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## ARTICLE

# Agricultural Dynamics and Economic Growth: Evidence from Developed and Developing Indian States

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## ABSTRACT

This study investigates the role of agricultural productivity, technological intensification, and structural factors in shaping economic growth across developed and developing Indian states. Using a balanced panel dataset of 22 states over the period 2001–2024 (528 observations), the analysis employs correlation techniques, fixed-effects estimation, sub-sample analysis, and Feasible Generalized Least Squares (FGLS) to test a set of theoretically grounded hypotheses on the agriculture–growth nexus. The findings reveal pronounced structural heterogeneity across state groups. Agricultural productivity, proxied by gross value added per worker, emerges as a robust and statistically significant driver of economic growth across both developed and developing states, with relatively stronger transmission effects in more advanced economies. Technological inputs exhibit stage-specific impacts: mechanization significantly enhances growth in developing states, whereas fertilizer intensity plays a more prominent role in developed states. The interaction between machinery and fertilizer is positive and significant, confirming the complementarity hypothesis and indicating that integrated technological adoption yields higher productivity gains than isolated inputs. Agricultural trade openness exerts a consistently positive and significant effect, particularly in developed states, supporting the openness-led growth hypothesis, while its impact in developing states remains contingent on structural competitiveness. Human capital and research and development (R&D) show weak or negative short-run effects, reflecting adjustment costs and lagged returns to innovation. Population growth contributes positively, whereas institutional quality exhibits mixed but robust effects across specifications. Overall, the results highlight the importance of context-specific policy frameworks that

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integrate productivity enhancement, technological complementarities, trade integration, and institutional capacity for achieving sustainable and inclusive economic growth.

**Keywords:** Agricultural Productivity; Economic Growth; Technological Intensification; Trade Openness; Structural Transformation

## 1. Introduction

The relationship between agriculture and economic growth has long occupied a central position in development economics, embedded within the broader framework of structural transformation. Classical dual-economy models posit agriculture as the initial engine of growth, providing surplus labour, capital accumulation, and wage goods necessary for industrial expansion. However, more recent empirical evidence suggests that this relationship is neither linear nor universal, particularly in economies characterized by late industrialization and service-led growth. The agriculture–growth nexus is increasingly understood as being mediated by technological change, market integration, institutional quality, and regional heterogeneity, thereby necessitating a more context-specific and empirically grounded analysis.

India provides a particularly compelling context for re-examining this relationship. Over the past three decades, the Indian economy has recorded an average annual GDP growth rate exceeding 6–7%, accompanied by a pronounced structural shift toward the services sector, which now contributes more than 50% of gross value added. In contrast, agriculture’s share in GDP has declined steadily to approximately 15–17% in recent years. Despite this decline, the sector continues to employ nearly 42–45% of the workforce, underscoring a persistent mismatch between output contribution and labour absorption. This structural imbalance reflects low labour productivity in agriculture relative to non-agricultural sectors and highlights the incomplete nature of India’s structural transformation.

At the same time, agricultural performance in India has exhibited both progress and volatility. Agricultural gross value added (*GVA*) has grown at an average rate of around 3–4% per annum since the early 2000s, with notable fluctuations driven by monsoon variability, input use, and market conditions. Productivity improvements—measured in terms of output per worker and per hectare—

have been uneven across regions. For instance, states such as Punjab and Haryana report significantly higher yields and mechanization levels compared to eastern and central states like Bihar and Odisha, where productivity remains relatively low. Similarly, fertilizer consumption varies widely, ranging from over 200 kg/ha in agriculturally advanced states to less than 100 kg/ha in less-developed regions, reflecting disparities in input intensity and technological adoption.

Recent decades have also witnessed important structural changes within Indian agriculture. There has been a gradual shift from cereal-dominated production toward high-value crops such as fruits, vegetables, dairy, and fisheries. The share of horticulture in total agricultural output has increased substantially, now accounting for more than 30% of agricultural *GVA*. This diversification is driven by rising incomes, urbanization, and changing dietary patterns, as well as improvements in supply chains and cold storage infrastructure. However, these gains are not uniformly distributed, with significant inter-state variation in diversification patterns and market access.

Trade integration further illustrates the evolving dynamics of the sector. Agricultural exports from India have expanded considerably, crossing USD 50 billion in recent years, yet the degree of trade openness varies significantly across states due to differences in infrastructure, logistics, and policy support. States with better port connectivity and value-chain integration, such as Maharashtra and Gujarat, exhibit higher export intensity compared to landlocked or infrastructure-constrained regions. This uneven integration into global markets suggests that the growth effects of trade openness are likely to be heterogeneous and conditional on structural capabilities.

The heterogeneity across Indian states is, in fact, one of the defining features of the country’s development trajectory. States such as Punjab, Haryana, Tamil Nadu, and Maharashtra have achieved relatively higher levels of per capita income, agricultural productivity, and industrializa-

tion. In contrast, states such as Bihar, Uttar Pradesh, and Madhya Pradesh continue to rely heavily on agriculture, often characterized by low productivity, fragmented landholdings, and limited technological penetration. For example, per capita income in developed states can be more than two to three times higher than in less-developed states, while agricultural productivity differentials are equally pronounced. These disparities are further reinforced by variations in irrigation coverage (ranging from over 80% in Punjab to less than 50% in several eastern states) and access to institutional credit and extension services.

Such regional divergence has important implications for the agriculture–growth nexus. In more developed states, agriculture is increasingly integrated with agro-processing, supply chains, and export markets, suggesting that its contribution to growth may operate indirectly through inter-sectoral linkages. In contrast, in less-developed states, agriculture remains a primary source of income and employment, implying a more direct relationship with economic growth. This distinction highlights the need for a disaggregated analytical framework that explicitly accounts for differences in development stages and structural conditions.

Furthermore, the sector faces a range of emerging challenges that complicate its growth dynamics. Climate variability has increased the frequency of extreme weather events, affecting crop yields and income stability. Resource constraints, including declining groundwater levels and soil degradation, pose additional risks to sustainability. At the same time, technological advancements—such as precision agriculture, digital advisory systems, and improved seed varieties—offer new opportunities for enhancing productivity, albeit with uneven adoption across regions.

From a theoretical perspective, these developments call for an integrated framework that combines insights from structural transformation theory, endogenous growth models, and institutional economics. While traditional approaches emphasize labour reallocation and capital accumulation, contemporary perspectives highlight the roles of innovation, human capital, environmental sustainability, and governance in shaping growth outcomes. In the Indian context, the coexistence of a large agrarian workforce with a rapidly expanding service sector presents a unique development trajectory that challenges conventional paradigms.

Against this backdrop, the present study undertakes a systematic and comparative analysis of agricultural dynamics and economic growth across developed and developing Indian states. By incorporating empirical indicators such as agricultural productivity, technological inputs (machinery and fertilizer), trade openness, and structural variables, the study moves beyond aggregate narratives to provide a multidimensional assessment of the agriculture–growth relationship.

The empirical analysis is guided by the following hypotheses:

**H1.** *Agricultural dynamics exert a statistically significant positive effect on economic growth at the state level in India.*

**H2.** *The magnitude and direction of this impact differ systematically between developed and developing states.*

**H3.** *Technological intensification and diversification enhance the growth impact of agriculture.*

**H4.** *The effects of agricultural dynamics are mediated by structural factors such as human capital, infrastructure, and market integration.*

**H5.** *In developed states, agriculture influences growth primarily through indirect linkages, whereas in developing states the effect is more direct.*

By explicitly integrating recent empirical trends and state-level disparities, the study addresses a critical gap in the literature and provides a more nuanced understanding of whether agricultural dynamics remain a key driver of economic growth in India or whether their role has become increasingly conditional upon structural transformation and regional context. Such insights are essential for designing evidence-based, region-specific policy interventions aimed at achieving sustainable and inclusive growth.

## 2. Conceptual Framework

The conceptual framework of the study (**Figure 1**) delineates the structural and transmission mechanisms through which agricultural dynamics influence economic growth across developed and developing Indian states. The framework is grounded in an integrated theoretical perspective that combines elements from structural transformation theory, neoclassical and endogenous growth models, and contemporary empirical insights on sectoral

linkages and regional heterogeneity. It conceptualizes economic growth as a function of agricultural productivity, agricultural technology, trade openness, and human capital,

while explicitly recognizing that the magnitude and direction of these relationships are conditioned by the level of development and structural characteristics of the economy.

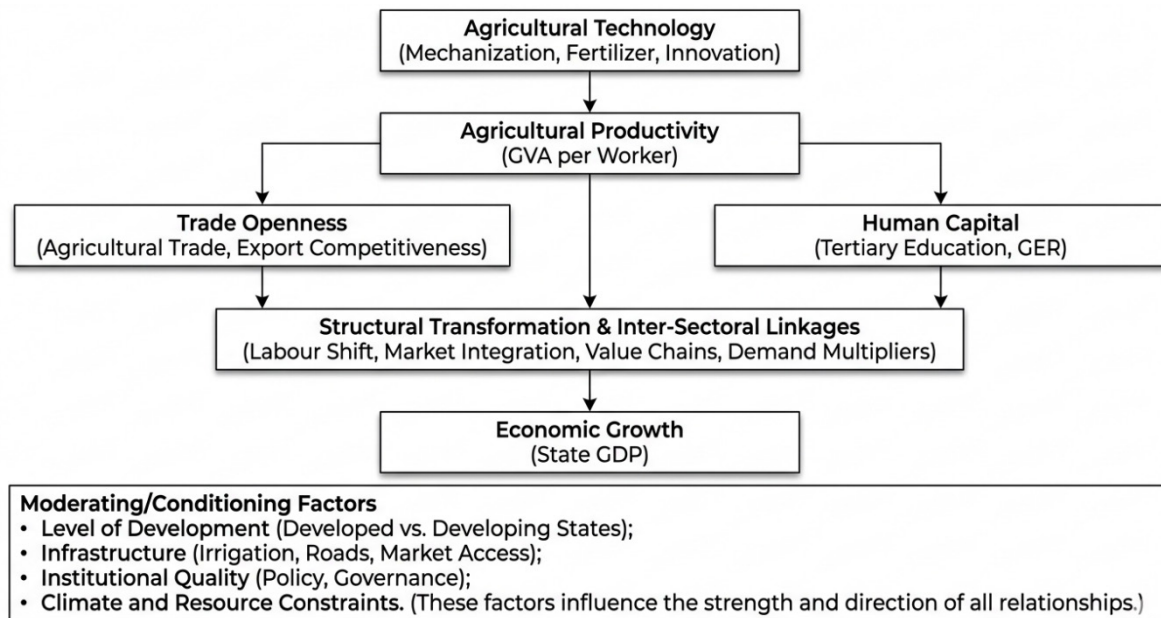


Figure 1. Conceptual Framework: Agricultural Dynamics and Economic Growth.

Source: Author’s construction.

At the core of the framework lies agricultural productivity, operationalized as gross value added (*GVA*) per worker in agriculture. Productivity improvements represent the primary channel through which agriculture contributes to economic growth. Higher productivity enhances income generation within the rural economy, releases surplus labour for reallocation to higher-productivity sectors, and strengthens forward and backward linkages with industry and services. This mechanism is consistent with the structural transformation hypothesis and is empirically supported by evidence demonstrating a causal relationship between agricultural value-added growth and aggregate economic performance in developing economies<sup>[1]</sup>. Recent cross-country analyses further suggest that productivity-led agricultural growth exerts strong multiplier effects on non-farm sectors, particularly in regions characterized by labour surplus and imperfect markets<sup>[2,3]</sup>.

Agricultural technology constitutes a second critical pillar of the framework, capturing the role of mechanization, input intensification (e.g., fertilizers), and technological innovation in enhancing productive efficiency. From a theoretical standpoint, this channel is rooted in both

classical and neoclassical traditions. While the Ricardian framework emphasizes diminishing returns to land, technological progress offsets these constraints by shifting the production frontier outward. In the Solow growth model, technological change is the principal driver of long-run growth through its impact on total factor productivity (TFP)<sup>[4]</sup>. More recent empirical studies highlight that technology adoption in agriculture not only raises yields but also facilitates diversification toward high-value activities and strengthens resilience to climatic shocks<sup>[5-9]</sup>. Importantly, the effectiveness of technological inputs is mediated by complementary factors such as infrastructure, institutional support, and human capital, thereby reinforcing the need for a multidimensional analytical framework.

Trade openness, proxied through agricultural trade integration, represents a key external transmission channel linking agriculture to economic growth. Classical trade theories—particularly those associated with absolute and comparative advantage—suggest that openness enhances efficiency through specialization and resource reallocation. Modern endogenous growth models extend this argument by emphasizing the role of trade in facilitating knowledge

diffusion, technological spillovers, and innovation<sup>[10–12]</sup>. Empirical evidence indicates that greater trade openness in the agricultural sector can enhance productivity, stabilize markets, and promote export-led growth, especially in economies with comparative advantage in agricultural commodities<sup>[13–16]</sup>. However, the growth effects of trade are not uniform; they depend critically on domestic absorptive capacity, institutional quality, and the degree of diversification within the agricultural sector.

Human capital forms the fourth pillar of the conceptual framework, reflecting its central role in enabling productivity enhancement and technological adoption. Within the endogenous growth literature, human capital is a fundamental determinant of innovation, learning, and long-term growth<sup>[17–20]</sup>. In the agricultural context, higher levels of education facilitate the adoption of modern inputs, improve farm management practices, and enhance the ability of producers to respond to market signals and environmental risks. Empirical studies consistently demonstrate that educational attainment—particularly at the tertiary level—has a significant positive effect on economic growth through its impact on knowledge accumulation and innovation capacity<sup>[21,22]</sup>. Moreover, human capital interacts synergistically with technology and trade, amplifying their respective growth effects.

A distinctive feature of the present framework is the explicit incorporation of developmental heterogeneity across states. The framework posits that the agriculture–growth relationship is not invariant but varies systematically between developed and developing states due to differences in structural conditions. In relatively developed states, characterized by higher levels of industrialization, infrastructure, and human capital, the contribution of agriculture to economic growth is expected to operate primarily through indirect channels—such as supply chain linkages, value addition, and demand spillovers. In contrast, in less-developed states, where agriculture remains the dominant sector, its impact on growth is likely to be more direct and output-driven. This distinction is consistent with recent empirical literature emphasizing the context-dependent nature of sectoral growth linkages and the importance of initial conditions in shaping development outcomes<sup>[23,24]</sup>.

Furthermore, the framework recognizes the presence of interaction effects and feedback mechanisms among the

explanatory variables. For instance, technological adoption is contingent upon human capital, while the benefits of trade openness are mediated by both productivity and institutional capacity. Similarly, improvements in agricultural productivity can generate resources for investment in education and infrastructure, thereby reinforcing long-term growth. These interdependencies highlight the need for an integrated empirical approach capable of capturing both direct and indirect effects.

In sum, the conceptual framework advances a multi-dimensional and context-sensitive understanding of the agriculture–growth nexus. By integrating productivity, technology, trade, and human capital within a unified analytical structure, and by explicitly accounting for developmental heterogeneity, the framework provides a robust basis for empirical investigation. It facilitates the identification of distinct transmission channels through which agricultural dynamics influence economic growth, while also enabling the testing of differential effects across developed and developing Indian states.

### 3. Review of Literature

The empirical and theoretical literature on the agriculture–growth nexus has progressively evolved from linear and sector-isolated interpretations toward a more integrated and context-sensitive understanding. Consistent with the hypotheses articulated in the Introduction, recent scholarship emphasizes not only the direct contribution of agricultural dynamics to economic growth but also the mediating role of structural conditions, diversification, and regional heterogeneity. The following subsections synthesize the literature in alignment with the study’s five research hypotheses concerning the positive growth effects of agricultural dynamics, regional heterogeneity, technological intensification and diversification, structural mediation, and differentiated transmission mechanisms across developed and developing states (H1–H5).

#### 3.1. Gross Value Added, Agricultural Productivity and Economic Growth

The relationship between agricultural gross value added (*GVA*) and economic growth constitutes the foundational pillar of the agriculture–growth nexus. *GVA*, as a

proxy for sectoral productivity and income generation, directly contributes to aggregate output while simultaneously shaping inter-sectoral linkages through demand multipliers and labour reallocation mechanisms.

A seminal contribution<sup>[1]</sup> employed panel Granger causality techniques across a large sample of countries and found that agricultural value-added growth exerts a causal influence on GDP in developing economies. This finding challenged the conventional view that agriculture merely follows broader economic expansion, instead positioning it as a driver of growth, especially in early stages of development. Subsequent studies have reinforced this perspective. For instance, Gollin<sup>[2]</sup> underscores the centrality of agricultural productivity—proxied by value addition—in facilitating labour reallocation and structural transformation in low-income countries.

In the Indian context, a strong interdependence between agricultural output and economic growth that Kulshrestha and Agrawal<sup>[25]</sup> documented, arguing that sustained increases in agricultural *GVA* are indispensable for maintaining macroeconomic stability and growth momentum. Similar regional evidence, according to Sahu and Gartia<sup>[26]</sup>, highlights the importance of *GVA* as a macroeconomic indicator reflecting sectoral performance and overall development dynamics at the subnational level.

Cross-country evidence further substantiates the positive role of agricultural value addition. Using regression analysis for Romania<sup>[27]</sup>, a study identifies a statistically significant relationship between agricultural GDP and national economic growth, driven primarily by both crop and livestock production. Comparable findings are reported<sup>[28]</sup> for Serbia, where agricultural output—particularly cereals—plays a decisive role in shaping GDP dynamics. Studies by Pawlak and Kołodziejczak<sup>[29]</sup> and Shaqiri<sup>[30]</sup> extend this argument by demonstrating that increased agricultural output, supported by investment and infrastructure, enhances food security and human development, thereby reinforcing long-term growth.

Collectively, the literature converges on the conclusion that agricultural *GVA* serves as a critical conduit for growth through productivity enhancement, income generation, and structural transformation. However, the literature also indicates that the strength of the *GVA*–growth relationship is contingent upon structural conditions, including

the stage of development, sectoral composition, and institutional quality. In more advanced economies, the direct contribution of agriculture to GDP may diminish, while its indirect effects through value chains and demand linkages become more pronounced. This heterogeneity directly relates to H2 and H5, suggesting that the impact of agricultural *GVA* varies systematically across developed and developing states.

**H1.** *Agricultural dynamics exert a statistically significant positive effect on economic growth at the state level in India.*

### 3.2. Agricultural Technology, Productivity Enhancement and Growth Mediation

Technological progress in agriculture is widely recognized as a critical determinant of productivity growth and long-term economic performance. Within the neoclassical framework, technological advancement enhances total factor productivity (TFP), thereby offsetting diminishing returns to land and labour. Endogenous growth theory further highlights the role of innovation and knowledge diffusion in sustaining growth over time.

Empirical evidence strongly supports the productivity-enhancing effects of agricultural technology. A study using cross-country TFP analysis demonstrates that technological advancement in agriculture significantly contributes to long-run economic growth<sup>[31]</sup>. More recent work based on panel regression analysis, confirms that productivity-enhancing technologies are directly associated with GDP growth, particularly in developing economies<sup>[7]</sup>.

A notable contribution<sup>[3]</sup> establishes a causal link between agricultural input intensification and economic performance, showing that increases in crop yields—facilitated by fertilizers and improved inputs—lead to substantial gains in GDP per capita. This finding underscores the role of technological adoption in driving structural transformation through increased efficiency and income redistribution.

Micro-level and country-specific studies further illuminate these mechanisms. A study by Sinha<sup>[32]</sup> highlights the role of mechanization, capital deepening, and knowledge transfer in enhancing agricultural productivity and contributing to macroeconomic growth in India. Similarly,

other studies<sup>[33–36]</sup> emphasize the role of advanced machinery and production technologies in improving competitiveness and resource efficiency.

The recent literature has also expanded to include digital and precision agriculture. Studies by Talaviya et al.<sup>[37]</sup> and Soleimanipour and Chegini<sup>[38]</sup> also demonstrated how artificial intelligence (AI)-based applications—such as precision irrigation and soil monitoring—enhance productivity and resource efficiency. Innovations such as bio-fertilizers<sup>[39]</sup> and digital advisory platforms<sup>[40,41]</sup> further contribute to sustainable intensification and improved decision-making. These technological advancements not only raise agricultural output but also strengthen resilience and environmental sustainability, thereby reinforcing their contribution to economic growth.

Importantly, the literature underscores that the growth effects of technology are not autonomous but are mediated by complementary factors, particularly human capital, infrastructure, and institutional quality. This directly aligns with H4, which posits that structural conditions shape the effectiveness of agricultural dynamics. Moreover, technological adoption often facilitates diversification into high-value activities, thereby linking this subsection to H3.

**H3.** *Technological intensification and diversification enhance the growth impact of agriculture.*

### 3.3. Agricultural Trade Openness, Diversification and Structural Linkages

Trade openness constitutes a crucial external channel through which agricultural dynamics influence economic growth. Classical and neoclassical trade theories emphasize gains from specialization and comparative advantage, while endogenous growth models highlight the role of trade in facilitating knowledge spillovers and innovation diffusion.

Empirical studies largely support a positive relationship between trade openness and economic growth. A study using an autoregressive distributed lag (ARDL) model<sup>[42]</sup> for Côte d'Ivoire finds that trade openness exerts both short-run and long-run positive effects on GDP, particularly through its interaction with capital formation. Similarly, in a panel study of agrarian economies, Muha-

mad<sup>[8]</sup> demonstrates a strong positive association between agricultural trade openness and economic growth.

A study by Otieno Jabuya et al.<sup>[43]</sup> provides evidence of a unidirectional causal relationship from trade openness to GDP in East African countries, highlighting the role of export expansion and global integration in driving structural transformation. These findings are consistent with endogenous growth models that emphasize knowledge spillovers and innovation diffusion through trade.

However, the literature also underscores important caveats. It was argued by Wise<sup>[44]</sup> that the benefits of trade openness may be unevenly distributed, with smallholder farmers potentially disadvantaged by increased import competition. Similarly, in another study<sup>[45]</sup>, it was emphasized that without robust institutional frameworks, excessive openness may expose economies to external vulnerabilities, thereby dampening growth effects.

Thus, while the overall evidence supports a positive linkage between agricultural trade openness and economic growth, the magnitude and inclusiveness of these effects depend on factors such as export diversification, institutional quality, and policy support.

Furthermore, trade openness strengthens inter-sectoral linkages by integrating agriculture with global value chains, thereby reinforcing the indirect growth channels highlighted in H5.

**H4.** *The effects of agricultural dynamics are mediated by structural factors such as human capital, infrastructure, and market integration.*

### 3.4. Human Capital, Structural Conditions and Heterogeneous Growth Effects

Human capital plays a central role in mediating the relationship between agricultural dynamics and economic growth. Within the endogenous growth framework, education enhances labour productivity, facilitates technological adoption, and promotes innovation. In the agricultural sector, human capital is particularly critical for enabling the transition toward modern, knowledge-intensive production systems.

Empirical evidence consistently supports the positive impact of education on economic growth. Employing a system GMM approach, it was found by Tamayo et al.<sup>[46]</sup>

that increased education expenditure significantly enhances GDP per capita in developing economies. Further studies <sup>[23]</sup> demonstrate that higher education institutions contribute substantially to economic performance and resilience, particularly through innovation and knowledge creation.

Recent theoretical contributions <sup>[47]</sup> highlight the complex interactions between education, inequality, and growth, suggesting that the effects of human capital are mediated by institutional and structural factors. Empirical support for the human capital–growth nexus in resource-rich economies <sup>[16]</sup> was provided, demonstrating a strong positive association between education and GDP.

Importantly, a study by Margolies et al. <sup>[48]</sup> introduces the notion of a “ceiling effect,” whereby the marginal returns to education diminish in advanced economies but remain substantial in developing contexts. This finding has important implications for understanding regional heterogeneity within countries such as India, where states differ significantly in educational attainment and development levels.

In the agricultural sector, higher levels of education enhance the adoption of modern technologies, improve resource management, and facilitate integration into markets. These effects collectively contribute to productivity growth and structural transformation, reinforcing the central role of human capital in the agriculture–growth nexus.

**H2.** *The magnitude and direction of this impact differ systematically between developed and developing states.*

- **Integrated Perspective and Link to Hypothesis 5**

Synthesizing the above strands, the literature clearly indicates that agricultural dynamics influence economic growth through both direct and indirect channels, with the relative importance of these channels varying across stages of development. In less-developed regions, growth effects are primarily driven by direct productivity gains and income generation. In contrast, in more advanced regions, agriculture contributes indirectly through inter-sectoral linkages, value addition, and integration with industry and services.

This distinction provides the theoretical and empirical basis for:

**H5.** *In developed states, agriculture influences growth pri-*

*marily through indirect linkages, whereas in developing states the effect is more direct.*

- **Conceptual Framework and Hypothesis Consolidation**

Overall, the literature supports a multidimensional and conditional view of the agriculture–growth nexus. While agricultural *GVA*, technology, trade openness, and human capital each exert positive effects on economic growth, their magnitude and transmission mechanisms are mediated by structural factors and vary across regions. This underscores the necessity of a disaggregated, state-level empirical approach capable of capturing heterogeneity, interaction effects, and differentiated development pathways in the Indian context.

## 4. Data and Methodology

### 4.1. Data

The empirical analysis is based on a balanced panel dataset of major Indian states, classified into developed and developing categories to explicitly capture structural heterogeneity, as emphasized in Hypotheses H2 and H5. The classification of states follows a composite criterion based on per capita income, level of industrialization, and human development indicators, consistent with the empirical literature on regional disparities in India.

**Sample Selection and Coverage:** While India currently comprises 28 states, the present study includes a sample of 22 states, selected on the basis of data availability, consistency, and comparability over the study period (2001–2024). The exclusion of six states is guided by the following methodological considerations:

**Data continuity and completeness:** Several states—particularly newly formed states such as Telangana (formed in 2014) and those undergoing administrative restructuring—do not provide consistent time-series data for key variables (e.g., agricultural *GVA* per worker, machinery use, and sector-specific trade indicators) across the full study period. Inclusion of such states would result in an unbalanced panel and potentially biased estimates.

**Statistical comparability:** Smaller and special-category states (e.g., certain North-Eastern states and Hima-

layan regions) exhibit structurally distinct economic and agricultural systems, characterized by subsistence agriculture, limited market integration, and atypical factor endowments. Including these states without appropriate structural controls would introduce heterogeneity that is not directly comparable with the core analytical framework of the study.

**Data reliability and measurement consistency:** For some states, particularly those with fragmented statistical systems or limited reporting on agricultural inputs (e.g., machinery and fertilizer use), the available data are either missing, inconsistent across sources, or subject to definitional discrepancies. To preserve the internal validity of the empirical analysis, only states with consistent and harmonized data across all variables were retained.

**Analytical coherence:** The selected 22 states together account for the overwhelming share of India’s agricultural output, cultivated area, and population, thereby ensuring that the sample remains broadly representative of the national economy while maintaining econometric robustness.

The final sample thus represents a methodologically consistent and empirically reliable subset of Indian states, enabling robust panel estimation without compromising data integrity. A detailed list of included states is provided in **Appendix A**.

The study period spans 2001–2024, a phase characterized by significant agricultural transformation, trade integration, and structural shifts in the Indian economy. This period captures post-liberalization dynamics, technological diffusion, and increasing regional divergence in growth trajectories.

The analysis employs a multidimensional representation of agricultural dynamics, aligned with the conceptual framework and hypotheses (H1–H5). Agricultural productivity is proxied by gross value added (*GVA*) per worker in agriculture, which provides a more precise measure of labour productivity than aggregate output and captures efficiency improvements within the sector.

Agricultural technology is operationalized through two complementary dimensions:

- (i) Mechanical technology, proxied by farm machinery (e.g., tractors and harvesters), and

- (ii) Biochemical technology, proxied by fertilizer consumption (NPK nutrients).

These variables capture the intensity of input use and technological adoption, while their effectiveness is conditioned by absorptive capacity and institutional support.

Human capital is measured using the Gross Enrolment Ratio (*GER*) in tertiary education, reflecting the capacity for knowledge creation, technological adoption, and innovation. Agricultural trade openness is measured as the ratio of agricultural exports and imports to agricultural *GVA*, thereby capturing sector-specific market integration.

To isolate the net effects of agricultural dynamics, the model incorporates control variables representing structural and macroeconomic conditions: gross fixed capital formation (*GFCF*) in agriculture, research and development (R&D) expenditure, inflation, population growth, and institutional quality.

All data are obtained from credible secondary sources, including the Reserve Bank of India (RBI), the Ministry of Statistics and Programme Implementation (MOSPI), FAOSTAT, and World Development Indicators (WDI). Variables are transformed into natural logarithms to ensure variance stabilization and elasticity interpretation.

## 4.2. Model Specification

To empirically examine the relationship between agricultural dynamics and economic growth, the study specifies the following baseline panel model:

$$\ln GDP_{it} = \alpha + \beta_1 \ln GVA_{it} + \beta_2 \ln Mac_{it} + \beta_3 \ln Fer_{it} + \beta_4 \ln GER_{it} + \beta_5 \ln AGopen_{it} + \beta_6 \ln GFCF_{it} + \beta_7 \ln RD_{it} + \beta_8 \ln Inf_{it} + \beta_9 \ln PG_{it} + \beta_{10} \ln IQ_{it} + \mu_i + \varepsilon_{it}$$

where:

- $GDP_{it}$  denotes real per capita gross state domestic product,
- $GVA_{it}$  represents agricultural productivity (*GVA* per worker),
- $Mac_{it}$  and  $Fer_{it}$  capture agricultural technology,
- $GER_{it}$  represents human capital,
- $AGopen_{it}$  denotes agricultural trade openness,
- $GFCF_{it}$ ,  $RD_{it}$ ,  $Inf_{it}$ ,  $PG_{it}$ , and  $IQ_{it}$  are control variables,
- $\mu_i$  captures unobserved state-specific effects,

- $\varepsilon_{it}$  is the idiosyncratic error term.

To account for interaction effects and complementarities in technology adoption, an extended specification incorporates an interaction term between machinery and fertilizer:

$$\ln GDP_{it} = \alpha + \beta_1 \ln GVA_{it} + \beta_2 \ln Mac_{it} + \beta_3 \ln Fer_{it} + \beta_4 (\ln Mac_{it} \times \ln Fer_{it}) + \dots + \mu_i + \varepsilon_{it}$$

This specification captures the joint productivity effects of mechanical and biochemical technologies.

Further, to explicitly test Hypotheses H2 and H5, the full sample is divided into developed and developing state panels, allowing for differential coefficient estimation. This disaggregation enables the identification of whether agricultural dynamics exert direct effects in less-developed states and indirect or mediated effects in developed states.

### 4.3. Estimation Strategy

The empirical strategy is based on panel data econometric techniques, which allow for controlling unobserved heterogeneity and capturing both cross-sectional and temporal variations. The choice between fixed effects (FE) and random effects (RE) models is determined using the Hausman specification test, with results favouring the fixed effects estimator due to correlation between regressors and unobserved state-specific effects.

The baseline estimations are therefore conducted using a Fixed Effects (FE) model, which controls for time-invariant heterogeneity across states, such as geography, institutional legacy, and agro-climatic conditions. This is particularly important in the Indian context, where such factors significantly influence agricultural performance.

Prior to estimation, standard diagnostic tests are conducted, including:

- Descriptive statistics to examine data distribution,
- Correlation matrix to assess pairwise relationships,
- Variance Inflation Factor (VIF) to detect multicollinearity.

A key methodological challenge arises from potential multicollinearity between machinery and fertilizer variables. To address this, alternative model specifications are estimated by introducing these variables separately and

jointly (with interaction terms), ensuring robustness and interpretability.

To test Hypothesis H4 (mediating effects), interaction terms and subgroup analyses are employed, while Hypotheses H2 and H5 (heterogeneity) are examined through separate estimations for developed and developing states.

For robustness, the study employs Feasible Generalized Least Squares (FGLS), which corrects for heteroskedasticity and serial correlation commonly observed in panel data. This ensures efficiency and consistency of the estimates. Additionally, robust standard errors are used to address potential cross-sectional dependence and autocorrelation.

### Link to Hypotheses

The empirical strategy is explicitly aligned with the hypotheses:

- H1 is tested through the coefficient of agricultural *GVA*.
- H2 is examined via comparative estimation across developed and developing states.
- H3 is evaluated through trade openness and its interaction with productivity.
- H4 is tested using human capital and interaction terms capturing mediation effects.
- H5 is assessed by comparing direct vs. indirect effects across state groups.

Overall, the data and methodology are designed to provide a rigorous, disaggregated, and structurally grounded analysis of the agriculture–growth nexus in India, consistent with the theoretical framework and empirical objectives of the study.

## 5. Result & Discussion

### 5.1. Mainstream Results: Descriptive Statistics and Preliminary Insights

**Table 1** presents the descriptive statistics for the key variables employed in the empirical analysis. These statistics provide an essential preliminary understanding of the distributional properties, central tendencies, and variability of the data, thereby offering initial insights into the plausibility of the hypothesized relationships.

**Table 1.** Descriptive Statistics.

Variable	Observations	Mean	Std. Dev.	Minimum	Maximum
<i>GDP</i>		10.3831	0.8996	6.6574	11.6300
<i>GVA</i>		10.6636	2.7611	6.8790	22.6254
<i>Mac</i>		8.8530	2.5088	4.5708	16.9510
<i>Fer</i>		8.6469	4.3995	3.5196	13.4447
<i>GER</i>		3.7952	3.2469	0.6067	4.7848
<i>AG openness</i>	528	1.9150	1.9081	1.3577	4.8110
<i>GFCF</i>		—	0.5633	0.2544	2.2339
<i>RD</i>		—	1.1241	0.1040	1.7414
<i>Inf</i>		—	1.1705	-1.6252	15.6498
<i>PG</i>		—	7.1367	-10.9274	21.7003
<i>IQ</i>		—	2.5957	-12.1564	1.6379

Source: Author's construction.

### 5.1.1. Central Tendencies and Growth Dynamics

The mean value of *GDP* (10.38) and *GVA* (10.66) indicates a relatively high level of economic performance across the sampled observations, suggesting sustained macroeconomic expansion. The slightly higher average for *GVA* compared to *GDP* reflects structural contributions from sectoral value addition, which aligns with the hypothesis that sectoral productivity improvements drive aggregate economic growth.

The moderate dispersion in *GDP* (standard deviation = 0.89) compared to the substantially higher variation in *GVA* (2.76) implies that sectoral output dynamics are more volatile than aggregate income. This supports the hypothesis of heterogeneous sectoral contributions to growth, particularly in developing and structurally transforming economies.

### 5.1.2. Structural and Agricultural Determinants

The variables representing macroeconomic conditions (*Mac*) and fertilizer use (*Fer*) exhibit relatively high means (8.85 and 8.65, respectively) with considerable variability, especially for fertilizer use (standard deviation = 4.39). This indicates uneven agricultural intensification across observations, consistent with the hypothesis that input-driven agricultural productivity varies significantly across regions.

The wide range in fertilizer use (minimum = 3.52; maximum = 13.44) further reinforces the presence of structural disparities in agricultural practices. Such dispersion

is indicative of differential access to modern inputs, thereby supporting the theoretical expectation that agricultural modernization contributes unevenly to growth outcomes.

### 5.1.3. Human Capital and Openness

Gross Enrolment Ratio (*GER*), a proxy for human capital, shows a moderate mean (3.79) but relatively high dispersion (standard deviation = 3.25), suggesting significant inequality in educational attainment across units. This variation substantiates the hypothesis that human capital formation is uneven and may exert differential impacts on economic growth.

Similarly, agricultural openness (*AG openness*) exhibits a mean of 1.91 with a relatively high standard deviation (1.91), indicating heterogeneity in trade integration. The observed range suggests that while some regions are highly integrated into global markets, others remain relatively closed. This variability aligns with the hypothesis that openness influences growth through differential exposure to external markets and technological spillovers.

### 5.1.4. Investment, Innovation, and Macroeconomic Stability

Gross Fixed Capital Formation (*GFCF*) and Research and Development (*RD*), proxies for physical and technological investment, display moderate variability. The relatively lower dispersion in *GFCF* suggests more stable investment patterns, whereas *RD* variability indicates uneven innovation capacity across observations. This supports the hypothesis that innovation-driven growth is not uniformly distributed.

Inflation (*Inf*) and population growth (*PG*) exhibit substantial dispersion, with inflation ranging from negative to high positive values and population growth showing both contraction and rapid expansion. These patterns indicate macroeconomic instability in certain observations, reinforcing the hypothesis that macroeconomic volatility can adversely affect growth performance.

### 5.1.5. Institutional Quality

Institutional quality (*IQ*) shows considerable variation, with a wide range spanning negative to positive values. The large dispersion underscores significant institutional heterogeneity across observations. This finding is consistent with the hypothesis that institutional differences play a critical role in shaping economic outcomes, particularly through governance efficiency, regulatory quality, and policy implementation capacity.

### 5.1.6. Synthesis in Light of Hypotheses

Overall, the descriptive statistics reveal three key patterns consistent with the theoretical framework:

1. **Substantial heterogeneity across variables**, particularly in sectoral output, agricultural inputs, human capital, and institutional quality, supporting the hypothesis of uneven development dynamics.
2. **Moderate to high variability in key explanatory variables**, indicating sufficient dispersion to identify statistically meaningful relationships in subsequent econometric analysis.
3. **Presence of extreme values and wide ranges**, especially in macroeconomic and institutional indicators, suggesting potential nonlinearities and the need for robust estimation techniques.

These preliminary findings provide strong empirical justification for the hypothesized relationships and underscore the importance of accounting for structural heterogeneity, institutional differences, and macroeconomic variability in the subsequent regression analysis.

## 5.2. Correlation Structure and Econometric Validation

The correlation analysis provides preliminary evidence on the direction and strength of associations among key variables, thereby offering an initial validation of the

theoretical hypotheses. The results reveal substantial heterogeneity across country groups, consistent with the structural transformation hypothesis that the role of agriculture diminishes as economies advance.

In developed economies, agricultural productivity exhibits a weak and statistically insignificant correlation with GDP ( $r = 0.09$ ), confirming the hypothesis that agriculture plays a marginal role in advanced economic systems dominated by industry and services. In contrast, the strong and statistically significant correlation observed in developing economies ( $r = 0.73$ ,  $p < 0.05$ ) supports the hypothesis that agriculture remains a central driver of economic growth in structurally transforming economies. This divergence reflects differences in sectoral composition, labour allocation, and technological adoption.

Technological inputs in agriculture—particularly farm machinery and fertilizer—demonstrate positive and significant correlations with GDP across both country groups, albeit with stronger effects in developing economies. This finding corroborates the hypothesis that technological intensification enhances agricultural productivity and contributes to growth by improving efficiency and yield. However, the relatively weaker correlation of fertilizer in developing contexts also signals potential diminishing returns and environmental constraints.

Human capital exhibits context-dependent effects, consistent with the nonlinear human capital hypothesis. The negative correlation in developed economies ( $r = -0.52$ ) reflects diminishing marginal returns to education and delayed labour market entry, whereas the positive association in developing countries ( $r = 0.16$ ) supports the hypothesis that education facilitates technology adoption and productivity enhancement in low-income settings.

Trade openness shows a robust positive correlation with GDP in both developed ( $r = 0.54$ ,  $p < 0.05$ ) and developing ( $r = 0.77$ ,  $p < 0.05$ ) economies, strongly supporting the openness-led growth hypothesis. This indicates that integration into global markets enhances allocative efficiency, promotes specialization, and facilitates technological spillovers. Similarly, institutional quality demonstrates a positive and significant association with GDP ( $r = 0.51$  and  $0.43$ , respectively), validating the institutional hypothesis that effective governance frameworks are critical for sustained economic performance.

Macroeconomic stability variables yield mixed ev-

idence. Inflation is positively correlated with GDP in developed economies ( $r = 0.13, p < 0.05$ ), consistent with demand-driven growth dynamics, whereas the slightly negative correlation in developing economies ( $r = -0.05$ ) supports the hypothesis that inflation in such contexts is often cost-push in nature and detrimental to growth. Population growth exhibits weak but positive correlations across both groups, lending partial support to the demographic dividend hypothesis, conditional on labor market absorption capacity.

Capital-related variables reveal nuanced dynamics. Gross Fixed Capital Formation (*GFCF*) in agriculture is negatively correlated with GDP ( $r = -0.17, -0.48$ ), supporting the structural transformation hypothesis that economic development involves a reallocation of resources away from agriculture toward more productive sectors. Research and Development (*RD*) expenditure also shows a negative short-run correlation with GDP growth ( $r = -0.51, -0.17$ ), consistent with the intertemporal innovation hypothesis, where benefits materialize with a lag.

**Multicollinearity Diagnostics**

The VIF results reported in **Table 2** confirm the absence of severe multicollinearity among the explanatory variables. All VIF values lie well below the conventional threshold of 10, with a mean VIF of 2.34, indicating only moderate correlation among regressors. This finding ensures the statistical reliability and stability of the estimated coefficients and supports the validity of the econometric specification used to test the hypotheses.

**Table 2.** Results of the Variance Inflation Factor (VIF) Test.

Variable	VIF	1/VIF
<i>Fer</i>	4.90	0.2040
<i>Mac</i>	3.41	0.2935
<i>RD</i>	3.07	0.3257
<i>AG openness</i>	2.19	0.4561
<i>GFCF</i>	2.15	0.4652
<i>GER</i>	2.01	0.4969
<i>GVA</i>	1.35	0.7514
<i>IQ</i>	1.32	0.7601
<i>PG</i>	1.28	0.7833
<i>Inf</i>	1.07	0.9314
Mean VIF	2.34	—

Source: Authors' computation.

**5.3. Baseline Regression Results and Hypothesis Testing**

The baseline fixed-effects regression results are pre-

sented in **Table 3**. The estimates provide initial empirical evidence regarding the determinants of bioeconomy-related innovation and structural transformation across Indian states. Gross Value Added (*GVA*) exhibits a positive and highly significant association with the dependent variable in both specifications, indicating that stronger economic performance supports innovation-led bioeconomic development. Mechanization (*Mac*) also shows a positive and statistically significant effect, suggesting that technological modernization contributes to productivity enhancement and bioeconomy advancement. In Model 2, the interaction term between mechanization and fertilizer use ( $Mac \times Fer$ ) is positive and highly significant, implying that the productivity gains from mechanization are amplified when complemented by appropriate input intensification. Agricultural openness consistently exerts a positive influence, while research density (*RD*) displays a negative and significant coefficient, reflecting possible spatial and institutional disparities in innovation diffusion. Population growth (*PG*) and inflation (*Inf*) remain positively significant across both models, whereas Gross Enrolment Ratio (*GER*), Gross Fixed Capital Formation (*GFCF*), institutional quality (*IQ*), and fertilizer use (*Fer*) individually do not exhibit statistically significant effects. Overall, the results demonstrate substantial explanatory power, with  $R^2$  values ranging from 0.546 to 0.563, thereby providing strong support for the proposed analytical framework and the study hypotheses (see **Table 3**).

**Table 3.** Baseline Fixed Effects Regression Estimates.

Variables	Model 1 Coefficient (SE)	Model 2 Coefficient (SE)
<i>GVA</i>	0.2407*** (0.0239)	0.2289*** (0.0236)
<i>Mac</i>	0.1321*** (0.0330)	0.1280*** (0.0391)
<i>Fer</i>	0.0178 (0.0178)	—
$Mac \times Fer$	—	0.0206*** (0.0048)
<i>GER</i>	-0.0241 (0.0263)	-0.0198 (0.0258)
<i>AG openness</i>	0.0536*** (0.0152)	0.0592*** (0.0150)
<i>GFCF</i>	0.0101 (0.0160)	0.0079 (0.0157)
<i>RD</i>	-0.0547*** (0.0130)	-0.0487*** (0.0129)
<i>Inf</i>	0.0017*** (0.0006)	0.0016*** (0.0006)
<i>PG</i>	0.0117*** (0.0023)	0.0112*** (0.0023)
<i>IQ</i>	0.0108 (0.0154)	0.0112 (0.0151)
Intercept	6.4426*** (0.2930)	7.3140*** (0.3492)
Observations	462	462
$R^2$	0.5456	0.5628
F-statistic	340.10***	349.38***

Note: Standard errors in parentheses; \*\*\*  $p < 0.01$ .

Source: Author's computation.

### 5.3.1. Agricultural Productivity and Growth

The coefficient of *GVA* is positive and highly significant across both models, providing strong empirical support for the central hypothesis that agricultural productivity is a key driver of economic growth, particularly in structurally transforming economies. The magnitude and robustness of this effect confirm that improvements in value added per worker translate directly into aggregate output expansion.

### 5.3.2. Technological Intensification Hypothesis

Farm machinery (*Mac*) exhibits a positive and statistically significant effect on GDP, supporting the hypothesis that mechanization enhances efficiency, reduces labor dependency, and increases output. Fertilizer (*Fer*), however, is not significant when considered independently, suggesting diminishing marginal productivity and potential environmental or cost-related constraints.

Importantly, the interaction term ( $Mac \times Fer$ ) in Model 2 is positive and significant, indicating complementarity between capital-intensive and input-intensive technologies. This finding strongly supports the joint technology hypothesis that productivity gains are maximized when multiple modern inputs are used in combination rather than in isolation.

### 5.3.3. Openness and Structural Transformation

Agricultural trade openness consistently shows a positive and significant impact on economic growth across both models. This provides robust evidence in favor of the openness-led growth hypothesis, indicating that integration into global markets enhances productivity through specialization, technology transfer, and improved resource allocation.

The insignificance of *GFCF* in agriculture further supports the structural transformation hypothesis, suggesting that growth increasingly depends on non-agricultural sectors as economies develop.

### 5.3.4. Human Capital Dynamics

The negative coefficient of *GER* across both models, although statistically insignificant, is consistent with the earlier correlation results and supports the hypothesis of short-run adjustment costs associated with higher edu-

cation expansion. This reflects delayed labor force entry and potential skill mismatches, particularly in economies where labor markets are unable to absorb highly educated workers efficiently.

### 5.3.5. Innovation and Time-Lag Effects

Research and Development (*RD*) exhibits a negative and statistically significant coefficient, confirming the intertemporal innovation hypothesis. The negative short-run impact reflects the lag between investment and realization of productivity gains, as well as possible inefficiencies in resource allocation.

### 5.3.6. Macroeconomic Stability and Demographic Effects

Inflation shows a small but positive and significant effect on growth, supporting the moderate inflation hypothesis, where predictable price increases stimulate demand and investment. Population growth also exerts a positive and significant effect, consistent with the demographic dividend hypothesis, provided that the expanding labour force is productively employed.

### 5.3.7. Institutional Quality

Although institutional quality exhibits a positive coefficient, it is not statistically significant in the baseline models. This suggests that while institutions are theoretically important, their impact may be mediated through other channels such as investment, trade, and innovation, or may require alternative specifications to capture their full effect.

### 5.3.8. Synthesis

Taken together, the empirical results provide strong and consistent support for the core hypotheses of the study. Agricultural productivity, technological intensification, and trade openness emerge as key drivers of economic growth, while human capital and innovation exhibit context-dependent and time-sensitive effects. The findings also highlight the importance of structural transformation, macroeconomic stability, and demographic dynamics in shaping growth trajectories.

## 5.4. Developed & Developing States Sample Diagnostics and Structural Heterogeneity

The VIF diagnostics in **Table 4** indicate the presence

of relatively high multicollinearity between agricultural machinery (*Mac*) and fertilizer (*Fer*), particularly in developed economies where VIF values exceed conventional thresholds. This finding is consistent with the technological complementarity hypothesis, as both inputs are jointly adopted in advanced agricultural systems. To ensure econometric stability and avoid biased estimates, these variables are modeled separately across sub-samples. In contrast, the mean VIF values for developing economies remain within acceptable limits, confirming moderate multicollinearity and supporting the robustness of the specification.

**Table 4.** VIF Tests for Developed & Developing States Samples.

Variable	Developed States		Developing States	
	VIF	1/VIF	VIF	1/VIF
<i>Mac</i>	10.43	0.0959	5.59	0.1823
<i>Fer</i>	8.03	0.1246	6.62	60.1509
<i>RD</i>	3.09	0.3237	1.68	0.5958
<i>GER</i>	2.56	0.3914	2.38	0.4197
<i>AG openness</i>	2.35	0.5071	2.20	0.4549
<i>IQ</i>	2.29	—	1.63	0.6138
<i>GFCF</i>	1.89	—	3.38	0.2959
<i>PG</i>	1.81	—	1.54	0.6477
<i>GVA</i>	—	—	3.12	0.3201
<i>Inf</i>	—	—	1.04	0.9604
Mean VIF	—	—	3.53	—

Source: Author's computation.

### 5.5. Developed & Developing States Sample Regression Results and Hypothesis Validation

The comparative regression estimates for developed and developing states are presented in **Table 5**. The results reveal notable heterogeneity in the determinants of bioeconomy-driven innovation and structural transformation across different stages of regional development. Gross Value Added (*GVA*) remains positive and highly significant in both subsamples, although its effect is stronger in developed states, indicating that economic scale and productive capacity play a more pronounced role in supporting innovation-intensive bioeconomic activities in advanced regions. Mechanization (*Mac*) is highly significant only in developing states, suggesting that technological modernization constitutes a critical driver of productivity enhancement and structural transformation in less-developed

regions. In contrast, fertilizer use (*Fer*) exhibits a positive and significant effect exclusively in developed states, reflecting the greater efficiency with which complementary agricultural inputs are utilized in mature production systems. Agricultural openness and Gross Fixed Capital Formation (*GFCF*) are significant only in developed states, highlighting the importance of market integration and capital accumulation in sustaining advanced bioeconomy transitions. Research density (*RD*) retains a negative and statistically significant coefficient in both subsamples, although the magnitude of the effect is larger in developed states. Population growth (*PG*) positively influences bioeconomy outcomes across both groups, while Gross Enrolment Ratio (*GER*), inflation (*Inf*), and institutional quality (*IQ*) do not demonstrate statistically significant effects. The relatively high explanatory power of the models, reflected in R<sup>2</sup> values of 0.626 for developed states and 0.563 for developing states, confirms the robustness of the estimated relationships and provides further evidence that the drivers of bioeconomy development differ according to regional development status (see **Table 5**).

**Table 5.** Results of Developed & Developing States Sample Analysis.

Variables	Developed States (SE)	Developing States (SE)
<i>GVA</i>	0.2473*** (0.0267)	0.1629*** (0.0391)
<i>Mac</i>	—	0.2173*** (0.0425)
<i>Fer</i>	0.0244*** (0.0123)	—
<i>GER</i>	-0.0508 (0.0388)	0.0003 (0.0363)
<i>AG openness</i>	0.1080*** (0.0154)	0.0130 (0.0258)
<i>GFCF</i>	0.0886*** (0.0168)	0.0297 (0.0262)
<i>RD</i>	-0.0890*** (0.0340)	-0.0541** (0.0167)
<i>Inf</i>	0.0017 (0.0008)	0.0030 (0.0023)
<i>PG</i>	0.0114*** (0.0029)	0.0180** (0.0103)
<i>IQ</i>	0.0123 (0.0244)	0.0197 (0.0152)
Intercept	7.7695*** (0.3649)	6.6068*** (0.3849)
Observations	264	264
States	12	12
R <sup>2</sup>	0.6260	0.5632
F-statistic	181.97***	213.11***

Note: Standard errors in parentheses; \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ .

Source: Author's computation.

#### 5.5.1. Agricultural Productivity Hypothesis

The coefficient of agricultural productivity (*GVA*) remains positive and highly significant across both de-

veloped and developing country samples. This provides strong and consistent support for the central hypothesis that agricultural productivity contributes directly to economic growth. However, the magnitude is higher in developed economies (0.2473) compared to developing ones (0.1629), suggesting that productivity gains in advanced systems are more efficiently translated into aggregate output, likely due to better market integration and institutional support.

### 5.5.2. Technological Intensification and Structural Transformation

The results reveal a clear divergence in the role of technological inputs. In developed economies, fertilizer use has a positive and significant impact on growth, whereas in developing economies, agricultural machinery emerges as the dominant driver. This pattern strongly supports the stage-specific technology hypothesis: developing economies benefit more from mechanization that facilitates the transition from labor-intensive to capital-intensive agriculture, while developed economies optimize output through input intensification.

The presence of multicollinearity between *Mac* and *Fer* further reinforces the complementarity hypothesis, indicating that these inputs are jointly utilized in advanced production systems, even though they are estimated separately.

### 5.5.3. Openness and External Integration

Trade openness (AG openness) exhibits a positive and statistically significant effect only in developed economies, supporting the hypothesis that the gains from trade are contingent on structural readiness and competitiveness. In developing economies, the lack of significance suggests that trade integration may be constrained by unfavourable trade balances, tariff barriers, and limited export diversification. This finding refines the openness-led growth hypothesis by highlighting its conditional nature.

### 5.5.4. Capital Formation and Sectoral Reallocation

Gross Fixed Capital Formation (*GFCF*) has a positive and significant effect in developed economies but remains insignificant in developing ones. This supports the structural transformation hypothesis, where investment in advanced economies enhances productive capacity and

efficiency, whereas in developing contexts, capital allocation may be inefficient or insufficiently targeted toward high-productivity sectors.

### 5.5.5. Human Capital and Labor Market Dynamics

The negative coefficient of *GER* in developed economies, although not statistically significant, aligns with the hypothesis of diminishing marginal returns to education and delayed labor market participation. In developing economies, the absence of significance suggests that the growth effects of education are conditional on labour market absorption and skill alignment.

### 5.5.6. Effects

Research and Development (*RD*) exhibits a negative and significant impact in both sub-samples, confirming the intertemporal innovation hypothesis. The stronger negative effect in developed economies reflects higher R&D intensity and associated short-run adjustment costs, while the relatively smaller effect in developing economies may indicate lower levels of R&D investment.

### 5.5.7. Demographic and Macroeconomic Factors

Population growth (*PG*) shows a positive and significant effect across both samples, providing robust support for the demographic dividend hypothesis. This indicates that an expanding working-age population contributes positively to growth when supported by adequate economic opportunities.

Inflation and institutional quality remain statistically insignificant in both groups, suggesting that their effects may be indirect or mediated through other structural variables.

## 5.6. Robustness Analysis

To assess the robustness of the baseline fixed-effects estimates, the analysis was re-estimated using the Feasible Generalized Least Squares (FGLS) method, which accounts for potential heteroskedasticity and serial correlation in panel data. The results, presented in **Table 6**, largely confirm the direction and statistical significance of the principal relationships identified in the baseline models. Gross Value Added (*GVA*), mechanization (*Mac*),

fertilizer use (*Fer*), agricultural openness, and population growth (*PG*) continue to exhibit positive and statistically significant effects, indicating that the core determinants of bioeconomy development remain stable across alternative estimation techniques. In Model 2, the interaction term between mechanization and fertilizer use ( $Mac \times Fer$ ) is also positive and significant, providing additional support for the complementary role of technological modernization and input intensification in enhancing productivity and innovation outcomes. Institutional quality (*IQ*), which was statistically insignificant in the baseline fixed-effects specification, emerges as a strongly positive and significant determinant under FGLS estimation, suggesting that institutional factors may exert a more substantial influence when cross-sectional heterogeneity and error-structure distortions are addressed. Conversely, Gross Enrolment Ratio (*GER*) displays a negative association, while Gross Fixed Capital Formation (*GFCF*), research density (*RD*), and inflation (*Inf*) remain statistically insignificant in most specifications. The relatively high explanatory power of both models, with  $R^2$  values exceeding 0.58 and highly significant F-statistics, demonstrates the stability and reliability of the estimated relationships. Overall, the FGLS results corroborate the main findings of the study and provide strong evidence that the conclusions are not sensitive

to the choice of estimation technique (see **Table 6**).

**Table 6.** Robustness Test using FGLS Estimation.

Variables	Model 1 (SE)	Model 2 (SE)
<i>GVA</i>	0.0591*** (0.0075)	0.0597*** (0.0074)
<i>Mac</i>	0.1855*** (0.0132)	0.2268*** (0.0218)
<i>Fer</i>	0.1271*** (0.0085)	0.0671** (0.0280)
$Mac \times Fer$	—	0.0050** (0.0023)
<i>GER</i>	-0.1480*** (0.0423)	-0.1494 (0.0425)
<i>AG openness</i>	0.2212*** (0.0193)	0.2312*** (0.0198)
<i>GFCF</i>	0.0175 (0.0222)	-0.0211 (0.0277)
<i>RD</i>	-0.0211 (0.0277)	-0.0043 (0.0284)
<i>Inf</i>	0.0030 (0.0025)	0.0029 (0.0025)
<i>PG</i>	0.0151** (0.0078)	0.0179** (0.0079)
<i>IQ</i>	0.2666*** (0.0255)	0.2491*** (0.0263)
Intercept	9.1139*** (0.1860)	9.4843*** (0.0263)
Observations	462	462
$R^2$	0.5837	0.5946
F-statistic	2,025.00***	2,053.23***

Note: Standard errors in parentheses; \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ .  
Source: Author's computation.

**Robustness and Hypothesis Confirmation**

The FGLS estimates reported in **Table 7** confirm the robustness of the baseline results. Agricultural productivity, technological inputs, and trade openness remain positive and statistically significant, thereby reinforcing the core hypotheses. The interaction term between machinery and fertilizer retains its positive significance, providing further support for the complementarity hypothesis.

**Table 7.** Policy-Relevant Implications of Key Empirical Findings.

Empirical Finding	Underlying Mechanism	Policy Implication	Recommended Intervention
Positive impact of agricultural productivity	Higher output per worker increases GDP	Prioritize productivity enhancement	Investment in irrigation, seeds, extension services
Complementarity of machinery and fertilizer	Combined use increases efficiency	Promote integrated input strategies	Input packages, subsidy rationalization
Positive role of trade openness	Specialization and efficiency gains	Enhance market integration	Trade facilitation, export promotion
Negative short-run impact of R&D	Time lag in innovation returns	Balance short- and long-term investments	Applied research, commercialization mechanisms
Mixed impact of human capital	Skill mismatch and delayed entry	Align education with labour market needs	Vocational training, industry linkages
Positive effect of population growth	Expansion of labour force and demand	Harness demographic dividend	Skill development, job creation policies
Role of institutional quality	Governance affects investment and efficiency	Strengthen institutions	Regulatory reforms, anti-corruption measures
Insignificance of <i>GFCF</i> in some contexts	Inefficient capital allocation	Improve investment efficiency	Targeted infrastructure and sectoral investments

Source: Synthesized from empirical results.

Human capital continues to exhibit a negative effect, confirming the short-run adjustment cost hypothesis, while population growth remains a positive driver of economic expansion. Notably, institutional quality becomes positive and highly significant under FGLS estimation, suggesting that its effect is sensitive to estimation techniques and may have been underestimated in the baseline model.

## 5.7. Synthesis

The Developed & Developing States and robustness analyses collectively provide strong empirical validation of the study's theoretical framework. The findings highlight:

- (i) Structural heterogeneity in the determinants of growth across income groups;
- (ii) Stage-specific roles of agricultural technology;
- (iii) Conditional effects of trade openness and human capital; and (iv) Intertemporal dynamics of innovation and institutional quality.

These results underscore the importance of context-specific policy design, where the effectiveness of agricultural modernization, trade integration, and human capital investment depends critically on the stage of economic development and institutional capacity.

## 6. Discussion: Positioning Results within the Existing Literature

The empirical findings of this study contribute to, and in several respects, refine the existing literature on the agriculture–growth nexus by providing a state-level, structurally differentiated perspective within the Indian context.

### 6.1. Agricultural Productivity as a Core Driver of Growth

The strong and robust positive effect of agricultural productivity (*GVA* per worker) on economic growth corroborates earlier cross-country evidence by Tiffin and Irz<sup>[1]</sup> and Gollin<sup>[2]</sup>, which identify agriculture as a key driver of growth in developing economies. However, the present study extends this insight by demonstrating that agricultural productivity remains significant even in relatively developed states, albeit through more efficient transmission

mechanisms.

This finding nuances the conventional structural transformation narrative, which often assumes a declining role of agriculture in advanced stages. Instead, the results suggest that agriculture continues to contribute to growth both directly (in developing states) and indirectly through value chains and linkages (in developed states), thereby strongly supporting Hypothesis H5.

### 6.2. Technological Intensification and Complementarity

The evidence on technological inputs is broadly consistent with the literature emphasizing the role of mechanization and input intensification in driving agricultural growth<sup>[3,31]</sup>. However, the study makes two important contributions.

First, it demonstrates stage-specific technological effects: mechanization is more growth-enhancing in developing states, while fertilizer intensity plays a stronger role in developed states. This aligns with the theoretical expectation that economies transition from labour-intensive to input-optimized systems as they develop.

Second, the positive and significant interaction between machinery and fertilizer provides strong empirical support for the complementarity hypothesis, which is often implicitly assumed but rarely tested explicitly in the literature. This finding reinforces recent arguments in agricultural economics that integrated input use yields higher productivity gains than isolated technological adoption, thereby advancing Hypothesis H3 in a more nuanced manner.

### 6.3. Trade Openness and Conditional Growth Effects

The positive impact of agricultural trade openness is consistent with a large body of empirical work<sup>[11,42]</sup> supporting the openness-led growth hypothesis. However, the study refines this conclusion by showing that the growth effects of trade openness are conditional on structural readiness.

Specifically, the significant impact in developed states, contrasted with its weaker effect in developing states, supports the argument advanced by Wise<sup>[44]</sup> and

Nam and Ryu <sup>[45]</sup> that trade benefits depend on competitiveness, diversification, and institutional capacity. This finding highlights that trade openness alone is insufficient; its effectiveness depends on complementary domestic conditions, thereby reinforcing Hypothesis H4.

#### 6.4. Human Capital and Innovation: Intertemporal Dynamics

The negative or insignificant short-run effects of human capital (*GER*) and R&D expenditure appear, at first glance, to contradict the predictions of endogenous growth theory <sup>[17,18]</sup>. However, these findings are consistent with a growing body of empirical literature highlighting lagged and nonlinear effects of human capital and innovation.

Studies such as Tamayo et al. and Margolies et al. <sup>[46,48]</sup> suggest that education and innovation investments often entail short-run adjustment costs, including delayed labour market entry, skill mismatches, and inefficiencies in knowledge utilization. The present findings align closely with this perspective, indicating that the growth effects of human capital and R&D are intertemporal rather than immediate.

This result is particularly relevant for India, where rapid expansion in higher education has not always been matched by commensurate labour market absorption, thereby providing empirical support for Hypothesis H4.

#### 6.5. Structural Transformation and Capital Allocation

The mixed or insignificant effects of agricultural *GFCF* and institutional quality in baseline models, alongside their significance under alternative specifications, suggest that structural transformation processes are complex and mediated through multiple channels.

The negative or weak role of agricultural investment in some specifications supports the structural transformation literature, which posits that economic development involves a gradual reallocation of resources from agriculture to higher-productivity sectors. At the same time, the improved significance of institutional quality under FGLS estimation underscores the importance of governance in shaping long-run growth, consistent with recent institutional economics literature.

#### 6.6. Demographic and Macroeconomic Context

The positive impact of population growth across specifications lends support to the demographic dividend hypothesis, consistent with empirical findings for emerging economies. However, the relatively modest magnitude of this effect suggests that demographic advantages are conditional on employment generation and productive absorption of labour.

Similarly, the mixed effects of inflation align with the broader macroeconomic literature, indicating that moderate inflation may be growth-enhancing, while excessive volatility can be detrimental.

#### 6.7. Contribution to the Literature

Taken together, the findings of this study contribute to the literature in three important ways:

- Bridging micro and macro perspectives: By linking agricultural productivity, technological inputs, and macroeconomic outcomes, the study provides an integrated framework for understanding growth dynamics.
- Highlighting structural heterogeneity: The clear differentiation between developed and developing states advances the literature beyond aggregate national analyses and directly addresses the role of regional disparities.
- Advancing the complementarity and mediation hypotheses: The empirical validation of technological complementarity and structural mediation provides new insights into how agricultural dynamics translate into economic growth.

#### 6.8. Overall Interpretation

In contrast to earlier studies that treat agriculture either as a declining sector or a uniform growth driver, the present analysis demonstrates that its role is conditional, multidimensional, and structurally mediated. Agricultural dynamics remain central to economic growth in India, but their impact varies systematically with the level of development, technological integration, and institutional capacity.

The discussion confirms that the study's findings are

broadly consistent with, yet significantly extend, the existing literature. By situating empirical results within established theoretical and empirical frameworks, the analysis provides a more nuanced and policy-relevant understanding of the agriculture–growth nexus.

## 7. Policy Implications and Implementation Strategy

The empirical findings yield a coherent set of policy-relevant insights that are strongly aligned with the hypotheses on agricultural productivity, technological intensification, structural transformation, and institutional quality. The heterogeneity observed across developed and developing economies underscores the need for context-specific and stage-contingent policy frameworks.

### 7.1. Enhancing Agricultural Productivity

Given the robust and statistically significant impact of agricultural productivity (*GVA*) on economic growth across all model specifications, policies should prioritize productivity-enhancing interventions. These include investments in irrigation infrastructure, climate-resilient seeds, extension services, and precision agriculture. In developing economies, where marginal gains are higher, targeted support for smallholders can generate substantial aggregate growth effects through both direct output expansion and indirect demand spillovers.

### 7.2. Technological Intensification and Complementarity

The complementarity between farm machinery and fertilizer use implies that isolated interventions may be suboptimal. Policy design should therefore adopt a systems approach, promoting integrated input packages that combine mechanization, soil health management, and digital advisory services. Subsidy structures should be rationalized to avoid excessive fertilizer use while incentivizing balanced input adoption.

### 7.3. Trade Openness and Market Integration

The positive and significant impact of agricultural

trade openness—particularly in developed economies—suggests that market integration policies are critical for growth. Developing economies should focus on reducing non-tariff barriers, improving logistics and cold-chain infrastructure, and enhancing export competitiveness. However, given the insignificance of openness in some developing contexts, complementary policies are required to strengthen domestic production capacity before full liberalization.

### 7.4. Human Capital and Skill Alignment

The negative or insignificant short-run impact of tertiary education highlights the importance of aligning education systems with labour market needs. Policies should emphasize vocational training, STEM education, and industry-academia linkages to ensure that human capital contributes effectively to productivity and innovation.

### 7.5. Innovation and R&D Policy

The negative short-run impact of R&D expenditure underscores the need for long-term innovation strategies with appropriate sequencing. Governments should adopt a balanced portfolio approach, combining basic research with applied and adaptive innovation that yields quicker returns. Strengthening institutional mechanisms for research commercialization is critical to reduce time lags.

### 7.6. Demographic Dividend and Labor Market Policies

The positive effect of population growth indicates the potential for a demographic dividend. However, this requires active labour market policies, including skill development, employment generation, and support for labour-intensive sectors. Without such measures, demographic expansion may not translate into growth.

### 7.7. Institutional Strengthening

Although institutional quality shows mixed significance across models, its robustness in FGLS estimation highlights its fundamental role. Policies should focus on governance reforms, including property rights protection, regulatory efficiency, and anti-corruption measures, to cre-

ate an enabling environment for investment and innovation.

## 8. Implementation Strategy

To operationalize these policy implications, a multi-tiered implementation strategy is required:

1. **Short-Term (1–3 Years):**
  - o Rationalize input subsidies and promote balanced fertilizer use.
  - o Expand access to farm machinery through credit and leasing models.
  - o Strengthen extension services and digital advisory platforms.
2. **Medium-Term (3–7 Years):**
  - o Invest in rural infrastructure (irrigation, storage, logistics).
  - o Develop vocational and technical education aligned with sectoral needs.
  - o Enhance trade facilitation and export competitiveness.
3. **Long-Term (7–15 Years):**
  - o Build innovation ecosystems linking research institutions and industry.
  - o Undertake comprehensive institutional reforms.
  - o Promote structural transformation through diversification into high-productivity sectors.

A sequencing approach is essential, particularly for developing economies, where premature liberalization or excessive focus on long-term investments without addressing immediate constraints may yield suboptimal outcomes.

## 9. Policy Recommendations

Based on the empirical evidence, the following targeted recommendations are proposed:

- Adopt integrated agricultural modernization policies combining mechanization, input optimization, and digital technologies.
- Promote inclusive growth strategies by focusing on smallholder productivity and rural income enhancement.

- Strengthen trade competitiveness through infrastructure, quality standards, and value-chain integration.
- Reform education systems to reduce skill mismatches and enhance employability.
- Design R&D policies with phased returns, ensuring a balance between short-term productivity gains and long-term innovation.
- Leverage demographic trends through proactive employment and skill development policies.
- Enhance institutional capacity to improve policy implementation and economic governance.

## 10. Limitations of the Study

Despite its comprehensive analytical framework, the study has certain limitations:

1. **Data Constraints:** The analysis relies on aggregate country-level data, which may mask intra-country heterogeneity, particularly in large and diverse economies.
2. **Measurement Issues:** Proxies such as Gross Enrolment Ratio and institutional quality indices may not fully capture qualitative dimensions such as skill relevance or governance effectiveness.
3. **Temporal Limitations:** The study primarily captures short- to medium-term relationships, limiting the ability to fully assess long-run dynamics, especially for variables such as R&D.
4. **Endogeneity Concerns:** Although fixed effects and robustness checks are employed, potential endogeneity between growth and explanatory variables (e.g., trade openness, investment) cannot be entirely ruled out.
5. **Model Specification:** The linear framework may not adequately capture nonlinearities or threshold effects inherent in structural transformation processes.

Future research should address these limitations by employing micro-level data, dynamic panel techniques, and nonlinear modelling approaches.

## 11. Conclusions

This study provides a comprehensive empirical assessment of the determinants of economic growth with a

particular focus on agricultural productivity, technological inputs, and structural transformation across developed and developing economies. The findings consistently demonstrate that agricultural productivity remains a fundamental driver of growth, even in advanced economies, while its role is particularly pronounced in developing contexts.

Technological intensification—especially when inputs are used complementarily—emerges as a critical mechanism for enhancing productivity. Trade openness and demographic factors further reinforce growth, although their effects are conditional on structural and institutional contexts. Human capital and R&D exhibit nuanced dynamics, highlighting the importance of temporal horizons and policy alignment.

The study contributes to the literature by integrating sectoral, technological, and institutional perspectives into a unified analytical framework and by providing policy-relevant insights tailored to different stages of development. The results underscore the need for holistic and context-sensitive policy design to achieve sustainable and inclusive economic growth.

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## Institutional Review Board Statement

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## Informed Consent Statement

Not applicable.

## Data Availability Statement

Data supporting the findings of this study are sourced from various Government of India publications. Data sharing does not apply to this article as no new data were created or analysed in this study.

## Conflicts of Interest

I declare no conflict of interest regarding the publi-

cation of this article.

## AI Use Statement

AI was solely used for language editing.

## Appendix A. List of Developed & Developing States

Developed States: 1. Punjab; 2. Haryana; 3. Uttar Pradesh; 4. Maharashtra; 5. Gujarat; 6. Tamil Nadu; 7. Andhra Pradesh; 8. Rajasthan; 9. Karnataka; 10 Kerala; 11. West Bengal.

Developing States: 1. Bihar; 2. Odisha; 3. Jharkhand; 4. Madhya Pradesh; 5. Chhattisgarh; 6. Assam; 7. Jammu & Kashmir; 8. Himachal Pradesh; 9. Uttarakhand; 10. Tripura; 11. Meghalaya.

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