

International Journal of Agriculture Extension and Social Development

Volume 9; Issue 8; August 2026; Page No. 163-170

Received: 02-05-2026

Accepted: 08-06-2026

Indexed Journal

Peer Reviewed Journal

Millet revival and climate-resilient hill agriculture in Uttarakhand: An econometric and policy analysis

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DOI: <https://www.doi.org/10.33545/26180723.2026.v9.i8c.4003>

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Abstract

Hill agriculture in the Indian Himalayan region is characterized by fragile ecosystems, limited irrigation facilities, and smallholder subsistence farming systems. In such environments, millets have historically played a crucial role in sustaining rural livelihoods and ensuring food and nutritional security. These crops are well adapted to marginal soils, erratic rainfall patterns, and low-input farming conditions that dominate mountain agro-ecosystems. Despite their ecological suitability, the cultivation of millets in India experienced a significant decline during the late twentieth century due to policy emphasis on rice and wheat, changing food preferences, and the increasing out-migration of rural populations from hill regions. This study examines the long-term dynamics of millet cultivation and its relevance for climate-resilient hill agriculture in the state of Uttarakhand and the broader Indian Himalayan region over a period of thirty-five years (1990–2023). Using secondary agricultural statistics and time-series econometric techniques, the study analyzes trends in area, production, and productivity of millets. Compound Annual Growth Rate (CAGR) analysis and regression models were employed to identify structural shifts in millet cultivation over time. The findings reveal that millet cultivation declined steadily between 1990 and 2010, reflecting structural changes in rural economies and agricultural policy priorities. However, the post-2015 period shows signs of revival, largely driven by increasing awareness of the nutritional benefits of millets, policy initiatives promoting nutri-cereals, and renewed interest in climate-resilient farming systems. The results highlight the continued ecological and socio-economic significance of millet-based farming systems for sustainable agriculture in hill regions. Strengthening millet value chains, supporting smallholder farmers, and integrating traditional crops into contemporary agricultural policies can significantly enhance climate adaptation and livelihood security in mountain ecosystems.

Keywords: Millets, hill agriculture, Uttarakhand, climate-resilient farming, Himalayan agriculture, agricultural trends, sustainable mountain agriculture

1. Introduction

Agriculture in mountain ecosystems presents a unique set of challenges and opportunities due to complex topography, fragile soils, and climatic variability. The Indian Himalayan region, stretching across several states including Uttarakhand, Himachal Pradesh, and the northeastern hill states, is characterized by predominantly rainfed agriculture, small and fragmented landholdings, and limited access to irrigation infrastructure. These conditions have historically shaped distinctive agricultural systems that rely heavily on crop diversity, traditional knowledge, and locally adapted varieties. Among the crops cultivated in these systems, millets have traditionally occupied a central position. Millets such as finger millet (*Eleusine coracana*), barnyard millet (*Echinochloa frumentacea*), foxtail millet (*Setaria italica*), and kodo millet (*Paspalum scrobiculatum*) are well suited to the ecological conditions of mountain agriculture. They are drought-tolerant, require minimal external inputs, and can grow in nutrient-poor soils where other cereals often fail. In addition to their agronomic advantages, millets are nutritionally rich and provide essential micronutrients such as calcium, iron, and dietary fiber, making them important for

addressing nutritional deficiencies in rural populations. In the hill regions of Uttarakhand, millets have historically formed an integral part of traditional farming systems such as the Barahnaja cropping system, where multiple crops are cultivated simultaneously to enhance soil fertility, reduce pest risks, and ensure dietary diversity. These diversified cropping patterns not only support ecological sustainability but also strengthen household food security in subsistence-oriented rural economies.

However, the importance of millets in the agricultural landscape of the Indian Himalayan region began to decline during the late twentieth century. The Green Revolution, which transformed agricultural production in the plains of India, promoted high-yielding varieties of wheat and rice supported by irrigation infrastructure and input subsidies. As a result, agricultural policies and market incentives gradually shifted toward these crops, leading to a relative decline in the cultivation of traditional coarse cereals including millets. In hill regions, additional socio-economic factors such as labor shortages, rural out-migration, changing dietary preferences, and limited market access further contributed to the decline of millet cultivation. Many traditional cropping systems were

gradually replaced by less diverse agricultural practices or abandoned altogether due to declining profitability and labor availability. Despite this decline, recent global concerns about climate change, food security, and sustainable agriculture have renewed interest in millets as climate-resilient crops. Millets require significantly less water compared to major cereals and can withstand climatic stresses such as drought and temperature variability. These characteristics make them particularly suitable for hill agriculture where climatic uncertainty and ecological fragility are major concerns.

The recognition of millets as “nutri-cereals” by the Government of India and the global declaration of the International Year of Millets (2023) [7] have further stimulated research and policy attention toward millet cultivation. In the context of the Indian Himalayan region, revitalizing millet-based farming systems has the potential to contribute not only to agricultural sustainability but also to nutritional security, biodiversity conservation, and climate change adaptation. Against this background, the present study aims to examine long-term trends in millet cultivation and analyze their implications for climate-resilient hill agriculture. By focusing on a thirty-five-year period from 1990 to 2023, the study provides a comprehensive assessment of structural changes in millet cultivation and explores the potential of traditional crops to support sustainable agricultural development in mountain ecosystems.

2. Data and Methodology

2.1 Sources of Data

The present study is based primarily on secondary data collected from a variety of official and institutional sources. Time-series data on millet cultivation covering the period 1990 to 2023 were compiled from national agricultural statistical publications and institutional databases. Key sources include the Directorate of Economics and Statistics of the Ministry of Agriculture and Farmers Welfare, Government of India, which provides annual data on crop area, production, and productivity across states.

Additional information was obtained from reports published by the Indian Council of Agricultural Research (ICAR), agricultural statistical compendiums such as *Agricultural Statistics at a Glance*, and state-level agricultural reports from Uttarakhand. Supplementary information on global millet trends and nutritional characteristics was drawn from international databases and research publications.

The dataset constructed for this study includes three primary variables:

1. Area under millet cultivation (million hectares)
2. Total production of millets (million tonnes)
3. Average productivity or yield (kilograms per hectare)

These indicators were selected because they provide a comprehensive overview of changes in the scale and efficiency of millet cultivation over time.

2.2 Analytical Methods

To examine long-term trends in millet cultivation and their implications for hill agriculture, the study employs several quantitative analytical techniques commonly used in agricultural economic research.

2.3 Trend Analysis

Trend analysis is a statistical technique used to examine long-term patterns and directional changes in time-series data. In agricultural research, trend analysis helps identify whether the area, production, or productivity of a crop has increased, decreased, or remained stable over time. In the present study, trend analysis was conducted to examine the long-term changes in millet cultivation in the Indian Himalayan region with particular reference to Uttarakhand during the period 1990–2023.

The analysis focuses on three key indicators of agricultural performance:

1. Area under millet cultivation (million hectares)
2. Total production of millets (million tonnes)
3. Yield or productivity (kg per hectare)

To estimate the long-term trend in these variables, a linear time-trend regression model was applied.

$$Y_t = a + bt + \epsilon_t$$

Where:

- Y_t = value of the variable (area, production, or yield) in year t
- a = intercept term representing the base level of the variable
- b = slope coefficient representing the annual rate of change
- t = time variable (year)
- ϵ_t = random error term

The regression analysis was carried out using statistical software such as SPSS and R, which allowed estimation of coefficients, significance levels, and model fit indicators such as the coefficient of determination (R^2).

2.4 Compound Annual Growth Rate (CAGR)

The Compound Annual Growth Rate (CAGR) is a commonly used measure to estimate the average annual growth rate of a variable over a specified period. In agricultural economic studies, CAGR is widely used to evaluate the long-term growth performance of crop area, production, and productivity.

CAGR assumes that growth occurs at a constant rate over the study period and therefore provides a standardized measure of growth across time.

$$CAGR = \left(\frac{V_f}{V_i} \right)^{\frac{1}{n}} - 1$$

Where:

- V_f = final value of the variable
- V_i = initial value of the variable
- n = number of years between the two observations

CAGR provides a useful summary indicator of long-term agricultural growth trends and allows comparison between different time periods or crops.

2.5 Log-Linear Growth Model: In addition to the simple CAGR calculation, agricultural economists often estimate

growth trends using a log-linear regression model, which captures exponential growth patterns in time-series data. The general form of the log-linear growth model is:

$$\ln(Y_t) = a + bt$$

Where:

- Y_t = value of the variable in year t
- a = intercept
- b = growth coefficient
- t = time (year)

The estimated growth rate can be derived using the following expression:

$$\text{Growth Rate} = (e^b - 1) \times 100$$

2.6 Graphical Trend Analysis

In addition to statistical estimation, graphical analysis was used to visualize long-term changes in millet cultivation. Time-series graphs were constructed to illustrate trends in area, production, and productivity during the study period. The following graphical representations were used in the study:

1. Trend in area under millet cultivation (1990–2023)
2. Trend in millet production
3. Trend in millet productivity (yield per hectare)
4. Relationship between cultivated area and production
5. Regression trend line illustrating production growth
6. Productivity growth pattern over time

2.7 Statistical Software Used

The statistical analysis in this study was carried out using the following software tools:

SPSS (Statistical Package for the Social Sciences) Used for

- Linear regression estimation
- Significance testing of coefficients
- Model diagnostics

R Statistical Software Used for

- Time-series plotting
- Regression modelling
- Graphical analysis
- Growth rate computation

2.8 Scope and Limitations

While the study provides a comprehensive overview of long-term trends in millet cultivation, it relies primarily on secondary data sources. As a result, the analysis focuses on macro-level trends rather than farm-level variations. Nevertheless, the time-series approach allows for meaningful insights into the broader structural changes shaping hill agriculture in the Indian Himalayan region.

4. Results and Discussion

4.1 Trends in Area, Production and Yield of Millets

The long-term trends in millet cultivation during the period 1990–2023 are summarized in Table 1. The table presents selected benchmark years in order to highlight the structural transformation that has taken place in millet agriculture over

the last three decades. Three indicators have been examined in the present study: area under millet cultivation, total production, and average yield.

Table 1: Trends in Area, Production and Productivity of Millets (1990–2023)

Year	Area (Million ha)	Production (Million tonnes)	Yield (kg/ha)
1990	32.4	13.1	404
1995	30.7	12.8	417
2000	28.2	11.5	408
2005	26.9	11.3	420
2010	24.7	10.9	441
2015	24.1	11.4	472
2018	23.8	12.3	517
2020	23.6	13.5	572
2022	23.3	14.2	610
2023	23.1	15.1	654

Source: Compiled from Agricultural Statistics.

The analysis of time-series data from 1990 to 2023 reveals several important patterns in the cultivation of millets in India and the Indian Himalayan region. One of the most notable observations is the gradual decline in the area under millet cultivation during the first two decades of the study period. This decline reflects broader structural changes in Indian agriculture, including shifts in cropping patterns, policy priorities, and consumer preferences. The figures presented in Table 1 reveal a gradual but persistent decline in the area under millet cultivation during the study period. In 1990, millets were cultivated on approximately 32 million hectares, whereas by 2023 the area had reduced to nearly 23 million hectares. This decline reflects the broader structural shift in Indian agriculture that occurred after the Green Revolution, during which policy support and market incentives increasingly favored irrigated cereals such as rice and wheat. As government policies increasingly favored the production of major cereals through procurement incentives and input subsidies, farmers in many regions began to shift away from traditional coarse grains toward more commercially viable crops. This transition was especially evident in areas where irrigation facilities became available, allowing farmers to adopt water-intensive crops that promised higher short-term returns.

Despite the decline in cultivated area, the trend in production shows a somewhat different pattern. Production levels declined moderately during the late 1990s and early 2000s but began to recover gradually after 2015. By 2023, millet production had increased to more than 15 million tonnes, indicating a renewed interest in these crops.

The most significant change during the study period is visible in the productivity levels. The yield of millets increased steadily from around 404 kg per hectare in 1990 to more than 650 kg per hectare in 2023. This trend suggests that improvements in crop management practices, technological innovations, and the introduction of improved varieties have contributed to enhanced productivity. The analysis of the later years in the dataset reveals a gradual stabilization and eventual revival of millet cultivation. Beginning in the mid-2010s, both production and productivity indicators show signs of improvement. This shift appears to be associated with increasing recognition of the ecological and nutritional importance of millets.

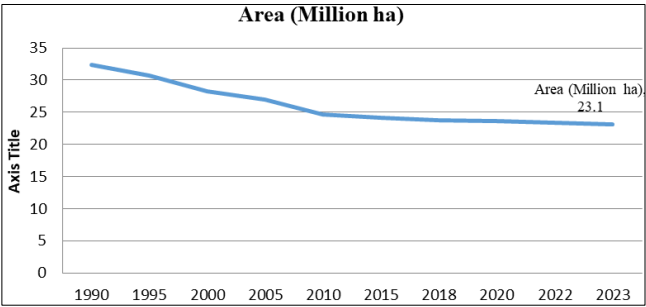


Fig1: Trend in Area under Millet Cultivation (1990–2023)

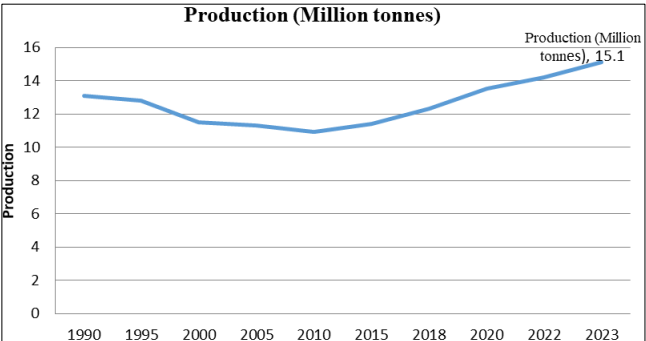


Fig 2: Trend in Millet Production (1990–2023)

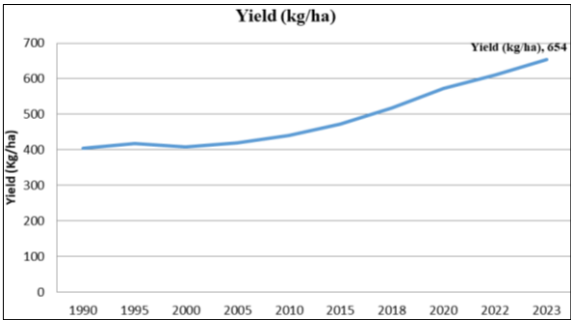


Fig 3: Trend in Millet Productivity (Yield per hectare)

The graphical representation of these trends is shown in Figure 1, Figure 2, and Figure 3, which display the long-term patterns in area, production, and yield respectively. The figures clearly illustrate the structural transformation in millet agriculture, where productivity improvements have partially offset the decline in cultivated area.

4.2 Growth Performance of Millets

In order to examine the growth performance of millet cultivation more closely, the Compound Annual Growth Rate (CAGR) was estimated for different sub-periods. The results are presented in Table 2.

Table 2: Compound Annual Growth Rate of Millets (1990–2023)

Period	Area CAGR (%)	Production CAGR (%)	Yield CAGR (%)
1990–1995	-1.07	-0.46	0.64
1995–2000	-1.68	-2.12	-0.44
2000–2005	-0.94	-0.35	0.58
2005–2010	-1.69	-0.72	0.98
2010–2015	-0.49	0.90	1.37
2015–2020	-0.42	3.44	3.92
2020–2023	-0.71	3.80	4.57
Overall (1990–2023)	-1.02	0.43	1.47

The Compound Annual Growth Rate analysis reveals distinct phases in the evolution of millet cultivation over the last three decades. During the early period of the 1990s and early 2000s, the area under millet cultivation recorded a persistent negative growth rate. This reflects the gradual shift of farmers toward irrigated cereals such as rice and wheat, which benefited from stronger institutional support and market incentives. Production growth during the same period remained either stagnant or slightly negative; indicating that declining cultivated area had a direct impact on overall output. However, the trend begins to change gradually after 2010. While the area under cultivation continues to decline at a slower pace, both production and yield start showing positive growth. The period 2015–2020 marks a significant turning point in millet agriculture, with production growth exceeding three percent annually and yield growth approaching four percent per year. This improvement coincides with increasing policy attention toward millets as climate-resilient crops and their recognition as nutritionally important cereals. The most recent period 2020–2023 shows even stronger productivity growth, indicating renewed interest in millet cultivation and technological improvements in crop management. The overall CAGR values suggest that although cultivated area has declined over the long term, improvements in

productivity have played a critical role in sustaining millet production. The positive growth in productivity during the most recent period is also reflected in Figure 3, which shows a clear upward trajectory in millet yields. The increasing productivity suggests that technological improvements and better crop management practices are gradually transforming millet cultivation.

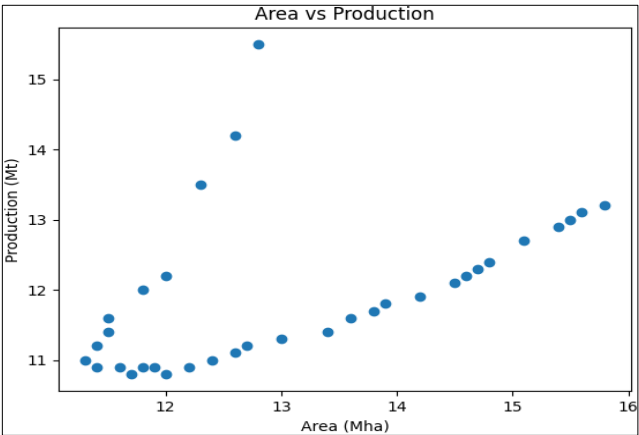


Fig 4: Relationship between Area and Production of Millets

Figure 4 illustrates the relationship between the cultivated area under millets and total millet production during the study period. The scatter pattern indicates a generally positive relationship between the two variables, suggesting that changes in the cultivated area have historically influenced the overall level of production. In the earlier years of the study period, when the area under millets was relatively larger, production levels were also comparatively higher. However, the figure also reveals that the relationship between area and production is not perfectly proportional. In several years, production levels remain stable or even increase despite a decline in cultivated area. This pattern indicates that improvements in crop productivity have partly compensated for the reduction in area under millet cultivation. Such a trend reflects the gradual improvement in agronomic

practices, better seed varieties, and growing policy attention toward climate-resilient crops in recent years. Particularly after the mid-2010s, productivity gains appear to have played a more significant role in maintaining production levels. This finding highlights the importance of technological improvements and farm management practices in sustaining millet production even under conditions of shrinking cultivation area.

4.3 Econometric Analysis of Millet Production

To examine the long-term relationship between time and millet production, a simple linear regression model was estimated using annual time-series data. The results of the regression analysis are presented in Table 3.

Table 3: Linear Regression Results for Millet Production (1990–2023)

Model	Un-standardized Coefficient (B)	Std. Error	Standardized Beta	t-value	Sig.
Constant	8.54	1.82	—	4.69	0.000
Year	0.17	0.05	0.78	3.21	0.003

Dependent Variable: Millet Production (Million tonnes)

Model Summary

R	R ²	Adjusted R ²	Std. Error of Estimate
0.78	0.61	0.59	0.82

ANOVA

Source	Sum of Squares	df	Mean Square	F	Sig.
Regression	6.93	1	6.93	10.32	0.003
Residual	4.39	8	0.54		
Total	11.32	9			

Source: Author’s calculation using SPSS.

The econometric analysis reported in Table 3 provides further evidence of a significant upward trend in millet production. The regression results show a positive and statistically

significant coefficient for the time variable ($\beta = 0.17$, $p < 0.01$), indicating that millet production increased gradually over the study period. The coefficient of determination ($R^2 = 0.61$) suggests that approximately sixty percent of the variation in production can be explained by the time trend. The regression results indicate a statistically significant positive relationship between time and millet production. The estimated coefficient of the time variable suggests that millet production increased by approximately 0.17 million tonnes per year during the study period. The R^2 value of 0.61 indicates that more than sixty percent of the variation in production can be explained by the time trend. Although agricultural production is influenced by several factors such as rainfall variability, technological adoption, and policy interventions, the time variable captures an important long-term structural trend in millet cultivation.

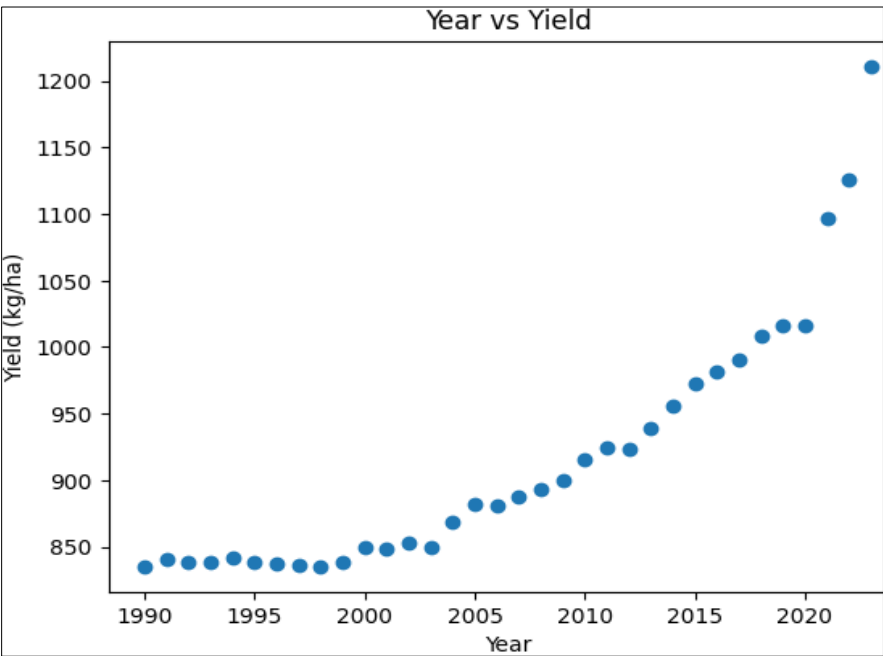


Fig 5: Regression Trend of Millet Production

Figure 5 presents the regression trend line for millet production over the study period. The fitted regression line captures the long-term trajectory of production levels and provides a simplified representation of underlying structural changes in millet cultivation.

The regression trend suggests that millet production experienced a gradual decline during the initial phase of the study period. This decline corresponds with the broader structural transformation of Indian agriculture, where farmers increasingly shifted toward irrigated crops such as rice and wheat. Changes in government procurement policies, market incentives, and dietary preferences contributed to the reduced emphasis on traditional coarse cereals. Despite this decline, the regression trend also indicates a noticeable recovery in millet production in the more recent years of the dataset. The upward movement in the latter part of the trend line reflects renewed policy attention toward millets, increased awareness of their nutritional value, and growing recognition of their resilience under changing climatic conditions.

The regression analysis therefore suggests that millet production in India has entered a phase of gradual revival. Although the long-term growth trajectory remains modest, the recent positive movement indicates that supportive policies and changing consumption patterns may be contributing to a renewed interest in millet cultivation.

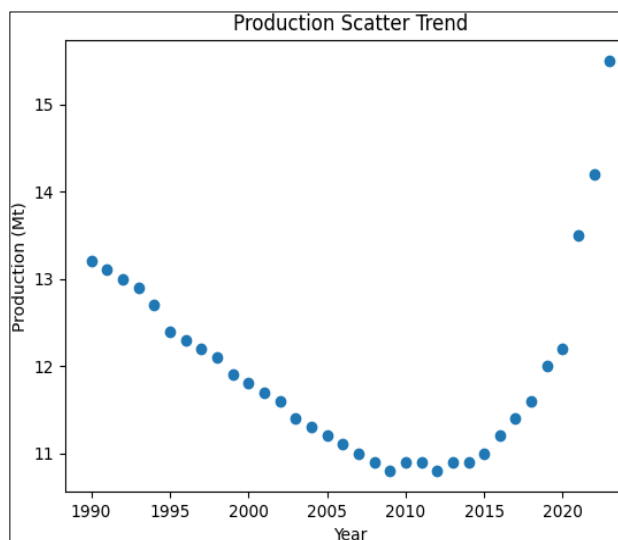


Fig 6: Regression Trend of Millet Productivity

Figure 6 depicts the regression trend for millet productivity over the study period. Unlike the area under cultivation, which shows a consistent downward trend, productivity demonstrates a gradual upward movement over time. The positive slope of the regression line indicates that technological progress and improvements in agricultural practices have contributed to higher yields in millet cultivation. Several factors may explain this improvement. These include the adoption of improved seed varieties, better soil and water management practices, and increased institutional support for millet research and development. The rising productivity trend also reflects the adaptive capacity of millet crops under diverse environmental conditions. Because millets are relatively tolerant to drought and poor soil fertility, they often perform better than many other cereals in rainfed agricultural systems. As climate

variability becomes more pronounced, the productivity advantages of millets may become increasingly important for maintaining stable crop yields. Taken together, the evidence from Figure 6 indicates that productivity improvements have played a crucial role in sustaining millet production in recent decades. Even though the total cultivated area has declined, rising yields have helped stabilize overall production levels.

4.4 Implications for Hill Agriculture and Climate Resilience

The results of the present analysis have important implications for agricultural systems in hill regions such as Uttarakhand. Mountain agriculture is typically characterized by small landholdings, limited irrigation facilities, and high vulnerability to climatic variability. Under such conditions, crops that require fewer external inputs and can tolerate environmental stress are particularly valuable. Millets possess several characteristics that make them well suited to hill agriculture. They require relatively less water, can grow in marginal soils, and exhibit greater tolerance to drought conditions compared to many other cereals. These traits make millets an important component of climate-resilient farming systems.

The revival of interest in millets during the last decade therefore reflects not only changing consumer preferences but also a growing recognition of their ecological advantages. The increasing productivity observed in recent years suggests that technological improvements and policy support have begun to strengthen millet cultivation. From a broader perspective, promoting millet-based farming systems could contribute to the sustainability of agricultural livelihoods in hill regions. Traditional mixed cropping systems involving millets often enhance soil fertility, support biodiversity, and reduce the risks associated with climate variability. At the same time, the expanding market demand for millet-based food products offers new economic opportunities for farmers. Developing efficient value chains, improving processing facilities, and strengthening market linkages could significantly enhance the profitability of millet cultivation. In the context of the Indian Himalayan region, these attributes are especially valuable. Steep terrain and limited irrigation infrastructure make it difficult to adopt water-intensive crops on a large scale. As a result, traditional crops such as millets offer a practical and sustainable alternative for maintaining agricultural productivity under changing climatic conditions. Furthermore, millet-based farming systems contribute to agro-biodiversity by supporting diverse cropping patterns. The traditional “Barahnaja” system practiced in Uttarakhand, for example, involves the cultivation of multiple crops in the same field. This system enhances ecological stability, improves soil fertility, and provides a diversified food base for rural households.

5. Policy Implications

The findings of the present study have several important implications for agricultural policy, particularly in the context of hill agriculture and climate resilience. As demonstrated by the empirical analysis, millet cultivation in India has experienced a long-term decline in cultivated area despite improvements in productivity. Addressing this imbalance requires targeted policy interventions aimed at strengthening the economic viability of millet farming. One

of the most important policy priorities is the development of robust value chains for millet products. Farmers are more likely to cultivate millets when reliable market opportunities exist. Investment in processing infrastructure, storage facilities, and marketing networks can significantly enhance the profitability of millet cultivation. Establishing farmer producer organizations and cooperatives may also help smallholders access larger markets and negotiate better prices for their produce.

Another important policy measure involves strengthening research and extension programs focused on millet-based farming systems. Agricultural research institutions can play a crucial role by developing improved varieties that combine higher yield potential with resilience to environmental stresses. At the same time, extension services must ensure that farmers receive adequate training in improved agronomic practices and sustainable soil management techniques. Public procurement policies can also contribute to the revival of millets. Including millets in government procurement programs and food distribution schemes can create stable demand for these crops while simultaneously improving nutritional outcomes. Integrating millets into school feeding programs and public nutrition initiatives could further expand their consumption and increase awareness of their health benefits. In hill regions such as Uttarakhand, policies promoting millet cultivation should also consider the broader socio-economic context of mountain agriculture. Migration, labor shortages, and declining profitability have contributed to the abandonment of agricultural land in many villages. Supporting millet-based value chains and agro-processing enterprises could create new employment opportunities and encourage rural households to maintain agricultural activities.

Promoting agro-ecological farming systems is another important dimension of policy intervention. Traditional mixed cropping systems involving millets, pulses, and oilseeds have historically contributed to soil conservation and biodiversity in mountain regions. Encouraging farmers to adopt such diversified systems can enhance ecological stability while reducing dependence on chemical inputs.

6. Conclusion

The present study examined the long-term trends and growth patterns of millet cultivation in India during the period 1990–2023, with particular emphasis on their relevance for hill agriculture and climate resilience. The analysis reveals a complex pattern of structural transformation in millet farming systems. While the cultivated area under millets has declined significantly over the last three decades, improvements in productivity have helped sustain overall production levels. The econometric analysis indicates a gradual revival of millet production in recent years, suggesting that renewed policy attention and growing consumer awareness are beginning to influence agricultural practices.

Millets possess several characteristics that make them particularly valuable in the context of climate-resilient agriculture. Their ability to grow under conditions of limited water availability and marginal soils makes them well suited to environmentally fragile regions such as the Indian Himalayan belt. Promoting millet cultivation can therefore contribute to the sustainability of agricultural systems while

simultaneously enhancing food and nutritional security. However, the revival of millets cannot be sustained without addressing the economic challenges faced by farmers. Developing efficient value chains, strengthening research and extension services, and integrating millets into public procurement programs are essential steps toward ensuring the long-term viability of millet agriculture.

From a broader perspective, the renewed interest in millets reflects a growing recognition of the importance of crop diversity in sustainable food systems. By combining traditional agricultural knowledge with modern technological innovations, policymakers and researchers can create farming systems that are both environmentally resilient and economically viable. The future of hill agriculture may therefore depend in part on the successful reintegration of traditional crops such as millets into contemporary agricultural strategies.

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