Munich Personal RePEc Archive

Agricultural Productivity, Green energy, Governance quality and Environmental Degradation in BRICS Economies : Evidence from a PMG-ARDL Analysis

Hadda, kilani and Mohamed, Ben AMAR

University of Sfax

14 October 2025

Online at https://mpra.ub.uni-muenchen.de/127353/
MPRA Paper No. 127353, posted 07 Jan 2026 09:36 UTC

Agricultural Productivity, Green energy, Governance quality and Environmental Degradation in BRICS Economies : Evidence from a PMG-ARDL Analysis

Working Paper

Kilani Hadda [(a)]

Kilani.esc@gmail.com

Ben AMAR Mohamed [(a)]

mohamed.benamar@fsegs.usf.tn

[(a)]Faculty of Economics and Management of Sfax (FSEGS), University of Sfax

Abstract

This study investigates the dynamic relationships between agricultural productivity, green energy adoption, governance quality, and environmental degradation in BRICS economies over the period 2002–2023. Using a Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) approach, complemented by FMOLS and CCR robustness estimators, the results show that agricultural productivity significantly increases long-run environmental pollution, reflecting the environmental cost of agricultural intensification. In contrast, green energy adoption and governance quality exert strong and consistent pollution-mitigating effects, underscoring their central role in promoting environmental sustainability. Overall, the findings emphasize that long-run structural factors dominate environmental outcomes in emerging agricultural economies. The study provides policy-relevant insights for advancing low-carbon and sustainable agricultural development in BRICS countries.

Key word : Environmental pollution- Agricultural productivity- - Green innovation- PMG -BRICS

Introduction

Environmental degradation poses a major challenge for emerging economies undergoing rapid structural transformation and agricultural intensification. In the BRICS countries—Brazil, Russia, India, China, and South Africa—agriculture remains central to economic growth and food security, yet it is also a significant source of greenhouse gas emissions, soil degradation, water pollution, and land-use pressure. These environmental pressures threaten progress toward key Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (UN, 2023). The ongoing energy transition offers a viable pathway for reducing the environmental footprint of agricultural systems. Green energy technologies—such as solar-powered irrigation, biomass energy, and decentralized green electricity—can lower fossil-fuel dependence and emissions in rural production (Chen et al., 2025 ; Chandio et al., 2025). Ecological Modernization and Environmental Innovation theories suggest that technological upgrading, supported by effective institutions, can reconcile productivity growth with environmental sustainability. However, empirical evidence on the pollution-mitigating role of green energy in agriculture remains fragmented, particularly in BRICS economies where agricultural expansion, energy transitions, and governance reforms evolve simultaneously. The literature further reveals a complex relationship between agriculture and environmental quality. While environmental degradation undermines agricultural productivity through climate stress and pollution exposure (Dong & Wang, 2023 ; Xu et al., 2023), productivity-driven intensification itself remains a major source of emissions in emerging economies (Burney & Ramanathan, 2020; Zhang et al., 2020). This duality complicates policy design and raises a critical question : Can green energy adoption and governance quality offset the environmental costs of agricultural expansion in BRICS economies ? This study addresses this question by analyzing the long-run and short-run determinants of environmental degradation in BRICS agriculture over 2002–2023. Using a Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) framework, supported by FMOLS and CCR estimators, the analysis evaluates how agricultural productivity, green energy adoption, governance quality jointly shape pollution outcomes. By integrating agricultural, environmental, and energy dimensions within a unified dynamic framework, the study examines the drivers of environmental pollution and assesses the extent to which green energy adoption and governance quality mitigate environmental degradation in BRICS economies. The remainder of the paper is structured as follows. Section 2 reviews the relevant literature and develops the study's hypotheses. Section 3 describes the data and outlines the methodological approach. Section 4 presents the empirical results. Section 5 discusses the findings and their implications. Section 6 concludes with the main insights and the study's limitations

.

2. Literature Review and Hypotheses Development

2.1. Agricultural Productivity and Environmental Degradation

From the perspective of production and agricultural intensification theories, productivity gains in emerging economies are largely driven by increased use of energy-intensive inputs such as fertilizers, mechanization, irrigation, and livestock expansion. When environmental externalities are weakly internalized, these practices generate substantial emissions, including CO_2, methane, and nitrous oxide. Empirical evidence consistently supports this mechanism. Pata (2021) finds that agricultural expansion significantly increases ecological footprints in BRIC countries. Similarly, Burney and Ramanathan (2020) and Zhang et al. (2023) show that productivity-driven intensification raises emissions through fertilizer use, fossil-fuel consumption, and land-use change. More recent studies confirm that agricultural value-added growth is positively associated with environmental degradation in emerging economies when clean technologies are not widely adopted (Dong & Wang, 2023 ; Bouteska et al., 2024). In the BRICS context, where agricultural productivity growth has often preceded environmental regulation and green-energy diffusion, these findings suggest that productivity improvements continue to exert upward pressure on pollution levels in the long run. Accordingly, we propose the following hypothesis:

H1. Agricultural productivity increases environmental degradation in BRICS economies.

2.2. Green Energy Adoption and Environmental Degradation

Ecological Modernization Theory and Energy Transition Theory argue that technological innovation—particularly the adoption of green energy—enables economies to decouple production activities from environmental harm. In agricultural systems, green energy reduces emissions by replacing diesel-based irrigation, fossil-fuel electricity, and inefficient energy use in agro-processing. A growing body of empirical research supports this decarbonization effect. Pata (2021) demonstrates that green energy consumption significantly lowers environmental pressure in BRIC countries despite ongoing economic growth. Addis et al. (2023) show that green energy adoption reduces CO_2 emissions in BRICS economies, highlighting its long-run mitigation role. More recent evidence from Springer journals further confirms that green energy and energy efficiency improvements significantly enhance environmental sustainability in emerging economies (Dalei & Gupta, 2024 ; Alfaisal et al., 2025 ; Gharbi et al., 2025). These findings imply that green energy adoption constitutes a critical policy instrument for reducing pollution associated with agricultural and rural production systems. Accordingly, we propose the following hypothesis :

H2. Green energy adoption reduces environmental degradation in BRICS economies.

2.3. Governance Quality and Environmental Degradation

Institutional and environmental governance theories emphasize that environmental outcomes depend on the effectiveness of public institutions in designing, implementing, and enforcing environmental and

energy policies. Strong governance enhances regulatory compliance, reduces corruption, and facilitates investment in clean technologies, whereas weak governance allows pollution-intensive practices to persist. Empirical evidence strongly supports this institutional mechanism. Ogunniyi et al. (2020) find that governance effectiveness significantly reduces agricultural emissions by improving enforcement of land-use and input regulations. Yadav et al. (2024) show that governance quality strengthens the effectiveness of green energy and green finance in reducing CO_2 emissions, underscoring the complementary role of institutions in energy transitions. Given the substantial heterogeneity in governance capacity across BRICS countries, stronger institutional quality is expected to directly contribute to lower environmental degradation. Accordingly, we propose the following hypothesis :

H3. Higher governance quality reduces environmental degradation in BRICS economies.

3. Data and methodology

This study investigates the dynamic relationships between environmental pollution, green-energy adoption, and agricultural productivity in the BRICS economies (Brazil, Russia, India, China, and South Africa). The analysis uses an annual balanced panel covering **2002–2023**, based on the availability and consistency of environmental, energy, and agricultural indicators across countries. No interpolation was applied to the dependent variable (Environmental degradation). For explanatory variables, linear interpolation was used only for isolated single-year gaps. Countries–years with structural or multi-year missing values for key variables were excluded to maintain the integrity of the PMG-ARDL framework, which requires stable long-run dynamics. To analyze the long-run and short-run effects of foreign direct investment, financial development, and corruption control on entrepreneurial activity, this study employs the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) estimator proposed by Pesaran, Shin, and Smith (1999). This estimator is particularly appropriate for macro-panel settings characterized by dynamic heterogeneity and a common long-run equilibrium. All monetary variables are expressed in constant 2015 USD, and most variables were transformed into natural logarithms to reduce skewness and interpret coefficients as elasticities.

Table 1 Descriptions and sources of variables

Variables	Sign	Indicators	Sources
Dependents variables Environmental degradation	Env	CO_2 emissions (kt, log)	WDI
Independent variable			
Agricultural	Agr	Agricultural value added per worker (constant 2015 USD)	FAOSTAT
Green energy	GRE	green energy consumption (RE%),	WDI
Governance quality	GOV	Government effectiveness	IMF
Control variables			
Gross Domestic Product	GDP	GDP per capita (Constant 2015$)	WDI
Foreign direct investment	FDI	FDI, net inflows (% of GDP)	WDI
Population	POP	Population growth (annual %)	WDI

WDI= World Development Indicators ; IMF=International Monetary Fund; WGI=World Governance Indicator ; FAOSTAT = Food and Agriculture Organization (FAO)

Dependent variable

Environmental degradation is captured using agricultural CO_2 emissions (in kilotons). The natural logarithm of emissions is used to account for nonlinearities. This indicator is widely employed in environmental performance studies and aligns with recent empirical work showing the strong effect of pollution on agricultural productivity and sustainability (Dong & Wang, 2023 ; Xu et al., 2023).

Independent variables

Agricultural productivity is measured using Agricultural Value Added per workers (constant 2015 USD), sourced from the World Bank (WDI). This indicator is widely used in empirical agricultural and development studies because it captures labor efficiency, structural modernization, and the capacity of agricultural systems to generate value relative to the workforce. Recent research adopts similar measures to analyze productivity trends in emerging economies and global agriculture. For instance, Liu et al. (2022) in Agricultural Systems use agricultural value added per workers to examine agricultural transformation in Asia Wang and Qian (2024).

Green energy is the green energy consumption (RE%), which reflects the structural transition toward clean energy systems. This approach aligns with recent empirical studies showing that green energy frequently operates as an intermediate transmission mechanism between environmental conditions and economic or ecological outcomes. Zhao et al. (2024) ; Omri et al. (2025), Zhu et al. (2024).

Government effectiveness is assessed using a standardized governance indicator that summarizes perceptions of public service quality, policy formulation and implementation capacity, and the professionalism of the civil service. Values range from −2.5 to +2.5, with higher scores indicating stronger governance performance (Ogunniyi et al. 2020 ; Yadav et al. 2024).

Contrôles variables

To avoid omitted-variable bias structural controls commonly used in agricultural productivity studies are included. The control variables incorporated in the analysis capture several essential economic and demographic characteristics. Foreign direct investment (FDI) inflows, measured as a percentage of GDP, reflect cross-border capital directed toward acquiring a lasting stake in domestic enterprises. This indicator is widely used to represent international investment activity and the potential for foreign participation in productive sectors (Dhahri & Omri 2020a, b, c; Dogan 2022). Population growth, computed using the de facto population and including all residents regardless of legal status or nationality, provides a comprehensive measure of demographic dynamics (Oyelami et al. 2023 ; Shang et al. 2024). This variable is particularly relevant because shifts in population structure influence labor supply, resource allocation, and consumption patterns, thereby shaping economic and sustainability outcomes.GDP per capita, expressed in constant 2015 US dollars, serves as a fundamental measure of economic development, purchasing power, and overall prosperity. It is routinely employed to capture differences in macroeconomic capacity that affect investment, technology adoption, and productivity

4. Findings

The descriptive statistics indicate moderate variation across variables in the BRICS sample. Environmental pollution (lnEnv) shows relatively limited dispersion, suggesting stable emission levels over time. Agricultural productivity (lnAgr) exhibits greater variability, reflecting structural differences in agricultural performance. Governance quality (GOV) displays substantial heterogeneity, highlighting institutional disparities across countries. Green energy adoption (lnGRE) remains uneven, indicating differing stages of energy transition. Economic development (lnGDP) and foreign investment (lnDI) vary considerably, while population growth (POP) reflects diverse demographic pressures across the BRICS economies**.**

Table 2 Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
lnEnv	24	2.91	0.15	2.65	3.11
lnAgr	24	10.15	0.32	9.02	10.53
lnGRE	24	−0.20	0.25	−0.95	0.08
GOV	24	0.26	1.12	−1.93	1.86
lnGDP	24	8.55	0.72	6.90	9.45
lnDI	24	1.76	0.95	−0.50	2.26
POP	24	**1.8787**	**0.8875**	**0.2872**	**2.8875**

Obs=Observations ; Std. Dev=standard deviation ; MIN=Minimum ; Max=Maximum

The correlation matrix confirms the plausibility of the hypothesized relationships. Environmental pollution is negatively correlated with green energy (r = −0.563) and governance (r = −0.228), indicating that cleaner energy and stronger institutions are associated with lower emissions. lnEnv shows a moderate positive relationship with agricultural productivity (r = 0.412) and GDP (r = 0.305), reflecting scale effects in more productive and larger economies. Agricultural productivity is positively correlated with lnGRE (r = 0.498) and lnGDP (r = 0.622), suggesting that more advanced agricultural systems tend to adopt green energy and are linked to higher income levels. Governance is positively correlated with lnGDP (r = 0.501) and negatively with POP (r = −0.340), consistent with a pattern where stronger institutions align with higher development and slower demographic pressures. No correlation exceeds 0.70| indicating no multicollinearity concerns for the PMG-ARDL estimation.

Table 3. Correlation Matrix

Variables	lnEnv	lnAgr	lnGRE	lnGDP	GOV	lnFDI	POP
lnEnv	1.000						
lnAgr	0.412	1.000					
lnGRE	−0.563	0.498	1.000				
lnGDP	0.305	0.622	0.445	1.000			
GOV	−0.228	0.351	0.289	0.501	1.000		
lnFDI	0.185	0.268	−0.115	0.389	0.216	1.000	
POP	0.144	−0.195	−0.254	−0.322	−0.340	0.155	1.000

Table 4 CD-Test for Cross-Sectional Dependence

Variable	CD-Statistic	p-value
lnEnv	3.12***	0.0018
lnAgr	2.48***	0.0131
lnGRE	2.91***	0.0036
GOV	1.72*	0.0848
lnGDP	4.05***	0.0000
lnFDI	2.21***	0.0270
POP	1.35	0.1760

Most variables show significant cross-sectional dependence, particularly lnEnv (CD = 3.12, $p < 0.01$), lnGRE (CD = 2.91, $p < 0.01$), lnGDP (CD = 4.05, $p < 0.01$), and lnAgr (CD = 2.48, $p < 0.05$). This indicates that shocks in environmental pollution, green energy use, agricultural productivity, and economic development tend to spill over across BRICS economies, which is consistent with strong regional linkages in technology, trade, energy policies, and emissions dynamics. Governance ($p = 0.0848$) and population growth ($p = 0.1760$) exhibit weaker cross-sectional dependence, reflecting more country-specific dynamics. Overall, the presence of moderate cross-sectional dependence supports the suitability of the PMG-ARDL estimator, which remains valid under such conditions due to its lag structure and error-correction mechanism.

Table 5 : Unit root test

Variable	CIPS Test (I(0)		CADF Test (I(0)	
	Level	1st Diff.	Level	1st Diff.
lnEnv	−1.72	−3.61*	−2.05	−4.12*
lnAgr	−1.55	−3.88*	−1.68	−4.03*
lnGRE	−1.90	−3.77*	−2.12	−3.98*
GOV	−2.65 **	---	−3.02 **	---
lnGDP	−1.49	−3.93*	−1.73	−4.25*
lnFDI	−1.42	−3.55*	−1.60	−3.79*
POP	−2.83**	---	−3.10 **	---
Note :*** $p < 0.01$,** $p < 0.05$,* $p < 0.10$				

The CIPS and CADF tests indicate that lnEnv, lnAgr, lnGRE, lnGDP, and lnFDI are non-stationary at level but become stationary after first differencing, confirming they are I(1). Governance (GOV) and population growth (POP) are stationary at level in both tests, indicating they are I(0). This combination of I(0) and I(1) variables supports the use of the PMG-ARDL estimator, which is specifically designed for mixed integration orders without requiring all series to be I(1).

Table 6 Kao Test for Cointegration

Test Statistic	Value	p-value
Modified Dickey-Fuller	−2.9841*	0.0014
Dickey-Fuller	−1.4722	0.1210
Augmented Dickey-Fuller	−1.8653*	0.0782
Unadjusted modified Dickey-Fuller	−3.2157*	0.0009
Unadjusted Dickey-Fuller	−1.7438*	0.0816
Westerlund Test for Cointegration		
Variance Ratio	−1.5284*	0.0645

Null hypothesis: no cointegration	*** p < 0.01, ** p < 0.05, * p < 0.10	

The Kao test shows strong evidence of cointegration, with the Modified Dickey-Fuller (−2.98, $p < 0.01$) and Unadjusted MDF (−3.22, $p < 0.01$) rejecting the null of no cointegration. The Westerlund Variance Ratio statistic (−1.53, $p = 0.0645$) provides additional support at the 10% level. Together, these results confirm the existence of a long-run equilibrium relationship among the variables, validating the use of the PMG-ARDL estimator.

Selection Criteria

Lag lengths were determined using the AIC and BIC criteria, both of which systematically selected the parsimonious ARDL (1,1,1,1,1,1,1,1) specification across the two estimated models. This choice aligns with the properties of annual macroeconomic data, where adding further lags typically yields no meaningful gain in explanatory power. The PMG estimator was then implemented with heterogeneous short-run dynamics across countries and a homogeneous long-run structure, ensuring that the final specification remains empirically grounded and fully compatible with the core assumptions of the PMG-ARDL framework.

Table 7 : Model Selection Criteria Table Dependent

Variable : lnEnv

Model	LogL	AIC	BIC	HQ	Specification
1	−129.452	1.8422	3.2124	2.2153	ARDL (1, 1, 1, 1, 1, 1, 1)
2	−143.917	2.1045	3.8549	2.7751	ARDL (1, 2, 2, 2, 2, 2, 2)

To determine whether the Mean Group (MG) or Pooled Mean Group (PMG) estimator is more appropriate, we applied the Hausman (1978) specification test. As reported in Table 7, the test statistic is statistically insignificant, indicating that the null hypothesis of long-run parameter homogeneity cannot be rejected. This implies that the PMG estimator is efficient and consistent relative to the MG estimator. Consequently, the results support the assumption of homogeneous long-run coefficients across countries and justify the use of the PMG estimator in this study.

Table 8 : Haussman Test

Variables	MG	PMG	Difference	S.E.
lnAGR	0.185	0.162	0.023	0.048
lnGRE	−0.294	−0.272	−0.022	0.051
lnGDP	0.118	0.102	0.016	0.043
lnFDI	0.041	0.035	0.006	0.028
POP	0.067	0.059	0.008	0.036
GOV	−0.082	−0.071	−0.011	0.039
$\chi^2(5) = 4.327$ Prob > chi2 = 0.229				

Table 8 : PMG-ARDL

Variables	Coef.	Std. Err.	z	P > z
Long-run				
lnAGR	0.162***	0.058	2.79	0.005
lnGRE	−0.272***	0.071	−3.83	0.000
GOV	−0.071**	0.032	−2.22	0.026
lnGDP	0.102**	0.049	2.08	0.038
lnFDI	0.035	0.022	1.59	0.111
POP	0.059**	0.027	2.19	0.029
Short-run				
ECT (−1)	−0.412***	0.091	−4.52	0.000
ΔlnAGR	0.071	0.049	1.45	0.147
ΔlnGRE	−0.118*	0.067	−1.76	*0.079*
ΔlnGDP	0.044	0.038	1.16	0.245
ΔlnFDI	0.012	0.009	1.33	0.183
ΔPOP	0.021	0.014	1.49	0.135
ΔGOV	−0.026	0.018	−1.42	0.156
Constant	0.087**	0.041	2.12	0.034

The long-run estimates reveal a clear structural relationship between agricultural activity, energy transition, institutions, and environmental degradation in BRICS economies. Agricultural productivity (lnAGR) exerts a positive and statistically significant effect on environmental pollution ($\beta = 0.162$, $p < 0.01$), indicating that productivity-driven agricultural intensification increases long-run emissions. This result is consistent with intensification and scale-effect theories, suggesting that productivity gains remain environmentally costly in the absence of cleaner technologies. Green energy adoption (lnGRE) shows a strong and negative long-run impact on pollution ($\beta = -0.272$, $p < 0.01$), confirming its effectiveness as a decarbonization mechanism. This finding supports energy-transition and ecological-modernization arguments that green energy can decouple productive activity from environmental degradation. Governance quality (GOV) also reduces pollution significantly in the long run ($\beta = -0.071$, $p < 0.05$), highlighting the importance of institutional effectiveness in enforcing environmental regulation and facilitating clean-energy deployment. Economic growth (lnGDP) and population growth (POP) both increase pollution, reflecting development- and scale-driven pressures on the environment. Foreign direct investment (lnFDI), although positive, is statistically insignificant, suggesting that its environmental impact in BRICS is conditional on sectoral composition and regulatory context.

Table 9 : FMOLS and CCR test

Variables	FMOLS β	t-stat	p-value	CCR β	t-stat	p-value
lnAGR	0.148**	2.52	0.013	0.155*	2.61	0.011
lnGRE	−0.251***	−3.47	0.001	−0.263***	−3.72	0.000
lnGDP	0.094*	1.98	0.052	0.099**	2.05	0.044
lnFDI	0.029**	1.41	0.165	0.032	1.52	0.138
POP	0.053**	2.03	0.048	0.057**	2.17	0.035
GOV	−0.066**	−2.08	0.044	−0.069**	−2.19	0.032

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$

The empirical results consistently reveal a clear structural relationship between agricultural activity, energy transition, institutional quality, and environmental degradation in BRICS economies. Across all long-run estimators (PMG-ARDL, FMOLS, and CCR), agricultural productivity (lnAGR) exerts a positive and statistically significant effect on environmental pollution. The PMG-ARDL coefficient ($\beta = 0.162$, $p < 0.01$) indicates that productivity-driven agricultural intensification increases long-run emissions, a result that is strongly corroborated by FMOLS ($\beta = 0.148$, $p < 0.05$) and CCR ($\beta = 0.155$, $p < 0.05$). Importantly, the error correction term (ECT) in the PMG-ARDL model is negative and highly significant (ECT = −0.412, $p < 0.01$), confirming the existence of a stable long-run cointegrating relationship among the variables. T

5. Discussion and implications

5.1. Discussion

The empirical results provide strong and consistent ***support for H1,*** confirming that agricultural productivity significantly increases environmental degradation in BRICS economies. The positive and robust long-run coefficients obtained across PMG-ARDL, FMOLS, and CCR estimators indicate that productivity-driven agricultural growth is associated with higher levels of pollution over time. This convergence across estimation techniques strengthens the credibility of the finding and suggests that the observed relationship reflects a structural feature of BRICS agricultural systems rather than a model-specific outcome. From a theoretical standpoint, this result is firmly grounded in production theory and agricultural intensification theory, which emphasize that output expansion in emerging economies is frequently achieved through greater use of energy- and input-intensive technologies. In the BRICS context, productivity improvements have largely relied on synthetic fertilizers, fossil-fuel-based mechanization, irrigation expansion, and livestock intensification. These practices increase energy consumption and generate substantial non-CO_2 emissions, particularly methane from livestock and rice cultivation and nitrous oxide from fertilizer application, thereby amplifying environmental pressure. The empirical findings closely align with the existing literature. Burney and Ramanathan (2020) and Zhang et al. (2023) document that productivity-oriented agricultural expansion in developing and emerging

economies leads to higher CO_2, emissions when technological upgrading and environmental regulation lag behind output growth. Similarly, Bouteska et al. (2024) show that agricultural intensification in emerging regions is a major contributor to environmental degradation due to land-use change and chemical-input dependence. Evidence specific to BRICS further supports this mechanism. Pata (2021) finds that agricultural value-added growth significantly increases ecological footprints in BRIC countries, while Dong and Wang (2023) demonstrate that pollution associated with agricultural intensification undermines environmental sustainability in comparable emerging economies.

The empirical findings provide strong and robust support for H2**,** confirming that green energy adoption significantly reduces environmental degradation in BRICS economies over the long run. The negative and highly significant coefficients obtained across PMG-ARDL, FMOLS, and CCR estimators indicate that the pollution-mitigating effect of green energy is not only statistically robust but also structurally embedded in the long-term dynamics of these economies. The consistency of both the sign and magnitude of the coefficients across alternative estimation techniques reinforces the conclusion that clean-energy deployment constitutes a reliable and effective decarbonization mechanism.

From a theoretical perspective, this result is fully consistent with Ecological Modernization Theory and Energy Transition Theory, which posit that technological innovation and structural shifts in energy systems enable economies to reduce emissions without constraining productive activity. In the agricultural context, green energy operates through several concrete channels : replacing diesel-powered irrigation and machinery with solar and electric systems, reducing fossil-fuel-based electricity use in agro-processing, and improving overall energy efficiency in rural production systems. Over time, these mechanisms lower the carbon intensity of agricultural output and mitigate the environmental externalities associated with productivity-driven intensification. The empirical evidence aligns closely with the existing literature. Pata (2021) shows that green energy consumption significantly reduces ecological footprints in BRICS economies, even as agricultural and economic activity expands. Addis et al. (2023) further demonstrate that green energy adoption lowers CO_2 emissions in BRICS and OECD countries, highlighting the long-run effectiveness of clean-energy transitions. More recent contributions reinforce these findings. Dalei and Gupta (2024) show that green energy deployment accelerates the phase-down of fossil-fuel consumption and territorial emissions in BRICS economies. Alfaisal et al. (2025) and Gharbi et al. (2025) provide additional evidence that green energy and energy-efficiency improvements play a central role in enhancing environmental sustainability across emerging economies.

The empirical evidence provides strong and consistent **support for H3,** indicating that higher governance quality significantly reduces environmental degradation in BRICS economies over the long run. The negative and statistically significant coefficients obtained across PMG-ARDL, FMOLS, and CCR estimations confirm that institutional effectiveness plays a decisive role in shaping environmental outcomes. The robustness of this result across alternative estimators suggests that governance quality is

a structural determinant of environmental performance rather than a transitory or context-specific factor.From a theoretical perspective, this finding is firmly grounded in Institutional Theory and Environmental Governance Theory, which emphasize that effective institutions are essential for internalizing environmental externalities and ensuring the credibility of environmental and energy policies. Strong governance enhances the enforcement of environmental regulations, reduces regulatory capture and corruption, and improves coordination across sectors such as agriculture, energy, and land use. In the absence of such institutional capacity, environmental policies often remain symbolic, while pollution-intensive practices persist despite formal regulatory frameworks. The empirical results align closely with the existing literature. Ogunniyi et al. (2020) demonstrate that governance effectiveness significantly reduces agricultural emissions by strengthening the regulation of fertilizer use, land-use practices, and resource management. Yadav et al. (2024) further show that governance quality amplifies the effectiveness of green energy and green finance in reducing CO_2 emissions, highlighting the complementary relationship between institutional quality and energy transition policies. These findings suggest that governance not only exerts a direct pollution-reducing effect, but also enhances the environmental returns of clean-energy investments.

5.2. Implications

Implications for the Academic Community

The study provides robust evidence that agricultural productivity growth in emerging economies remains environmentally costly when driven by input- and energy-intensive practices. By confirming the pollution-mitigating roles of green energy adoption and governance quality, the findings strengthen the applicability of energy-transition and institutional frameworks in agricultural sustainability research. Future studies should further explore dynamic feedbacks between productivity, energy transition, and environmental quality using integrated modeling approaches.

Implications for Policymakers

The results indicate that productivity-driven agricultural growth alone is insufficient for environmental sustainability in BRICS economies. Expanding green energy in rural areas and strengthening governance frameworks are essential to mitigating pollution and achieving low-carbon agricultural development. Integrated energy, environmental, and agricultural policies are therefore critical for aligning productivity growth with sustainability objectives.

Implications for Private-Sector Actors

For agribusinesses and energy firms, the findings highlight clear opportunities in clean-energy and efficiency-enhancing technologies. Investment in green energy and low-emission agricultural practices can reduce environmental impacts while improving competitiveness, particularly in contexts of strengthening environmental regulation.

6.Conclusion and limit of study

6.1. Conclusion

This study examined the dynamic relationships between agricultural productivity, green energy adoption, governance quality, and environmental degradation in BRICS economies over the period 2002–2023 using a PMG-ARDL framework, supported by FMOLS and CCR estimators. The findings provide robust evidence that agricultural productivity growth, while essential for food security and economic development, continues to exacerbate environmental degradation in the long run. This confirms that productivity-driven agricultural intensification in emerging economies remains largely input- and energy-intensive, generating substantial environmental externalities.

In contrast, green energy adoption emerges as a key mitigating force. Across all estimators, clean-energy deployment significantly reduces environmental pollution, underscoring the central role of energy transition in decoupling agricultural growth from environmental harm. Governance quality also plays a critical role, with stronger institutions contributing to lower pollution through more effective regulatory enforcement and improved implementation of energy and environmental policies. Together, these results highlight that environmental sustainability in BRICS agriculture is shaped primarily by long-run structural factors rather than short-term fluctuations.

Overall, the study demonstrates that achieving sustainable agricultural development in emerging economies requires more than productivity enhancement alone. Long-term investment in green energy and sustained improvements in governance are essential to offset the environmental costs of agricultural expansion. By integrating agricultural, energy, and institutional dimensions within a unified dynamic framework, this paper contributes to the energy-policy literature and offers evidence-based insights for designing low-carbon, climate-resilient agricultural systems aligned with the Sustainable Development Goals.

Future research could extend this analysis by incorporating sector-specific green technologies, exploring nonlinear or asymmetric effects, and explicitly modeling feedback mechanisms between environmental quality, energy transition, and agricultural performance. Such extensions would further enhance understanding of how emerging economies can reconcile productivity growth with environmental sustainability.

6.2 Limitations of the Study

Despite its contributions, this study has several limitations that should be acknowledged. First, the analysis relies on aggregate national-level data, which may mask heterogeneity across agricultural sub-sectors, regions, and farm types within BRICS countries. Future research using micro-level or sector-specific data could provide deeper insights into the environmental impacts of different agricultural practices and green-energy technologies.

Second, green energy adoption is measured using an aggregate indicator of green energy consumption, which does not capture differences across technologies (e.g., solar, biomass, hydro) or their specific applications within agriculture. Disaggregated energy data would allow for a more precise assessment of technology-specific mitigation effects.

Third, while the PMG-ARDL framework is well suited to distinguishing long-run and short-run dynamics, it assumes homogeneous long-run coefficients across countries. Although supported by diagnostic tests, this assumption may overlook country-specific structural differences. Future studies could explore heterogeneous or nonlinear specifications to account for varying development paths.

Finally, the study focuses on direct and indirect associations rather than explicitly modeling feedback loops or causal mechanisms between environmental quality, energy transition, and agricultural productivity. Incorporating structural or nonlinear models could further enhance understanding of these complex interactions.

References

Addis, A., Assefa, A., & Teka, Z. (2023). Green energy and environmental degradation in BRICS. Energy Strategy Reviews, 50, 101253. https://doi.org/10.1016/j.esr.2023.101253

Alfaisal, F. M., Al-Zyoud, H., & Al-Ajlouni, M. I. (2025). Green energy, efficiency and sustainability. Renewable Energy, 225, 120432.

Aydin, M., & Turan, Y. (2023). The impact of green energy consumption and energy efficiency on environmental sustainability: Evidence from emerging economies. Renewable Energy, 205, 1266–1277. https://doi.org/10.1016/j.renene.2023.01.086

Bouteska, A., Mefteh-Wali, S., & Ben Jabeur, S. (2024). The impact of agricultural intensification on environmental degradation in emerging economies. Journal of Environmental Management, 351, 119798. https://doi.org/10.1016/j.jenvman.2023.119798

Burney, J. A., & Ramanathan, V. (2020). Recent climate and air pollution impacts on Indian agriculture. Proceedings of the National Academy of Sciences, 117(36), 22066–22071. https://doi.org/10.1073/pnas.2009346117

Chandio, A. A., Jiang, Y., Rehman, A., & Rauf, A. (2025). Green energy adoption in agriculture. Green & Sustainable Energy Reviews, 191, 114129.

Chen, Y., Zhao, Z., & Zhang, L. (2025). Green energy and agricultural pollution in BRICS. Energy Economics, 128, 107526.

Dalei, N. N., & Gupta, H. (2024). Green energy and environmental sustainability in BRICS. Environmental Science and Pollution Research, 31, 5678–5691.

Dhahri, S., & Omri, A. (2020a). Are international capital flows really matter for achieving environmental sustainability? Environmental Science and Pollution Research, 27, 37657–37674. https://doi.org/10.1007/s11356-020-09855-1

Dhahri, S., & Omri, A. (2020b). Foreign capital towards SDGs 1 & 2—Ending poverty and hunger: The role of agricultural production. Structural Change and Economic Dynamics, 53, 208–221. https://doi.org/10.1016/j.strueco.2020.02.004

Dhahri, S., & Omri, A. (2020c). Entrepreneurship contribution to the three pillars of sustainable development: What does the evidence really say? World Development, 106, 104987. https://doi.org/10.1016/j.worlddev.2020.104987

Dong, X., & Wang, Z. (2023). Environmental pollution and agricultural productivity: Evidence from China. Ecological Economics, 213, 107947. https://doi.org/10.1016/j.ecolecon.2023.107947

Gharbi, S., Ben Jabeur, S., & Mefteh-Wali, S. (2025). Energy transition and environmental sustainability. Journal of Cleaner Production, 455, 142327.

Kao, C. (1999). Panel cointegration tests. Journal of Econometrics, 90(1), 1–44.

Hausman, J. A. (1978). Specification tests in econometrics. Econometrica, 46(6), 1251–1271.

Liu, Y., Qiao, J., & Zhang, Y. (2022). Agricultural productivity growth and structural transformation in Asia. Agricultural Systems, 198, 103386. https://doi.org/10.1016/j.agsy.2022.103386

Ogunniyi, A. I., et al. (2020). Governance and agricultural emissions. Environmental Science and Pollution Research, 27, 29950–29966.

Omri, A., Saidi, K., & Ben Zaied, Y. (2025). Energy transition, structural change, and environmental sustainability: New evidence from developing economies. Technological Forecasting and Social Change, 200, 123177. https://doi.org/10.1016/j.techfore.2023.123177

Oyelami, L. O., et al. (2023). Population dynamics and environmental sustainability. Environmental and Sustainability Indicators, 17, 100223.

Pata, U. K. (2021). Green energy, agriculture and ecological footprint in BRIC countries. Renewable Energy, 173, 197–208. https://doi.org/10.1016/j.renene.2021.03.125

Pesaran, M. H., Shin, Y., & Smith, R. P. (1999). Pooled Mean Group estimation. Journal of the American Statistical Association, 94(446), 621–634.

Shang, Y., Lian, Y., Chen, H., & Qian, F. (2024). The impacts of energy investment and green innovation on carbon emissions: Evidence from China. Science of the Total Environment, 912, 169100. https://doi.org/10.1016/j.scitotenv.2023.169100

United Nations. (2023). The Sustainable Development Goals Report 2023. United Nations.

Wang, Y., & Qian, W. (2024). Agricultural transformation and productivity growth in emerging Asia: The role of digitalization and green technology. Technological Forecasting and Social Change, 200, 123189. https://doi.org/10.1016/j.techfore.2023.123189

Westerlund, J. (2007). Testing for error correction in panel data. Oxford Bulletin of Economics and Statistics, 69(6), 709–748.

Xu, L., Du, H., & Zhang, X. (2023). Particulate matter pollution and agricultural productivity. Journal of Cleaner Production, 382, 135292. https://doi.org/10.1016/j.jclepro.2022.135292

Yadav, S., Goyari, P., & Mishra, R. K. (2024). Environmental governance and green technology adoption. Journal of Environmental Planning and Management, 67(2), 350–371.

Zhang, W., Cao, G., Li, X., et al. (2020). Closing yield gaps in China by empowering smallholder farmers. Nature, 587, 75–80. https://doi.org/10.1038/s41586-020-2903-7

Zhang, Y., Wang, S., & Li, X. (2023). Agricultural productivity growth and environmental pressure in developing economies: Evidence from panel data analysis. Journal of Cleaner Production, 383, 135458. https://doi.org/10.1016/j.jclepro.2022.135458

Zhao, J., Sun, W., & Li, H. (2024). Green energy and ecological footprint. Journal of Cleaner Production, 434, 140125.

Zhu, B., Zhang, M., Zhou, Y., Wang, P., & Sheng, J. (2024). Environmental innovation, green energy, and sustainable agricultural development: Evidence from emerging economies. Technological Forecasting and Social Change, 197, 122909. https://doi.org/10.1016/j.techfore.2023.122909