CH_4 sources—namely rice cultivation, enteric fermentation, and manure management—on Indonesia's total agricultural emissions. Leveraging an extensive annual dataset spanning 1970 to 2022, it evaluates not only the temporal behavior of emissions but also structural changes associated with post-2008 climate policy reforms, such as REDD+ and the National Action Plan for Greenhouse Gas Reduction (RAN-GRK). To the best of our knowledge, this is the first empirical investigation to apply a combined ARDL, DOLS, and Newey–West estimation approach in this context. By integrating source-specific variables with policy-sensitive modeling, the study contributes new insights that bridge the methodological divide between sectoral emission inventories and dynamic policy evaluation—offering a more nuanced and actionable evidence base for climate-smart agriculture.

This study aims to examine the short- and long-run drivers of agricultural methane (CH_4) emissions in Indonesia using a dynamic econometric approach. It focuses on quantifying emissions from rice cultivation, enteric fermentation, and manure management, while assessing the structural effects of post-2008 climate policies. By combining source-specific analysis with policy-sensitive modeling, the study generates new empirical evidence to inform climate-smart agricultural interventions. The findings hold relevance not only for Indonesia's Nationally Determined Contributions (NDCs) but also for broader methane mitigation strategies across tropical agricultural economies.

The paper is organized as follows: Section 2 details the methodology and modeling framework; Section 3 presents the empirical results; Section 4 discusses the findings in the context of sustainability goals; Section 5 outlines policy implications; and Section 6 concludes with key contributions and directions for future research.

THEORETICAL REVIEW

Model Specification and Econometric Framework

The central hypothesis posits that increased agricultural intensity, especially from rice cultivation and livestock activity, is positively associated with methane emissions. The long-run equilibrium relationship is estimated using the following log-linear model:

Long-run equation:

$$lnCH4_{AGR} = \beta_0 + \beta_1 lnRICE + \beta_2 lnENTERIC + \beta_3 lnMANURE + \beta_4 after2008 + \varepsilon_t$$

where ε_t is the stochastic error term.

The primary estimation method is the Autoregressive Distributed Lag (ARDL) model, selected for its flexibility in handling regressors with mixed integration orders I(0) and I(1), and its suitability for moderate sample sizes (Pesaran et al., 2001). Unlike VECM, which requires all variables to be I(1), ARDL offers greater flexibility and reliability with a moderate time span and avoids spurious regression outcomes associated with non-stationary variables (Nkoro & Uko, 2016). The ARDL approach also enables estimation of an associated Error Correction Model (ECM) to quantify short-term deviations from the long-run equilibrium. The inclusion of the after2008 dummy in the ARDL formulation ensures the model can capture long-term structural shifts in the policy environment.

Estimation Strategy and Robustness Validation

Lag length for the ARDL model is selected using the Akaike Information Criterion (AIC), which balances model fit with parsimony. To ensure robustness and mitigate autocorrelation, the study incorporates two alternative estimation techniques. First, Dynamic Ordinary Least Squares (DOLS) is applied to address endogeneity by including leads and lags of differenced regressors (Stock & Watson, 1993). Second, the Newey-West estimator is used to produce heteroskedasticity- and autocorrelation-consistent (HAC) standard errors (Newey & West, 1987), improving inference reliability.

Diagnostic Tests

Several diagnostic tests are conducted to assess model quality. Stationarity is tested using the Augmented Dickey-Fuller (ADF) test (Dickey & Fuller, 1979). Cointegration is examined via the ARDL Bounds Testing procedure (Pesaran et al., 2001). Residual autocorrelation is tested using the Breusch-Godfrey LM test, and model specification is verified using the Ramsey RESET test. Structural stability is assessed with the CUSUM and CUSUMSQ tests (Brown et al., 1975), allowing the model's parameters to be validated over time.

This analytical framework offers insights not only into the emissions dynamics of a key agricultural economy but also informs targeted mitigation strategies, supporting Indonesia's and global commitments to sustainable agricultural development and climate resilience.

METHODOLOGY

This study applies a quantitative, time-series econometric approach to analyze the dynamic relationship between agricultural activities and methane (CH_4) emissions in Indonesia, spanning the period from 1970 to 2022. Employing an exploratory–explanatory design, the research aims to identify the long-term and short-term determinants of CH_4 emissions from agriculture and assess their statistical and policy implications in light of sustainable development objectives.

Research Design and Scope

The study is designed as a quantitative analysis employing annual time-series data at the national level. The framework is exploratory in identifying the major sources of methane emissions and explanatory in quantifying their dynamic impact. Covering the period 1970–2022, this timeline was selected to reflect both the evolution of Indonesia's agricultural sector and significant shifts in international climate governance, such as the implementation of REDD+ and the Bali Action Plan. The research scope centers on Indonesia but draws broader relevance from the implications for low- and middle-income agricultural economies facing similar sustainability challenges.

To further clarify the flow of analytical stages used in this study, Figure 1 presents a visual representation of the econometric strategy. The diagram illustrates the research pathway from agricultural activities to CH_4 emissions, through the ARDL framework, and extending to robustness checks such as the DOLS estimator, HAC correction, and structural dummy post-2008. This flowchart contextualizes the econometric decisions and their alignment with Indonesia's policy commitments.

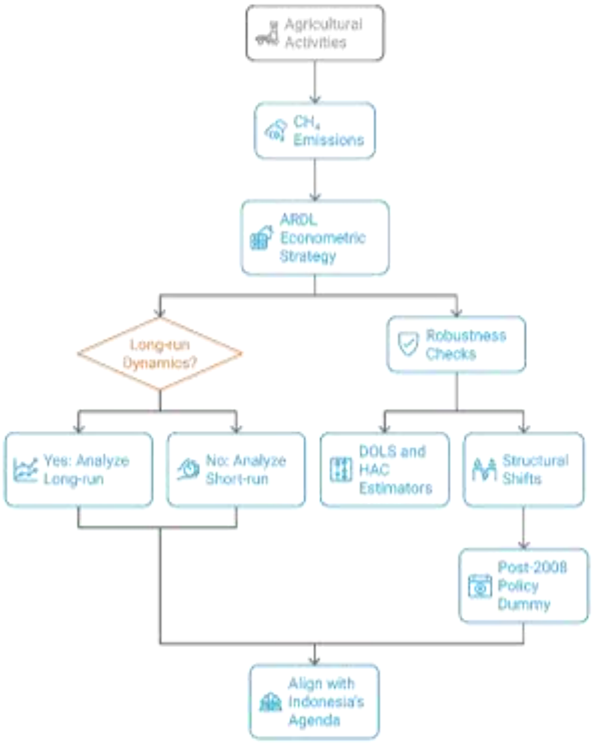

Figure 1. Research Design Flow for CH_4 Emissions from Agricultural Activities

Data Source, Variables and Operationalization

All variables are sourced from FAOSTAT, the official statistical database maintained by the Food and Agriculture Organization of the United Nations. FAOSTAT offers standardized and internationally recognized records compiled using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The use of this single comprehensive database enhances consistency and reproducibility. All data are open-access and fully documented, supporting transparency and allowing for future replication.

The study employs one dependent variable and three independent variables to capture the most significant sources of methane emissions from agricultural activities. The operational definitions, measurement units, and data sources for each variable are summarized in Table 1.

Table 1. Operational Definitions and Units of Agricultural Methane Emission Variables

Symbole	Variable Name	Operational Definition	Unit
$lnCH4_{AGR}$	CH_4 emissions from agriculture	Methane emissions produced from total agricultural activities, including crops and livestock, as classified by IPCC Agriculture (Code 99576). This includes emissions from enteric fermentation,	kt CH_4

	(IPCC Agriculture)	manure management, and flooded rice cultivation.	
$lnRICE$	CH_4 emissions from rice cultivation	Methane emissions generated from anaerobic decomposition of organic materials in flooded paddy fields. Represents the CH_4 contribution of rice farming practices.	kt CH_4
$lnENTERIC$	CH_4 emissions from enteric fermentation	Methane emissions from digestive processes in ruminants, particularly due to microbial fermentation and released via eructation. This is a major contributor to livestock emissions.	kt CH_4
$lnMANURE$	CH_4 emissions from manure management	Methane emissions from livestock manure under anaerobic management systems, such as storage tanks or lagoons. This pathway generates significant CH_4 if not properly treated.	kt CH_4

All variables are log-transformed to reduce heteroskedasticity, correct for non-normal distribution, and interpret coefficients as elasticities (Wooldridge, 2015). To account for structural policy shifts, a binary dummy variable after2008 is introduced to capture the post-2008 environmental policy climate, following the launch of Indonesia's National Action Plan on GHG Reduction (RAN-GRK) and the REDD+ initiative (Bappenas, 2011; UNFCCC, 2007).

RESULTS

This section presents the empirical findings of the study in accordance with the econometric strategy outlined in the methodology. The analysis is divided into three subsections, beginning with summary statistics and diagnostic evaluations to assess the suitability of the dataset for time-series modeling. It then proceeds to report the estimation results of the Autoregressive Distributed Lag (ARDL) model, followed by robustness checks using Dynamic Ordinary Least Squares (DOLS) and the Newey–West estimator. The primary objective is to investigate both the short-run and long-run effects of agricultural activities—particularly rice cultivation, enteric fermentation, and manure management—on methane (CH_4) emissions in Indonesia during the period 1970–2022. Special attention is given to evaluating structural changes in the post-2008 period, in line with Indonesia's evolving climate policy framework.

Summary Statistics and Preliminary Diagnostics

Prior to model estimation, a comprehensive assessment of the data was conducted to ensure that key econometric assumptions were satisfied. This subsection provides descriptive statistics, coefficient of variation (Coef. Var), unit root tests for stationarity, and multicollinearity diagnostics for all variables included in the model. Table 2 displays the central tendencies (mean), dispersion (standard deviation), and variability (Coef. Var) of each variable. The coefficient of variation values suggest moderate variability for agricultural CH_4 emissions (0.15), rice cultivation (0.12), enteric fermentation (0.24), and manure management (0.44), indicating acceptable dispersion in the sample. The dummy variable after2008, included to capture structural policy shifts, exhibits high variability due to its binary format (0 or 1).

To assess stationarity, the Augmented Dickey–Fuller (ADF) test was applied to each variable. None of the variables were found to be stationary at level, but all achieved stationarity at first difference, confirming they are integrated of order one [I(1)]. This supports the appropriateness of the ARDL model, which accommodates regressors with mixed integration orders. Multicollinearity among the regressors was assessed using the Variance Inflation Factor (VIF). All VIF values were well below the conventional threshold of 10, with a mean VIF of 1.30. The highest VIF was observed for enteric fermentation (1.53), which still falls within acceptable limits. These results confirm that the dataset satisfies the key preconditions for time-series modeling using ARDL, ensuring the reliability and validity of the subsequent estimations.

Table 2. Descriptive Statistics, Coefficient of Variation, and Diagnostic Test Results

Variable	Obs	Mean	Std. Dev.	Coef. Var	Min	Max
CH4_AGR	53	3099.423	465.4649	0.1502	2245.39	3640.76
RICE	53	2210.784	266.9859	0.1208	1669.78	2529.36
ENTERIC	53	770.2617	188.4542	0.2447	487.43	1140.93
MANURE	53	88.0249	38.5479	0.4379	33.64	170.29
after2008	53	0.2830	0.4548	1.6069	0	1

ARDL Model Selection and Long-run Estimation

The ARDL model was estimated to capture both the short- and long-run relationships among the variables. Model selection relied on the Akaike Information Criterion (AIC) and Final Prediction Error (FPE), which jointly identified an optimal lag structure of ARDL(3,2,1,2,1). This lag specification was selected to ensure parsimony while adequately capturing the temporal dynamics. The Johansen cointegration test confirmed a long-run equilibrium relationship among the variables. Furthermore, the bounds testing approach strongly rejected the null hypothesis of no level relationship, with the F-statistic exceeding the upper critical bound at the 1% level. Table 3 shows the long-run and short-run estimation results of the ARDL model, along with the associated robustness indicators. The output confirms statistically and economically significant effects of agricultural sources on methane emissions, both in the immediate and long-term perspectives.

Table 3. ARDL Estimation Results: Long-run and Short-run Dynamics

Component	Coefficient	t-statistic	Significance
Long-run			
lnRICE	0.7218	31.11	***
lnENTERIC	0.2157	20.09	***
lnMANURE	0.0369	5.51	***
after2008	0.0016	2.52	**

Short-run			
ΔlnCH4_AGR(t-1)	0.1263	2.63	**
ΔlnCH4_AGR(t-2)	0.0315	1.72	*
ΔlnRICE(t-1)	-0.5744	-5.07	***
ΔlnRICE(t-2)	-0.0769	-2.46	**
ΔlnENTERIC(t-1)	-0.1535	-4.39	***
ΔlnMANURE(t-1)	-0.0324	-2.62	**
Δafter2008	-0.007	-2.41	**
Constant	0.0001	0.22	n.s.
ECM(t-1)	-1.8165	-11.61	***
Robustness Indicators			
χ^2 Series	3.795	[0.2845]	no serial correlation
χ^2 ARCH	2.231	[0.1352]	no ARCH effects
χ^2 Breusch-Pagan Test	0	[0.9442]	homoskedasticity assumed
Ramsey RESET test	1.52	[0.2221]	no model misspecification
R-squared	0.9973		
Adjusted R-squared	0.9962		

Note: Statistical significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, n.s. = not significant. ECM represents the speed of adjustment toward long-run equilibrium. Diagnostic tests support model reliability.

The long-run coefficients indicate that a 1% increase in CH_4 emissions from rice cultivation is associated with a 0.7218% increase in total agricultural methane emissions, confirming the prominent role of flooded rice fields as key CH_4 contributors. Emissions from enteric fermentation also significantly influence total emissions, with a 1% increase yielding a 0.2157% rise in total CH_4. Though smaller in magnitude, emissions from manure management remain statistically significant, while the after2008 dummy confirms a shift in post-policy emissions trends. In the short run, lagged changes in CH_4 emissions from rice cultivation and enteric fermentation exert negative effects, supporting correction toward long-run equilibrium. The negative and significant error correction term (ECM) of -1.8165 reinforces this convergence.

These findings underscore the responsiveness of agricultural CH_4 emissions to recent changes and the stabilizing effect of structural policy interventions. To further support long-run reliability, a Johansen cointegration test was also conducted and confirmed the presence of stable long-run equilibrium relationships. While the ARDL Bounds test alone can establish cointegration, the Johansen method provides additional assurance of robustness. Future studies may complement this with breakpoint or rolling window tests to track potential shifts in long-run parameters over time.

Robustness Checks and Model Diagnostics

To validate the reliability of the ARDL model, robustness checks were conducted using two alternative estimators: Dynamic Ordinary Least Squares (DOLS) and the Newey-West Heteroskedasticity and Autocorrelation Consistent (HAC) method. These methods are particularly useful in controlling for endogeneity, autocorrelation, and heteroskedasticity—key issues in time-series econometrics involving environmental data. The DOLS approach, by including leads and lags of the differenced explanatory variables, corrects for potential endogeneity in the long-run regression. As shown in Table 4, the coefficients for rice cultivation, enteric fermentation, and manure management remain statistically significant and consistent in magnitude with the ARDL estimates. The policy dummy variable (after2008) also retains its positive and significant effect, suggesting structural influence of post-REDD+ climate policy in Indonesia.

Table 4. Robustness Validation: DOLS and Newey-West Estimations

Method	lnRICE Coef.	lnENTERIC Coef.	lnMANURE Coef.	after2008 Coef.	Notes
DOLS	0.6756 ***	0.1939 ***	0.0648 ***	0.0034 **	Includes leads and lags
Newey-West	0.6874 ***	0.2188 ***	0.0500 ***	0.0049 *	HAC standard errors applied

Note: Statistical significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Likewise, the Newey-West estimation, which adjusts for autocorrelation and heteroskedasticity in the residuals, yields similar coefficient signs and significance levels. This consistency across methods affirms the robustness of the original ARDL model and supports the conclusion that rice cultivation and enteric fermentation are primary long-run drivers of agricultural CH_4 emissions in Indonesia.

In addition to alternative estimators, several diagnostic tests were conducted to evaluate the overall specification and stability of the ARDL model. The Breusch-Godfrey LM test confirmed the absence of serial correlation ($p = 0.2845$), while the ARCH-LM test and Breusch-Pagan test suggested no heteroskedasticity ($p = 0.1352$ and $p = 0.9442$, respectively). The Ramsey RESET test ($p = 0.2221$) indicated that the model is correctly specified, with no omitted variable bias. These diagnostics collectively support the reliability and statistical adequacy of the ARDL model used in this study.

The consistent results across different estimation strategies and diagnostic tests underscore the robustness of the findings and reinforce the conclusion that agricultural methane emissions in Indonesia are predominantly driven by rice cultivation and livestock-related sources, particularly enteric fermentation, with evidence of policy-induced structural shifts post-2008.

DISCUSSION

This study aimed to investigate the long-run and short-run determinants of methane (CH_4) emissions from the agricultural sector in Indonesia from 1970 to 2022. Through the ARDL framework complemented by DOLS and Newey-West robustness checks, we explored how emissions from rice cultivation, enteric fermentation, and manure management influence the total CH_4 emissions, while also assessing the role of post-2008 environmental policy shifts. This section discusses the empirical findings in light of the research objectives and situates them within the broader context of sustainable agriculture and climate change mitigation.

Rice Cultivation and Methane Emissions

Rice cultivation stands out as the most prominent and statistically significant long-run driver of agricultural methane (CH_4) emissions in Indonesia. The ARDL and robustness estimations consistently demonstrate that a 1% increase in methane emissions from rice paddies corresponds to a 0.7218% increase in total agricultural CH_4 emissions. This strong elasticity reflects the biological processes occurring in continuously flooded rice fields, where oxygen limitation creates anaerobic conditions conducive to methanogenic microbial activity (Bachelet & Neue, 1993; Yan et al., 2009). As such, rice systems—particularly those under traditional water management—constitute a major source of CH_4 emissions and represent a critical area for climate mitigation.

Short-run dynamics suggest that the system tends to correct itself over time. The statistically significant negative coefficients of the lagged differenced rice variables imply that deviations in methane output—driven by short-term shocks such as weather anomalies or abrupt management changes—are followed by adjustments toward equilibrium. This points to the inherent adaptive behavior of Indonesia's rice-based agricultural emissions, shaped by both seasonal farming cycles and evolving responses to policy and environmental conditions.

Given this outsized contribution, rice cultivation offers a strategic entry point for methane mitigation aligned with sustainable agriculture. Prior research has shown that water-saving techniques such as Alternate Wetting and Drying (AWD), along with improved irrigation scheduling and organic soil management, can significantly reduce CH_4 emissions without yield penalties (Linquist et al., 2011). Since irrigated rice is a dominant staple in Indonesia, these interventions hold potential for co-benefits—simultaneously lowering GHG emissions and enhancing water efficiency—consistent with the country's Nationally Determined Contributions (NDCs) under the Paris Agreement.

Nevertheless, the implementation of these mitigation practices must take into account Indonesia's substantial regional diversity. Agro-ecological conditions, socio-cultural practices, and access to water infrastructure vary widely across provinces, influencing both the feasibility and effectiveness of AWD and related technologies (Gu et al., 2022; Kovilpillai et al., 2024). Empirical studies report that AWD can reduce emissions by as much as 73%, but its uptake depends on local factors such as water availability and institutional capacity (Karki et al., 2023; Win et al., 2020). This calls for regionally calibrated policy frameworks that optimize emission reductions while preserving productivity and resilience.

Environmental shocks such as El Niño events or extended droughts also play a role in emission dynamics. During periods of climatic stress, farmers may revert to continuous flooding to secure crop yields, inadvertently intensifying CH_4 emissions (Masuda et al., 2022; Wu et al., 2023). Conversely, periods of sufficient rainfall and successful AWD deployment can suppress methane production (Ito et al., 2023; Liang et al., 2024). Integrating these climate feedbacks into irrigation and emission strategies is essential for improving system-wide resilience and effectiveness.

Socioeconomic constraints are equally important in shaping farmers' adoption of methane-reducing practices. In many low-income farming communities, uptake is hindered by limited access to information, credit, and training. Studies emphasize the importance of farmer education and incentive-based approaches—such as targeted subsidies or carbon-market participation—to overcome these barriers (Islam et al., 2020; Rathnayake & Mizunoya, 2023; Wang et al., 2021). Therefore, policy mechanisms must be designed not only to promote technological effectiveness but also to accommodate social inclusion and equity.

Engaging farmers directly in policy development enhances the legitimacy and adoption of mitigation programs. Participatory approaches help surface context-specific insights and ensure that interventions align with local needs, cultural norms, and food security objectives (Hossain & Islam, 2022; Minamikawa et al., 2021). In this way, methane reduction in rice cultivation becomes a pathway not only toward environmental sustainability but also toward broader rural development.

As illustrated in Figure 2, rice cultivation has a significantly higher long-run elasticity than other CH_4 sources, highlighting its strategic importance. These findings reinforce the urgent need for a multidimensional response—one that balances scientific evidence, regional adaptation, farmer engagement, and national policy coherence—to effectively mitigate methane emissions from Indonesia's rice sector and advance its sustainable development agenda.

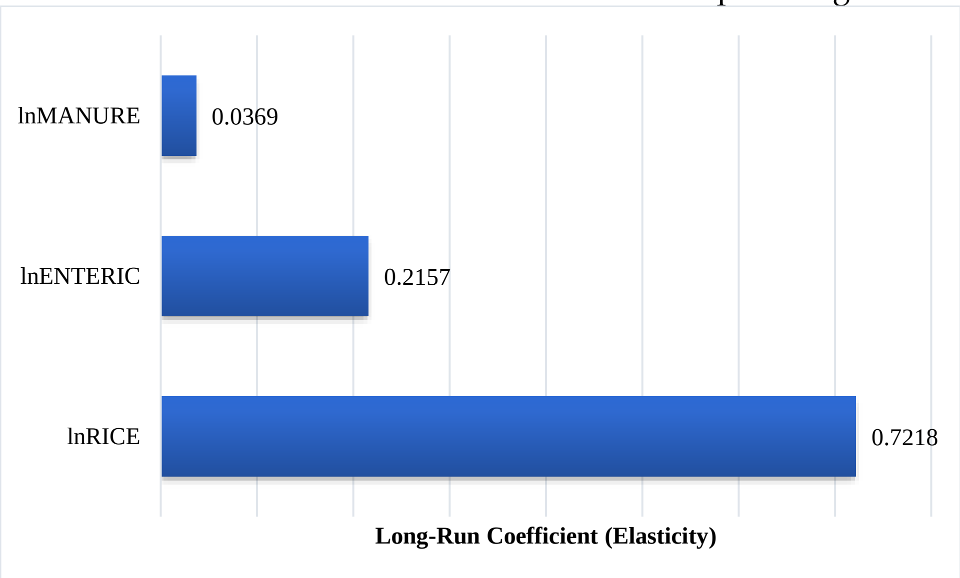

Figure 2. Long-Run Contributions of CH_4 Sources Based on ARDL Estimation Results.

Enteric Fermentation and Livestock-Based Emissions

Enteric fermentation emerges as a consistently significant long-term driver of agricultural methane (CH_4) emissions in Indonesia. The ARDL model, corroborated by DOLS and Newey-West robustness tests, estimates that a 1% rise in CH_4 emissions from ruminant digestion is associated with a 0.22% increase in total agricultural emissions. This result underscores the pivotal role of biological methane production in livestock systems, particularly in tropical smallholder settings where cattle and buffalo are central to rural livelihoods. Methane is generated during the digestive process of ruminants, in which specialized microorganisms break down fibrous plant material in the rumen, releasing CH_4 as a metabolic byproduct (Moon et al., 2024; Tang et al., 2015).

Short-run dynamics suggest a degree of self-correction in the emission pattern. The negative and significant short-run coefficients for lagged changes in enteric CH_4 indicate that emission shocks—due to factors like feed variation, disease outbreaks, or changes in herd size—tend to dissipate over subsequent periods. This reflects the inherently adaptive nature of smallholder livestock systems and indicates that emission levels may stabilize as management practices adjust over time.

Scientific advances in feed science provide clear pathways for reducing methane emissions while maintaining, or even enhancing, livestock productivity. Dietary improvements—such as higher-quality forage, legumes, and methane-reducing feed additives like tannins, oils, or seaweed-based compounds—have been shown to suppress methanogenesis by altering rumen fermentation processes (Amriana et al., 2024; Jackson et al., 2021). These interventions not only reduce environmental impacts but also improve key productivity indicators, including feed conversion efficiency and milk yield. Moreover, strategies emphasizing digestibility and non-conventional feed inputs can simultaneously meet climate targets and support economic viability among smallholders (Gu et al., 2022).

However, technological solutions must be complemented by institutional mechanisms that ensure their accessibility and scalability. Agricultural extension programs play a key role in disseminating knowledge about sustainable livestock practices and providing training in methane-reducing techniques, such as improved grazing management, integrated forage systems, and composting of manure (Shiddieqy et al., 2024; Weller et al., 2016). Additionally, the formation of cooperatives can reduce input costs through pooled procurement of supplements and enhance peer-to-peer learning among farmers. Policy incentives—such as subsidies, performance-based payments, or participation in carbon offset schemes—can further motivate the adoption of low-emission practices (Yang et al., 2024).

To strengthen the alignment between climate goals and livestock development, policy frameworks must recognize the dual importance of emission reduction and food security. National programs that incorporate climate-smart livestock strategies should emphasize inclusivity, economic viability, and regional flexibility. For instance, pilot projects co-developed with farmer cooperatives and local governments could demonstrate scalable models of low-emission livestock systems that maintain productivity while reducing methane intensity (Bhatia et al., 2023; Sun et al., 2016). Such projects should prioritize transparency in impact measurement and incorporate diverse success metrics, including socioeconomic outcomes and environmental performance.

Rather than treating environmental sustainability and rural development as competing objectives, the integration of emission-reduction strategies into livestock policy presents an opportunity to achieve both. By fostering innovation, strengthening institutions, and providing targeted support to farmers, Indonesia can advance toward a more climate-resilient agricultural sector. Such an approach ensures that emission reductions are not only technically feasible but also socially equitable and economically sustainable (Cheng et al., 2010; Zhao et al., 2015). These insights are transferable to other developing economies where smallholder livestock systems play a central role in both food security and climate mitigation.

Policy Transition and Post-2008 Methane Emission Dynamics

The empirical evidence from the ARDL estimation demonstrates a significant structural shift in Indonesia's agricultural methane (CH_4) emissions beginning in 2008—a turning point that aligns with the launch of major national climate policy frameworks such as REDD+ and the National Action Plan for Greenhouse Gas Emission Reduction (RAN-GRK). The long-run coefficient of the after2008 dummy variable is positive and statistically significant (0.0016; $p < 0.05$), indicating that the post-2008 period marked a structural transformation in emission dynamics, possibly driven by changes in institutional priorities, investment patterns, and policy implementation strategies. Conversely, the short-run coefficient is negative and significant (-0.0070; $p < 0.05$), suggesting that early policy interventions yielded immediate, albeit temporary, reductions in methane emissions.

These contrasting effects point to a dual narrative: on one hand, early climate initiatives likely spurred behavior change and initial mitigation gains—reflected in short-term emission declines. On the other, the long-run trend implies that broader sectoral transformations may not have been fully sustained, potentially due to implementation gaps, resource constraints, or rebound effects following initial interventions. Such insights affirm the importance of differentiating short-term programmatic impacts from long-term structural shifts in emission trajectories.

This pattern is further substantiated by the time-series trend illustrated in Figure 3, which shows CH_4 emissions peaking and fluctuating in the years following 2008. While minor downturns are visible—such as in 2013 and 2016—overall emissions remain elevated, with moderate reductions followed by rebounds. The data suggest that post-policy declines, although visible in some years, were not consistent enough to reverse the structural growth trend.

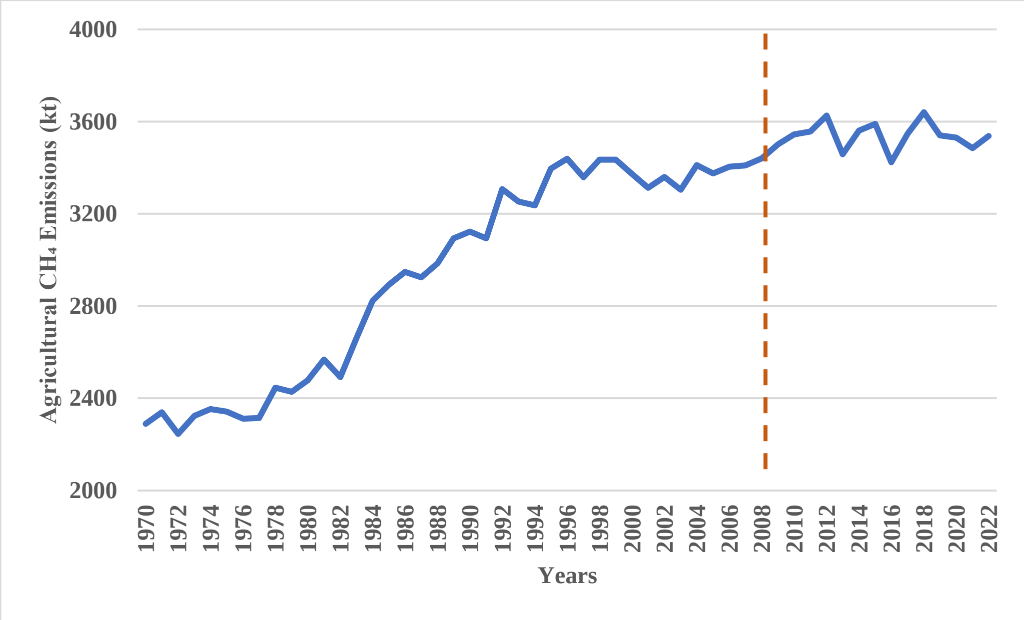

Figure 3. CH_4 Emissions Trend Before and After 2008
Source: FAOSTAT, author's calculation

A visual depiction of CH_4 emissions from agriculture (1970–2022), highlighting the period before and after the implementation of Indonesia's post-2008 climate policy frameworks. Complementary research supports these observations. Studies show that post-2008 interventions, including the introduction of Alternate Wetting and Drying (AWD) and improvements in manure management, had tangible impacts in reducing methane emissions at pilot scales (Kumar et al., 2016; LaHue et al., 2016). However, national-scale implementation has lagged due to inconsistent training, limited technology dissemination, and the absence of strong farmer engagement mechanisms. Such gaps have limited the effectiveness and permanence of these otherwise promising strategies.

Beyond technical implementation, institutional limitations remain a major constraint. As highlighted by Amriana et al. (2024) and Rathnayake & Mizunoya (2023), many smallholder farmers face barriers such as insufficient financial support, lack of extension services, and uncertainty around the economic benefits of low-emission practices. Without targeted incentives or education programs, voluntary adoption remains limited, especially in rural regions where economic survival takes precedence over environmental concerns.

To overcome these constraints, future climate policy must emphasize integration between emission reduction and food security goals. Participatory policy design—rooted in farmer needs and localized conditions—will be essential for improving policy relevance and adoption. Aligning methane mitigation strategies with socio-economic incentives, such as carbon credit schemes, results-based payments, or market access for sustainable products, could improve feasibility and farmer buy-in.

At the institutional level, improved inter-agency coordination between the ministries of environment, agriculture, and rural development will help align objectives, reduce policy fragmentation, and create clearer pathways for implementation. Additionally, establishing robust monitoring and evaluation systems will be key to tracking outcomes and making adaptive improvements based on evidence.

In essence, while post-2008 policy frameworks have laid the foundation for more sustainable agricultural practices in Indonesia, their effectiveness hinges on bridging the gap between national ambition and local implementation. Sustainable transformation will require not only financial investment and technological support but also inclusive governance and continuous engagement with farming communities. The ARDL results and visual trends confirm that early gains must be consolidated through deeper reforms, ensuring that Indonesia's agricultural development does not come at the cost of its climate commitments.

Policy Implications

The findings of this study underscore the critical need for Indonesia to embed methane (CH_4) mitigation strategies into its broader agricultural development agenda. Given the persistent and significant contributions of rice cultivation and enteric fermentation to agricultural CH_4 emissions, policies should prioritize the upscaling of proven mitigation practices. These include Alternate Wetting and Drying (AWD) irrigation in paddy systems and improved livestock diets that reduce enteric methane production. To ensure adoption, especially among smallholder farmers, targeted support is essential—ranging from agricultural extension services and on-site training to subsidies that lower the upfront costs and risks of technology adoption.

At the institutional level, the post-2008 climate policy frameworks, such as REDD+ and the RAN-GRK, have marked important milestones but face challenges in sustained implementation. The contrasting short- and long-run effects observed in the ARDL results suggest that while early interventions had temporary success, long-term mitigation has been undermined by policy fragmentation, inconsistent enforcement, and insufficient sub-national alignment. Strengthening vertical coordination between ministries and local governments, along with integrating methane-specific targets into Indonesia's enhanced Nationally Determined Contributions (NDCs), can improve accountability and continuity in policy delivery.

To further accelerate progress, Indonesia should explore innovative climate finance mechanisms. Expanding access to carbon credit markets, piloting performance-based incentives, and introducing eco-labeling schemes for low-emission rice and livestock products can create tangible rewards for emission reductions. Aligning environmental outcomes with economic incentives will be key to transforming mitigation from a policy aspiration into a farmer-driven movement—ensuring that emission reductions support both climate goals and rural development.

CONCLUSIONS AND RECOMMENDATIONS

This study investigates the key drivers of methane (CH_4) emissions from Indonesia's agricultural sector over the period 1970–2022. The results show that rice cultivation and enteric fermentation are the most dominant and statistically significant contributors to long-run CH_4 emissions. A 1% increase in emissions from rice paddies is associated with a 0.7218% rise in total agricultural CH_4 emissions, underscoring the role of anaerobic decomposition in flooded rice systems. Enteric fermentation contributes an additional 0.2157% increase, reflecting the influence of ruminant livestock systems. Manure management also has a positive and significant effect, albeit with smaller elasticity, suggesting cumulative impact. Furthermore, the inclusion of a post-2008 policy dummy reveals a statistically significant structural shift, indicating that Indonesia's REDD+ and RAN-GRK frameworks have produced short-term mitigation gains but still face challenges in sustaining long-term reductions.

To address these emissions, policy interventions must prioritize context-specific methane mitigation strategies. In rice cultivation, alternate wetting and drying (AWD), improved irrigation control, and regionally tailored water management techniques should be scaled up. In the livestock sector, improving feed quality, promoting dietary additives, and enhancing manure handling practices are critical. These actions must be supported through expanded agricultural extension services, participatory education, and incentive mechanisms, particularly for smallholder farmers operating under financial and informational constraints. Aligning mitigation efforts with food security and rural development priorities remains crucial to ensure both adoption and long-term sustainability.

Looking forward, Indonesia's agricultural climate policy must transition from fragmented pilot efforts to a more integrated, systemic approach. Given the shared challenges across tropical agrarian nations—such as water-intensive rice cultivation, smallholder livestock systems, and limited institutional capacity—findings from Indonesia’s experience offer valuable insights for countries like Vietnam, Bangladesh, the Philippines, and others in Southeast and South Asia. These economies can adapt similar econometric tools and policy lessons to quantify and mitigate CH_4 emissions in their contexts. Thus, the policy relevance of this study extends beyond Indonesia, contributing to a broader knowledge base for climate-smart agriculture in the Global South.

FURTHER STUDY

This advanced research confirms that Indonesia’s agricultural methane emissions are primarily driven by rice cultivation and enteric fermentation, with policy interventions since 2008 delivering only short-term mitigation effects. The findings emphasize the need for integrated, context-specific strategies in rice and livestock systems, supported by strong institutional and incentive frameworks, while offering transferable insights for methane mitigation in other tropical agrarian economies of the Global South.

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