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Convergence in pearl millet production across desert and non-desert districts of Rajasthan

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ABSTRACT

Rajasthan, the largest state in India by area, is the leading producer of pearl millet (*Pennisetum glaucum*) in the country. The state is geographically divided into desert and non-desert districts, with 61 per cent of its area classified as desert.This study examines whether production disparities across 27 original districts of Rajasthan narrowed between 1980–81 and 2019–20, analyzing 11 desert and 16 non-desert districts separately. Sigma convergence is assessed using the linear trend in the annual coefficient of variation, while the bivariate beta-convergence specification relates production growth to initial production levels. The reported sigma coefficients are not statistically significant for the all districts, desert districts and non-desert offering no evidence of a consistent linear decline in relative dispersion. The beta coefficient is negative and significant for the all districts and non-desert but not for desert districts. These estimates suggest an inverse relationship between initial production and growth but do not indicate a clear reduction in production dispersion. These findings pertain to aggregate production rather than yield, efficiency, or household welfare. This advocate for a distinct research and policy approach focused on climate risks, crop-livestock systems, and locally appropriate diversification. The study highlights the need for targeted policy interventions to address the unique challenges faced by desert districts and to promote equitable growth across all districts.

Keywords: Pearl millet; Rajasthan; production disparities; Coefficient of Variation; σ-convergence; β-convergence; Desert Areas; Non-Desert Areas

INTRODUCTION

The largest state in India by land area, Rajasthan is an important agricultural state and the nation's top producer of pearl millet (*Pennisetum glaucum*). The desert area and the non-desert area are the two main geographical divisions of the state. The Thar Desert, a desert region, makes up around 61per cent of the entire state. Extreme weather characteristics, such as low rainfall, high temperatures, and sandy soils, define this dry region. These variables limit the kinds of crops that may be farmed and need resilient farming methods, which pose serious issues for agriculture.

Despite these difficult conditions, pearl millet has become the primary crop in desert areas due to its drought endurance and ability to grow on poor soil. Despite these challenging circumstances, pearl millet has emerged as the main crop in desert regions because of its resistance to drought and capacity to flourish in poor soil. Rajasthan's non-desert areas, which make up over 39 per cent of the state, have more fertile soil, better access to water supplies, and more ideal weather for farming. In addition to pearl millet, these areas are home to a wider variety of crops, such as wheat, mustard, and legumes.Due to these geographical and climatic variations, Rajasthan's desert and non-desert regions have very different agriculture techniques and productivity. Traditional rain-fed farming practices, which heavily rely on monsoonal rainfall, are prevalent in arid locations. On the other hand, irrigation infrastructure, such as tube wells and canals, improve agricultural output and enable more intensive farming methods in the non-desert regions.

Developing focused policies and interventions requires an understanding of the agricultural dynamics of Rajasthan's desert and non-desert regions. In this complex and demanding climate, these measures could support sustainable agricultural practices, increase crop yields, and guaranty food security.

Because of its genetic diversity and ability to adapt to challenging conditions, pearl millet is essential for agricultural sustainability and food security. Pearl millet plays a crucial role in food security and agricultural sustainability due to its genetic diversity and adaptability to harsh environments. This diversity is vital for breeding programs aimed at improving yield and resistance to stress factors such as drought, pests, and diseases.In the context of agricultural practices and productivity, Kelley *et al.* (1996) emphasized the critical role of straw yield and quality in the adoption of pearl millet cultivars in Rajasthan. The limited adoption of improved varieties in drought conditions highlights the need for cultivars that are better adapted to low-rainfall environments. Weltzien *et al*. (1995) further discussed the evolution of farmers' roles in pearl millet breeding programs, where active collaboration has led to the development of varieties that better meet farmers' needs. In western Rajasthan, Manga and Kumar (2011) and Yadav *et al.* (2001) noted that hybrids offer significant advantages in both yield and fodder production, although local cultivars remain preferred due to their lower risk of crop failure. Yadav *et al.* (2024) demonstrated that specific transplanting and treatment strategies can significantly improve the growth and yield of varieties like RHB-173.

From an economic perspective, Gautam and Singh (2019-20) provided a cost analysis of pearl millet cultivation in Rajasthan, revealing that human labour constitutes the highest cost component, and suggested that better input utilization could enhance profitability. Furthermore, Daduwal *et al.* (2024) discussed the potential of pearl millet as a climate-resilient fodder crop, with advancements in genomic resources and breeding strategies which poised to significantly improve its forage quality.

In the broader context of agricultural convergence, studies by Somasekharana *et al.* (2011) and Mukhopadhyay and Sarkar (2015) explored the dynamics of agricultural growth and productivity across Indian states, revealing varying degrees of convergence in agricultural output and foodgrains production. Yuan *et al.* (2021) extended this analysis to a global scale, finding no global convergence in agricultural efficiency but suggesting that international trade, improved irrigation, and structural transformation could enhance agricultural productivity and reduce disparities among countries.

A particularly relevant precursor is Sinha and Kulshrestha (2014), who examined agricultural area, production, and productivity across Rajasthan's districts, including desert and non-desert comparisons. More recently, Singh and Aneja (2025) investigated district disparities in agricultural development in north-eastern Rajasthan. The present study therefore does not introduce regional convergence analysis to Rajasthan. It extends that discussion through a pearl-millet-specific assessment over 1980–81 to 2019–20 and a joint interpretation of dispersion trends and initial-production–growth associations. The contribution is empirical and crop-specific rather than a new convergence estimator.

Research gap and objectives

Existing studies on pearl millet in Rajasthan primarily focuses on cultivation practices, variety performance, drought resilience, and profitability. While national-level studies examine convergence in agricultural development across different regions of India, state-level studies tend to prioritize aggregate crop production over specific crops. Consequently, there is a significant gap in understanding whether the disparities in pearl millet production across districts have narrowed over time and whether lagging districts are catching up with high-performing ones. Notably, there is a lack of concrete evidence or studies regarding sigma- and beta-convergence for pearl millet. This study addresses this gap by evaluating long-term convergence patterns across the diverse desert and non-desert districts of Rajasthan.

MATERIALS AND METHODS

Data: To analyze σ-convergence and β-convergence, data was collected from the Directorate of Economics and Statistics, Jaipur, using the annual publication '*Agriculture Statistics'*. This study examines the dispersion of pearl millet production growth rates across 27 districts of Rajasthan in which 11 desert and 16 non-desert districts over a 40-year period (1980-81 to 2019-20). Adjustments were made to account for the changes in district boundaries and the number of districts that occurred during the study period. These adjustments ensured that the analysis remained consistent and accurate despite the administrative changes. The study was able to provide a reliable assessment of pearl millet production trends across Rajasthan, allowing for meaningful comparisons and insights into convergence and growth patterns over time.

i. **σ – convergence:** Barro and Sala-i-Martin (1992) presented one of the seminal empirical applications of the convergence hypothesis, examining whether initially poor economies or regions grow faster than

initially rich ones. Their study established the β-convergence framework and demonstrated evidence of convergence among US states and, under certain conditions, across countries. Sala-i-Martin (1996) further developed the conventional approach to convergence by distinguishing between σ-convergence, absolute β-convergence, and conditional β-convergence. The study emphasized that β-convergence reflects the progress of initially lagging economies, whereas σ-convergence indicates a reduction in the dispersion across economies over time. These concepts provide a suitable analytical framework for examining whether disparities in pearl millet production across the districts of Rajasthan narrowed or widened during the study period.

In classical convergence theory, σ-convergence refers to the reduction in the dispersion of a cross-sectional distribution. Typically, studies use indicators such as absolute differences to measure these variations, with standard deviation being a common absolute index. σ-convergence is particularly interesting because, while β-convergence is necessary for σ-convergence, it is not sufficient on its own. Therefore, assessing σ-convergence by observing a decline in distribution dispersion is valuable.

As the sigma convergence measures the inter-regional inequality. When the dispersion of production of pearl millet across districts falls over time, there is σ - convergence.

The model is

$CV_t = \alpha + \delta t + \varepsilon_t$

There, CV = Coefficient of Variation

α = Intercept,

δ = Slope coefficient,

ε = Error term,

t= time (1980-81 to 2019-20)

ii. β-convergence : The Barro-type β-convergence regression is a widely used method in convergence studies.When the partial correlation between growth of pearl millet production over time and its initial level is negative, there is β -convergence.

The model is

$G.W_i = \alpha + \beta X_i \varepsilon_i$

There, G.W. = Growth rate (1980-81 to 2019-20) of pearl millet production

α = Intercept,

β = Slope Coefficient,

ε_i = Disturbanceterm,

X= Initial production,

i = Districts

RESULT AND DISCUSSION

i. Coefficient of variation

To assess inter-regional disparities in pearl millet production, sigma convergence is examined using the Coefficient of Variation (CV) over the period 1980–81 to 2019–20. The temporal trend in CV illustrates whether spatial inequality has narrowed or widened across all districts of Rajasthan, with specific comparisons between desert and non-desert districts.

A. Coefficient of variation for all districts

The coefficient of variation as see in Fig. 1 has bounded range over the years. It measures the dispersion of pearl millet production across districts over the years. So, this indicates that there is no trend of convergence or divergence over the studied period.

B. Coefficient of variation for desert Districts

Fig. 2 illustrates that the coefficient of variation trends for desert districts do not exhibit a clear positive or negative pattern over the study period. Therefore, it can be concluded that there is neither convergence nor divergence among the desert districts in terms of the variables analyzed.

C. Coefficient of variation for non-desert Districts

Fig. 3 presents the coefficient of variation trends for non-desert districts. The positive trend line suggests that disparities in pearl millet production among these districts have slightly increased over time, indicating a potential divergence rather than convergence.

Fig. 1: Coefficient of variation trends for all districts

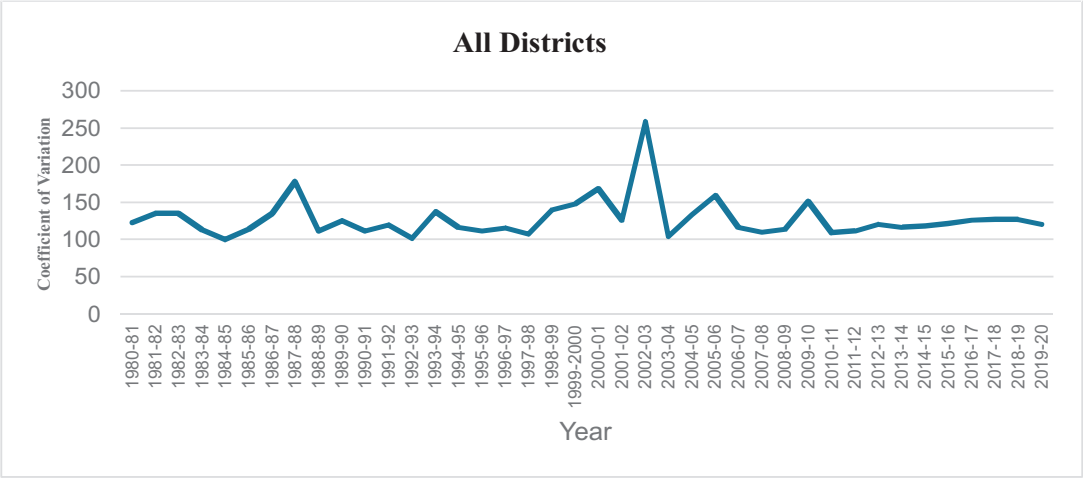


Fig. 2: Coefficient of variation trends for desert districts

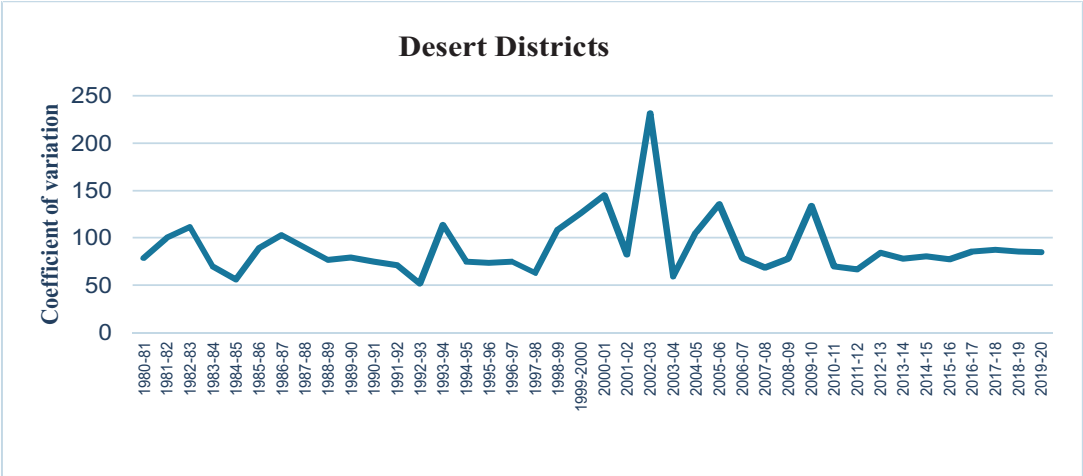
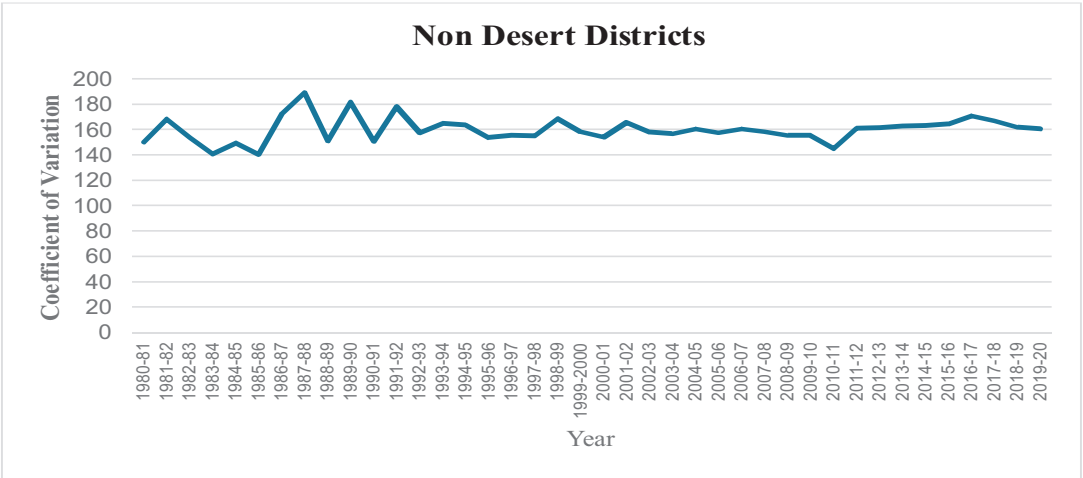


Fig. 3: **Coefficient of variation trends for non-desert districts**



I. **σ-convergence Model**

The σ-convergence model in table1 analyses the dispersion of growth rates across different districts over time, typically to assess whether regions are becoming more similar in their economic outcomes, such as agricultural production. The coefficient of variation (CV) is used as the dependent variable in this model.

1. All districts

The estimated time coefficient is 0.0085, indicating a very slight positive trend in production dispersion. However, the p-value is 0.9821, offering no statistically significant evidence of convergence or divergence. An R^2 of 0.000013 suggests that time explains only 0.0013 percent of the annual variation in the CV. The negative adjusted R^2 (- 0.026) indicates that, after accounting for model complexity, adding a linear time trend does not improve explanatory performance. The non-significant F-statistic (0.0005; p ≈ 0.982) further confirms this. Therefore, the results for the full sample do not confirm a systematic narrowing or widening of relative production disparities over the study period.

2. Desert districts

For the 11 desert districts, the time coefficient is 0.1131, indicating an estimated annual increase of approximately 0.113 percentage points in the CV. However, this coefficient is statistically insignificant (t = 0.2584; p = 0.7975); therefore, its positive sign cannot be interpreted as established divergence. An R^2 of 0.0018 indicates that the linear time trend explains approximately 0.1754% of the annual variation in production dispersion. The negative adjusted R^2 (- 0.024) and the insignificant F-test (F = 0.0668; p ≈ 0.797) also point to limited explanatory power. These results provide insufficient evidence of sigma convergence or divergence among the desert districts; they do not indicate whether inequalities remained constant or if the fluctuations observed were entirely random.

3. Non-desert districts

Among the 16 non-desert districts, the time coefficient is 0.0824, indicating an estimated annual increase of approximately 0.082 percentage points in the CV. However, this trend is not statistically significant (t = 0.6048; p = 0.5489). An R^2 of 0.0095 shows that time explains only 0.95% of the annual variation in production dispersion. The adjusted R^2 is negative (- 0.016), and the F-test is also insignificant (F = 0.3657; p ≈ 0.548). Consequently, there is no statistically significant evidence of consistent linear movement towards convergence or divergence (moving apart) within this group. These results do not rule out the possibility of minor episodes of narrowing or widening disparities during the study period.

The intercepts128.094, 88.0222, and 158.452 represent the fitted CV values when the time variable is zero. They reflect the dispersion at the initial period only if the first year is coded as zero. Their significant p-values do not establish convergence.

The Durbin-Watson statistics (2.1, 2.13, and 2.082) are close to two, indicating very low first-order residual autocorrelation, though they do not prove that the errors are independent. Each regression utilizes 40 annual CV observations, resulting in 38 residual degrees of freedom after estimating the intercept and time coefficient.

Table 1: Sigma convergence estimates for pearl millet production

Statistic	All Districts	Desert	Non-desert
Districts represented	27	11	16
Annual observations	40	40	40
Intercept	128.094	88.0222	158.452
Intercept standard error	8.93	10.2988	3.20618
Intercept t-statistic	14.33	8.547	49.42
Intercept p-value	< .0001	< .0001	< .0001
Time coefficient	0.0085	0.1131	0.0824
Time standard error	0.37	0.4377	0.1362
Time t-statistic	0.0225	0.2584	0.6048
Time p-value	.9821	.7975	.5489
R^2	0.000013	0.0018	0.0095
Adjusted R^2	- 0.026	- 0.024	- 0.016
F-statistic	0.0005	0.0668	0.3657
F degrees of freedom	1, 38	1, 38	1, 38
F-test p-value	.982	.797	.548
Durbin–Watson	2.1	2.13	2.082

A major explanation lies in the continued dependence of pearl millet on rainfed agriculture and highly variable monsoon conditions. Western Rajasthan is characterized by low and erratic rainfall, recurrent moisture stress, high temperatures, and considerable spatial variation in water availability. Singh and Kumar (2015) observed substantial climatic variability and water scarcity across the drylands of Rajasthan, while Panjala *et al*. (2023) identified extensive drought- and heat-stress-prone pearl millet areas and reported relatively low productivity in western Rajasthan. Such spatially uneven climatic exposure can cause production to rise sharply in some districts during favourable monsoon years while declining in others, thereby preventing a sustained reduction in inter-district dispersion.

The lack of convergence may also reflect the progressive diversification of Rajasthan's agricultural economy away from coarse cereals. Kiran and Punia (2025) documented a long-term decline in the share of cereals in Rajasthan's cropped area alongside a substantial increase in oilseeds and showed that irrigation is an important determinant of agricultural diversification. This structural change is particularly important because pearl millet increasingly competes for land with crops offering different combinations of profitability, marketability, and irrigation responsiveness. In southern and south-eastern Rajasthan, maize and soybean have become important components of *kharif* farming systems; soybean-based production systems are well established in south-eastern Rajasthan, while soybean markets in districts such as Pratapgarh, Chittorgarh, Bhilwara, and Banswara have exhibited significant long-term increases in wholesale prices. These developments provide an economic basis for farmers in relatively better-watered areas to allocate land away from traditional coarse cereals where alternative crops offer attractive returns.

A different pattern has emerged in the north-western and western desert districts, where the expansion of canal and groundwater irrigation has altered crop choice. Varghese and Singh (2016) noted that the development of the Indira Gandhi Canal contributed to the replacement of traditional *kharif* crops in parts of the Thar by cluster bean, fodder crops, groundnut,

and cotton, while wheat and mustard became important irrigated rabi crops. Similarly, evidence on Rajasthan's long-term cropping pattern indicates that soybean, cluster bean, wheat, and mustard achieved relatively greater persistence in cultivated area, while acreage continued to shift among competing crops (Verma et al., 2017). Thus, irrigation expansion did not necessarily generate uniform growth in pearl millet production; rather, it enabled districts with better access to water to diversify toward cotton, mustard, guar, wheat, and other commercially attractive crops. This heterogeneous response to irrigation can help explain why production disparities across desert districts did not consistently diminish.

Livestock and fodder demand provide an additional explanation for the persistence of pearl millet in some desert districts. Croplivestock systems remain central to livelihoods in western Rajasthan, where pearl millet contributes not only grain but also valuable stover. Varghese and Singh (2016) emphasized the importance of livestock to the Thar economy and the recurrent scarcity of fodder associated with rainfall variability. At the state level, Meena *et al*. (2018) estimated a sizeable deficit in feed and fodder availability and found crop residues to be the largest component of Rajasthan's fodder supply. Consequently, farmers may continue cultivating pearl millet even where grain yields are relatively low because its residues have substantial value for cattle, sheep, goats, and mixed crop–livestock production systems. This dual-purpose role may slow crop substitution in livestock-intensive districts while other districts diversify more rapidly, thereby maintaining spatial heterogeneity in production.

II. β - convergence Model

The β-convergence model is used to determine whether districts with initially lower levels of pearl millet production, including both desert and non-desert districts, are catching up with higher-producing districts over time.

Table 2 examines whether districts that initially had low pearl millet production between 1980–81 and 2019–20 experienced greater subsequent growth. The negative and statistically significant coefficient for initial production supports the presence of beta convergence within the reported specification.

1. All districts

The coefficient for initial production is -0.1050, with a t-statistic of -4.685 and a p-value of less than 0.0001. This indicates a statistically significant inverse relationship between initial production and subsequent growth: districts with low initial production generally recorded higher growth, whereas districts that were initially large producers saw lower growth. This result is consistent with beta convergence across the districts.

The R^2 value of 0.4675 indicates that initial production explains approximately 46.75% of the variation in growth rates across districts. The adjusted R^2 is also quite high at 0.4462. Furthermore, the F-statistic of 21.9526 (with $p = 0.000084$) confirms that the regression is statistically significant. However, this relationship does not prove that initially small producers increased their production in absolute terms; it could also reflect a more rapid decline in production among initially large producers.

2. Desert Districts

For the 11 desert districts, the initial production coefficient is negative (-0.026) but statistically insignificant ($t = -0.8597$; $p = 0.4123$). Although the sign indicates an inverse relationship between initial production and growth, the evidence is insufficient to establish beta convergence.

An R^2 of 0.075 indicates that initial production explains only 7.5% of the variation in growth rates. The negative adjusted R^2 (-0.027) shows that, after accounting for model complexity, this model offers little improvement over an intercept-only specification. The insignificant F-test ($F = 0.7390$; $p \approx 0.412$) confirms this result. Consequently, growth disparities within the desert group cannot be adequately explained by initial production alone. The small sample size also limits precision; thus, statistical insignificance does not necessarily imply the absence of convergence.

3. Non-Desert Districts

Among the 16 non-desert districts, the initial

production coefficient is -0.051, with a t-statistic of -3.340 and p = 0.0049. This negative relationship is significant at the 1% level, providing evidence of beta convergence: districts with lower initial production experienced higher subsequent growth compared to those with higher initial production.

An R^2 of 0.443 indicates that initial production explains approximately 44.3% of the variation in growth rates, while the adjusted R^2 is 0.404. The significant F-statistic (11.157; p = 0.0048) supports the explanatory relevance of the regression. However, the result does not distinguish between the growth of small producers and the decline of large producers. Determining which process prevailed requires an analysis of district-level production trajectories.

The intercepts18.4139, 7.155, and 10.607 - represent the estimated growth when the initial-production regressor equals zero. These are not average growth rates, and their practical significance may be limited if zero falls outside the range of observed data. Assessing the economic magnitude of the coefficients also requires verifying the scales used for production units and growth rates.

The table 2 supports beta convergence for the full sample and for non-desert districts but provides insufficient evidence for desert districts. A significant result in one group and an insignificant one in another does not establish a statistically significant difference between their coefficients; a direct interaction test is required for that. Furthermore, these beta results do not indicate declining production inequalitiesno such decline was observed in the sigma-convergence results presented in Table 1.

Table 2: Beta convergence estimates for pearl millet production

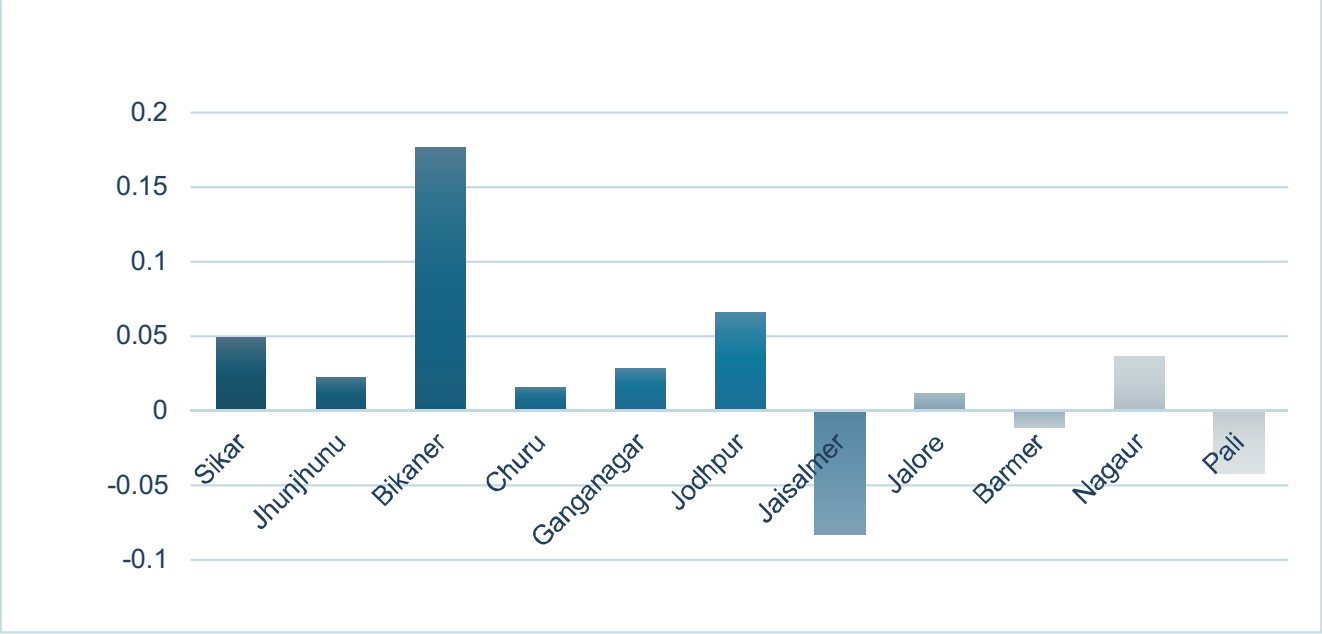
Statistic	All Districts	Desert	Non-desert
District observations	27	11	16
Intercept	18.4139	7.155	10.607
Intercept standard error	1.4763	1.683	1.1147
Intercept t-statistic	12.47	4.251	9.515
Intercept p-value	< .0001	.0021	< .0001
Initial-production coefficient	- 0.105001	- 0.026	- 0.051
Coefficient standard error	0.0224	0.031	0.0152
Coefficient t-statistic	- 4.685	- 0.8597	- 3.340
Coefficient p-value	< .0001	.4123	.0049
R^2	0.4675	0.075	0.443
Adjusted R^2	0.4462	- 0.027	0.404
F-statistic	21.9525	0.7390	11.157
F degrees of freedom	1, 25	1, 9	1, 14
F-test p-value	.000084	.412	.0048

i. Growth of Production

A. Production Growth rate of Desert Districts

Fig. 4 clearly indicates that growth rates based on 40 years data among desert districts are mixed, with some districts showing positive growth while others exhibit negative growth. A positive growth rate suggests a potential direct relationship between the initial production level and subsequent growth, while a negative growth rate implies an inverse relationship. Notably, three out of the eleven desert districts have experienced negative growth in pearl millet production over the period of study.

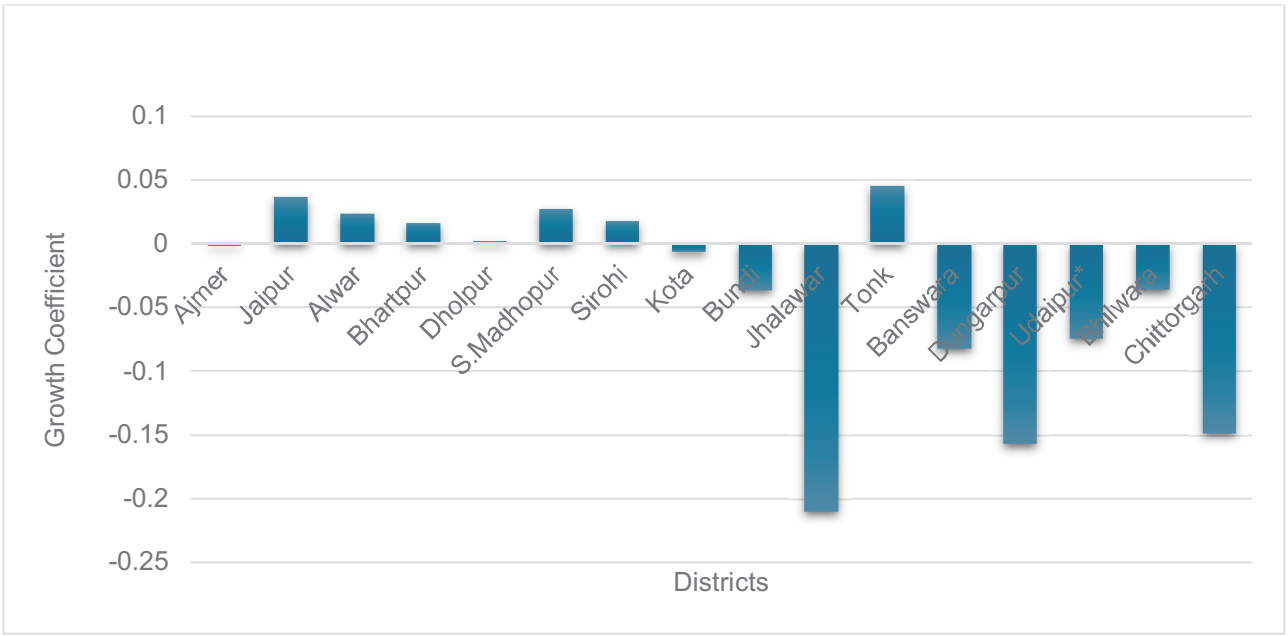
Fig.4: Growth rate coefficients of desert districts



B. Production Growth rate for Non-Desert Districts

Fig. 5 reveals that seven out of the sixteen non-desert districts exhibit positive growth in pearl millet production, while the remaining nine districts show negative growth. Notably, most of the districts with negative growth are located in the southern region of Rajasthan.

Fig.5 : Growth rate coefficients of non-desert districts



The pattern of overall growth in pearl millet production in Rajasthan has been mixed and uneven across different regions. Most desert districts recorded positive growth, with only 3 out of 11 districts showing negative growth, indicating a relatively better long-term production performance. In contrast, the growth pattern in non-desert districts was weaker; 9 out of 16 districts experienced negative growth, while only 7 showed positive growth. The prevalence of negative growth—particularly in the southern districts—suggests that the long-term trend of pearl millet production in non-desert areas of Rajasthan has been comparatively less favorable. Overall, the findings reveal significant disparities in production growth among districts, with desert districts generally outperforming non-desert districts during the study period.

CONCLUSION

The analysis of pearl millet production trends across Rajasthan from 1980-81 to 2019-20 reveals mixed results regarding convergence. The σ convergence model indicates no significant trend of convergence or divergence in production across the districts, with a poor model fit suggesting that time alone does not adequately explain the variation in production disparities. In contrast, the β-convergence model reveals significant convergence across the state's districts overall, particularly in non-desert districts, where districts with lower initial production levels have experienced higher growth rates, suggesting that these poorer districts in term of pearl millet production are catching up higher production districts over the years. However, in desert districts, the model does not indicate significant β-convergence, suggesting that initial production levels do not predict growth rates in these areas, and the model's poor fit highlights the need for considering additional factors influencing production growth.

Factors such as rainfall fluctuations, crop choice based on irrigation availability, alternatives like maize and soybean, fodder demand, and market incentives could potentially explain the varying production patterns, though their specific roles remain to be investigated. Based on these findings, policy interventions should focus on addressing the unique challenges faced by desert districts.

FUTURE SCOPE

The lack of significant convergence or divergence in the σ-convergence model suggests that time alone does not fully account for the variations in production disparities among districts. This finding opens up opportunities for future research to explore other factors, such as environmental, economic, and technological influences, that might explain these disparities even in productivity or area.

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DECLARATION OF AI USE

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