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Trend and Growth Patterns of Pearl Millet: A Regional Study in Major Districts of Eastern Uttar Pradesh, India

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ABSTRACT

This study evaluates the trends and growth patterns in area, production, and productivity of pearl millet across eight major districts of Eastern Uttar Pradesh (1993–94 to 2022–23) using smoothening techniques like three-year moving average (MA), LOESS (span = 0.50) and for growth pattern estimation using Linear Growth Rate (LGR), and Compound Growth Rate (CGR). The results reveal that the total cultivated area declined from 65.55 to 43.33 thousand hectares, while production also declined from 799.26 to 639.03 thousand quintals, although with moderate fluctuations over time. Meanwhile, productivity showed a steady and significant increase from 12.19 to 14.75 quintals per hectare, indicating consistent improvement in yield. At the district level, Ghazipur and Jaunpur showed positive growth trends, whereas Ayodhya and Mau experienced sharp declines in area and production. The findings suggest that the growth of pearl millet in the region is increasingly driven by improvements in productivity rather than expansion in cultivated area. The study highlights the need for district-specific strategies focusing on yield enhancement, improved farming practices, and better market support to sustain pearl millet cultivation in the region.

Keywords Moving average, Linear growth rate (LGR), Compound growth rate (CGR), LOESS smoothing.

INTRODUCTION

Pearl millet (*Pennisetum glaucum*) is one of the most drought-tolerant and nutritionally rich cereal crops, cultivated predominantly in the arid and semi-arid tropics under low rainfall and poor soil fertility conditions. Global annual production is estimated at approximately 30 million metric tonnes, with Africa and Asia together accounting for 98% of global area and 97% of production (Deevi *et al.* 2024). Among millets, pearl millet occupies approximately 75% of global millet area. Its exceptional resilience to drought and heat stress makes it an increasingly vital crop in the context of climate change and food security.

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Government of India has declared Year 2018 as the "Year of Millets" and FAO Committee on Agriculture (COAG) forum has declared Year 2023 as the "International Year of Millets".

India is the world's largest producer of pearl millet, contributing approximately 38.4% of global millet output (FAO 2023). The crop covers 55% of India's total millet area, with an average cultivated area of 13.28 million hectares. Rajasthan leads national production (32%), followed by Uttar Pradesh (18%), Karnataka (11%), and Maharashtra (11%) (APEDA 2024). High-yielding varieties, about 65 % of India's pearl millet area is now under improved cultivars (Yadav and Rai 2013). Recent analyses affirm that millets including pearl millet have considerable strategic importance for sustainable food and nutritional security in India (Singh *et al.* 2024).

Eastern Uttar Pradesh — comprising the districts of Azamgarh, Ayodhya, Ballia, Mau, Jaunpur, Bhadohi, Varanasi, and Ghazipur — represents an important but analytically underserved pearl millet zone within the AE2 TPE (Agro-Ecological Zone 2 Target Population Environment) characterised by moderate rainfall (900–1,100 mm), alluvial soils, and expanding groundwater irrigation. Despite the recognised importance of zone-specific analysis for varietal and management interventions (Garin *et al.* 2023), district-level growth pattern studies in this region remain scarce relative to better-growth regions such as Rajasthan and Bundelkhand. Recent Indian research demonstrates the value of integrating smoothing techniques like LOESS, Moving Average with multi-model evaluation frameworks for more robust agronomic inferences. As millets are basically grown in worse land of rainfed areas of the state and grown as an alternative crop, it is basically confronted with various constraints in its cultivation. Eastern Uttar Pradesh has experienced significant agrarian change, driven by factors such as changing cropping choices, access to irrigation, seed and input availability, and market linkages. Despite the crop's importance for marginal farmers and its role in climate resilient agriculture, there is very little region-specific research that shows how pearl millet cultivation patterns have changed and are evolving across districts in the region. According to Gyawali (2021), lack of domain-specific high-yielding varieties, high preference towards major cereals, and poor marketing infrastructure, particularly in marginal areas, are the constraints mainly considered for the inconsistent production of millet.

MATERIALS AND METHODS

The study uses secondary time-series data on area, production, and productivity for the period 1993–94 to 2022–23, covering major districts of Eastern Uttar Pradesh—Azamgarh, Ayodhya, Ballia, Mau, Jaunpur, Bhadohi, Varanasi, and Ghazipur—located between 24°N–27°N latitude and 81°E–84°E longitude. The data were collected from the *Sankhikiya Patrika*, published annually by the Economics and Statistics Division, Planning Department, Government of Uttar Pradesh (UPDES), and from the Directorate of Economics and Statistics (DES) https://updes.up.nic.in/ . The time variable is represented as, $t=1,2,3,\ldots,n$ corresponding to successive years of observation.

The data were analysed using smoothing techniques, growth rate estimation, and trend analysis. A three-year moving average and LOESS smoothing (span = 0.50) were applied to remove short-term fluctuations and capture the underlying trend. Linear Growth Rate (LGR) and Compound Growth Rate (CGR) were estimated using linear and log-linear functions.

Assessment of growth pattern

Linear growth rate

The LGR is calculated as the ratio of the estimated slope to the mean of the variable, expressed as a percentage:

$$LGR = \frac{\hat{b}}{\overline{y}_t} \times 100$$

where $\hat{b}$ is the estimated slope and $\overline{y}_t$ is the mean value of the variable over the study period.

Compound growth rate

The equation gives the compound function:

$$Yt = \alpha(1 + r)^t \text{ or } 1\,n\,Y_t = \ln a + t \ln (1+r)$$

The compound annual growth rate (CAGR) was computed as:

$$CGR\ (\%) = [\text{antilog}\ (b) - 1] \times 100$$

where, 't' is the time in years, 'Y_t' is the characteristics (area, production or productivity) and 'a' is constant and 'b = (1+ r)', 'r' is the compound growth rate. The term '(1 + r) t' represents the compounded growth.

LOESS Smoothing

Locally Estimated Scatterplot Smoothing (LOESS) was applied with a span parameter of f = 0.50. For each time point t_0, the fitted value $\hat{Y}\ (t_0)$ is obtained by minimising the locally weighted least squares:

$$\min_{\alpha,\beta} \sum_{i=1}^{n} w_i\ (t_0)\ (Y_i - \alpha - \beta t_i)^2$$

where $w_i\ (t_0)$ are tricube weights based on distance from t_0. (Cleveland and Devlin 1988).

Moving Average (MA)

A centred three-year moving average was applied to filter irregular short-term fluctuations caused by weather variability, market shocks, and measurement error:

$$MA_t = \frac{Y_{t-1}+Y_t+Y_{t+1}}{3}$$

where MA_t denotes the moving average for year t and Y_t represents the observation. (Gujarati and Porter 2009).

RESULTS AND DISCUSSION

Descriptive analysis of pearl millet across major districts of Eastern U.P. (1993-94 to 2022-23)

The present study summarises the descriptive statistics of area, production, and productivity over the 30-year period.

In Table 1 the average area under pearl millet cultivation was 37,585 ha, varying from 27,017 ha in 2005–06 to 68,377 ha in 1994–95. The high area in the early years was mainly due to Ballia district, which contributed 32,584 ha in 1993–94 before dropping sharply to below 820 ha by 1999–2000. Ghazipur had the largest area share, followed by Bhadohi, while Jaunpur and Varanasi showed moderate levels. In contrast, Ayodhya and Azamgarh had very little area under cultivation, highlighting the uneven distribution of the crop across districts. Yadav and Chakraborty (2025) also highlighted the importance of pearl millet cultivation in Uttar Pradesh and emphasized its role in local farming systems and food security.

Table 1. Descriptive analysis of pearl millet's Area (000' ha).

Districts	Mean	Min	Max	Std. Dev.
Azamgarh	0.21	0.032	0.979	0.204
Ayodhya	0.02	0.0012	0.144	0.033
Ballia	3.79	0.460	32.584	7.018
Mau	0.23	0.009	1.907	0.346
Jaunpur	6.07	3.156	12.33	1.831
Bhadohi	8.69	7.761	9.940	0.450
Varanasi	5.38	2.455	9.608	1.602
Ghazipur	13.18	7.043	17.322	2.380
Overall	37.585	27.017	68.376	8.768

In Table 2. Production followed a similar pattern to area, with an average of 456.57 thousand quintals. Ghazipur led production, followed by Bhadohi and Jaunpur, while Ballia showed high fluctuations due to its early decline. Bairwa *et al.* (2024) also reported that pearl millet production trends closely follow area fluctuations, particularly in regions experiencing structural changes in cropping pattern.

Table 2. Descriptive analysis of pearl millet's Production (000' quintal).

Districts	Mean	Min	Max	Std. Dev.
Azamgarh	3.08	0.58	14.42	2.851
Ayodhya	0.22	0.01	1.66	0.369
Ballia	47.32	9.93	303.90	66.241
Mau	3.72	0.16	41.99	7.365
Jaunpur	71.29	33.31	162.51	28.070
Bhadohi	102.91	64.55	169.68	24.088
Varanasi	62.81	30.69	135	25.491
Ghazipur	165.17	68.29	300.04	62.997
Overall	456.57	299.83	799.26	109.3412

Table 3. Descriptive analysis of pearl millet's Productivity (quintal/ha).

Districts	Mean	Min	Max	Std. Dev.
Azamgarh	16.20	7.86	25.07	4.35
Ayodhya	14.50	5.26	30.00	5.07
Ballia	15.50	7.86	24.34	4.37
Mau	16.00	9.27	25.24	3.98
Jaunpur	11.70	6.48	15.76	2.40
Bhadohi	11.80	7.54	19.41	2.63
Varanasi	11.70	7.04	18.40	2.65
Ghazipur	12.20	6.05	17.99	3.51
Overall	12.212	9.023	15.393	1.756

In Table 3. Productivity was more stable compared to area and production, with an average of 12.21 quintal/ha, ranging from 9.02 to 15.39 quintal/ha. Azamgarh recorded the highest average productivity, followed by Mau and Ballia, whereas Jaunpur, Bhadohi, and Varanasi had relatively lower yields. Overall, productivity improved steadily over time, even as the cultivated area fluctuated across the region. Yadav *et al.* (2021) also reported a consistent increase in pearl millet productivity due to genetic improvement and better crop management practices.

Graphical representation of pearl millet trend pattern

Figs. 1-3 present the actual data series alongside the LOESS and three-year moving average smooth for area, production, and productivity, respectively. These visualizations reveal the nature, timing, and magnitude of the underlying trends after filtering short-term inter-annual fluctuations.

Pattern of pearl millet area

The area trend (Fig. 1) shows a clear two-phase pattern. Total area declined sharply from 65.55 thousand ha in 1993–94 to 27.02 thousand ha in 2005–06, mainly due to a steep fall in Ballia district. This decline reflects a shift towards other crops and increased focus on irrigated wheat–rice systems. After this drop, the area gradually recovered and stabilised between 30,000 and 45,000 ha, reaching 43,325 ha in 2022–23. Overall, the turning point occurred around 1998–2001. At the district level, Ghazipur showed a positive trend, while Ayodhya and Mau continued to experience decline.

Pattern of pearl millet production

Production (Fig. 2) followed a pattern similar to area, declining from 799.26 thousand quintals in 1993–94 to a low point in the early 2000s, and then partially recovering to 639.03 thousand quintals by 2022–23, still below the initial level. The lowest production occurred around 2003–04, a few years after the decline in area, reflecting the combined effect of reduced cultivation and fluctuations in yield during that period. At the district level, Ghazipur and Jaunpur showed clear positive trends, supported by stable or improv-

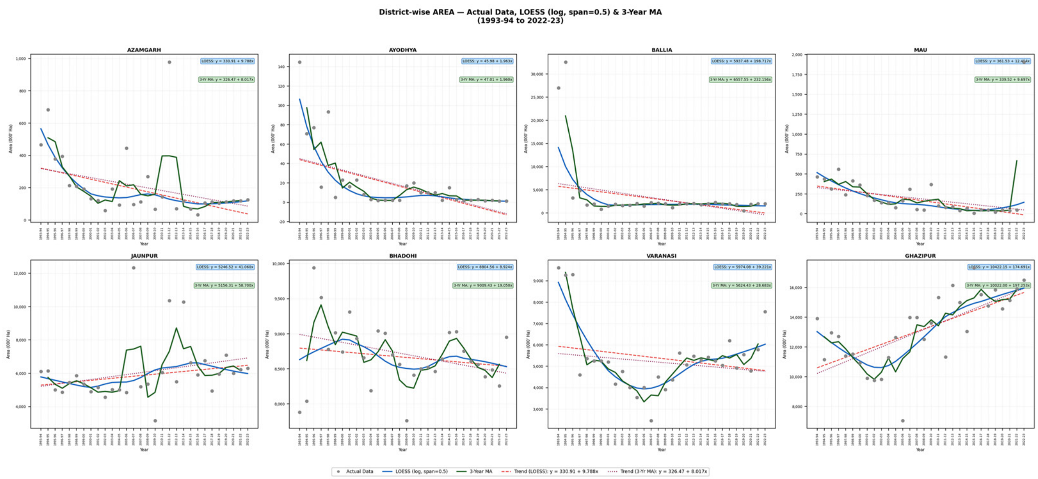

Fig. 1. Trend in pearl millet area (000' ha) across major districts of Eastern Uttar Pradesh: (1993–94 to 2022–23).

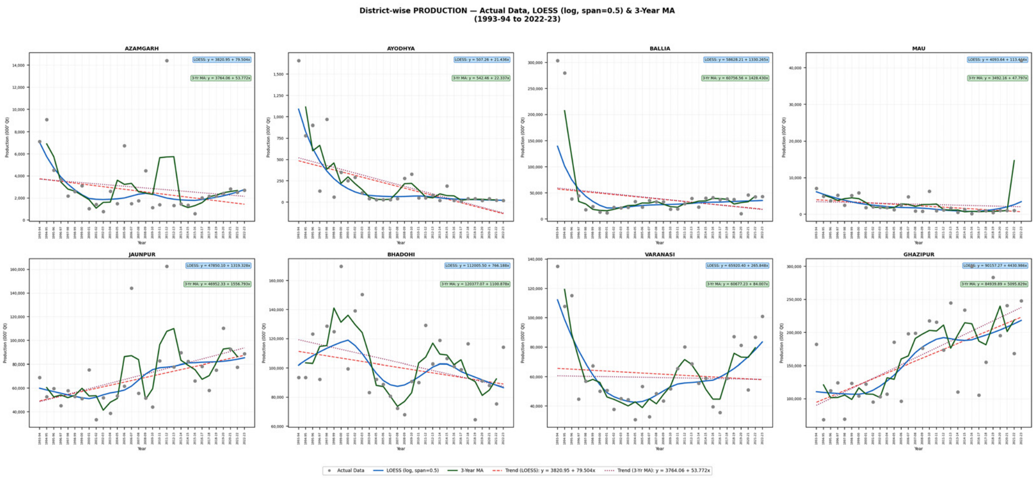

Fig. 2. Trend in pearl millet production (000' quintal) across major districts of Eastern Uttar Pradesh: (1993–94 to 2022–23).

ing cultivation and yields. In contrast, Ballia's sharp decline in area strongly affected overall production in the region.

Pattern of pearl millet productivity (quintal/ha)

The productivity trend (Fig. 3) differs clearly from area and production, showing a steady increase over the entire 30-year period. It rose from 12.19 quintal/ha in 1993–94 to 14.75 quintal/ha in 2022–23, with a peak in 2011–12. This consistent improvement indicates that yield gains were sustained over time, despite fluctuations in area and production. At the district level, Azamgarh and Ballia showed the strongest gains, while Bhadohi and Varanasi recorded modest improvements. Even in Ayodhya, where area declined, productivity remained stable, suggesting that cultivation has shifted towards more suitable land. (Satyavathi *et al.* 2021)

Growth pattern of pearl millet using linear and compound growth rates

Table 4. presents the LGR and CGR estimated from the actual, three-year moving average, and LOESS-smoothed series for area, production, and productivity across all eight districts and for the overall region.

Overall, the area did not show a clear long-term trend, staying close to zero growth (around −0.24%

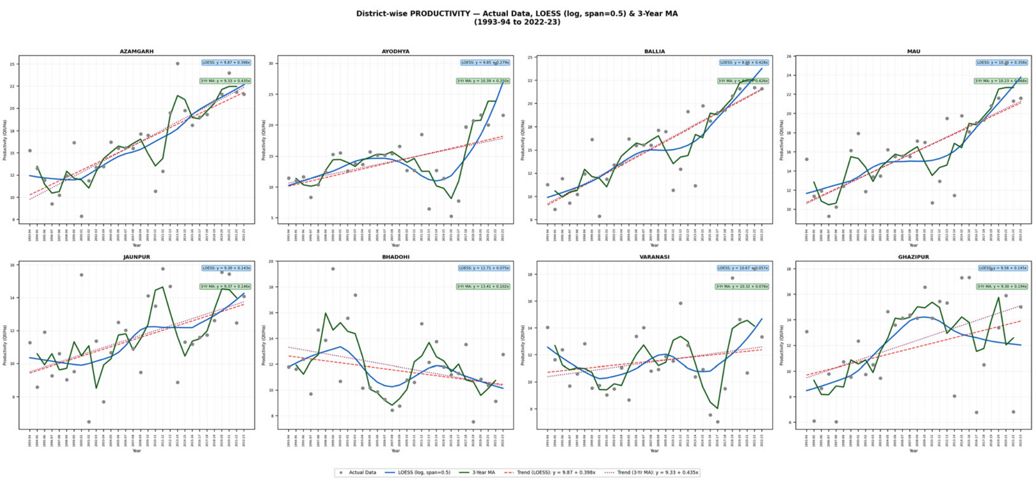

Fig. 3. Trend in pearl millet productivity (quintal/ha) across major districts of Eastern Uttar Pradesh: (1993–94 to 2022–23).

Table 4. Linear and compound growth rates of pearl millet area, production, and productivity - Eastern Uttar Pradesh (1993-94 to 2022-23).

Districts	LGR (%)								
	Area			Production			Productivity		
	Actual	LOESS	M A	Actual	LOESS	M A	Actual	LOESS	M A
Azamgarh	-4.38*	-5.46**	-3.96	-2.51	-3.08**	-1.83	2.46**	2.47**	2.47**
Ayodhya	-12.16**	-12.62**	-11.77**	-11.80**	-12.38**	-11.38**	1.99**	1.96**	1.96**
Ballia	-9.65*	-6.95**	-7.84*	-5.98*	-6.05*	-3.69	2.72**	2.73**	2.73**
Mau	-0.98	-7.39**	-5.12**	2.89	-0.61**	-1.73	2.17**	2.15**	2.15**
Jaunpur	0.80	0.70**	0.96*	1.97*	1.97**	2.19**	1.19**	1.26**	1.26**
Bhadohi	-0.11	-0.10**	-0.21**	-0.81	-0.79**	-1.06**	-0.70	-0.69**	-0.69*
Varanasi	-0.74	-0.73	-0.55	-0.42	-0.34	-0.14	0.62	0.55**	0.55
Ghazipur	1.38**	1.38**	1.50**	2.81**	2.78**	3.10**	1.36*	1.23**	1.23**
Overall	-0.52	-0.52	-0.11	0.46	0.46	0.88	0.87**	0.87**	0.87**

Table 4. Continued.

Districts	CGR (%)								
	Area			Production			Productivity		
	Actual	LOESS	M A	Actual	LOESS	M A	Actual	LOESS	M A
Azamgarh	-4.34**	-4.44**	-3.95	-2.09	-2.03**	-1.56	2.53**	2.50**	2.75**
Ayodhya	-11.25**	-11.57**	-11.02**	-10.94**	-10.87**	-10.62**	1.50	1.55**	1.44*
Ballia	-4.55**	-4.16**	-3.54**	-1.46	-1.47*	-0.56	2.80**	2.77**	2.80**
Mau	-7.07**	-6.80**	-7.52**	-4.74*	-4.50**	-5.01**	2.17**	2.15**	2.31**
Jaunpur	0.78	0.75**	0.98**	2.05**	2.02**	2.28**	1.25**	1.25**	1.25**
Bhadohi	-0.10	0.74**	-0.21**	-0.77	-0.75**	-1.01*	-0.66	-0.67**	-0.81*
Varanasi	-0.40	-0.32	-0.28	-0.06	0.02	0.12	0.45	0.45**	0.56
Ghazipur	1.39**	1.38**	1.51**	3.02**	2.99**	3.37**	1.36*	1.37**	1.74**
Overall	-0.24	-0.35	0.03	0.62	0.53	0.96	0.86**	0.89**	0.91**

to +0.03%) as the initial decline was balanced by a later recovery. Production increased slightly (about +0.62% to +0.96%), but the trend remained weak and somewhat unstable over time. At the same time, productivity showed a steady and significant increase across all series, growing by about +0.87% to +0.92% per year, suggesting that growth in the region is largely driven by improvements in yield.

At the district level, Ghazipur performed the best, with area and production increasing by about +1.39% and +3.02%, respectively, followed by Jaunpur with production growth of around +2.05%. Meanwhile, Ayodhya experienced the sharpest decline (area −11.25% and production −10.94%), while Ballia also saw a noticeable drop in area (−4.19%). Mau showed a decline in area (−7.07%) but recorded positive productivity growth (+2.17%), suggesting that farming is becoming more intensive even on reduced land.

Productivity growth was positive in most districts, especially in Azamgarh (+2.53%), Ballia (+2.80%), Mau (+2.17%), Jaunpur (+1.25%), and Ghazipur (+1.36%). Bhadohi remained almost unchanged (−0.66%), while Varanasi recorded only a slight increase (+0.45%). Overall, the results confirm that yield improvement has been consistent across the region, even where area and production have declined. The identical values of LGR for productivity under LOESS and 3-year moving average smoothing are attributed to the highly stable and near-linear trend in productivity data. Since LGR is based on linear regression, it is less sensitive to minor variations introduced by different smoothing techniques. However, CGR values differ because the logarithmic transformation used in its computation amplifies even small differences between smoothing methods.

CONCLUSION

This study examines how the area, production, and productivity of pearl millet have changed across eight districts of Eastern Uttar Pradesh from 1993–94 to 2022–23. It finds that both area and production declined sharply until around 1998–2001, followed by a partial recovery and stabilisation, largely influenced by major changes in Ballia district. In contrast, productivity shows a steady and consistent increase of about 0.87–0.92% per year across most districts, making it the main driver of growth in the region—likely due to improved crop varieties, better farming practices, and cultivation shifting to more suitable land. The analysis also highlights strong differences between districts: Ghazipur and Jaunpur show clear growth, Ayodhya and Mau continue to decline, while Bhadohi and Varanasi remain relatively stable. Overall, the results suggest that future progress in pearl millet cultivation will depend more on improving yields through better technology, inputs, and market support rather than expanding cultivated area, while district-specific strategies will be essential for effective planning.

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