



RESEARCH ARTICLE

Impact of climate change on millet productivity in India

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Abstract

Climate change is a major threat to agricultural productivity, particularly in semi-arid and rainfed regions where climate-resilient crops are vital for food and nutritional security. Using district-level panel data from International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Directorate of Economics and Statistics (DES), this study investigates the impact of climate change and resource allocation on millet productivity in major millet-producing states in India from 1966–2015. To estimate the impact of temperature, water deficit, irrigation, fertiliser, rainfall and crop diversification on millet productivity, a fixed-effect panel regression model is conducted. The results indicate that the effect of climate change differs among different millet crops of India. The productivity of overall millets, pearl millet and finger millets is considerably reduced by rising temperatures, while kharif sorghum, rabi sorghum and pearl millet are adversely affected by water deficit. The negative impact of interaction between temperature and irrigation suggests that irrigation alone is insufficient to mitigate heat stress. Even though millets are known as climate-resilient crops, their responses to climatic conditions vary among different types of millets. The results point out the necessity of crop-specific adaptation strategies, efficient resource management and consistent investment in resilient millet production to enhance sustainable agriculture, food and nutritional security in a situation of climate change in India.

Keywords: agro-climate variability; climate adaptation; climate resilience; fixed effects models; panel data analysis; sustainable agriculture

Introduction

Climate change has become a critical issue for worldwide agricultural sustainability, especially in semi-arid and rainfed areas where crop yields are heavily dependent on climatic conditions. Rising temperatures, unpredictable rainfall and extreme climate change threaten agricultural productivity, food security and rural livelihoods, revealing the necessity for the development of resilient agricultural systems. Enhancing agricultural production and providing food security are essential for sustainable development and directly help to achieve the sustainable development goals (SDGs), especially SDG 2 (Zero Hunger) (1, 2). Agricultural productivity increased food availability by maximising the efficient utilisation of land, water and other resources, while food security maximises nutritional outcomes, sustains rural livelihoods and promotes sustainable economic growth. Moreover, sustainable agricultural systems enhance resilience to climate-related threats, alleviate poverty and promote sustainable economic growth, thus helping to achieve the main objectives of the SDGs (3).

Climate change adversely impacts the development and growth of the economy by disrupting the health of human resources. Developing and low-income countries are particularly vulnerable because they are disproportionately exposed to rising temperatures, floods, cyclones and other extreme events. Extreme climate events reduce Gross Domestic Product (GDP) growth by lowering productivity, destroying assets and resources and increasing migration, among other effects (4). These impacts

emphasise the need to promote crops and production systems that are less sensitive to climatic variability and extreme events.

Historical evidence shows that millets are climate-resilient crops (5). Millet can be grown under adverse agro-climatic conditions, including low rainfall and poor soil quality, making it important for developing and emerging countries to bridge their nutritional gaps. Millets require fewer inputs to yield optimal food output. Hence, it can be one of the solutions for increasing food security. Millets are classified broadly into two categories. Major millets include sorghum and pearl millet, while minor millets comprise finger millet, foxtail millet, little millet, kodo millet, proso millet and barnyard millet.

Millets are highly rich in fibre, protein, iron, calcium and micronutrients. Moreover, they possess a low glycemic index, which helps in managing diabetes. These crops offer numerous advantages, such as their gluten-free status, which makes them suitable for individuals with gluten intolerance (6). It helps combat malnutrition and promote balanced diets. In terms of production costs, it requires less water and inputs than rice and wheat. Even though it is tolerant to heat, poor soils and erratic rainfall, it is ideal under climate stress. It also supports smallholder and marginal farmers with low production costs. There are dual benefits: grain for food and straw for animal fodder. It has also been found to be environmentally sustainable. Producing this enhances soil health and promotes biodiversity because it requires minimal fertiliser and pesticide use (7). Additionally, millets are deeply rooted, which helps

prevent soil erosion and improve soil structure (8). It also reduces greenhouse gas emissions compared to an intensive cereal system.

India is the leading producer of millets globally and significantly impacts their worldwide cultivation and consumption (9). Despite recent government initiatives, such as the National Food Security Mission and designation of 2023 as the International Year of Millets (2023), millet productivity remains showing significant spatial and temporal variability throughout the nation (10). This diversity is primarily influenced by the disparities in climatic conditions, irrigation access and resource endowments among districts of India. Moreover, agricultural policies have traditionally favoured rice and wheat through procurement support, irrigation projects and input subsidies, thus limiting technological progress and productivity in millet cultivation. Despite a developing body of literature examining the relation between climate change and agricultural productivity in India, three significant study gaps remain. Most prior research examines aggregate agricultural output or considers millets as an identical crop, providing insufficient information regarding the diverse responses of specific millet varieties to climate change. Secondly, current research primarily depends on national or state-level data, thus revealing significant district-level variability in climate change, consumption of resources and agricultural methodologies. Third, insufficient effort has been directed into examining whether irrigation and other farm-level resource utilisation characteristics can mitigate the adverse impacts of rising temperatures and water scarcity on various millet crops.

This study analyses a longitudinal district-level panel dataset (1966–2015), including the major millet-producing state of India, to solve such gaps. In contrast to aggregate data, district-level panel data contain both geographical and temporal variability while taking into consideration unknown district-specific features using a fixed-effect model. This study analyses total millets alongside kharif sorghum, rabi sorghum, pearl millets and finger millet individually, providing crop-specific evidence that enhances the current literature and provides targeted policy recommendations for climate adaptation and sustainable millets production. In addition, the study incorporates farm-specific inputs, such as fertiliser use, irrigation and cropping diversity, to estimate Simpson's Diversity Index (SDI). By assessing both aggregate millet productivity and the performance of major millet varieties, this study sheds light on how resource management and climate change impact agricultural sustainability. The results support policy debates on millets as a practical route to food security, climate-resilient agriculture and sustainable economic growth in India. Further evidence and detailed discussions related to this topic are presented in the literature review section, which offers an extensive overview of previous research and important theoretical and empirical discoveries.

Literature review

A systematically organised search approach was used for the literature review. Relevant studies were obtained from Scopus, Web of Science, Science Direct and Google Scholar with keywords including climate change, climate variability, millet production, temperatures and climate resilience. Priority was given to empirical studies using quantitative or econometric methods that showed millet production was affected by climate change. The chosen studies were carefully examined to determine the main findings, methodological strategies and research problems that guided the current analysis.

Impact of climate change

The adverse impact of climate change on agriculture and economic development is a major issue for all economies. Climate change intensifies abiotic stresses like drought, heat, salinity and nutrient deficiencies, severely impacting crop productivity and food security. Floods, droughts and cyclones are examples of extreme weather events that result in food shortages, injuries, displacement and mental health issues like stress, anxiety and depression. It has been found that there have already been quantifiable, significant health losses, both in terms of lives lost and financial expenses caused by climate change on a global scale. The authors urge that climate change be immediately acknowledged as a global health emergency, that attribution science be extended to underserved areas and that this evidence be used to promote funding for loss and damage, adaptation and accountability (9). Even according to the 2024 Lancet Countdown Report on Health and Climate Change in Small Island Developing States (SIDS), the health of people in small island developing states is already being significantly affected by climate change. These countries face escalating health crisis, financial turmoil and relocation in the absence of prompt, well-funded mitigation and adaptation initiatives. According to recent studies, rising temperatures, unpredictable rainfall and an increase in the frequency of extreme weather events are among the major risks posed by climate change to Thailand's agricultural sector (11). Extreme climate scenarios lead to significant yield declines, especially in rainfed systems, while moderate climate scenarios predict modest yield increases for irrigated rice due to CO₂ fertilisation (12). Water productivity is expected to decline and water scarcity will worsen as crop water requirements and irrigation demand rise significantly. Resource-poor households are disproportionately vulnerable to these effects, which negatively impact farmers' incomes, food security and livelihood stability. Agrarians in India are also disproportionately affected by rising temperatures and unpredictable precipitation (13). As a result, there is a significant loss of crop yield. Stronger institutional support, climate-resilient crops and better water management are necessary for effective adaptation. Climate change issues can be addressed by analysing their impacts across all sectors. It could be achieved by accurately assessing and adapting to future climate change and by modelling climate data use by research teams, harmonising modelling methods and embedding resilience and adaptability into both simulation and design practices (14). Even plants respond through molecular, biochemical and physiological mechanisms, but innovative strategies are needed to enhance resilience (15). Hence, there is a need for adaptable resources to support our economy and mitigate the impacts of climate change.

Millet and other crops

The threat climate change poses to Indian agriculture are widely discussed, especially regarding crop yields. Due to their minimal water requirements, strong tolerance to harsh temperatures, capacity to flourish in poor soil conditions and short growing seasons, millets are widely acknowledged as climate-resilient crops. They are also abundant in vital nutrients and comparatively resilient to environmental stress. However, millet productivity in India is negatively affected by factors such as illness, extreme heat, drought and the presence of anti-nutritional compounds. Millets have experienced significant production losses and a decline in consumption despite their ability to withstand climate stress (16). There is a need for biotechnological methods to improve crop yields

and quality to overcome the limitations of millet production. Previous study reflects that due to the deep-rooted system, sorghum, finger and pearl millets are drought-tolerant, although finger millets need more rainfall as compared to pearl millets (17). Other studies also suggest that, to secure food security in India, crops such as sorghum, finger millet and pearl millet are major instruments due to their climate resilience and ability to mitigate the impact of climate variability (18, 19).

Impact of climate change on crop production

Numerous studies indicate that climate change adversely affects overall economic productivity, primarily through its impact on agriculture. This study examines the most recent research on the detrimental effects of climate change on agricultural output, the major related challenges and potential adaptation strategies. Their strategies include adjusting crop planting densities and timing, rotating crops with legumes, agroforestry, mixed livestock systems, climate-resilient plants, fish and livestock breeds, monogastric livestock farming, early warning systems, decision-support systems, carbon sequestration; climate, water, energy and soil-smart technologies; and biodiversity promotion. Over the past decades, the production of millets in India has seen a steady increase, supported by reforming policy measures and rising consumer demand (20). Total millet production was around 13.21 million tonnes in 2021 and rose to 18.02 million tonnes in 2024–2025. Despite these positive trends, productivity improvement remains significantly divergent among states and districts due to variation in meteorological conditions, irrigation accessibility and resource endowment. The ongoing regional disparities indicate that improvement in overall production doesn't automatically result in consistent productivity increases. It emphasises the necessity for district-level empirical data to better understand the different effects of climate change on millet productivity.

Despite these advances, there is limited research on climate-resilient cereals, indicating an important gap in the sustainability literature. By addressing these gaps in the literature, this work advances previous studies. For instance, a previous study provides a narrative review of the biological and environmental factors that affect millet production; it lacks empirical analysis evaluating the effects of climate variability and farm-level management practices on millet productivity across Indian regions and crop types (21, 22). A state-level panel data approach is used in this study to close this gap. The study by earlier researcher examines major crops such as rice, wheat, corn, sorghum, pulses and oilseeds but does not explicitly focus on climate-resilient millets—finger millet, pearl millet and small millet—that are essential to dryland agriculture. Moreover, their analysis does not incorporate crop diversification or nutritional security dimensions (23). Further, it was observed that the productivity and climate resilience of finger millets; however, their analysis is graphically limited and primarily descriptive, limiting broader insights across agroclimatic zones and other important millets such as sorghum and pearl millet (24). Additionally, existing studies do not shed light on the role of SDI in evaluating resilience under climate stress, an essential metric. More broadly, there is a lack of understanding of heterogeneous responses across regions due to the absence of a comparative multi-crop and multi-state panel approach. These gaps indicate a need for a comprehensive study that examines how resource use, diversification and climate change relate to the millet crop.

Data source and methodology

Sorghum, pearl millet and finger millet are significant climate-resilient crops mainly grown in semi-arid regions of India due to their capacity to tolerate unfavourable climatic and soil conditions. Their role in this study depends on their resilience to climate change and their increasing economic and nutritional significance, as evidenced by the Government of India's declaration of 2018 as the national year of millets. The analysis employs an unbalanced district-level panel dataset that included major millet-producing states in India from 1966–2015, obtained from the International Crops Research Institute for Semi-Arid Tropics (ICRISAT) and the Directorate of Economics and Statistics (DES). During data cleaning, observations with absent values were eliminated and descriptive analysis along with the Variance Inflation Factor (VIF) was employed to evaluate multicollinearity. The VIF values varied from 1.28–8.38 with a mean of 2.20, indicating the absence of significant multicollinearity among explanatory variables. To mitigate any non-linearity, the average maximum temperature variable was mean-centred before the formulation of its quadratic term. To see crop diversification impact, which is measured by using SDI, a generally used methodology for evaluating the degree of crop diversification by examining the relative allocation of cultivable land among various crops. The index considers both the quantity of crops cultivated and the proportional area allocated for each crop. The higher SDI value indicated greater crop diversification, whereas a lower value shows crop specialisation. The SDI was calculated as:

$$SDI = 1 - \sum_{i=1}^N P_i^2 \quad (\text{Eq. 1})$$

Where P_i means the ratio of cultivated area for the i th crop to the overall crop to the overall cultivated area and n signifies the total number of crops cultivated. The SDI ranges from 0 to 1, with a value of 0 signifying total specialisation (cultivation of a single crop), while values near to 1 show increased crop diversification and more equitable allocation of cultivated area across several crops (25).

The panel method included pooled ordinary least squares (OLS), fixed effects and random effects models. The selection of the model was determined by the Hausman and Breusch-Pagan Lagrangian multiplier tests, which simultaneously indicated the use of a two-way fixed-effect model to account for unobserved heterogeneity across districts and common time-specific shocks. The empirical model is specified as follows:

$$\ln(Y_{it}) = \beta_0 + \beta_1 X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (\text{Eq. 2})$$

Where:

Y_{it} = Millets yield in district i during year t ;

X_{it} = vector of climate and agricultural management variables;

μ_i = district fixed effects;

λ_t = Year fixed effects;

ϵ_{it} = error term.

Description and analysis

Descriptive analysis

Descriptive analysis provides an overview of the climate-related, agricultural and ecological factors affecting millet productivity across Indian states. There are 8575 district-year observations, which reveal significant temporal and spatial changes across diverse agro-ecological zones. Table 1 shows that millet's average output of

Table 1. Descriptive analysis of climate and agricultural variables

Variable	Observations	Mean	Std. Dev.	Min	Max
Millet yield (kg/ha)	8575	900	488.56	0	4808.77
Kharif sorghum (kg/ha)	8575	752.80	525.70	0	6531.25
Rabi sorghum (kg/ha)	8575	318.00	647.60	0	10000
Pearl millet (kg/ha)	8575	673.71	567.89	0	4098.46
Finger millet (kg/ha)	8575	382.00	617.88	0	4230.77
Average annual maximum temperature (°C)	8575	31.80	2.55	7.18	35.91
Annual water deficit (mm)	8575	80.43	24.70	3.13	365.03
Proportion of millet irrigated area	8575	0.35	0.31	0.000013	1
Rainfall in high-rainfall states (mm)	3484	990.00	634.78	9.80	5289
Rainfall in low-rainfall states (mm)	2008	657.52	361.00	22.10	4508
Nitrogen consumption per hectare (kg/ha)	8575	86.80	95.82	0	847.83
Shannon Diversity Index (SDI)	8575	0.51	0.18	0	0.80
Annual rainfall (mm)	8575	910.86	526.41	9.10	5289
Annual minimum temperature (°C)	8575	19.68	2.36	-1.98	26.10

Water deficit: Squared value of average water deficit, representing the intensity of moisture stress experienced during the crop growing season. The squared term is included to capture the potential non-linear effect of water stress on millet productivity. Proportion of irrigated millet area: Measures the share of the total millet cultivation area that is irrigated within a district during a given year. It reflects the extent to which millet production depends on irrigation rather than rainfall. Minimum temperature: Annual average minimum temperature recorded for each district. This variable captures the influence of lower temperature conditions on crop growth and productivity.

900 kg/ha indicates average productivity levels. However, there are significant interstate differences in yield (Standard deviation (SD) = 489; range = 0–4809 kg/ha), reflecting heterogeneity in climatic conditions, input use and management practices (25, 26). Such variation suggests that productivity outcomes are highly sensitive to rainfall, better seed varieties or easier access to inputs. According to earlier studies, crop productivity and farmers' capacity to adapt to changing climate conditions can be significantly impacted by variations in rainfall patterns, the use of better seed varieties and greater access to agricultural inputs (27, 28). The average yield of kharif sorghum (752 kg/ha) is higher than that of rabi sorghum (318 kg/ha), indicating a seasonal reliance on monsoon rainfall. This may be due to the cultivation of kharif sorghum during the monsoon season, when soil moisture and precipitation are often more favourable for crop growth and increased yields. A recent study also demonstrates a significant relation between monsoon rainfall patterns and sorghum yields, particularly in rainfed agricultural systems, which is dependent on seasonal precipitation (26). High standard deviations are recorded for finger millets (382 kg/ha) and pearl millets (674 kg/ha), signifying considerable geographical and temporal heterogeneity in productivity among districts. This diversity presumably reflects changes in climatic circumstances, rainfall allocation, temperature fluctuations, irrigation availability and resource endowments, emphasising the necessity of analysing climate change impact on the productivity of millets. Most millet-growing locations are warm and semi-arid, according to climate indicators. The average monthly maximum temperature is roughly 31.8 °C and the minimum temperature is roughly 19.7 °C, both of which are consistent with millet-growing conditions. Nonetheless, the observed variability (SD = 2.7 °C) indicates cultivation in a wide variety of climatic zones, from hot plains to colder highland regions. Although the average annual rainfall is about 910 mm, the incredibly large variation (from 9.10 mm to over 5289 mm) suggests that India's climate is highly heterogeneous. The average monthly water deficit of 80 mm indicates recurrent moisture stress across many millet-producing areas, underscoring the significance of these crops in low-rainfall, drought-prone areas. The rainfall-dependent nature of millet agriculture is further highlighted by irrigation variables. Regional differences in irrigation infrastructure are evident: on

average, only 35 % of millet land out of the total land is irrigated, with a high standard deviation of 0.31. Since irrigation resources are usually devoted to water-intensive crops like rice, sugarcane and wheat, millets make up a minor share of irrigated crops.

The difference in rainfall between high-rainfall states (mean = 990 mm) and low-rainfall states (mean = 658 mm) emphasises the heterogeneity in India's climate. High-rainfall areas may have higher potential yields, but they may also see a decrease in millet area due to crop substitution for more lucrative cereals. According to studies, farmers in areas with superior irrigation systems and rainfall frequently switch to these crops due to increased market demand, higher financial returns and more policy support for major cereals (29, 30). On the other hand, millets remain essential for agricultural and food security in low-rainfall areas, underscoring their ecological and livelihood significance (31, 32). These are a crucial crop for maintaining rural livelihoods and guaranteeing food security in arid and semi-arid areas due to their capacity to withstand drought and grow in settings with little water.

Cropping diversification, measured using the SDI. It is used to measure crop diversity at the district level. It ranges from 0–0.8 and has an average value of 0.51, indicating moderate diversification across millet-growing regions. This suggests that farmers typically combine millets with pulses, oilseeds and other crops as a risk mitigation strategy. The SDI gauges the diversity of cropping patterns; higher values indicate greater diversity (a well-balanced crop mix), whereas lower values indicate monocropping dominance. Millet-growing regions often maintain a medium level of crop diversity, combining millets with pulses and oilseeds and occasionally with rice or maize, given the modest average SDI. Farmers' adaptive methods to address resource limits and climate risk are reflected in this moderate level of diversification. Because diverse cropping reduces susceptibility to rainfall variability and market shocks, areas with higher SDI values are likely more resilient (22, 33). By using a diverse cropping system, farmers can diversify production risks and increase stability in the face of shifting environmental conditions by using diverse cropping patterns. On the other hand, regions with low SDI may be more vulnerable to revenue instability and production risks.

Lastly, unequal input availability is indicated by the high mean value (87 kg/ha) and wide dispersion (SD = 96) of the variable total per hectare of NCA kg/ha, which represents nutrient application per hectare. Due to institutional or budgetary constraints, some farmers use large amounts of fertiliser, while others use small amounts.

Overall, the descriptive results show millet production as a resource-constrained but climate-resilient system with a wide range of yields, rainfall and irrigation access. The critical importance of millets in guaranteeing agricultural sustainability, food security and resilience in marginal areas is highlighted by the combination of low irrigation dependency, moderate crop diversification (as measured by SDI) and significant climatic variability. According to the findings, millet farmers' livelihoods may be strengthened and production gaps could be greatly reduced by increasing irrigation efficiency, improving input delivery and encouraging varied cropping systems, especially in rainfed and low-income areas.

Trends in millet cultivated area

Millet cultivation has experienced a considerable long-term reduction in the major millet-producing states of India during the last 5 decades, indicating notable transformations in the agricultural production system. As shown in Fig. 1, which shows the temporal trend of millet cultivation area among 10 major millet-producing states in India from 1966–2015. It shows a consistent decrease in millet cultivation in most selected states, although the level and rate of decline differ significantly among regions. A significant decrease in millet farming has been observed in Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Tamil Nadu and Uttar Pradesh, with the drop becoming clearer during the late 1980s. This trend coincides with the growth of irrigation, the implementation of high-yield crop cultivators and policy support for rice and wheat during the Green Revolution. Pigali and Hazell reported similar structural changes in Indian agriculture, linking the reduction of traditional coarse cereals to technological progress, public investment and policy incentives that mainly favoured major cereal crops (34, 35). Maharashtra and Karnataka continuously retained the greatest area

allocated to millet cultivation among the major millet-producing states, despite a steady decline over time. In contrast, Rajasthan shows significant annual changes, probably a sign of stronger reliance of rainfed agriculture on climate change. One major study revealed similar results about the tolerance of agricultural production to unpredictable weather conditions (36). Haryana experienced a significant decrease, while Uttarakhand maintained a relatively low but stable cultivation area over the period. A steady decline in millet cultivation was observed among the major millet-producing states (Fig. 1). This trend relates to the Agricultural Statistics at a glance, which reports a persistent decline in the area under coarse cereals despite recent government initiatives to promote nutri-cereals. The observable decline shows an overall structural transformation of Indian agriculture, highlighting the need to fully analyse the impact of changing climate conditions on millet-based production systems. Given that millets are mostly grown in rainfed environments, rising temperatures and climate uncertainty could lead to increased climate-adverse effects in such production systems, especially in semi-arid areas (36). Despite millets being known for their high nutritional level and adaptation to drought-affected and low-input conditions, making them significant climate-smart crops, their productivity could still be negatively impacted by increasing climate stress. The descriptive trends provide the fundamental background for the later regression result, which measures the impact of the factor of climate change on millet productivity in the major millet-producing states.

Trends in millet yield

Improving agricultural productivity has become more crucial as climate change creates more serious barriers to the food supply, especially in rainfed farming systems. Although the area allocated to millet cultivation has declined, millet yield has generally increased over time. This improvement indicates technological advancement in the productivity of crops and better agricultural methodologies (37). Millet yield increased consistently across all major millet-producing states from 1966–2015, although the rate of improvement varied among states (Fig. 2).

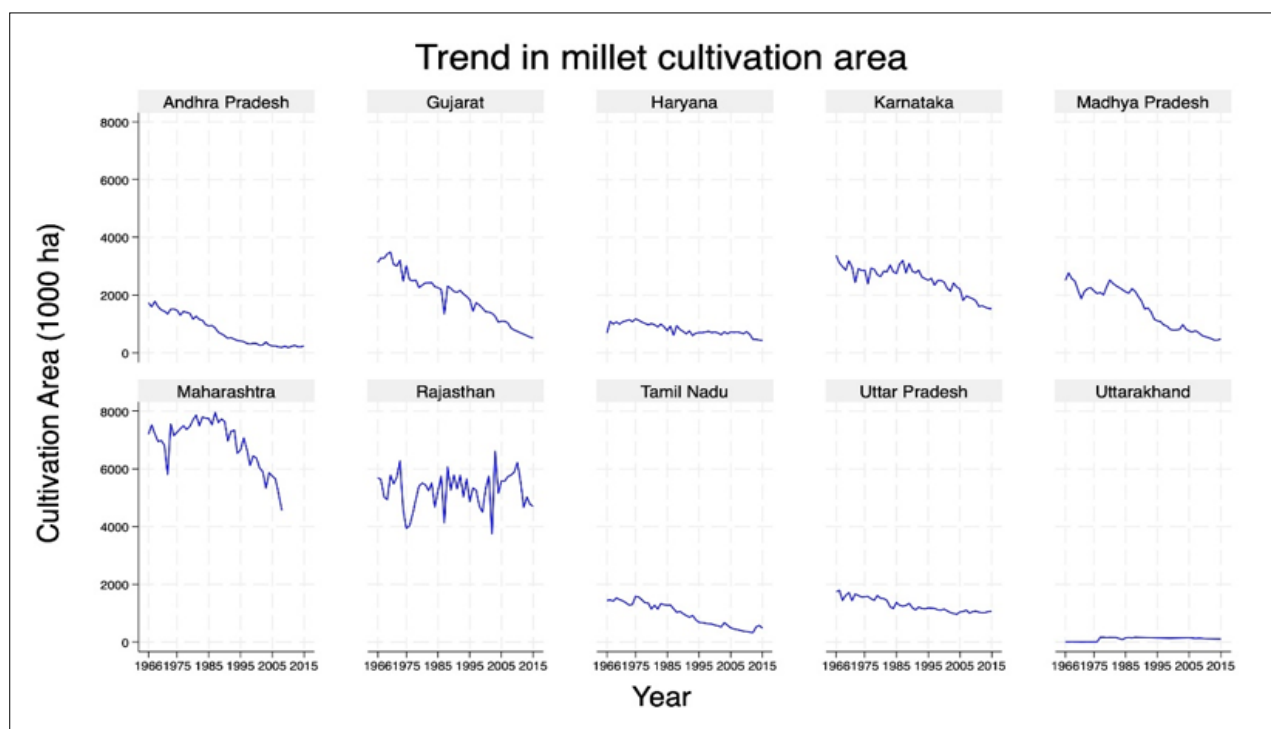


Fig. 1. Trends of area of cultivation of millets.

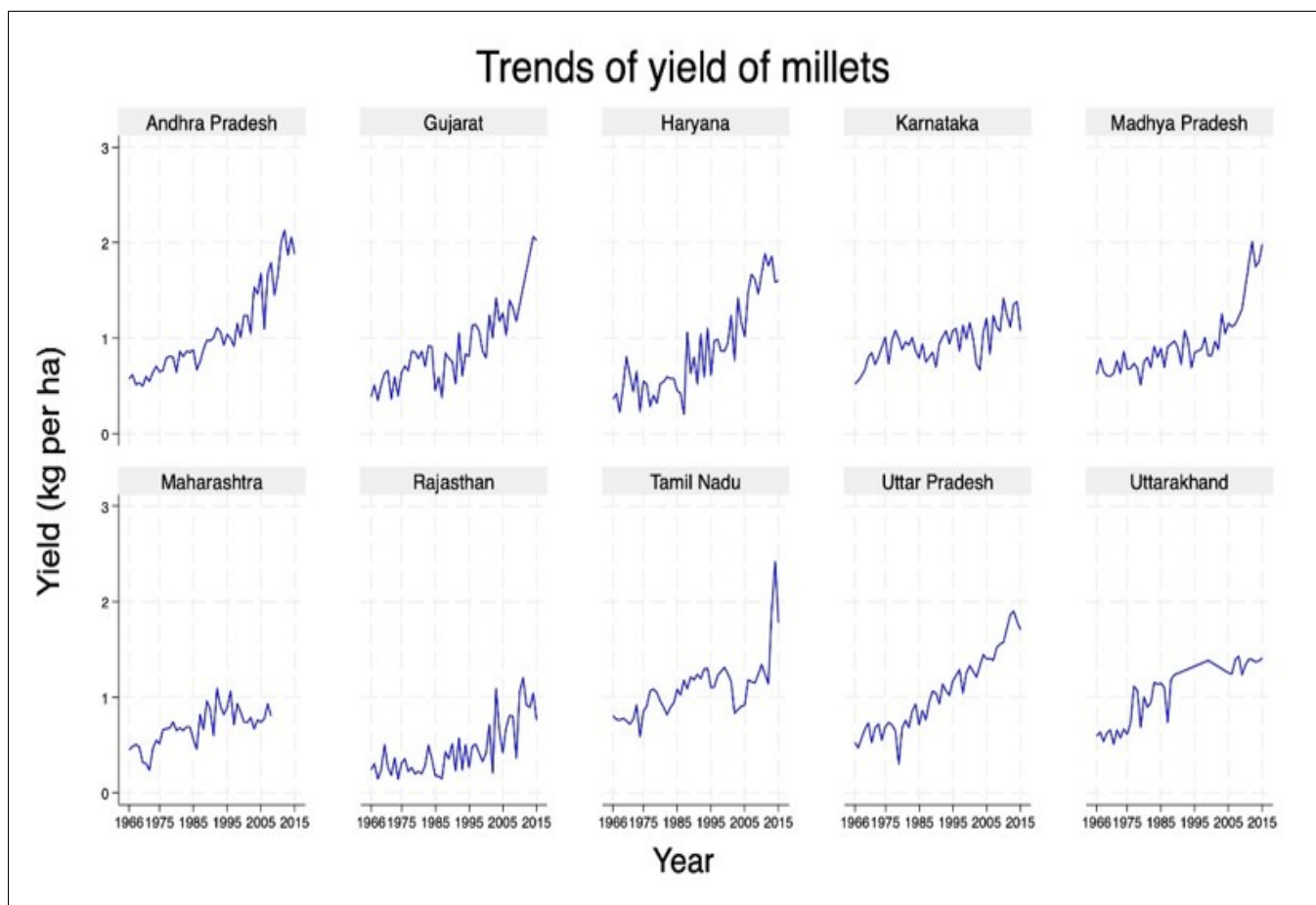


Fig. 2. Trends of yield of millets.

Andhra Pradesh, Gujarat, Haryana, Karnataka, Madhya Pradesh, Tamil Nadu, Uttar Pradesh and Uttarakhand all show steady increases in yield. In the last few years of study, Andhra Pradesh, Gujarat, Madhya Pradesh and Uttar Pradesh have shown the most significant improvement. Karnataka and Maharashtra both show a slow but steady rise in productivity. Rajasthan, on the other hand, had significant variation from 1 year to the next. This could be because growing millets in Rajasthan depends a lot on the weather and rains. It has been found that genetic improvement of pearl millet has happened significantly through long-term breeding programs and there has been the creation of better varieties (38).

Millets' productivity has become better over time, but variation among states shows that it is still sensitive to changes in weather. Crop performance is still being affected by rising temperatures, unpredictable rainfall and extreme weather events, especially in farming systems that depend on rain. Climate-smart farming methods are important for keeping crop productivity as weather conditions change over time (39). Millets are also known for being very healthy and helping to ensure there is enough food and nutrition (40).

Trends of minimum and maximum temperature

Climate change is significantly negatively impacting agricultural productivity, especially in rainfed farming systems. High temperatures can impact crop development, diminish crop duration, increase water loss and decrease agricultural output. Both maximum and minimum temperatures exhibited an overall upward trend across the major millet-producing states from 1966–2015, although the degree of warming varied among regions (Fig. 3). The evidence reveals a significant rise in both maximum and minimum temperature in Andhra Pradesh, Gujarat, Karnataka, Madhya

Pradesh, Tamil Nadu and Uttar Pradesh, with particularly significant warming observed in Tamil Nadu, Gujarat and Madhya Pradesh in the last years of the study period. Haryana and Maharashtra recorded relatively steady maximum temperatures with a gradual rise in minimum temperatures. Rajasthan consistently shows the highest maximum temperatures, indicating higher dependence of rainfed millets cultivation on rainfall variability and moisture availability. Conversely, Uttarakhand shows a unique temperature trend, characterised by a decrease in maximum temperature during the initial years and then a period of stability over the year. While minimum temperature showed a gradual increase. The historical evidence also shows similar results, which say that there are regional disparities in warming trends across the Himalayan regions (41). The warming trends shown in Fig. 3 also align with one study, which reported a notable rise in surface temperature in the Indian region, especially in minimum temperatures (41). The noted increase in temperature signifies that millet-producing areas are progressively subjected to climate stress. This is particularly significant as most millets are grown under rainfed conditions, exposing them to more effects of climate change.

Results and Discussion

Table 2 presents fixed-effect regression estimates of the association between yield and climatic variables, as well as non-climatic variables, across various millet crops. The results are presented individually for each type of millet because the size and significance of the coefficients vary by crop. Additionally, this model also contains fixed effects of districts and years, with standard errors at the district level to address serial correlation and heteroscedasticity.

Annual maximum and minimum temperature by state

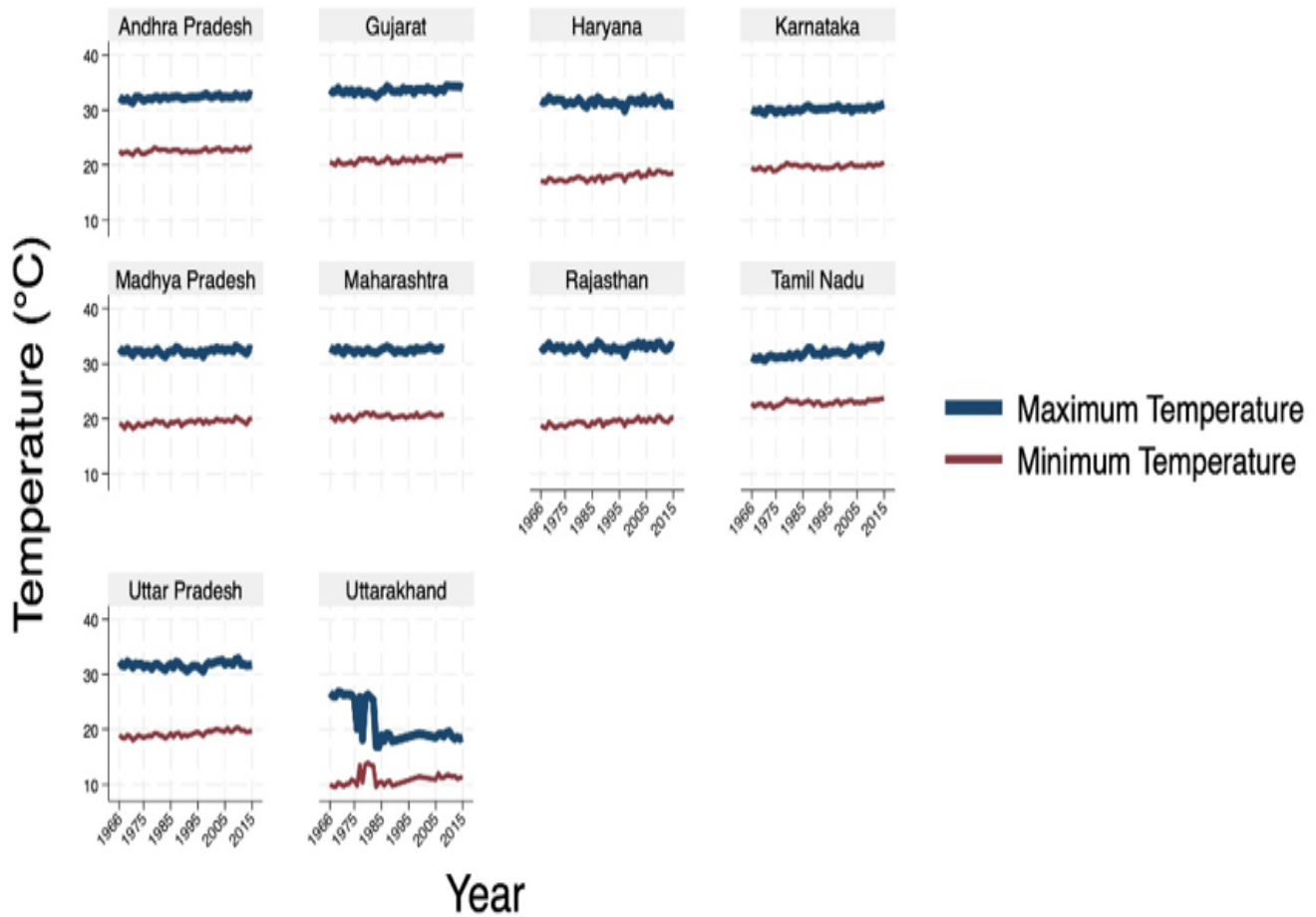


Fig. 3. Trends of maximum and minimum temperature.

Table 2. Fixed effects regression results for millet yields

Variables	Total millets	Kharif sorghum	Rabi sorghum	Pearl millet	Finger millet
Temperature × Irrigation Interaction	-0.117*** (0.043)	-0.350*** (0.056)	-0.086 (0.121)	-0.254*** (0.058)	0.017 (0.016)
Water deficit ²	-0.000006** (0.000003)	-0.000010*** (0.000004)	-0.000006** (0.000003)	-0.000028*** (0.000005)	0.000000 (0.000002)
Proportion irrigated millet area	0.009 (0.132)	0.042 (0.177)	0.201 (0.347)	0.051 (0.127)	0.218 (0.159)
Average temperature	-0.137*** (0.028)	-0.038 (0.037)	-0.136 (0.119)	-0.054 (0.033)	-0.076** (0.037)
Average temperature ²	-0.003 (0.002)	0.027*** (0.008)	0.035*** (0.012)	-0.014* (0.007)	0.001 (0.001)
Fertiliser application (log)	0.034* (0.020)	0.025 (0.030)	0.037 (0.048)	0.038* (0.022)	-0.060*** (0.021)
Shannon diversity index (SDI)	0.319* (0.164)	0.095 (0.166)	-0.308 (0.338)	0.326* (0.194)	-0.143 (0.158)
Minimum temperature	0.117*** (0.031)	0.098** (0.041)	-0.193** (0.080)	0.134*** (0.031)	0.126*** (0.033)
Constant	3.819*** (0.614)	4.151*** (0.781)	10.343*** (1.613)	3.482*** (0.618)	3.997*** (0.644)
Observations	8,515	7,730	2,933	6,944	2,895
Districts	203	196	94	189	123
Within R ²	0.360	0.262	0.195	0.422	0.304
District fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Clustered standard errors	Yes	Yes	Yes	Yes	Yes

Dependent variables are measured as the natural logarithm of yield (kg/ha). Clustered standard errors are reported in parentheses below coefficients. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. All models include district and year fixed effects.

Overall millet yield

For aggregate millet productivity, the interaction between maximum temperature and irrigation is negative and statistically significant, indicating that irrigation does not offset the adverse effects of heat stress. Previous research has revealed similar results, indicating that irrigation would not be sufficient to shield crops from the negative impacts of rising temperatures and heat stress, especially in semi-arid and climate-sensitive agricultural areas (42). Table 1 shows that a one-unit increase in the interaction term reduces yield by roughly 11.7 %, suggesting that irrigation cannot counteract the effects of heat stress. Water deficit squared has a significant negative effect, where the coefficient is -0.000006 and the p -value is 0.05, showing the negative impact of moisture stress on millet productivity. Since the proportion of irrigated millet land out of total cereal land is not significant, it shows that increasing irrigation coverage alone does not compensate for the fully adverse effect of heat stress. The average maximum temperature has a negative impact that is statistically significant, where the coefficient is -0.137 and $p < 0.001$, but its quadratic term is not. It reflects that there is no evidence of a non-linear temperature response. There is a positive impact of fertiliser on millet's productivity at a 10 % significance level. On the other hand, there is a positive impact of the SDI on millet productivity, which means that crop diversity improves resilience and output. Minimum temperature has a positive and highly significant index, which shows that warmer nights increase the amount of millet that is grown. Previous agricultural and regional development studies have also documented similar negative correlations between traditional crop farming patterns and socio-development indicators (43). This tendency might be the result of shifting land-use patterns, urban growth and a slow transition away from conventional farming methods and toward industrial and service-oriented economic pursuits.

Kharif sorghum

For kharif sorghum, the interaction between maximum temperature and irrigation has significantly negatively impacted the productivity of kharif millets (coefficient = -0.35) shown by Table 2. It indicates that the yield-enhancing function of irrigation declines in warmer temperatures. This study suggests that irrigation alone may not be sufficient to compensate for productivity losses due to heat. Even under irrigated conditions, rising temperatures can have an adverse effect on crop output, according to earlier research, especially when crops are subjected to extended heat stress during crucial growth phases (44). Additionally, there is a significantly negative impact of squared water deficit on the productivity of kharif millets, which indicates that increasing moisture stress puts significant constraints on the production of kharif sorghum.

The proportion of irrigated millet land indicates no statistically significant correlation with yield, which suggests that only increasing irrigated area is not sufficient for rising productivity, in consideration of meteorological and district-specific variables. Despite the linear temperature term lacking statistical significance, the positive quadratic term shows a nonlinear relation between temperature and the productivity of kharif sorghum. The fertiliser consumption and crop diversification, as evaluated by the SDI, do not seem to significantly impact the productivity of kharif sorghum. Conversely, minimum temperature shows a positive and statistically significant impact, suggesting that comparatively warmer night time situations may enhance crop development during the kharif season.

Rabi sorghum

The productivity of rabi sorghum shows a different variation compared to that of kharif sorghum. The interaction between maximum temperature and irrigation is not statistically significant, indicating that irrigation does not significantly affect the effect of maximum temperature on the productivity of rabi sorghum. Given that severe moisture stress can significantly lower yields even in seasons that are comparatively less reliant on rainfall, this shows that rabi crops are extremely vulnerable to drought conditions (43, 45). The outcome emphasises how crucial sufficient soil moisture and climate stability are to maintaining rabi season productivity. Rabi sorghum grown in areas with a higher concentration of irrigated millet may be linked to less suitable agro-ecological conditions or inefficient use of irrigation resources (46, 47). However, a negative coefficient on squared water deficit indicates that increasing moisture stress is a significant factor in reducing crop yield (48).

The proportion of irrigated area and fertiliser application does not have a statistically significant impact on productivity. However, the linear maximum temperature is insignificant; the positive and significant quadratic term suggests a nonlinear temperature-yield connection that highlights variability in crop response across different temperature ranges. Crop diversity does not substantially influence rabi sorghum yield. Unlike the kharif crop, minimum temperature has a substantial detrimental impact, suggesting that elevated nightly temperatures may negatively affect crop growth during the rabi season, which generally occurs in cooler climatic circumstances.

Pearl millet

It has been found that the productivity of pearl millet is highly affected by climate change. Table 2 shows that the interaction between temperature and irrigation shows a negative and statistically significant impact (coefficient = -0.254, $p < 0.01$), indicating that rising temperatures diminish irrigation effectiveness, resulting in an approximate 25.4 % decrease in yield for each unit rise in the interaction term. The square of water deficit shows a significant negative where the coefficient is 0.000028 and $p < 0.01$. It indicates that extreme moisture stress significantly decreases the yield of pearl millet. Although pearl millet is drought-tolerant, prolonged moisture stress reduces soil moisture availability during critical growth stages, limiting grain development and reducing productivity (49). Despite the statistical insignificance of the proportion of irrigated area of millet out of the total irrigated area and maximum temperature, the negative quadratic maximum temperature, whose coefficient value is 0.014 and $p < 0.10$, indicates that there are adverse effects of temperature increases at extreme maximum temperature levels. The use of fertiliser (coefficient = 0.038, $p < 0.10$) and the SDI (coefficient = 0.0326, $p < 0.10$) positively impact pearl millet productivity, suggesting that optimal nutrient management and diversified cropping systems can improve resilience in the face of climate change. Furthermore, minimum temperature shows positive and significant impacts (coefficient = 0.134, $p < 0.01$), indicating that increasing overnight temperature increases the productivity of pearl millets. The data indicate that pearl millet is especially affected by both heat and water stress, highlighting the need for climate-resilient management approaches.

Finger millet

The fixed-effects regression results show that climatic variables are more significant predictors for finger millet's productivity. The interaction of maximum temperature and proportion of irrigated millet area shows a positive, although statistically insignificant, coefficient, i.e., 0.017 and $p > 0.10$. The quadratic water deficit variable is statistically negligible, where the coefficient is 0.000000018 and $p > 0.10$, which suggests that increased water stress does not have a substantial nonlinear impact on crop productivity.

The coefficients of 0.218 and $p > 0.10$ for the proportion of irrigated millet area out of total irrigated area are positive, although not statistically significant at the 10 % level of significance. The estimated relationships show a positive correlation between irrigation coverage and the productivity of finger millets. Still, the lack of statistical significance suggests that irrigation alone does not substantially enhance productivity. So, we can say that irrigation-related factors do not significantly account for variability in finger millet production once district-specific characteristics and temporal impacts are considered.

On the other hand, temperature acts as a crucial factor impacting finger millet productivity. The findings suggest that a 1 °C rise in maximum temperature decreases the productivity of finger millets by 7.6 % and 5 % at a level of significance. This observation highlights the sensitive response of finger millet production to increasing daytime temperature. While the quadratic temperature factor positively impacts the productivity of finger millets at a 10 % level of significance. Additionally, a 1 % increase in fertiliser consumption decreases the productivity of finger millets by 0.06 %. These outcomes contradict traditional expectations and may show inefficient fertiliser utilisation, excessive nitrogen application, diminishing soil fertility or increased fertiliser usage in less productive regions. The SDI indicates crop diversification decreases the productivity of finger millets, but it is statistically significant.

In contrast to maximum temperature, minimum temperature has a positive and statistically significant impact on the productivity of finger millets. If the minimum temperature increases by 1 °C, then productivity will increase by 12.6 %, which suggests that overnight temperatures foster more favourable circumstances for the productivity of finger millets. The findings suggest that finger millet is predominantly affected by temperature conditions rather than irrigation considerations. Rising daytime temperatures decrease productivity, while nighttime temperatures improve yield, highlighting the divergent impact of several climate factors on finger millet productivity.

Before formulating policy implications, the reliability of the estimated model was evaluated through use of multicollinearity testing. Table 3 shows the VIF values varied between 1.28 and 8.39, averaging 2.20, suggesting multicollinearity was not a significant issue. Despite the average temperature exhibiting the highest VIF, it stayed below the widely recognised limit. Consequently, the projected coefficients appear to be consistent and the regression findings offer a reliable foundation for the policy suggestions presented further.

Policy implication

According to the results, crop-specific adaptation strategies work better than a policy approach that applies to all crops. Due to the significant negative impact of water deficit on pearl millet, policies

Table 3. Variance inflation factor (VIF) diagnostics

Variable	VIF	1/VIF
Temperature × Irrigation interaction	3.20	0.313
Water deficit ²	1.34	0.747
Proportion irrigated millet area	1.36	0.736
Average temperature	8.39	0.119
Average temperature ²	3.71	0.269
Fertiliser application (log)	2.49	0.401
Shannon diversity index (SDI)	1.28	0.783
Minimum temperature	3.86	0.259
Mean VIF	2.20	-

To evaluate the degree of multicollinearity among the factors that explain the data, VIFs were computed. The highest result of the VIF for average temperature is 8.39, which is still lower than the traditional criterion of 10. The presence of estimated models is not a significant cause for concern, as indicated by the mean VIF value of 2.20.

should focus on preserving soil moisture, collecting rainwater and using water efficiently to increase productivity as climate stress increases. It is important to support heat-tolerant types of finger millet because they fail to grow well when the maximum temperature goes up, while the adverse response to fertiliser consumption shows the specific nutrient management for the crop. The significant adverse impacts of temperature-irrigation interaction and water scarcity on kharif sorghum suggest that extensive water management, rather than only expanding irrigation, is necessary. Enhancing soil moisture management and strengthening its adaptability to increase night time temperature are crucial for maintaining the productivity of rabi sorghum.

Apart from crop-specification policies, agricultural policies must strengthen institutional assistance for millets cultivation by improving procurement systems and incentives for millets, especially in climate-sensitive and rainfed areas where recent policy support mainly emphasises rice and wheat. The current study did not differentiate between farm sizes; however, its findings are especially important for smallholder farmers, who face greater climate risks and would gain from targeted extension services, distribution of climate-resilient seeds and water conservation initiatives.

Conclusion

This research examined the impact of climate change on the productivity of overall millets and major millet crops in India, utilising district-level panel data from 1966–2015. The findings show that factors of climate change have varying impacts on millet crops, with increasing temperatures and water scarcity significantly decreasing the productivity of total millets, kharif sorghum and pearl millets, while finger millets show comparatively greater resilience to water stress. These findings indicate that climate affects millet crops variably, requiring specific adaptation measures for each crop. Targeted interventions can enhance climate resilience, augment millet output and promote sustainable agriculture, food security and nutritional security in India. Further study needs include additional variables, including the adoption of high-yielding varieties (HYV), market accessibility, soil type and extreme climatic events, as more extensive district-level data becomes accessible. Further research should assess the impact of crop-specific adaptation strategies and climate-smart technologies in enhancing millet productivity under possible future climate change scenarios.

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Authors' contributions

JKJ conducted the research, analysed and interpreted the data and drafted and revised the manuscript. SS and DB conceived the study and supervised the research. All authors read and approved the final manuscript.

Compliance with ethical standards

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