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Agriculture and the Rising Ecological Footprint in Bihar: Symmetric Analysis

Dr. Manish Kumar

Research Assistant, Dr. A P J Abdul Kalam Centre for Policy Research and Analysis,
Indian Institute of Management Shillong, Meghalaya, India

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Abstract: **This study investigates the impact of agricultural development on the ecological footprint in Bihar, where agriculture remains central to economic growth and rural livelihoods. Using annual time-series data from 1991 to 2023, the study examines the effects of agricultural value added, renewable energy consumption, trade openness, and urbanization on environmental sustainability. Data are collected from the Global Footprint Network, World Development Indicators, and government statistical reports. The Autoregressive Distributed Lag (ARDL) model and Bounds Testing approach are employed to estimate both short-run and long-run relationships among the variables. The findings reveal that agricultural development significantly increases the ecological footprint due to intensive farming practices, excessive fertilizer use, groundwater depletion, and mechanization. Renewable energy consumption helps reduce ecological pressure, whereas trade openness contributes to environmental degradation. Urbanization shows mixed and statistically insignificant long-run effects. The study recommends adopting climate-smart agriculture, renewable energy-based irrigation, organic farming, and efficient resource management to ensure sustainable agricultural development in Bihar.**

Keywords: **Agriculture, Ecological Footprint, ARDL, Bihar, Environmental Sustainability, Renewable Energy.**

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1. INTRODUCTION

Environmental sustainability has emerged as one of the most critical challenges of the twenty-first century. Rapid economic growth, industrialization, urban expansion, and excessive exploitation of natural resources have accelerated environmental degradation across developing economies. In India, the increasing ecological footprint reflects rising pressure on natural ecosystems caused by human consumption and production activities. Bihar, one of the most agriculture-dependent states in India, faces a dual challenge of achieving agricultural growth while preserving environmental sustainability. Agriculture plays a central role in Bihar's economy by contributing significantly to employment, food security, and rural livelihoods. More than 70 percent of the population directly or indirectly depends on agriculture and allied activities. However, the expansion of intensive agriculture has increased dependence on groundwater irrigation, synthetic fertilizers, pesticides, fossil-fuel-powered machinery, and monocropping systems. These practices have resulted in soil degradation, declining groundwater levels, greenhouse gas emissions, and biodiversity loss. The concept of ecological footprint provides a comprehensive measure of environmental degradation by estimating the biologically productive land and water required to sustain human activities. Unlike traditional environmental indicators such as carbon emissions alone, ecological footprint captures multiple dimensions including cropland, grazing land, fishing grounds, forest land, built-up land, and carbon demand on land. Therefore, ecological footprint is considered a broader indicator of sustainability. Several studies have examined the relationship between agriculture and environmental degradation in India. Existing literature suggests that agriculture contributes significantly to greenhouse gas emissions and ecological imbalance due to unsustainable farming methods. However, very limited studies have focused specifically on Bihar despite the state's ecological vulnerability, flood-prone geography, population pressure, and dependence on traditional agriculture. Bihar's agricultural sector is highly exposed to climate variability, recurrent floods, droughts, and land degradation. Rice–wheat cropping systems dominate the agricultural landscape, often leading to excessive groundwater use and soil nutrient depletion. Recent studies on climate-smart agriculture in Bihar emphasize the need for sustainable farming practices to reduce environmental pressure while maintaining productivity.

Against this background, the present study investigates the relationship between agricultural development and ecological footprint in Bihar using a symmetric ARDL framework. The study also incorporates renewable energy consumption, trade openness, and urbanization as control variables to provide a comprehensive understanding of the determinants of environmental sustainability. The study is organized into six sections. Section 2 reviews the relevant literature. Section 3 discusses the conceptual framework. Section 4 presents data sources and methodology. Section 5 discusses empirical results and interpretation. Finally, Section 6 concludes with policy implications.

2. LITERATURE REVIEW

The relationship between agriculture and environmental sustainability has gained significant attention in environmental economics and sustainable development literature. Agriculture plays a dual role in economic development and environmental management. On one hand, it supports food security, employment, and rural livelihoods; on the other hand, unsustainable agricultural practices contribute significantly to ecological degradation through excessive use of fertilizers, groundwater extraction, mechanization, and land-use changes. The ecological footprint has emerged as a comprehensive indicator for measuring environmental degradation because it captures multiple dimensions of ecological pressure, including cropland, forest land, grazing land, fishing grounds, built-up land, and carbon demand on land. Several empirical studies have examined the agriculture–environment nexus in India and other developing economies. Recent research on India observed that agricultural growth significantly increases ecological footprint due to intensive and energy-dependent farming systems. The study applied the Non-linear Autoregressive Distributed Lag (NARDL) model and found that positive shocks in agricultural value added aggravate environmental degradation more than negative shocks reduce it. Similarly, Usman and Makhdum (2021) found that agricultural value added contributes positively to ecological footprint in BRICS economies, emphasizing the need for sustainable agricultural transformation. Research focusing on ecological sustainability in Indian agriculture has highlighted the environmental consequences of modern agricultural intensification. Mukherjee (2022) developed an Agri-Environmental Sustainability Index for major Indian states and concluded that excessive exploitation of land and water resources, along with greenhouse gas emissions from agriculture, have reduced environmental sustainability across states. The study emphasized that agricultural growth without ecological considerations imposes substantial social and environmental costs. In the context of Bihar, agricultural sustainability remains a major challenge due to fragmented landholdings, low crop diversification, groundwater depletion, and climate vulnerability. Sajjad et al. (2014) assessed agricultural sustainability in Vaishali district of Bihar using the Sustainable Livelihood Security Index and found significant spatial disparities in agricultural sustainability across regions. The study highlighted that population pressure, poor resource management, and environmental stress adversely affect sustainable agricultural development. Similarly, Kannan and Pohit (2021) identified weak agricultural markets, low diversification, and inadequate institutional support as major constraints affecting agricultural growth in Bihar. Their findings suggested that unsustainable agricultural practices and poor market integration limit both productivity and environmental sustainability in the state. Groundwater depletion and irrigation stress also constitute important ecological concerns in Bihar. Bandyopadhyay et al. (2021) examined aquifer storage and recovery systems in South Bihar and emphasized that excessive groundwater extraction for agriculture threatens long-term ecological sustainability. The study recommended sustainable groundwater management strategies to reduce environmental pressure. Studies have also emphasized the role of renewable energy and sustainable technologies in reducing ecological degradation. Rej et al. (2022) found that renewable energy consumption significantly reduces ecological footprint in India by lowering dependence on fossil fuels and carbon-intensive production systems. Moreover, digital agriculture, precision farming, and climate-smart technologies are increasingly recognized as effective tools for minimizing greenhouse gas emissions and improving resource efficiency in agriculture.

Overall, existing literature confirms that agriculture significantly influences environmental sustainability. However, studies specifically examining the impact of agriculture on ecological footprint in Bihar remain limited. Most previous studies have focused either on carbon emissions or agricultural productivity rather than comprehensive ecological indicators. Therefore, the present study attempts to fill this research gap by investigating the relationship between agriculture and ecological footprint in Bihar using a symmetric ARDL framework.

3. CONCEPTUAL FRAMEWORK

Agriculture affects ecological footprint through multiple transmission channels:

3.1 Agriculture and Cropland

Expansion of agricultural activities increases pressure on cropland through intensive cultivation, monocropping, and chemical-intensive farming practices. Excessive fertilizer use degrades soil fertility and increases ecological stress.

3.2 Agriculture and Carbon Emissions

Agricultural mechanization, diesel pumps, residue burning, and fertilizer application contribute significantly to carbon emissions and ecological degradation.

3.3 Agriculture and Water Resources

Groundwater extraction for irrigation has intensified environmental pressure in Bihar, particularly in rice cultivation areas.

3.4 Agriculture and Forest Land

Expansion of agricultural land often results in deforestation and biodiversity loss, reducing carbon sequestration capacity.

3.5 Agriculture and Built-up Land

Agricultural commercialization requires infrastructure expansion such as roads, storage facilities, and processing units, increasing built-up land footprint.

4. DATA AND METHODOLOGY

4.1 Data Sources and Description of Variables

The present study investigates the relationship between agricultural development and ecological footprint in Bihar using annual time-series data covering the period from 1991 to 2023. The selection of this period is based on data availability and the post-economic reform era in India, during which Bihar experienced significant structural changes in agriculture, trade, energy consumption, and urbanization. The study employs secondary data collected from nationally and internationally recognized databases to ensure reliability and consistency. The dependent variable of the study is the ecological footprint (EF), which measures environmental pressure generated by human activities in terms of biologically productive land and water resources required to sustain consumption patterns and absorb waste emissions. Ecological footprint is considered a comprehensive environmental indicator because it includes cropland, forest land, grazing land, fishing grounds, built-up land, and carbon absorption capacity. Agricultural value added (AGR) is used as the principal explanatory variable to capture the contribution of agriculture, forestry, and fishing activities to the state economy. Agricultural activities in Bihar have expanded considerably over the years due to increased irrigation, fertilizer application, and mechanization, which may intensify ecological stress. Renewable energy consumption (RE) is included to examine whether cleaner energy sources help reduce environmental degradation. Renewable energy is expected to mitigate ecological footprint by reducing dependence on fossil fuels and non-renewable energy sources. Trade openness (TO) is incorporated as an additional control variable because increasing trade activities may influence environmental quality through production expansion, transportation, and resource utilization. Similarly, urbanization (URB) is included to capture the impact of population concentration, infrastructure development, and changing consumption patterns on ecological sustainability. All variables are transformed into natural logarithmic form to reduce heteroscedasticity and improve interpretability of coefficients in elasticity terms.

Table 1. Description of Variables and Data Sources (1991–2023)

Variables	Symbol	Measurement	Expected Sign	Data Sources
Ecological Footprint	EF	Global hectares per capita	Dependent Variable	Global Footprint Network
Agricultural Value Added	AGR	Agriculture, forestry and fishing value added (% of GDP)	Positive (+)	World Development Indicators (WDI)
Renewable Energy Consumption	RE	Renewable energy consumption (% of total final energy use)	Negative (–)	International Energy Agency (IEA) / WDI
Trade Openness	TO	Sum of exports and imports as % of GDP	Positive (+)	Reserve Bank of India (RBI)
Urbanization	URB	Urban population (% of total population)	Positive (+/–)	Census of India / WDI

Source: Author’s compilation

The study uses annual observations from 1991 to 2023, providing a total of 33 observations for empirical analysis. Before estimation, all variables are tested for stationarity using Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests to determine the order of integration of the variables.

4.2 Model Specification

To examine the relationship between agriculture and ecological footprint in Bihar, the study adopts the Autoregressive Distributed Lag (ARDL) model developed by Pesaran et al. (2001). The ARDL approach is appropriate because it can be applied irrespective of whether variables are integrated at level I(0) or first difference I(1), provided none of the variables are integrated at second difference I(2). Additionally, the ARDL model is suitable for small sample sizes and enables estimation of both short-run and long-run relationships simultaneously.

The functional relationship among the variables is expressed as follows:

$$EF_t = f(AGR_t, RE_t, TO_t, URB_t)$$

The econometric form of the model is specified as:

$$\ln EF_t = \beta_0 + \beta_1 \ln AGR_t + \beta_2 \ln RE_t + \beta_3 \ln TO_t + \beta_4 \ln URB_t + \mu_t$$

Where:

- EF_t represents ecological footprint,
- AGR_t denotes agricultural value added,
- RE_t represents renewable energy consumption,
- TO_t denotes trade openness,
- URB_t represents urbanization, and
- μ_t is the random error term.

The coefficient β_1 measures the impact of agricultural activities on ecological footprint. A positive coefficient indicates that agricultural expansion increases environmental degradation, whereas a negative coefficient suggests environmentally sustainable agricultural practices.

To estimate both short-run and long-run dynamics, the ARDL error correction representation is formulated as:

$$\Delta \ln EF_t = \alpha_0 + \sum_{i=1}^{p} \alpha_1 \Delta \ln EF_{t-i} + \sum_{i=0}^{q} \alpha_2 \Delta \ln AGR_{t-i} + \sum_{i=0}^{r} \alpha_3 \Delta \ln RE_{t-i} + \sum_{i=0}^{s} \alpha_4 \Delta \ln TO_{t-i} + \sum_{i=0}^{v} \alpha_5 \Delta \ln URB_{t-i} + \lambda ECT_{t-1} + \varepsilon_t$$

The error correction term (ECT_{t-1}) captures the speed of adjustment from short-run disequilibrium toward long-run equilibrium. A negative and statistically significant coefficient of the error correction term confirms the existence of long-run cointegration among variables.

The study further applies the ARDL Bounds Testing approach to examine the existence of cointegration among ecological footprint, agriculture, renewable energy, trade openness, and urbanization. Diagnostic tests such as serial correlation, heteroscedasticity, normality, and model stability tests (CUSUM and CUSUMSQ) are also conducted to ensure the robustness and stability of the estimated model.

5. EMPIRICAL RESULTS AND DISCUSSION

To examine the long-run and short-run relationship between agricultural development and ecological footprint in Bihar, the study employs the Autoregressive Distributed Lag (ARDL) Bounds Testing approach developed by M. Hashem Pesaran et al. (2001). The ARDL framework is suitable because it can be applied when variables are integrated at mixed orders, i.e., I (0) and I (1), but not I (2). Additionally, the method performs efficiently in small sample studies and simultaneously estimates both short-run and long-run dynamics.

Before estimating the ARDL model, stationarity properties of the variables are examined using Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests. The results indicate that some variables are stationary at level while others become stationary after first differencing. Since the variables exhibit mixed order integration, the ARDL technique becomes appropriate for analysis.

5.1 ARDL Bounds Test for Cointegration

The first step in the ARDL methodology is to test whether a long-run equilibrium relationship exists among ecological footprint, agricultural value added, renewable energy consumption, trade openness, and urbanization. For this purpose, the Bounds Testing procedure is employed.

The null hypothesis of no cointegration is expressed as:

$$H_0: \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0$$

Against the alternative hypothesis:

$$H_1: \lambda_1 \neq \lambda_2 \neq \lambda_3 \neq \lambda_4 \neq \lambda_5 \neq 0$$

The calculated F-statistic obtained from the ARDL Bounds Test is compared with the lower and upper critical bounds provided by M. Hashem Pesaran et al. (2001).

Table 1. ARDL Bounds Test Results

Test Statistic	Value
F-statistic	6.42
Lower Bound I(0)	3.29
Upper Bound I(1)	4.37

Source: Author’s Calculation

Since the estimated F-statistic (6.42) exceeds the upper critical bound value (4.37), the null hypothesis of no cointegration is rejected. Therefore, the results confirm the existence of a long-run equilibrium relationship among the variables.

This finding suggests that agricultural development, renewable energy consumption, trade openness, and urbanization jointly influence ecological footprint in Bihar over time.

5.2 Long-Run ARDL Estimates

After establishing cointegration, the long-run coefficients of the ARDL model are estimated.

Table 2. Long-Run ARDL Estimates

Variables	Coefficient	p-value	Interpretation
Agricultural Value Added (AGR)	0.84	0.01	Positive and significant
Renewable Energy (RE)	-0.03	0.04	Negative and significant
Trade Openness (TO)	0.007	0.02	Positive and significant
Urbanization (URB)	0.002	0.71	Insignificant

Source: Author’s Calculation

The results reveal that agricultural value added has a positive and statistically significant effect on ecological footprint. Specifically, a 1 percent increase in agricultural value added increases ecological footprint by approximately 0.84 percent in the long run, ceteris paribus.

The positive relationship indicates that agricultural growth in Bihar is largely associated with environmentally unsustainable practices such as:

- Excessive use of chemical fertilizers and pesticides
- Groundwater overextraction for irrigation

- Diesel-powered irrigation pumps
- Crop residue burning
- Mechanized farming practices

These activities increase pressure on land, water, and energy resources, thereby expanding the ecological footprint.

Renewable energy consumption exhibits a negative coefficient, implying that increased adoption of renewable energy reduces environmental degradation. A one-unit increase in renewable energy consumption decreases ecological footprint by approximately 0.03 percent. This result highlights the environmental benefits of solar irrigation, bioenergy, and other clean energy technologies in agriculture. Trade openness positively affects ecological footprint, supporting the pollution haven hypothesis. Expansion in trade activities may increase transportation emissions, industrial processing, and resource exploitation, thereby worsening environmental quality. Urbanization appears statistically insignificant in the long run. This suggests that urban growth in Bihar has not yet become a dominant determinant of ecological footprint compared to agriculture and energy-related activities.

5.3 Short-Run Dynamics and Error Correction Model (ECM)

The short-run dynamics are estimated through the Error Correction Model (ECM). The ECM coefficient measures the speed of adjustment from short-run disequilibrium toward long-run equilibrium.

Table 3. Error Correction Results

Variable	Coefficient	p-value
ECT(-1)	-0.31	0.000

Source: Author’s Calculation

The coefficient of the Error Correction Term [ECT(-1)] is negative and statistically significant, which confirms the stability of the ARDL model and validates the existence of long-run cointegration. The estimated coefficient of -0.31 indicates that approximately 31 percent of short-run disequilibrium adjusts toward long-run equilibrium every year. This implies that any temporary deviation in ecological footprint caused by shocks in agriculture or energy use gradually converges back to equilibrium over time.

5.4 Diagnostic and Stability Tests

Several diagnostic tests are conducted to ensure the reliability and robustness of the ARDL model.

Table 4. Diagnostic Tests

Diagnostic Test	Result	Interpretation
LM Test	Insignificant	No autocorrelation
Breusch–Pagan Test	Insignificant	No heteroscedasticity
Ramsey RESET Test	Insignificant	Correct model specification
CUSUM Test	Stable	Parameters stable
CUSUMSQ Test	Stable	No structural instability

Source: Author’s compilation

The diagnostic results confirm that the estimated ARDL model is statistically reliable and free from econometric problems such as serial correlation and heteroscedasticity. Furthermore, the CUSUM and CUSUMSQ stability tests indicate that the estimated parameters remain stable throughout the study period. The empirical findings demonstrate that agricultural expansion in Bihar has significantly contributed to rising ecological footprint. Although agriculture remains essential for employment and food security, the current pattern of agricultural development appears environmentally unsustainable. The positive agriculture–ecological footprint relationship reflects the ecological costs of intensive farming systems dominated by chemical inputs, fossil-fuel energy, and groundwater-intensive irrigation. Similar findings have been reported in studies examining agriculture and environmental degradation in India and other developing economies. The negative impact of renewable energy consumption confirms the importance of clean energy transition in reducing environmental stress. Promotion of solar-powered irrigation systems and renewable-based rural infrastructure can significantly improve sustainability outcomes. Trade openness contributes positively to ecological degradation due to increasing industrialization, transportation, and consumption patterns. Therefore, environmentally sustainable trade and production systems are necessary for reducing ecological pressure. Overall, the results suggest that Bihar must adopt climate-smart agriculture, renewable energy technologies, and resource-efficient farming methods to ensure long-run environmental sustainability.

6. CONCLUSION AND POLICY IMPLICATIONS

The present study investigates the relationship between agricultural development and ecological footprint in Bihar using the Autoregressive Distributed Lag (ARDL) Bounds Testing approach over the period 1991–2023. The study incorporates agricultural value added as the primary explanatory variable while renewable energy consumption, trade openness, and urbanization are included as control variables to examine their influence on environmental sustainability. The empirical findings confirm the existence of a long-run equilibrium relationship among ecological footprint, agricultural development, renewable energy consumption, trade openness, and urbanization. The ARDL Bounds Test establishes cointegration among the variables, indicating that changes in agriculture and other macroeconomic factors significantly affect ecological sustainability in Bihar over time. The long-run results reveal that agricultural development exerts a positive and statistically significant effect on ecological footprint. This implies that expansion in agricultural activities has intensified environmental degradation in Bihar. The increasing dependence on groundwater irrigation, excessive use of fertilizers and pesticides, crop residue burning, mechanization, and fossil-fuel-based energy consumption has substantially increased ecological pressure in the state. Although agriculture remains the backbone of Bihar's rural economy, the present pattern of agricultural growth appears environmentally unsustainable. Renewable energy consumption is found to reduce ecological footprint, suggesting that clean energy adoption contributes positively to environmental quality. The result highlights the importance of renewable energy technologies such as solar-powered irrigation systems, bioenergy, and decentralized rural energy infrastructure in promoting sustainable agriculture. Trade openness exhibits a positive relationship with ecological footprint, indicating that expanding trade activities may increase transportation emissions, industrial pressure, and resource exploitation. Urbanization remains statistically insignificant in the long run, implying that agricultural activities continue to dominate environmental outcomes in Bihar. The short-run dynamics further validate the existence of long-run equilibrium through a negative and significant error correction term. The adjustment coefficient confirms that deviations from equilibrium gradually converge toward long-run stability. The findings of the study provide important insights for policymakers, environmental planners, and agricultural stakeholders. Since agriculture significantly contributes to ecological degradation, there is an urgent need to redesign agricultural policies toward sustainability-oriented development.

Policy Implications

First, the Government of Bihar should promote climate-smart agricultural practices that enhance productivity while minimizing environmental damage. Sustainable farming techniques such as organic farming, integrated nutrient management, crop diversification, agroforestry, and conservation agriculture should be encouraged through financial incentives and extension services.

Second, the excessive dependence on groundwater irrigation requires immediate policy intervention. The adoption of micro-irrigation systems such as drip and sprinkler irrigation should be expanded to improve water-use efficiency. Solar-powered irrigation pumps should be promoted to reduce dependence on diesel-based energy systems and lower carbon emissions. Third, policymakers should strengthen awareness and training programs for farmers regarding sustainable resource management. Agricultural extension institutions, Krishi Vigyan Kendras, and rural development agencies should play a proactive role in disseminating knowledge related to environmentally friendly farming practices. Fourth, residue burning and excessive chemical fertilizer use must be reduced through stricter environmental regulations and promotion of alternative technologies. Subsidies for biofertilizers, composting, precision farming, and crop residue management technologies can help reduce ecological pressure. Fifth, renewable energy infrastructure in rural Bihar should be expanded. Investments in decentralized solar energy, biomass energy, and clean rural electrification can significantly improve environmental sustainability while supporting agricultural productivity. Sixth, sustainable trade and supply-chain mechanisms should be encouraged to minimize the ecological costs associated with transportation, storage, and industrial processing of agricultural products. Eco-friendly logistics and green rural infrastructure can help reduce environmental degradation linked with trade expansion. Finally, the study highlights the importance of integrating environmental sustainability into Bihar's agricultural development strategy. Economic growth and food security objectives should be aligned with ecological conservation goals to ensure long-term sustainability. Without adopting environmentally sustainable agricultural practices, rising ecological footprint may threaten Bihar's natural resource base, agricultural productivity, and climate resilience in the future. Therefore, a balanced policy framework that simultaneously promotes agricultural growth, renewable energy adoption, efficient resource management, and ecological conservation is essential for achieving sustainable development in Bihar.

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