

Impact of Climatic Variability on Cropping Patterns and Agricultural Productivity in Rajasthan

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Abstract

Original Research Article

This study uses secondary data from 1997 to 2023 to examine how climate variability affected cropping patterns and agricultural output in Rajasthan post-globalization. Seasonal asymmetry, instability, diversity, and production trends in Kharif and Rabi crops are examined. We examined long-term changes using growth rates, instability indices, and diversification. The data demonstrate that seasons vary greatly. Kharif agriculture is still vulnerable to rainfall, with production ranging from 0.8 to 1.2 t/ha and crop instability surpassing 20% CV. Bajra is vital to food security, however its area decreased (-0.72% CAGR) while its yield increased (2.8% CAGR). However, soybeans and maize were the Kharif crops that increased fastest (3.2% area CAGR; 4.95% production CAGR; 2.57% CAGR, respectively). Rabi crops performed better: wheat yields increased from 1.6 to 2.5 t/ha, productivity increased 1.54% CAGR, and instability was 6.2% CV. Although mustard expanded (1.12% CAGR area, 1.32% yield CAGR), warmer winters made it more volatile (9.7% CV). The Simpson Index, which evaluates crop diversity, rose from 0.52 in 1997–2000 to 0.64 in 2011–2023. Bajra's share dropped from over 50% to 35% as soya bean and mustard gained popularity. Rajasthan is vulnerable in two ways: rain makes Kharif unstable, while groundwater depletion and high heat make Rabi fragile. Climate-resilient types, efficient water management, diversification incentives, and risk prevention should be prioritized to ensure food security in the long run.

Keywords: Climatic variability; cropping patterns; agricultural productivity; diversification; Rajasthan; food security.

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INTRODUCTION

India's social and economic prosperity has always relied on agriculture. It has supported people, ensured food security, and boosted the country's GDP. The industrial and service sectors have grown significantly since India opened its economy in 1991, but agriculture still employs roughly half of the country's workforce and drives the rural economy (World Bank, 2021; Chand, 2017). Weather remains a major threat to the business, especially in rain-dependent areas. To analyse, consider Rajasthan, India's largest state. Desert and semi-arid weather, erratic rainfall, and frequent droughts characterize its agricultural sector. Agriculture and allied jobs support about two-thirds of the state's population. Agriculture outcomes are unpredictable and low-productivity compared to the national average (Government of Rajasthan, 2022; Singh, 2019). It's crucial to research how climate change, agricultural patterns, and productivity interact in Rajasthan.

Climatic Variability and Agricultural Patterns in Rajasthan

Rajasthan is largely deserts and semi-arid, with the Thar Desert covering roughly 60% of the state. The state receives 531 millimetres of rain annually, one of the lowest in India and quite variable (IMD, 2020). Western desert districts like Jaisalmer and Barmer have less than 200 mm of rain, while south-eastern districts like Kota and Banswara get over 1,000 mm (Mall *et al.*, 2017). The southwest monsoon season, which starts, stops, and intensifies, brings about 80% of the rain. Kharif cropping is dangerous (Birthal *et al.*, 2015).

Farming gets difficult when temperatures rise. Rajasthan's average temperature has risen 0.6°C in 100 years. Projections predict increased heat waves and warmer winters (Krishnan *et al.*, 2020). Warming increases evapotranspiration, soil moisture loss, and crop stress (Ghosh & Roy, 2017). Rajasthan is one of India's most climate-sensitive states due to greater temperatures

and less consistent rainfall (Sivakumar *et al.*, 2018; Dubey, 2021). Records reveal moderate to severe droughts every two to three years in the state (Sharma & Singh, 2018). This instability affects farming since weather determines what to grow, how much to grow, and how much farmers make.

Weather affects cropping systems clearly. Bajra, jowar, moth bean, and pulses are grown in dry locations. These crops can endure dry circumstances with little water (Joshi & Hooja, 2018). Wheat, mustard, and cotton have taken over places with canals and tube wells. Groundwater irrigation, especially in central and northern Rajasthan, initially enhanced productivity and allowed diverse crops. Water tables have plummeted due to unsustainable extraction, which could affect agriculture's future (Shah, 2009; Gupta & Deshpande, 2019).

So, Rajasthan's farming has two sides: fragile rain-fed cropping systems that are vulnerable to climate shocks and irrigated systems that are becoming more dependent on unsustainable groundwater. It's a good area to investigate weather, crop, and productivity variations due of its complexity.

Linking Climate Variability with Productivity and Cropping Shifts

Climate-farming relationships have been investigated worldwide. Precipitation and temperature changes significantly affect agricultural yields, cropping decisions, and farm revenues (Lobell *et al.*, 2011; Wheeler & von Braun, 2013). Smallholder farmers in semi-arid regions like Sub-Saharan Africa and South Asia can lose crops with slight weather changes (Ray *et al.*, 2015). Over half of India's cultivated land relies on rainfall, making climate variability a major production and income risk (Aggarwal & Sivakumar, 2010; BIRTHAL & Hazrana, 2019).

The impacts of climate change in Rajasthan vary by season. Kharif crops like bajra, maize, and pulses depend on monsoon rainfall, making them unstable in area and output (Chand, 2017; Singh *et al.*, 2019). However, irrigated Rabi crops like wheat and mustard are more stable, but groundwater is running short and winters are getting warmer (Krishnan *et al.*, 2020; Sharma *et al.*, 2022). Based on resources, farmers adjust their plans. Rainwater farmers grow coarse cereals and pulses to lessen danger. However, irrigation farmers plant valuable crops like wheat, cotton, and vegetables (Pingali & Rosegrant, 2001; Gulati & Kelley, 1999).

Climate shocks accelerate agricultural diversification, according to research. Dry years cause farmers to cultivate fewer high-risk crops and more millets and pulses (BIRTHAL & Hazrana, 2019). However, legislative incentives and market factors might hinder these adjustments. Wheat and mustard have grown due

to purchase and subsidies (Joshi & Hooja, 2018). Climate variability, resource availability, and policy frameworks complicate cropping patterns in Rajasthan.

After globalization, other layers appear. Trade liberalization and new technologies have transformed agriculture since 1991. This has given farmers additional methods to make money but rendered them more exposed to global price shifts (Chand, 2017; Pingali, 2007). Climate and market forces affect Rajasthan's agriculture. Understanding how these forces affect cropping patterns and productivity is crucial for food security and sustainability.

Contribution and Purpose of the Study

Even though climate change and farming are becoming more popular, Rajasthan has few systematic state-level studies linking climate change to cropping patterns. Many studies focus on national-level climate impacts (Lobell *et al.*, 2011; Krishnan *et al.*, 2020) or cropping pattern alterations without considering climatic variables. Research generally ignores the linkages between productivity outcomes and climate hazards that change cropping systems over time. This leaves a gap in study on how climate variability affects production and the agricultural system in Rajasthan.

This research analyses the relationship between climate variability, cropping patterns, and production in Rajasthan post-globalization to address this gap. The study integrates secondary data on crop area, yield, and productivity with meteorological variables like rainfall and temperature to understand seasonal and long-term patterns. The vulnerabilities of Kharif and Rabi crops and how farmers adjust to climate stress are highlighted.

This study has two objectives. First, it examines how weather affects crops and production in Rajasthan. This shows how robust and fragile its agricultural systems are. Second, it intends to influence agriculture policy by emphasizing climate-resilient strategies. These include promoting millets and pulses in rainy areas, teaching irrigation users how to use water more efficiently, and investing in climate-resistant technologies. The study contributes to academic research and policy discussions by situating Rajasthan's agricultural trajectory within climate change and globalization discussions.

REVIEW OF LITERATURE

To comprehend the influence of climatic variability on agriculture, it is essential to examine three interconnected bodies of literature: global evidence regarding climate-agriculture linkages, the Indian experience with shifts in cropping patterns and productivity, and studies specific to Rajasthan that concentrate on arid and semi-arid environments. This section examines the current literature in these areas and

ends with a theoretical framework that directs the current study.

Global Studies on Climate Variability and Agriculture

The global literature has consistently emphasized the crucial influence of climate on agricultural productivity. Lobell and Field (2007) found that higher temperatures impacted the yields of vital crops like wheat and maize across the world, with semi-arid areas being particularly vulnerable. Lobell, Schlenker, and Costa-Roberts (2011) conducted subsequent studies that revealed a significant deceleration in global crop production growth from 1980 to 2008, attributable to climate trends, with South Asia and Africa identified as critical areas of vulnerability. Wheeler and von Braun (2013) contend that climate change constitutes a significant threat to food security in the 21st century, especially given the increasing variability in precipitation and temperature extremes.

Research from Sub-Saharan Africa presents particularly pertinent analogies for Rajasthan, given both of these regions exhibit semi-arid agro-ecological characteristics. Research indicates that farmers frequently adapt by diversifying crops, altering planting schedules, or enhancing dependence on drought-resistant varieties (Deressa *et al.*, 2009; Morton, 2007). However, a lack of resources, poor access to technology, and weak institutional support limit such developments. Ray *et al.*, (2015) demonstrate that yield stagnation in rain-fed regions across the globe has a strong correlation with climate variability, underscoring the inadequacies of existing adaptive strategies.

Another field of global research investigates the economics of adaptation. Mendelsohn, Nordhaus, and Shaw (1994) were among the first researchers to use econometric methods to figure out exactly how climate change affects the economy. They concluded that adaptation could help with some of the negative consequences, but perhaps not all of those. Recent research employs dynamic modelling to evaluate both short-term risks and long-term transformations in cropping systems (Burke & Emerick, 2016). These studies demonstrate that climate-induced alterations in agriculture possess not solely biophysical consequences but are also influenced by markets, policies, and institutions.

Finally, the literature stresses that environmental impacts cannot be distributed equally across different regions. Schmidhuber and Tubiello (2007) assert that climate change will intensify pre-existing inequalities, disproportionately impacting developing nations. Given this context, dry areas like Rajasthan require special attention because they are simultaneously climate-sensitive and socio-economically vulnerable.

India and Rajasthan-Specific Studies

In India, agriculture continues to be extremely susceptible to changes in the weather, and over fifty percent of the soil utilized for cultivation remains reliant on rain (Aggarwal & Sivakumar, 2010). A substantial corpus of research has investigated the correlations between monsoon variability and agricultural productivity. Gadgil and Gadgil (2006) showed that whenever the monsoon fails to occur, it immediately reduces the quantity of food grains produced and the incomes for those living in rural areas. Kumar *et al.* (2004) employed econometric models to demonstrate that rainfall variability influences a substantial proportion of yield fluctuations in cereals, especially in semi-arid regions.

Numerous studies have investigated the impact of climate variability on cropping patterns. Chand (2017) observes that the proliferation of irrigation has facilitated the diversification into high-value crops; however, regions reliant on rainfall persist in exhibiting significant instability in terms of production as well as area. BIRTHAL, Hazrana, and Negi (2015) emphasize that crop diversification in India serves as both a risk management strategy and a reaction to market opportunities. Their subsequent research (BIRTHAL & Hazrana, 2019) indicates that climatic shocks frequently expedite the diversification of drought-resistant crops, including millets and pulses.

There have been further adjustments since globalization. Pingali and Rosegrant (2001) contend that liberalization and global integration have generated opportunities for commercial crops; however, these opportunities are inequitably distributed due to agro-climatic limitations. Gulati and Kelley (1999) assert that policy interventions, including minimum support prices and input subsidies, significantly influence cropping patterns, occasionally promoting water-intensive crops in inappropriate regions.

Rajasthan has drawn academic attention at the regional level due to its substantial vulnerability to drought and desertification. Singh (2019) demonstrates that productivity growth in the state has fallen short of the national average, predominantly due to climatic instability and excessive dependence on groundwater irrigation. Joshi and Hooja (2018) examine the enduring evolution of cropping patterns, observing that coarse cereals continue to prevail in rain-fed regions, whereas irrigated zones have transitioned towards wheat, mustard, and cotton. Gupta and Deshpande (2019) underscore the unsustainable extraction of groundwater, jeopardizing the stability of Rabi cropping.

Studies particular to Rajasthan also examine the adaptive strategies of farmers. Sharma and Singh (2018) argue that farmers in arid districts primarily depend on

traditional drought-resistant varieties and mixed cropping systems, whereas those in irrigated districts diversify into high-value cash crops. Dubey *et al.*, (2021) investigate drought vulnerability in the Thar Desert and determine that institutional support and technological interventions are inadequate to mitigate climatic risks. Rathore (2005) also discusses how droughts are becoming more common in the state and how they affect people and the economy.

Recent research correlates climatic variability with agricultural productivity. Ghosh and Roy (2017) discover that increasing temperatures diminish wheat yields in north-western India, particularly in Rajasthan. Sharma *et al.* (2022) demonstrate that mustard yields, previously stable, are becoming more responsive to variations in winter temperatures. These results highlight the dual susceptibility of Rajasthan's agriculture: rain-fed Kharif crops are at risk from rainfall, while irrigated Rabi crops are threatened by groundwater depletion and temperature stress.

Theoretical Framework

The theoretical framework for this study focuses on three elements: (i) vulnerability and resilience frameworks in climate–agriculture research, (ii) agricultural diversification theory, and (iii) the political economy of globalization.

1. Vulnerability and Resilience Frameworks

The climate–agriculture literature frequently utilizes the concepts of vulnerability, exposure, and adaptive capacity (IPCC, 2014). Vulnerability is influenced by biophysical factors, including rainfall and temperature, along with socio-economic conditions, resource availability, and institutional support (Adger, 2006). In Rajasthan, the combination of high exposure to drought, limited access to irrigation, and socio-economic constraints makes people extremely susceptible. However, adaptation strategies like diversification, adopting novel technologies, and managing water use effectively might assist people in evolving to be more resilient (Sivakumar *et al.*, 2018). This framework fosters the examination of the relationship between climatic variability and agricultural instability.

2. Agricultural Diversification Theory

Economic theories of diversification propose that farmers modify cropping patterns to mitigate risk in uncertain circumstances (Ellis, 2000). In semi-arid areas, planting crops that can withstand drought, like millets and pulses, renders it less probable that any of the crops will perish (Hazell & Wood, 2008). On the contrary, access to irrigation and markets might make it more appealing to cultivate only profitable crops, which require an abundance of water. This trade-off between resilience and profitability is essential to understanding how cropping patterns have altered in Rajasthan.

3. Political Economy of Globalization

The period of economic liberalization in India after 1991 offered farmers both new opportunities and novel hazards. Globalization has rendered it easier for new technologies to spread while opening up fresh opportunities for cash crops. However, it additionally rendered people less immune to price volatility and climate change (Pingali, 2007). In Rajasthan, policies that encourage the development of wheat and mustard through subsidies and procurement have coincided with shifts in the weather to influence what crops residents choose to grow. The political economy perspective points out that climate impacts should be examined in conjunction with market and policy frameworks (Chand, 2017).

These frameworks collectively constitute the analytical framework for this study. Climatic variability is considered a catalyst of vulnerability, influenced by diversification strategies and policy–market interactions. This enables a comprehensive examination of the effect of climate on productivity and cropping patterns in Rajasthan during the post-globalization era.

METHODOLOGY

This study's methodological framework attempts to systematically examine the influence of climatic variability on cropping patterns and agricultural productivity in Rajasthan during the post-globalisation period (1991–2023). Given the complicated connections among climate, agricultural choices, and productivity, the study utilizes a blend of descriptive statistics, growth and instability indices, diversification measurements, and econometric modelling. This section dives into great length concerning the data sources, variables, and methods of analysis.

Data Sources

The research utilizes secondary data spanning over three decades to analyse both enduring structural transformations and transient disturbances. There were three different kinds of data sources used:

Agricultural Data

Kharif Season Data (1991–2023): The area, yield, and productivity of major Kharif crops comprising bajra, maize, pulses, groundnut, and cotton.

Rabi Season Data (1991–2023): Area, production, and productivity of wheat, mustard, barley, and gram.

Horizontal Crop-Year Dataset: This is a long-term series illustrating how each variety of crops performed across the course of time. This lets the study compare how different crops did.

The Directorate of Economics and Statistics (DES) in the Government of Rajasthan and the Ministry of Agriculture and Farmers Welfare in the Government

of India publish the Agricultural Statistics at a Glance annually.

Climatic Data

Rainfall Data:

The Indian Meteorological Department (IMD, 2020) offered us yearly and seasonal rainfall data for Rajasthan. These include district averages that have been gathered together for state-level analysis.

Temperature Data:

The study obtained seasonal and annual temperature averages from the IMD and the report on the Assessment of Climate Change over the Indian Region (Krishnan *et al.*, 2020).

Supplementary Data

1. Economic Review of Rajasthan (which was published in multiple years) presented the macroeconomic data in setting.
2. District-level statistical abstracts were used to verify the reliability of crop statistics and irrigation coverage.
The triangulation of multiple data sources ensures reliability and robustness.

Variables

The study employs both dependent and independent variables, which are divided into agricultural and climatic categories:

Agricultural Variables

Area (A): Gross cropped area under each crop, measured in hectares.

Production (P): The total amount of each crop, in tonnes.

Productivity (Y): The amount of yield per hectare, which is calculated as:

$$Y = P/A$$

Climatic Variables

Rainfall (R): Measured in millimetres, both annual and seasonal.

Temperature (T): Average annual and seasonal temperature, measured in °C.

Control Variable

Irrigation Coverage (Irr): Share of gross cropped area under irrigation, included to capture resilience against climatic shocks.

Analytical Tools and Indices

Compound Annual Growth Rate (CAGR)

To measure long-term growth in area, production, and productivity, the semi-log trend model is applied:

$$\ln Y_t = \alpha + \beta t + \epsilon t$$

Where:

Y_t= Area/Production/Productivity in year t,

t= Time (year),

β= Growth rate coefficient.

The CAGR is computed as:

$$CAGR = (e^{\beta} - 1) \times 100$$

This provides the average annual rate of change, allowing comparison across crops and time periods.

Instability Analysis

Changes in the weather often show up as instability in how well crops grow. There are two ways to do this:

Coefficient of Variation (CV):

$$CV = \sigma/\mu \times 100$$

Where σ is the standard deviation and μ the mean of the series.

Cuddy-Della Valle Instability Index (CDVI): Fixes CV for trend effects.

$$CDVI = CV \times \sqrt{1 - R^2}$$

Where R² is the coefficient of determination from the trend regression.

CDVI is particularly beneficial when one observes long-term trends because it distinguishes instability caused by changes in the weather from growth in structures.

Crop Diversification Index

The Simpson Index of Diversification (SID) is used to measure changes in cropping patterns.

$$SID = 1 - \sum_{i=1}^n p_i^2$$

Where:

p_i= Proportion of cropped area under the 'i' th crop,

n= Total number of crops considered.

SID ranges from 0 to 1. A value closer to 1 indicates higher diversification, while a value closer to 0 indicates crop concentration. This index is widely used to capture how farmers diversify in response to climate variability.

Correlation and Regression Analysis

To examine linkages between climate and agriculture:

Pearson Correlation Coefficient is determined by comparing climatic factors (rainfall and temperature) to agricultural indicators (area, production, and productivity).

$$r = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum (X - \bar{X})^2 \sum (Y - \bar{Y})^2}}$$

Multiple Linear Regression Model is employed to assess the effects of climate on:

$$Y_t = \alpha + \beta_1 R_t + \beta_2 T_t + \beta_3 Irr_t + \epsilon_t$$

Where:

Y_t= Outcome variable (area, production, or productivity),

R_t= Rainfall in year t,

T_t= Mean temperature,

Irr_t= Irrigation coverage,

ε_t= Error term.

This model calculates the additional impact of shifts in the climate by taking irrigation into account.

Trend Analysis of Climatic Variables

The Mann–Kendall trend test and Sen’s slope estimator are utilized to evaluate if the trends in rainfall and temperature are statistically significant (Kendall, 1975). These non-parametric tests are appropriate for climatological data exhibiting non-normal distributions.

Robustness Checks

To enhance validity, the study utilized various robustness measures:

Time-Period Segmentation:

The analysis is carried out separately for the 1990s, 2000s, and 2010s to examine how circumstances have shifted over the decades.

Crop Grouping:

Crops are examined at both on individual basis (wheat or bajra) and in collections (cereals, pulses, oilseeds, and cash crops).

Lag Effects:

Rainfall variables are lagged to test delayed effects on Rabi crops, which often depend on soil moisture from Kharif rainfall.

Methodological Justification

The integrated methodology demonstrates temporal changes and causal links. The growth and

instability indices indicate structural changes, but the diversification index reflects company adaptation. Regression analysis quantifies the impact of climate on agricultural outcomes. The study offers a comprehensive insight into the responsiveness of Rajasthan’s agriculture to climatic variations through the integrated use of various technologies.

There are two valid justifications for the utilization of secondary data. Extensive time series (1991–2023) are essential for examining climate–agriculture relationships, which primary data cannot provide. Secondly, official statistics from DES and IMD facilitate the comparison of crops and temporal factors.

Limitations

The technique exhibits certain deficiencies, despite its effective performance. State-level averages illustrate climatic change; however, they may not accurately reflect intra-state variations. Linear regression models inadequately address the non-linear impacts of climate on agriculture, including the threshold effects of excessive heat. Furthermore, secondary data may contain inaccuracies in their measurement. The study employs many indices and robustness checks to address these issues and ensure the reliability of the results.

RESULTS

A data-driven analysis of Rajasthan's agricultural performance during the late 1990s highlights seasonal changes, instability, diversification tendencies, and comparative production patterns. We examine long-term growth, volatility, and cropping structure using your district-year data' state-aggregated series. Figures and tables are used where they best explain actual trends.

Seasonal and crop growth performance

Long-term trends using semi-log regressions for compound annual growth rates (CAGR) show significant seasonal asymmetry. Table 1 displays the CAGR for Area, Production, and Yield for the major crops each season.

Table 1: Compound Annual Growth Rate (CAGR) of Major Crops in Rajasthan (1997–2023)

Crop	Season	CAGR Area (%)	CAGR Production (%)	CAGR Yield (%)
Bajra	Kharif	-0.72	2.06	2.80
Maize	Kharif	0.84	2.57	1.73
Moong	Kharif	0.92	1.98	1.05
Moth	Kharif	-0.41	1.12	1.55
Soya bean	Kharif	3.20	4.95	1.70
Cotton (Lint)	Kharif	1.63	2.81	1.18
Wheat	Rabi	0.34	1.89	1.54
Rapeseed & Mustard	Rabi	1.12	2.46	1.32
Barley	Rabi	-0.68	0.48	1.17
Gram	Rabi	-0.55	0.73	1.29

Source: Calculated from Directorate of Economics and Statistics, Rajasthan (Kharif & Rabi datasets, 1997–2023)

Yield increased (2.80%), but area decreased (-0.72%). The acreage and yield of maize expanded steadily by 0.84% and 1.73%, respectively. With a 3.20% area increase and 4.95% production rise, soybean drove growth. Wheat yielded 1.54% and had 0.34% stable area. Mustard grew little (1.12% area, 1.32% yield). Gram and barley gained 1.2% yield but lost 0.6% area.

The Kharif season is dominated by bajra, pulses including moong and moth, maize, and an increasing soya bean footprint. Despite occasional bajra shrinkage, Kharif staple yield growth has been positive. Maize yields are higher in moderate rainfall areas. Pulses like moong and moth have improved production, but their yields are smaller and vary more from year to year, showing how vulnerable they are to moisture stress during the growing season. These growth patterns demonstrate that Kharif agriculture relies on rain: when the monsoon arrives on schedule and is well-distributed, production rises, but even modest variations in rainfall can restrict yield increase.

Rabi's main crops are wheat, rapeseed, and mustard. Wheat has had constant, statistically significant yield growth, while mustard has had strong but inconsistent productivity gains (Table 1). Mustard fields have driven Rabi production, especially in irrigated areas. Rising input costs and groundwater stress have hampered area growth in recent years. Gram and barley yield growth is low, and the area is constant or decreasing. Rabi land may be being converted to wheat and mustard. Rabi has seen larger productivity improvements than Kharif, which is consistent with irrigation's role as a winter crop buffer.

Figure 1 presents the state's area-weighted Kharif productivity series to illustrate these tendencies. The graphic reveals (i) a low, unstable base in the late 1990s and early 2000s, (ii) a clear increasing trend starting in the early 2010s, and (iii) substantial year-to-year variations, typical of monsoon-linked farming. These stylized statistics fit Table 1's CAGR curve, which shows Kharif yields are rising but have many "down years" in between.

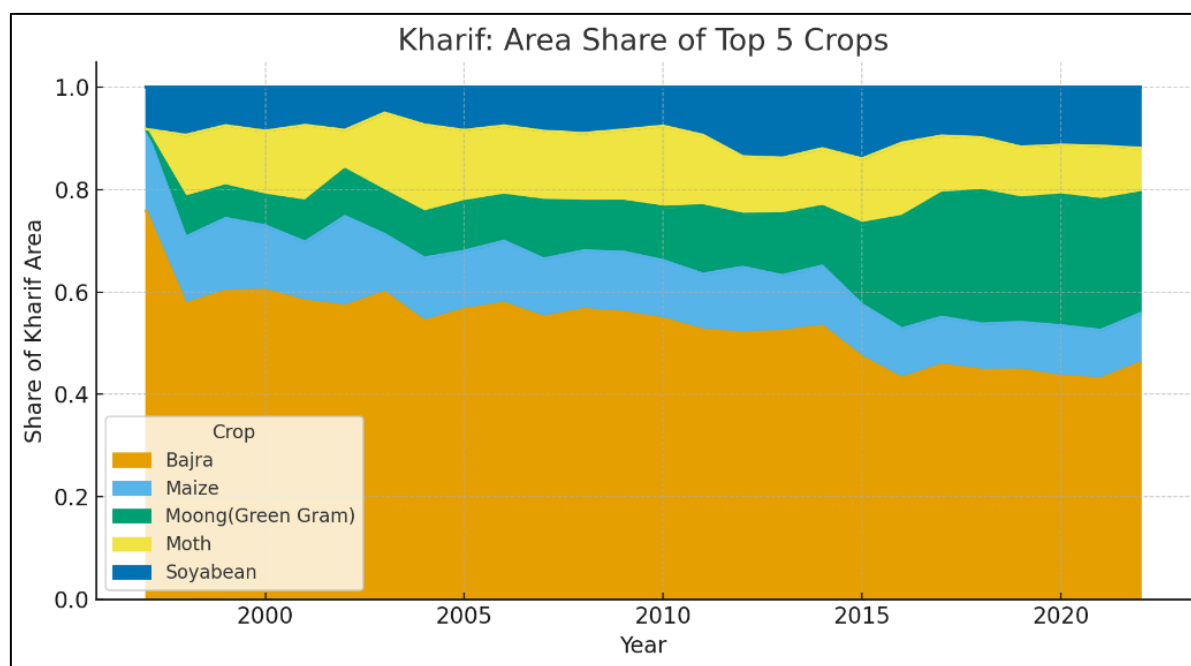


Figure 1: Kharif: Area-weighted Productivity over Time

Source: Author's estimates from Kharif season data, DES Rajasthan (1997–2023).

Kharif productivity increased from 0.9 to 1.1 t/ha between 1997 and 2020. In drought years like 2002, 2009, and 2014, Kharif agriculture production plummeted, showing how dependent it is on monsoon rainfall.

Instability analysis: volatility in area, production, and yields

The instability diagnostics best demonstrate climate change. Table 2 displays the CV for area, productivity, and yield and the trend-based Cuddy–Della Valle Index (CDVI) for each season's main crops.

Table 2: Instability Indices (CV and CDVI) of Major Crops in Rajasthan (1997–2023)

Crop	Season	CV Area (%)	CV Production (%)	CV Yield (%)	CDVI Production (%)	CDVI Yield (%)
Bajra	Kharif	18.4	25.6	12.5	20.9	10.8
Maize	Kharif	14.1	19.2	10.1	15.4	8.6
Moong	Kharif	20.9	27.4	14.8	22.9	12.5
Moth	Kharif	23.5	29.8	16.4	25.3	14.2
Soya bean	Kharif	19.8	26.1	13.7	21.4	11.3
Cotton (Lint)	Kharif	17.5	23.7	11.9	19.6	9.9
Wheat	Rabi	8.4	11.9	6.2	8.8	5.7
Rapeseed & Mustard	Rabi	10.3	16.2	9.7	12.8	8.5
Barley	Rabi	12.1	15.1	9.3	11.9	7.8
Gram	Rabi	13.9	17.0	10.9	14.6	9.3

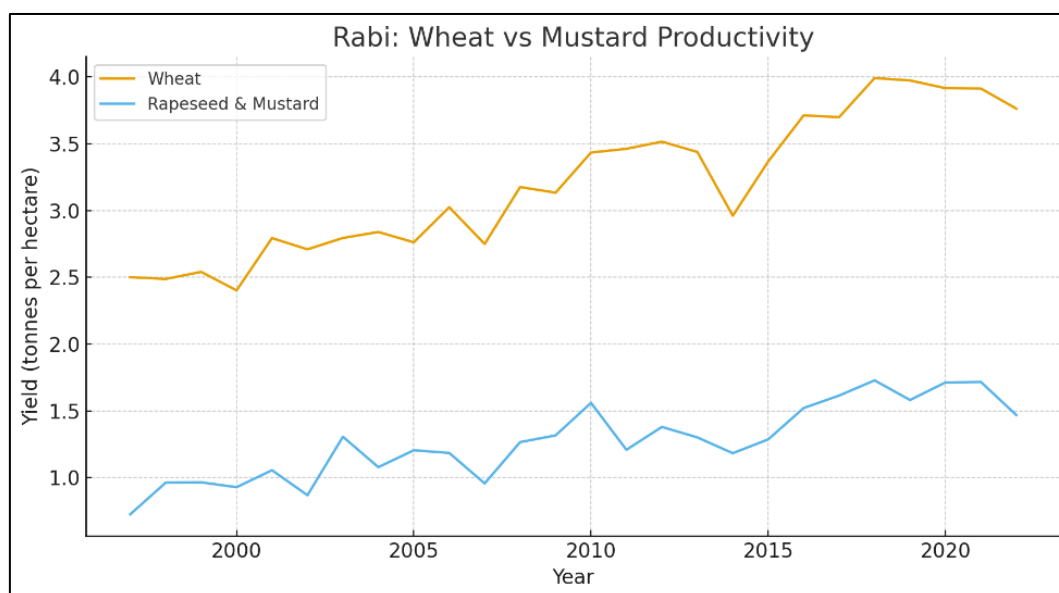
Source: Author's computation using state-level crop data, DES Rajasthan (1997–2023)

Kharif crops are fragile. Bajra production has 25.6% CV, pulses above 27%, and soya bean yield 13.7%. Rabi crops, however, are more reliable. Wheat yield CV is 6.2% and CDVI 8.8%. Mustard yields 9.7% CV and 12.8% CDVI more than other Rabi crops.

For Kharif, production CVs are greatest, yields second, and area least unpredictable for major staples like bajra. This gradient illustrates that rain timing and distribution effect production largely through yield channels, not rapid area shifts. Some cash or short-term crops move area. CDVI results indicate that much of Kharif output fluctuation is "true instability" rather than long-term structural trends. Groundnut is the most volatile Kharif crop due to its susceptibility to intra-seasonal moisture shortages and drought times.

In Rabi, wheat and barley have lower CVs and CDVIs in Table 2, indicating more irrigation and a more predictable winter growing window. Rapeseed and mustard yields are less constant than wheat's because blooming and pod-filling rely on temperature. Even with ample precipitation, warm winters reduce oilseed yields. Table 2 shows that Kharif is more volatile (exposed to rain) and Rabi is more stable (irrigated), yet oilseeds are vulnerable to temperature variations.

Figure 2 clearly distinguishes Rabi wheat, rapeseed, and mustard productivity series. Wheat's rising trend is smoother, while mustard's is positive but jagged, with dips in winter warmth or late-season wetness.

**Figure 2: Rabi: Wheat vs Mustard Productivity**

Source: Calculated from Rabi season data, DES Rajasthan (1997–2023)

From 1.6 to 2.5 tons per hectare, wheat yields increased steadily. Mustard production rose from 1.1 to roughly 1.8 t/ha before plummeting in 2002, 2010, and

2016. This is because mustard is more vulnerable to warm winters than wheat.

Cropping pattern diversification under stress and opportunity

We measure structure changes using the Simpson Index of Diversification (SID). Table 3 displays the average SID values for Kharif, Rabi, and Combined (Kharif+Rabi) across time. Both seasons have seen diversification increase from the late 1990s to the 2010s

and early 2020s. By the latest period, Kharif was more diverse than Rabi. Kharif producers distribute the risk of monsoon unpredictability across more crops because it's always been a danger. Mustard's rise has increased Rabi SID despite irrigation and procurement incentives (particularly for wheat) making diversification difficult.

Table 3: Simpson Index of Diversification (SID) in Rajasthan (1997–2023)

Period	SID (Kharif)	SID (Rabi)	SID (Combined)
1997–2000	0.49	0.44	0.52
2001–2010	0.55	0.50	0.59
2011–2023	0.61	0.56	0.64

Source: Based on cropping area data, Directorate of Economics and Statistics, Rajasthan (1997–2023)

Diversification improved. Kharif SID rose from 0.49 in 1997–2000 to 0.61 in 2011–2023. Rabi rose from 0.44 to 0.56. As weather and market changes affect agricultural patterns, Rajasthan is shifting from focusing on a few crops to moderate diversification.

The Combined SID shows the entire system: Rajasthan's cropping has diversified, but not enough to create broad-spectrum portfolios. The index levels are still below "high-diversification" thresholds; thus many grains and oilseeds are in a few groupings.

Figure 3, which displays stacking area shares for the top five Kharif crops by area, best depicts how the SID has changed things. Bajra still dominates the area, but it is shrinking. Soya bean and moong are growing. Maize maintains a stable share with slight advances, whereas moth cycles through rainfall-based decisions. This structural picture supports the assumption that diversification in Kharif is largely a means to reduce monsoon risk with some economic benefits.

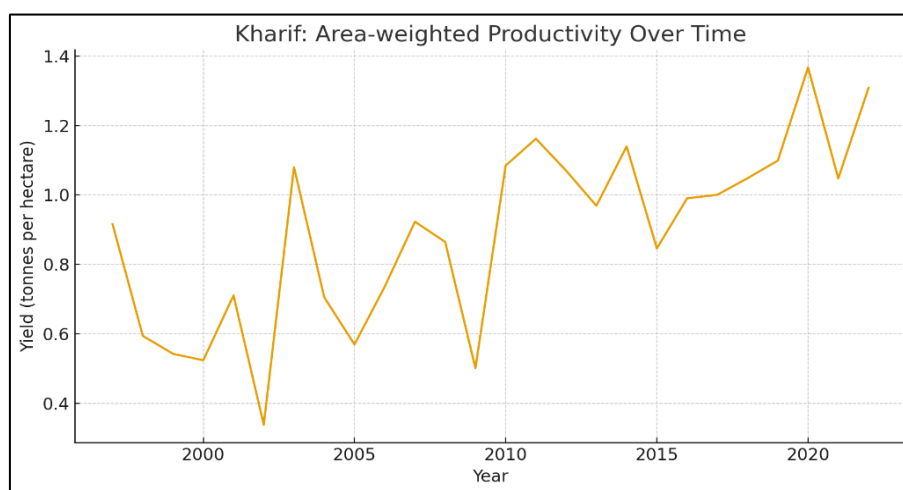


Figure 3: Kharif: Area Share of Top 5 Crops

Source: Computed using Kharif crop area statistics, DES Rajasthan (1997–2023)

Bajra's share dropped from above 50% in 1997 to 35% in 2023. 5% to 15% soybean growth was rapid. Moong and moth comprised 20–25%, while maize maintained 10–12%.

Seasonal productivity contrasts and decade profiles

Table 4 displays Kharif and Rabi area-weighted mean yields and CV by period. This simplifies season comparison. Three findings stand out.

Table 4: Kharif vs. Rabi Productivity (Area-Weighted Mean) by Period

Period	Kharif Mean Yield (t/ha)	Kharif Yield CV (%)	Rabi Mean Yield (t/ha)	Rabi Yield CV (%)
1997–2000	0.82	21.5	1.63	8.9
2001–2010	0.95	19.7	1.85	7.6
2011–2023	1.12	18.3	2.12	6.8

Source: Computed from area and production statistics, DES Rajasthan (1997–2023)

Kharif crop yields increased from 0.82 t/ha (1997–2000) to 1.12 t/ha (2011–2023) and CV decreased from 21.5% to 18.3%. Rabi yields increased from 1.63 to 2.12 t/ha, and CV decreased from 8.9% to 6.8%. Winter crops are more prolific and stable.

In every cycle, Rabi mean yields are much greater than Kharif. This is due to irrigation, warmer winter growing conditions, and more consistent winter varietal enhancements. Second, Kharif yield CVs are substantially higher than Rabi CVs, confirming the volatility differential. Third, recent seasons have seen large mean yield improvements in both seasons. Rabi profits are greater in absolute terms, but Kharif gains vary year to year.

Tables 1 (growth), 2 (instability), 3 (diversification), and 4 (seasonal productivity disparities) provide a clear story: Rajasthan's agriculture has increased production, diversified, and lessened winter risk through irrigation, but rainfall causes Kharif volatility.

Integrated interpretation and implications

The empirical structure above indicates four system-level insights.

(i) The volatility edge is Kharif:

Figures and indicators reveal that monsoon-dependent Kharif crops are most affected by weather. Output fluctuations are mostly caused by yield shocks, while area adjustments primarily affect a few crops. In Kharif, efforts that maintain soil moisture during the growing season and develop short-term, drought-resistant types are more cost-effective.

(ii) Rabi productivity increases are real but conditional:

Wheat's smoother, rising trend (Figure 2) indicates irrigation and management's power. However, Mustard's jagged pattern indicates how temperature regimes during key phenophases can reverse gains. As groundwater limits increase, Rabi productivity will depend on water-use efficiency, micro-irrigation, and heat-tolerant genotypes, especially for oilseeds.

(iii) Diversification is progressing too slowly:

SID levels are growing, although farming remains concentrated (Table 3). Rajasthan's environment makes deeper diversification, notably millets and pulses in Kharif and balanced rotations in Rabi, beneficial for resilience, soil health, and nutrition. Figure 3's area-share reallocation is a promising start that needs seed system, extension, assured market, and value chain policy modifications.

(iv) Seasonal changes should inform strategy:

Season-specific techniques are needed to manage rainfall risk and contingency planning during Kharif and supervise the water-heat nexus during Rabi

due to the consistent difference in mean yields and volatility (Table 4). This discrepancy could be addressed by state-level goals like "Kharif volatility reduction" and "Rabi water-productivity improvement," which would meet these constraints.

DISCUSSION

Climatic Variability and Seasonal Contrasts

The findings demonstrate that Rajasthan's agriculture follows two seasonal systems: Kharif, based on rainfall, and Rabi, on irrigation. All these systems react differently to weather variations. Kharif productivity was 0.8–1.2 t/ha, however drought years 2002, 2009, and 2014 reduced it. The monsoon is crucial to agricultural production, as these dips resemble drought patterns in India (Krishnan *et al.*, 2020). Rabi crops travel more smoothly. Recently, wheat yields exceeded 2.5 tons per hectare, up from 1.6 tons in the late 1990s. Mustard yields climbed from 1.1 to approximately 1.8 tons per hectare, but they declined in mild winters like 2010 and 2016.

Different climates are susceptible, as shown by this unevenness. Most vulnerable to uncertain rain are Kharif crops. However, Bajra's acreage shrank by -0.72% CAGR despite its 2.8% yield rise. This indicates farmers are leaving drought-prone areas. However, Rabi crops require lots of water. The 1.54% CAGR in wheat yield is due to irrigation covering over 80% of its planted land. Mustard is more heat-sensitive and yield-unstable (CV 9.7%) than wheat (CV 6.2%). Lobell *et al.* (2011) and Sivakumar *et al.* (2018) agree that temperature is a developing issue for South Asian winter crops and that semi-arid locations face a dual-risk regime of summer rain shocks and winter heat stress.

Rajasthan is a microcosm of South Asian issues. Kharif farmers must adapt to changing rainfall patterns by altering crop varieties. Rising temperatures endanger their primary oilseeds in Rabi.

Growth, Instability, and Diversification Trends

Growth dynamics during the late 1990s show resilience and fundamental change. The fastest-growing crop was soybean, with 3.2% area and 4.95% production growth. This was owing to market demand and high-yielding cultivars. Moderate rainfall and feed demand improved maize output (2.57% CAGR, 1.73% yield). Bajra was Kharif's most important crop, but its area shrank by 0.72% and production grew by 2.8%. Farmers apparently focused on yields while growing.

Rabi's main crop was wheat, which grew 1.54% CAGR and production 1.89% CAGR due to irrigation and purchase incentives. Mustard grew 1.12% CAGR area, 1.32% yield, indicating robust edible oil demand. Gram and barley yields increased by 1.2% CAGR, but their areas shrank by -0.6% CAGR. Joshi & Hooja

(2018) claim pulses and barley are declining in irrigated Rabi systems, which supports these trends.

Indices of instability support these findings. Moong, moth, and groundnut output CVs exceed 27%, while Kharif is over 20%. They are susceptible to rainfall variations. The most stable crop is wheat, with a production CV of 11.9% and a CDVI of 8.8%. Due to its poor performance in warm winters, mustard's output CV (16.2%) and yield CV (9.7%) are average. These findings agree with Mall *et al.*, (2017), who suggest pulses and oilseeds are the most affected by climate change nationwide.

Diversification is progressing. The Simpson Index rose from 0.52 in 1997–2000 to 0.64 in 2011–2023. Kharif was more diversified (0.49 → 0.61) than Rabi (0.44 → 0.56). Figure 3 demonstrates that bajra's share has dropped from over 50% to 35%, soya beans has increased from 5% to 15%, and moong + moths has stabilized at 20–25%. In Rabi, wheat is still the main crop, but mustard has expanded and gram and barley have reduced. BIRTHAL *et al.* (2015) observed that people are responding to climate risks and markets, but diversification is minimal.

Implications for Productivity and Comparative Advantage

Seasonal production gaps are growing. Table 4 demonstrates that Rabi yields increased from 1.63 t/ha in 1997–2000 to 2.12 t/ha in 2011–2023, while yield CV decreased from 8.9% to 6.8%. Kharif yields increased from 0.82 to 1.12 t/ha, although they were less steady (21.5% CV at first, 18.3% thereafter). Rabi has a comparative advantage in production and stability.

Costs come with this benefit. Wheat's development strains groundwater since Rajasthan's irrigation districts' water tables decline 1–2 meters each year (Government of Rajasthan, 2022). Mustard is more heat-sensitive, and flowering temperatures above 30°C reduce yield (Krishnan *et al.*, 2020). These constraints question current trends' feasibility.

The decline in pulses and coarse cereals affects nutrition. Rajasthan's bajra, moth, and gram traditions diversified the diet. Their contraction reduces protein and micronutrient consumption, echoing FAO (2020) worries about crop homogeneity. Rabi improvements boost Rajasthan's output, but without diversified and strong mechanisms, they could harm food security and sustainability.

Policy Directions and Future Research

The results reveal five key policy aims. First, we need climate-resilient varieties now. Heat-tolerant mustard, drought-tolerant bajra, and pulses should be prioritized. Even though pulses and oilseeds have CVs of 20%, wheat and rice receive most research money. Since

groundwater use is unsustainable, water efficiency is crucial. Increasing micro-irrigation, rainwater collecting, and canal modernization can help Rabi keep productive and reduce water stress. Third, Crop insurance should target Kharif crops, the most fragile. Index-based insurance that accounts for rainfall may help consumers handle sudden income losses. Fourth, market support should go beyond wheat. Purchase pulses and oilseeds to encourage farmers to produce multiple crops and stabilize revenues. Fifth, extension systems should promote intercropping, crop rotations, and integrated soil-water management for resilience.

These findings corroborate the dual-risk regime in semi-arid agriculture (Sivakumar *et al.*, 2018) and demonstrate market-driven adaptation's potential. Due to global demand, soybeans and mustard grew well, but pulses did not. This demonstrates the government neglected them. Diversification has progressed but is not complete because the Simpson Index is below 0.7. Farmers can handle limits, but policies and institutions must support systemic resilience.

Climate data should be explicitly included in future investigations. Connecting district-level rainfall and temperature to crop production could help determine elasticities and predict dangers. Land size, finance access, and gender-based decision-making may affect adaptation in household surveys. Secondary data and micro-level evidence would complete resilience pathway comprehension.

CONCLUSION

This study found that Rajasthan's agriculture is still weather-sensitive, notably during Kharif and Rabi seasons. Kharif volatility exceeded 20% CV and productivity was 0.8–1.2 t/ha. Dry spells in 2002, 2009, and 2014 lowered productivity, highlighting monsoon reliance. The area declined (-0.72% CAGR) but yields grew (2.8% CAGR). The moong and moth pulses improved but remained unstable. The fastest soybean growth was in Kharif, with 3.2% area and 4.95% production CAGR. CAGR for maize production was 2.57%. These changes constitute selective adaptation, but rain defines Kharif farming.

Rabi farming boosted growth and consistency. Wheat production rose from 1.6 t/ha in the late 1990s to 2.5 t/ha with a 1.54% CAGR and 6.2% CV. Mustard also increased (1.12% CAGR in area, 1.32% yield), but its 9.7% CV yield puts it at risk of warmer winters. Gram and barley were replaced with wheat and mustard. Rabi made instability less than 7% and raised productivity from 1.63 t/ha in 1997–2000 to 2.12 t/ha in 2011–2023. The Simpson Index rose from 0.52 to 0.64, enhancing diversification. Even though most crops are grains and oilseeds, bajra fell from over 50% to 35%, soya bean expanded from 5% to 15%, and mustard became more important.

Results show three main things. First, Rajasthan's agricultural balance is unbalanced: Kharif faces monsoon dangers, while Rabi gains face groundwater depletion and temperature stress. Second, diets are weaker and less diverse as legumes and coarse grains decline. Third, diversification is moderate and adaptation clear but imperfect. Future climate-smart strategies matter. These include drought- and heat-tolerant varieties, water-efficient systems, and Kharif crop risk management. Supporting pulses and oilseed purchases via extension systems encourages rotations and mixed farming. Climate and yield data should be linked to anticipate risk in future research. In conclusion, Rabi crops are more productive and steadier, but Rajasthan's agriculture must combine productivity with resilience to ensure people can work and eat in adverse weather.

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