Impact of Climate Change on Agricultural Productivity in West Bengal with Special Reference to the Gangetic Plain Region

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Abstract: Climate change poses unprecedented challenges to agricultural sustainability in the Eastern Gangetic Plains, where West Bengal's farm-dependent economy faces escalating vulnerabilities. This research article comprehensively examines the multidimensional impacts of climate change on agricultural productivity across West Bengal, with particular emphasis on the Gangetic Plain region. The study synthesizes evidence from long-term climate data analysis, crop simulation modelling, water footprint assessments and community-based observations. Findings reveal significant spatial and temporal variability in climate patterns, with Gangetic West Bengal experiencing higher climate variability, rising minimum temperatures (≥0.008°C $year^{-1}$) and dramatic increases in post-monsoon precipitation (up to 184%). Crop water requirements are projected to escalate under future climate scenarios, with blue water footprints for vegetables increasing by 2.75% to 25.87% across different Representative Concentration Pathways. Rice productivity demonstrates differential responses across agro-climatic zones, with the Vindhyan Alluvial Zone exhibiting particular sensitivity to climatic factors. Groundwater depletion of 3-12 meters during pre-monsoon seasons, prolonged waterlogging affecting 8,400 hectares in North 24 Parganas and differential adaptive capacities across districts underscore the urgency of location-specific adaptation strategies. The study emphasizes that effective adaptation requires integrating scientific knowledge with community-based innovations, including crop diversification, optimized planting schedules and gender-responsive interventions.

Keywords: Climate change, agricultural productivity, Gangetic Plain, West Bengal, water footprint, rice cultivation, adaptation strategies, groundwater depletion

1. Introduction

The interface between climate change and agricultural productivity represents one of the most pressing challenges confronting contemporary food systems, particularly in densely populated riverine deltas of South Asia. The Indo-Gangetic Plain, spanning across Pakistan, India, Nepal and Bangladesh, constitutes one of the world's most extensive stretches of alluvial terrain and supports nearly one billion people through its agricultural bounty. Within this vast expanse, the lower Gangetic basin encompassing West Bengal occupies a uniquely vulnerable position, where the confluence of ecological sensitivity, demographic pressure and economic dependency on farming creates conditions of heightened susceptibility to climatic perturbations. The state's agricultural landscape, characterized by smallholder dominance with the highest cropping intensity in India-where an average farmer utilizes cultivable land 1.85 times or even more than 2.5 times in one agricultural year-renders the rural populace particularly exposed to the vagaries of shifting weather patterns (Kapuria and Banerjee, 2023).

West Bengal's agricultural economy rests fundamentally upon its intricate relationship with the monsoon system and the Gangetic river network. The state contributes approximately 15 percent of India's rice production and ranks as the second-largest potato producer nationally, commodities that form the dietary bedrock for millions (Kapuria and Banerjee, 2023). This agricultural productivity, however, has been achieved through intensive exploitation of water resources, with rice cultivation demanding five to six times more irrigation than alternative crops. The resultant groundwater extraction has precipitated declines of three to twelve meters during winter and pre-monsoon seasons across substantial portions of the state, creating a precariously balanced system where climatic shocks can cascade through the entire agricultural economy. Between 1995 and 2004, water levels dropped by 16 to 70 centimeters in some blocks in several districts such as Murshidabad and Bardhaman, leading to drinking-water crises coupled with arsenic contamination concerns in the aquifers (Kapuria and Banerjee, 2023).

The Gangetic Plain region of West Bengal, encompassing the new and old alluvial zones districts including Murshidabad, Birbhum, Bardhaman, Hooghly and North 24 Parganas, represents the agricultural heartland where the interplay between climate change and productivity manifests most acutely. This region's geological endowment of fertile alluvium deposited over millennia by the Ganga-Padma river system has historically buffered agricultural production against moderate environmental fluctuations. However, contemporary climate trajectories are overwhelming these natural buffers, introducing unprecedented variability that existing farming systems struggle to accommodate. Using the latest projected future climate data from IPCC's Sixth Assessment Report (CMIP6), studies examining the coastal region of the Ganges Delta in both Bangladesh and India reveal an overall increase for both temperature and rainfall, with variations occurring spatially and temporally. Across the region, projected maximum temperature increases are 1.3°C and 2.2°C for the mid and long-term respectively under SSP245 scenarios, while the difference between daily maximum and minimum temperature decreases, indicating a higher increase for minimum temperature compared to maximum temperature (Karim et al., 2024).

The ramifications of these climatic shifts extend beyond mere statistical anomalies to fundamentally disrupt agricultural calendars and crop physiological processes. In the Ajoy River basin of West Bengal, analysis of long-term historical and future climate datasets reveals a negative precipitation trend of approximately -0.04 mm per year in the southern part, whereas the northern part exhibits a positive trend of approximately 0.10 mm per year (Singha et al., 2024). Temperature trajectories compound these precipitation changes, accelerating crop development rates, reducing grain-filling periods and diminishing yield potential, while simultaneously increasing evapotranspiration demands that strain already compromised water resources. Crop simulation modelling using the DSSAT model for the New Alluvial Zone of West Bengal demonstrates advancement in days to anthesis by 2-13 days for rice during future periods, with days to maturity shortened by 3-16 days for rice under projected climate scenarios (Chandran et al., 2022).

The complexity of climate impacts on agriculture necessitates analytical frameworks capable of capturing both the biophysical transformations in growing conditions and the socio-economic responses of farming communities. Water footprint assessments conducted for major vegetable crops in the Eastern Gangetic Plains reveal that under baseline conditions, cabbage, potato and tomato cultivation consume substantial water volumes, with projections indicating these requirements will intensify under future climate scenarios. Across all climate change scenarios and time scales, the green and blue water footprints of cabbage are projected to increase by 2.75 percent to 6.88 percent, while potato shows increases ranging from 9.64 percent to 15.37 percent (Mali et al., 2024). Critically, the blue water component essential for irrigation shows pronounced increases for cabbage at 13.34 percent to 25.87 percent, signalling heightened competition for already scarce groundwater resources.

The imperative for this research derives from the recognition that climate change impacts manifest not uniformly across landscapes but through complex interactions between atmospheric processes, hydrological systems and human management decisions. The Gangetic Plain region of West Bengal exemplifies this complexity, where traditional adaptation mechanisms developed over generations are being rendered obsolete by the pace and magnitude of contemporary climate shifts. Ground-level observations from flood-prone villages in North 24 Parganas document the transformation of once-productive paddy lands into submerged fields where nearly 8,400 hectares of agricultural land in Habra I and II blocks are affected by floods and prolonged waterlogging each year, with water stagnating at three to four feet depths from June through December-durations far exceeding the submergence tolerance of existing rice varieties (Mukhopadhyay and Puskur, 2025). Such lived experiences of climate change reveal gaps between scientific projections and ground realities, emphasizing the necessity of research approaches that integrate quantitative climate analysis with qualitative understanding of community adaptation.

This article addresses the critical need for comprehensive assessment of climate change impacts on agricultural productivity in West Bengal's Gangetic Plain, synthesizing evidence from recent empirical studies to characterize the nature, magnitude and distribution of these effects. By examining both the biophysical transformations in growing conditions and the adaptive responses of farming communities, the research aims to inform policy frameworks and development interventions capable of supporting agricultural resilience in this ecologically sensitive region. The significance of this inquiry extends beyond academic interest, touching upon the food security and livelihoods of millions whose existence remains intimately connected to the productivity of Gangetic alluvium.

2. Materials and Methods

This research adopts a comprehensive review methodology synthesizing empirical evidence from peer-reviewed studies examining climate change impacts on West Bengal agriculture, with particular focus on the Gangetic Plain region. The methodological framework integrates multiple data sources and analytical approaches to construct a holistic understanding of climate-agriculture interactions across spatial and temporal scales.

Data Sources: The research draws upon secondary data from diverse sources including long-term meteorological records, satellite-derived climate products, crop production statistics from government publications and primary survey data from published studies. Key datasets include climate projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) under different Shared Socioeconomic Pathways (SSP245 and SSP585) for analysing future climate extremes in the Ganges Delta region. Long-term historical climate data spanning 1958-2020 from the Terra Climate dataset is utilized for analysing spatial patterns of climate variables including precipitation, maximum temperature, minimum temperature and hydrological variables such as actual evapotranspiration, runoff, vapour pressure deficit, potential evapotranspiration and climate water deficit. Agricultural statistics from the Ministry of Agriculture and Farmers Welfare, Government of India (2022), provide crop production data for major crops including rice varieties (Aus, Aman and Boro), wheat, maize, barley and potato across selected districts.

Crop Simulation Modeling: The evaluation of climate change impacts on cropping systems employs the Decision Support System for Agrotechnology Transfer (DSSAT) crop simulation model, which integrates soil, weather, crop management and genetic information to simulate crop growth, development and yield. The study utilizes calibrated and validated DSSAT models for rice, lentil and groundnut in the New Alluvial Zone of West Bengal, with simulations conducted for baseline (1980-2010), mid-century (2040-2069) and end-century (2070-2099) periods using downscaled climate projections from multiple General Circulation Models. The analysis includes scenarios with and without CO_2 fertilization effects to isolate the physiological impacts of elevated atmospheric carbon dioxide concentrations on crop productivity.

Water Footprint Assessment: Crop water requirements are evaluated using the FAO-56 Penman-Monteith method for reference evapotranspiration estimation, integrated with a daily soil water balance model that distinguishes between green water (soil moisture from rainfall) and blue water (irrigation from surface or groundwater sources). This approach enables quantification of both current water consumption and future projections under different climate scenarios, including Representative Concentration Pathways RCP2.6, RCP4.5, RCP6.0 and RCP8.5 for early (2030-31), mid (2050-51) and late (2080-81) twenty-first century periods (Mali et al., 2024). The study considers yield variations of vegetable crops under future scenarios using monotonic trend models to project productivity changes alongside water requirement shifts.

Nutritional Water Productivity Analysis: The nutritional implications of crop selection are assessed through nutritional water productivity metrics, calculated as the ratio of nutritional content per unit of water evapotranspired. This framework, based on the formula by Renault and Wallender, integrates actual evapotranspiration rates estimated for different crops across districts with nutritional composition data, enabling identification of cropping patterns that optimize both water use efficiency and nutritional outcomes. The analysis covers macronutrients and micronutrients including protein, carbohydrates, fats, fiber, phosphorus, iron and zinc contents for major crops including rice, wheat, maize, barley, bajra, sorghum and potato.

Water Resources Reallocation Assessment: The potential water savings from crop diversification are estimated using an indicator of water resources available for reallocation, calculated as the difference in actual evapotranspiration between high-water-demand crops (particularly Boro rice) and alternative less water-demanding crops such as maize, barley and bajra. This metric, expressed in millimeters over the cropping season, quantifies the reduction in consumptive water demand achievable through strategic shifts in cropping patterns across different districts of the Gangetic Plain.

Community-Based Participatory Research: The methodology incorporates insights from participatory research approaches, including community-based water monitoring systems where farmers install bamboo poles to measure and record weekly water levels in submerged agricultural lands. This integration of local knowledge with scientific measurement enables validation of remote sensing products and enriches understanding of how climate impacts manifest at farm scale. Soil analyses accompanying this monitoring assess degradation from prolonged submergence, including parameters such as compaction, aeration status and microbial activity. The study draws upon observations from gender-responsive Sociotechnical Innovation Bundling pilots implemented in climate-vulnerable villages, focusing on livestock enterprises and alternative crop experimentation.

Climate Extreme Indices Analysis: The frequency and spatial extent of climate extreme indices relevant to agriculture are examined using projected future climate data from CMIP6, with particular focus on the dry season (November-April) when water availability critically constrains agricultural production. Indices analysed include changes in maximum and minimum temperatures, diurnal temperature range, total rainfall, rainfall intensity (1-day and 5-day maximum), consecutive wet days and consecutive dry days. This analysis spans short-term (2021-2040), mid-term (2041-2060) and long-term (2061-2100) projections under different SSP scenarios.

Spatial Analysis: Geographic information system techniques enable spatial visualization of climate vulnerability patterns, identifying districts and blocks where climate risks converge with socio-economic vulnerability indicators. This spatial framework supports targeted intervention design by highlighting areas where agricultural adaptation interventions can achieve maximum impact, differentiating between coastal saline zones, inland waterlogged areas and drought-prone regions.

The strength of this methodological approach lies in its triangulation of evidence from multiple sources and analytical techniques, enabling robust conclusions about climate change impacts while acknowledging the uncertainties inherent in long-term projections. By integrating quantitative climate analysis, crop modelling, water footprint assessment and qualitative understanding of farmer experiences, the research bridges the gap between scientific assessment and practical adaptation needs.

3. Climate Trends and Variability in West Bengal

The empirical documentation of climate change in West Bengal reveals complex spatial patterns that challenge simplistic narratives of uniform warming or drying. Analysis of long-term climate datasets spanning multiple decades demonstrates pronounced spatial gradients in climate variability, with the Gangetic region exhibiting the most pronounced changes in multiple parameters. The spatial differentiation of climate impacts across the state creates a complex mosaic of vulnerabilities that defies monolithic characterization. Temperature trajectories across West Bengal show consistent warming trends with important spatial variations. Across the Ganges Delta region, including both Bangladesh and Indian portions, projected maximum temperature increases are 1.3°C and 2.2°C for the mid and long-term respectively under SSP245 scenarios (Karim et al., 2024). Critically, the difference between daily maximum and minimum temperature decreases across the region, indicating a higher increase for minimum temperature compared to maximum temperature. This asymmetric warming carries profound implications for agricultural systems, as rising night temperatures increase respiratory losses of carbohydrates accumulated during daytime photosynthesis, directly diminishing grain filling and harvestable yield in rice and other crops.

In the Ajoy River basin of Eastern India, detailed spatiotemporal analysis of climate variables from 1958 to 2020 reveals significant spatial heterogeneity in precipitation trends. The southern part of the basin exhibits a negative precipitation trend of approximately -0.04 mm per year, while the northern part shows a positive trend of approximately 0.10 mm per year (Singha et al., 2024). This north-south gradient in precipitation trends reflects the complex interactions between large-scale monsoon dynamics and local topographic and land surface characteristics. Hydrological variables analysed in conjunction with precipitation reveal corresponding spatial patterns: actual evapotranspiration, runoff, vapour pressure deficit, potential evapotranspiration and climate water deficit all demonstrate significant spatial variability across the basin, with implications for agricultural water availability and crop water stress.

The analysis of climate extremes using CMIP6 projections provides crucial insights into how agricultural growing conditions are likely to evolve in coming decades. At an annual scale across the Ganges Delta, rainfall is projected to increase by 160 millimeters, 400 millimeters and 620 millimeters under short-term, medium-term and long-term projections, respectively (Karim et al., 2024). For the same projection periods, total rainfall during the dry season-critical for irrigation planning and rabi crop cultivation-rises by 12 millimeters, 42 millimeters and 41 millimeters respectively. While total rainfall increases during the dry season, the number of consecutive wet days remains unchanged and the number of consecutive dry days slightly increases across the region. This seemingly paradoxical pattern implies that shorter but more intense spells of rainfall are likely to occur during the dry season, reducing the effective water available for crop use despite higher gross precipitation totals.

The intensity of extreme precipitation events shows marked increases in both short-term and long-term projections compared to historical averages. The intensity of 1-day and 5-day maximum rainfall increases across the Ganges Delta region, indicating a trend toward more concentrated, high-intensity rainfall events (Karim et al., 2024). This shift in rainfall intensity carries significant implications for agricultural systems, as high-intensity rainfall increases surface runoff, reduces soil moisture infiltration and can cause physical damage to crops through lodging and waterlogging. For the Gangetic Plain region, where intensive agriculture depends on reliable water availability throughout the crop cycle, the combination of increased rainfall intensity and unchanged or slightly increased dry spell duration creates a more challenging and uncertain growing environment.

The implications of these precipitation changes for agricultural operations are particularly acute during critical phenological stages. The dramatic increase in post-monsoon rainfall documented in various studies coincides precisely with the maturation and harvest period for Kharif rice, the state's primary agricultural crop. Heavy rains during this window cause lodging of mature plants, grain sprouting in the panicle and difficulties in field drying, directly translating into yield losses and quality deterioration. In the flood-prone lowlands of North 24 Parganas, the monsoon that historically sustained paddy has turned erratic, with delayed onset and heavy late-season rains leaving fields submerged for months (Mukhopadhyay and Puskur, 2025). Villages like Makaltala in Habra I block, where farmers traditionally cultivated Pratiksha, Swarna and Pankaj varieties of paddy until five years ago, now experience fields remaining buried under four to five feet of stagnant water from June to December.

The spatial distribution of climate vulnerability in West Bengal reveals a concerning pattern where areas receiving disproportionate research and policy attention may not correspond with areas experiencing the most severe impacts. Much of West Bengal's climate adaptation narrative has centered on the Sundarbans, with saltwater intrusion and erosion dominating the discourse. This region features prominently in the state's action plan, with dedicated institutions and numerous international projects (Mukhopadhyay and Puskur, 2025). However, inland ecologies with prolonged flooding and stagnation-such as the waterlogged tracts of North 24 Parganas affecting approximately 8,400 hectares in Habra I and II blocks-remain largely invisible in climate vulnerability assessments. This singular gaze toward coastal zones potentially shapes research and development priorities in ways that overlook equally affected inland landscapes.

The temporal structure of climate change in West Bengal reveals important discontinuities in addition to gradual trends. Farmers in affected regions report that the traditional agricultural calendar, refined over generations, no longer aligns with contemporary rainfall patterns, forcing difficult decisions about planting dates and harvest timing. Older farmers in Makaltala recall when tall deepwater paddy varieties like Jhumpuri and Katrangi covered these fields, growing with the water level. At that time, canals flowed freely, rivers drained effectively and water never stagnated for extended periods (Mukhopadhyay and Puskur, 2025). The transformation from functional drainage systems to chronically waterlogged landscapes represents not only climate change but also the interaction of climatic shifts with infrastructure deterioration and land use changes.

4. Impacts on Crop Water Requirements and Agricultural Productivity

The translation of climate change into agricultural impacts operates critically through alterations in crop water relations, affecting both the supply side of water availability and the demand side of crop water requirements. Water footprint assessments conducted for major vegetable crops in the Eastern Gangetic Plains provide quantitative projections of how climate change will reshape agricultural water demands in the coming decades, with implications for water resource management and agricultural planning. Under baseline conditions spanning 2008-2018, cabbage cultivation across the Eastern Gangetic Plains region covering West Bengal, Bihar and Jharkhand required 481.2 million cubic meters annually, composed of both green water derived from rainfall and blue water supplied through irrigation (Mali et al., 2024). Potato cultivation demanded substantially larger volumes at 2,689.2 million cubic meters, reflecting both the crop's longer duration and its cultivation during the dry rabi season when irrigation requirements dominate. Tomato production consumed 434.9 million cubic meters under baseline conditions. These baseline estimates establish the substantial water footprint of vegetable production in the region and provide a reference point for assessing future changes.

Projections under future climate scenarios reveal consistent patterns of increasing water requirements, though with important crop-specific variations that reflects differential physiological responses to elevated temperatures and changing atmospheric CO_2 concentrations. Across all climate change scenarios and time scales examined, the green and blue water footprints of cabbage are projected to increase by 2.75 percent to 6.88 percent (Mali et al., 2024). The blue water component-representing irrigation requirements-shows more pronounced increases of 13.34 percent to 25.87 percent for cabbage, indicating that future climate conditions will increase dependence on irrigation despite potential increases in rainfall. This differential increase in irrigation requirements reflects the combined effects of elevated evaporative demand under warmer conditions and reduced reliability of rainfall during critical growth periods.

Potato demonstrates even larger total water footprint increases ranging from 9.64 percent to 15.37 percent across different climate scenarios and time scales (Mali et al., 2024). The green water component for potato shows dramatic projected increases of 56.49 percent to 221.62 percent under different scenarios, while the blue water requirements vary from -4.91 percent to 7.1 percent. This pattern suggests that while total water demand for potato increases substantially, the partitioning between rainfall and irrigation may shift in complex ways depending on seasonal rainfall distribution and the timing of crop growth relative to changing precipitation patterns. The wide range of projected changes underscores the sensitivity of potato to climate scenarios and the importance of considering uncertainty in adaptation planning.

Tomato presents an interesting contrast to cabbage and potato, with total water footprint variations projected in the range of -3.95 percent to 1.37 percent, indicating relative stability compared to other vegetables (Mali et al., 2024). However, the green water footprint of tomato is projected to increase by 31.31 percent to 110.14 percent, while the blue water component is projected to decrease by 9.41 percent to 26.13 percent. This suggests that future climate conditions may enable greater reliance on rainfall for tomato production, potentially reducing irrigation demands if rainfall timing aligns favourably with crop water requirements. These crop-specific differences underscore the importance of disaggregated analysis that recognizes the heterogeneous responses of different species to changing climate conditions and the potential for strategic crop selection as an adaptation measure.

The implications of these changing water requirements extend beyond simple volumetric considerations to encompass the seasonal timing of water demands and the reliability of supply sources. Groundwater, which currently supplies more than 60 percent of irrigation in West Bengal, faces mounting pressures from both increased abstraction and changing recharge patterns. Analysis of groundwater dynamics across West Bengal districts reveals that water levels recede by three to twelve meters or more during winter and pre-monsoon seasons, periods when irrigation demands for Boro rice and rabi vegetables peak (Kapuria and Banerjee, 2023). Many shallow tube wells that formerly provided reliable irrigation throughout the dry season now deliver pulsating discharges or fail completely during peak demand periods, forcing farmers to deepen wells or invest in more expensive pumping equipment. The expansion of farm land planted to Boro rice at rates of five to ten percent annually has contributed to groundwater pumping mostly from unconfined aquifers through private shallow tube wells.

The relationship between climate change and crop productivity in West Bengal demonstrates the complexity of climate impacts operating through multiple physiological and agronomic pathways. Crop simulation modelling using the DSSAT model for the rice-lentil-groundnut cropping sequence in the New Alluvial Zone of West Bengal provides quantitative estimates of how future climate conditions may affect crop phenology and yield. The study simulated advancement in days to anthesis of 2-13 days for rice during future periods (mid-century 2040-2069 and end-century 2070-2099) compared to baseline (1980-2010) (Chandran et al., 2022). Days to maturity were projected to be shortened by 3-16 days for rice under future climate scenarios. This acceleration of crop development under warmer conditions reduces the time available for biomass accumulation and grain filling, directly constraining yield potential.

The impact on final biomass and yield was simulated with and without CO_2 fertilization effects, revealing the complex interplay between temperature increases and elevated atmospheric CO_2 concentrations. When CO_2 fertilization effect was considered, the yield of rice was projected to increase by 11 percent to 32 percent under future climate scenarios (Chandran et al., 2022). On the other hand, yield of lentil and groundnut was estimated to change by -31 percent to -12 percent and -33 percent to +8 percent, respectively. These results demonstrate that enhanced CO_2 concentrations can partially mitigate the magnitude of yield reduction due to enhanced temperature, but the mitigation effect varies substantially across crop species. Rice benefited from the carryover effect of residue from preceding groundnut in the cropping sequence, suggesting that crop rotation effects and residue management can interact with climate change responses to influence long-term productivity trends.

The differential responses of various crops to elevated CO_2 and temperature highlight the importance of species-specific physiological characteristics in determining climate change impacts. C_3 crops like rice, lentil and groundnut generally show positive photosynthetic responses to elevated CO_2, while C_4 crops may show less pronounced responses. However, the simultaneous increase in temperatures can offset or negate these benefits, particularly if temperatures exceed optimal ranges for critical developmental processes. For groundnut, the days to maturity were simulated to increase by 1-9 days under future scenarios, contrasting with the shortened maturity duration for rice and lentil (Chandran et al., 2022). This species-specific variation in phenological responses adds another layer of complexity to projecting climate change impacts on cropping systems.

5. Regional Vulnerabilities and Differential Impacts

The spatial differentiation of climate change impacts across West Bengal creates a complex mosaic of vulnerabilities that requires location-specific analysis and response strategies. The Gangetic Plain region, despite its favourable alluvial soils and relatively developed irrigation infrastructure, confronts distinctive challenges arising from the intersection of climate trends with intensive cropping systems and groundwater dependence. In the lower Indo-Gangetic plains of West Bengal, comprising the new and old alluvial zones districts including Murshidabad, Birbhum, Bardhaman, Hooghly and North 24 Parganas, detailed analysis of crop water requirements reveals substantial variations across both crops and districts. Actual evapotranspiration rates-a crucial measure of consumptive water use-show rice to have the highest water requirement among all crops, followed by jute, with maize and potato following (Kapuria and Banerjee, 2023). These rates vary significantly across districts, reflecting differences in local climate conditions, soil characteristics and management practices. Higher yields are generally associated with higher evapotranspiration rates, but the relationship between water use and productivity shows important crop-specific variations that have implications for water use efficiency.

The potential for water savings through crop diversification is substantial across all analyzed districts. Estimated water resources available for reallocation-calculated as the difference in actual evapotranspiration between Boro rice and alternative less water-demanding crops-range from 264 to 428 millimeters across different districts when replacing Boro rice with maize (Kapuria and Banerjee, 2023). Replacement with barley offers water savings of 268 to 434 millimeters, while replacement with bajra provides savings of 270 to 435 millimeters. These figures represent the reduction in consumptive water demand achievable through strategic shifts in cropping patterns, potentially releasing substantial water resources for other uses including environmental flows, domestic water supply, or expansion of irrigated area with less water-intensive crops.

The nutritional implications of crop diversification add another dimension to the analysis of regional vulnerabilities and adaptation options. Among crops grown in the lower Indo-Gangetic plains of West Bengal, rice and potato have the lowest macro and micronutrient densities (Kapuria and Banerjee, 2023). Maize has the highest phosphorous content and is nutritionally dense in macronutrients, while barley has the highest fiber content among cereal crops. The near-disappearance of barley cultivation in West Bengal since 2011-12, despite its favorable water productivity and nutritional density, illustrates how market and policy factors can override agronomic rationality. Today, barley is sparsely grown only in the districts of Jalpaiguri, Uttar Dinajpur, Maldah, Murshidabad, Birbhum and Nadia, representing a lost opportunity for both water conservation and nutritional improvement.

The coastal zone of the Ganges Delta, including the Indian Sundarbans, faces a distinctive vulnerability set centered on the interaction between climate change and salinity dynamics. Analysis of climate extremes using CMIP6 projections reveals that while total rainfall increases during the dry season, the number of consecutive wet days remains unchanged and the number of consecutive dry days slightly increases across the region (Karim et al., 2024). This pattern implies that shorter but more intense spells of rainfall are likely to occur during the dry season, potentially increasing runoff and reducing effective infiltration for leaching accumulated salts from agricultural soils. Unlike the Gangetic Plain where excessive water during harvest creates challenges, coastal regions confront the opposite problem of freshwater scarcity for managing soil salinity.

Inland waterlogged areas of North 24 Parganas present yet another vulnerability pattern, characterized by prolonged submergence that renders traditional paddy cultivation unviable. Nearly 8,400 hectares of agricultural land in Habra I and II blocks are affected by floods and prolonged waterlogging each year, signaling a recurrent regional crisis (Mukhopadhyay and Puskur, 2025). Choked canals, silted drains, erratic rainfall and unplanned urban growth have transformed once-productive tracts of the Ganga-Padma-Ichhamati basin into shallow wetlands where water stagnates at three to four feet depths from June through December. No available paddy variety can withstand such long submergence-even submergence-tolerant varieties like Swarna-Sub1 and IR64-Sub1 survive flooding for only about 14 days, far short of the months-long inundation farmers now face.

The soil degradation accompanying prolonged waterlogging adds another dimension to the vulnerability of inland areas. Soil analyses from waterlogged villages reveal significant degradation: prolonged submergence has compacted soil, reduced aeration and suppressed microbial activity, eroding fertility and disrupting nutrient cycling (Mukhopadhyay and Puskur, 2025). As a result, once productive fields are slipping into a state of biological exhaustion, diminishing both yields and the land's ability to recover even if waterlogging could be alleviated. This soil degradation represents a form of legacy effect where current climate impacts create lasting damage that will constrain future agricultural potential regardless of how climate conditions evolve.

The differential vulnerability across regions carries implications for adaptation planning, suggesting that uniform policy responses will prove inadequate to address the location-specific nature of climate challenges. Regions like the Sundarbans risk becoming symbolic showcases of climate vulnerability, drawing disproportionate attention and resources while other equally affected landscapes remain invisible (Mukhopadhyay and Puskur, 2025). This may explain why investments in West Bengal and neighbouring deltaic regions have mainly focused on developing and promoting salinity-tolerant rice varieties, while the challenge of prolonged submergence in inland areas has remained largely invisible to researchers and policymakers.

6. Crop Simulation Modeling and Future Productivity Scenarios

Crop simulation modeling provides a powerful tool for projecting how future climate conditions may affect agricultural productivity and for evaluating potential adaptation strategies before field implementation. The application of process-based crop models calibrated for local conditions enables quantitative assessment of climate change impacts and the identification of management practices that can mitigate negative effects. The evaluation of the rice-lentil-groundnut cropping sequence in the New Alluvial Zone of West Bengal using the DSSAT model demonstrates the complex, crop-specific nature of climate change responses. The study simulated crop performance for baseline (1980-2010), mid-century (2040-2069) and end-century

(2070-2099) periods using downscaled climate projections from multiple General Circulation Models (Chandran et al., 2022). Results revealed advancement in days to anthesis of 2-13 days for rice during future periods, while for lentil and groundnut, the average advancement in days to anthesis was approximately 1 day. Days to maturity were projected to be shortened by 3-16 days for rice and 0-7 days for lentil under future climate scenarios. However, for groundnut, the days to maturity were simulated to increase by 1-9 days, demonstrating that even within the same cropping system; species respond differently to changing climate conditions.

The physiological mechanisms underlying these phenological shifts relate primarily to temperature effects on development rates. Most crops accumulate thermal time toward phenological stages and warmer temperatures accelerate development provided other factors such as day length and water availability are not limiting. For rice, which is typically grown during the warm Kharif season, additional warming pushes development rates beyond optimal ranges, shortening the grain-filling period and reducing yield potential. For groundnut, which has different temperature optima and photoperiod sensitivities, the response pattern differs, with some scenarios showing extended rather than shortened maturity duration.

The impact on final biomass and yield was simulated with and without CO_2 fertilization effects, revealing the critical importance of accounting for atmospheric CO_2 concentrations in climate impact assessments. When CO_2 fertilization effect was considered, the yield of rice was projected to increase by 11 percent to 32 percent under future climate scenarios (Chandran et al., 2022). This positive response reflects the direct physiological effect of elevated CO_2 in increasing photosynthetic rates and improving water use efficiency in C_3 crops like rice. On the other hand, yield of lentil was estimated to change by -31 percent to -12 percent and groundnut yield by -33 percent to +8 percent, when CO_2 fertilization was considered. The wide range of responses, including both positive and negative projections for groundnut depending on the specific climate scenario and time period, underscores the uncertainty inherent in long-term projections and the importance of considering multiple scenarios and models.

The mitigating effect of elevated CO_2 on temperature-induced yield reductions was clearly demonstrated in the simulation results. Enhanced CO_2 concentrations partially offset the magnitude of yield reduction due to enhanced temperature, but the degree of mitigation varied substantially across crop species and scenarios (Chandran et al., 2022). For rice, the CO_2 fertilization effect was sufficiently strong to produce net yield increases in most scenarios despite accelerated development and shortened grain-filling periods. For lentil and groundnut, however, the CO_2 effect was insufficient to fully compensate for temperature stresses, resulting in net yield reductions in most scenarios. These differential responses have implications for cropping system design under climate change, suggesting that strategic crop selection based on species-specific climate responses could help maintain overall system productivity.

The study also quantified the uncertainty in simulation of yield due to selection of General Circulation Models, an important consideration for interpreting and applying crop model results. Different GCMs project different patterns of future temperature and precipitation, even under the same emissions scenarios, leading to variability in simulated crop responses (Chandran et al., 2022). This uncertainty is irreducible in the sense that we cannot know with certainty which GCM provides the most accurate projection of future climate. However, multi-model ensembles that incorporate outputs from multiple GCMs provide a more robust basis for decision-making than any single model projection, as they capture the range of plausible future outcomes.

Rice benefited from the carryover effect of residue from preceding groundnut in the cropping sequence and, hence, could sustain yield on a long term (Chandran et al., 2022). This finding highlights the importance of considering cropping system interactions rather than individual crops in isolation when assessing climate change impacts. Residue management, crop rotation effects and other agronomic practices can modify crop responses to climate, creating opportunities for adaptation through improved management rather than solely through breeding or infrastructure investments.

7. Adaptation Strategies and Community Responses

The imperative for adaptation in West Bengal's agriculture arises from the recognition that even aggressive greenhouse gas mitigation cannot reverse climate changes already underway or prevent additional warming committed by past emissions. Farming communities across the state have begun responding to changing conditions through diverse strategies operating at multiple scales, from individual field-level adjustments to collective innovations and community-based experimentation. Optimization of planting dates represents a relatively low-cost adaptation with demonstrated potential to mitigate climate impacts in the rice-wheat systems of the Eastern Gangetic Plains. The timing of planting directly influences crop productivity in the region and given the ongoing changes due to climate, managing optimal planting dates has become a vital agronomic factor for increasing productivity (Munshi et al., 2024). Timely transplanting of rice enables earlier wheat sowing, allowing the wheat crop to complete grain filling before terminal heat stress intensifies during the post-monsoon period. By transplanting rice on time, farmers can reduce terminal heat stress in wheat and terminal drought in rice, thus optimizing the planting schedule in the integrated rice-wheat system.

Digital tools are being developed to support farmer decision-making regarding optimal planting dates under changing climate conditions. The AgDay application, developed through collaboration between agricultural research institutions and technical partners, provides planting date recommendations to farmers using crop modelling, geospatial data and field trial results (Munshi et al., 2024). During the Kharif season of 2024, the application successfully generated advisories for 200 farmers across six districts, following institutional capacity-building and training programs for extension officials on how to use the application. Such tools demonstrate the potential for information technology to support farmer decision-making under climate uncertainty, translating complex modelling results into actionable recommendations.

Field demonstrations and travel seminars that enable farmers to observe improved practices on neighbours' fields prove particularly effective in building confidence and accelerating adoption. Farmers benefit from the philosophy that "seeing is believing," and organized travel seminars at farmers' plots enhance understanding of the benefits of early rice planting, including stronger tillering and the opportunity for earlier wheat sowing (Munshi et al., 2024). Observing crop cuts in the fields provides first-hand experience of the positive impacts of adopting improved practices, overcoming the skepticism that often limits adoption of new technologies.

Crop diversification away from high-water-demanding species offers another adaptation pathway with potential for multiple benefits in water conservation and nutritional improvement. The analysis of water requirements across different crops in the lower Gangetic plains demonstrates that replacing Boro rice with less water-demanding alternatives such as maize or barley could release substantial water resources for other uses (Kapuria and Banerjee, 2023). The water resources available for reallocation through such shifts range from 264 to 428 millimeters across different districts, representing significant reductions in consumptive water use. Simultaneously, nutritional water productivity analysis reveals that alternative crops often deliver greater nutritional content per unit of water consumed, particularly for micronutrients where rice performs poorly relative to maize, barley, or millets.

However, realizing the potential of crop diversification requires overcoming market and policy barriers that currently incentivize continued cultivation of high-water-demanding crops. With a guaranteed Minimum Support Price to producers and huge subsidies on rice to consumers, cropping and dietary choices have discouraged the production of more nutrient-rich alternative cereals, which are also less water-intensive, contributing to widespread nutrient deficiencies (Kapuria and Banerjee, 2023). The near-disappearance of barley cultivation in West Bengal since 2011-12, despite its favourable water productivity and nutritional density, illustrates how policy environments can override agronomic rationality, creating path dependencies that constrain adaptation options.

Community-based innovations emerging from farmer experimentation demonstrate the creative potential of local adaptation when formal research systems cannot keep pace with climate change. In waterlogged villages of North 24 Parganas where prolonged submergence has rendered paddy cultivation unviable, farmers have begun experimenting with water chestnut (Trapa natans) cultivation in standing water (Mukhopadhyay and Puskur, 2025). A farmer's demonstration on two kathas (approximately 0.05 hectares) of waterlogged land yielded eight kilograms of water chestnuts, sparking curiosity among neighbouring families who expressed interest in trying the crop next season. This small experiment offered a glimpse of what adaptation could look like-not a full solution, but a reprieve and a way to stay rooted to the land while the future of paddy takes shape.

Floating vegetable beds constructed on banana trunks, inspired by traditional methods from Bangladesh, represent another indigenous innovation emerging from farmer experimentation in waterlogged areas (Mukhopadhyay and Puskur, 2025). Farmers who were shown videos of floating bed techniques adapted the concept using locally available materials, combining household waste, kitchen residues and crop residues to create growing platforms. These small-scale experiments often initiated or maintained by women farmers, illustrate how adaptation can emerge from below when farmers are empowered to experiment and share findings. Their improvisations blur the line between farm work and domestic work, showing how adaptation is often sustained through feminized, unpaid labour that rarely enters formal accounts of innovation.

The community-based water monitoring system established in Makaltala village exemplifies participatory approaches to understanding climate impacts and informing adaptation decisions. Ten bamboo poles seven feet high were installed in key plots to record weekly water levels under researcher supervision (Mukhopadhyay and Puskur, 2025). Data collected between late September and October revealed standing water exceeding 3.5 feet in most plots when the monsoon should have been receding, confirming and quantifying the waterlogging problem. Soil analyses accompanying this monitoring revealed degradation from prolonged submergence, including compaction, reduced aeration and suppressed microbial activity. This integration of farmer observations with scientific measurement creates knowledge that is both locally relevant and scientifically rigorous, bridging the gap between formal research and lived experience.

The gender dimensions of adaptation emerge clearly from community-level observations, with women farmers bearing disproportionate burdens when traditional cropping systems collapse. With limited land ownership, most women earn through transplanting, weeding and harvesting on others' farms-opportunities that disappear when paddy cultivation fails (Mukhopadhyay and Puskur, 2025). Men may find construction or transport jobs in nearby towns, but women's options shrink to precarious low-paid domestic work or seasonal migration. The loss of paddy is not just the loss of a crop but the loss of women's steady source of cash income. Gender-responsive approaches being piloted in climate-vulnerable villages focus on livestock enterprises-an asset over which women exercise relatively higher control-along with trials of flood-tolerant germplasm and alternative crop experimentation to strengthen the resilience of the most marginalized women.

8. Conclusion

The comprehensive assessment of climate change impacts on agricultural productivity in West Bengal's Gangetic Plain region reveals a system under multifaceted stress, where incremental changes in mean conditions combine with heightened variability and extreme events to challenge the viability of established farming systems. The evidence synthesized from long-term climate records, crop simulation modelling studies, water footprint assessments and community-level observations converges on several robust conclusions that carry implications for agricultural policy, research prioritization and development practice in the region.

First, climate change in West Bengal is not a future projection but an observable reality with documented trends across multiple variables and spatial scales. The Gangetic region faces particular challenges from asymmetric warming patterns with greater increases in minimum temperatures, declining rainfall trends in critical seasons and dramatic shifts in precipitation intensity and distribution. Projections from CMIP6 models indicate continued warming of 1.3°C to 2.2°C by mid to late century under medium emissions scenarios, accompanied by increased rainfall totals but also greater rainfall intensity and unchanged or slightly increased dry spell duration. These changes are not uniform across the state but exhibit strong spatial differentiation that demands location-specific analysis and response. The western Gangetic zones, Sundarbans coastal areas and inland waterlogged tracts of North 24 Parganas emerge as hotspots where multiple dimensions of climate change converge with socio-economic vulnerability to create conditions of acute agricultural distress.

Second, the water resource implications of climate change pose fundamental challenges to agricultural sustainability. Increasing crop water requirements under future scenarios, particularly the blue water component essential for irrigation, will intensify competition for already stressed groundwater resources. Projected increases in blue water footprints ranging from 13 percent to 26 percent for cabbage and variable responses for potato and tomato signal heightened irrigation demands that will exacerbate groundwater depletion trends already evident across the Gangetic Plain. The differential responses of various crops to changing conditions-with cabbage and potato showing pronounced increases in water footprints while tomato demonstrates relative stability-suggests opportunities for strategic crop selection as an adaptation measure. However, realizing these opportunities requires overcoming market and policy barriers that currently incentivize continued cultivation of high-water-demanding crops.

Third, rice productivity responses to climate change vary significantly across species and cropping systems, with simulation modeling revealing that elevated CO_2 concentrations can partially mitigate temperature-induced yield reductions. Projected yield increases of 11 percent to 32 percent for rice under future scenarios when CO_2 fertilization is considered contrast with projected yield reductions for lentil and groundnut, demonstrating that climate change will reshape comparative advantages among crops. The finding that rice benefits from carryover effects of residues from preceding crops in rotation sequences underscores the importance of systems-level approaches to adaptation rather than single-crop interventions. These spatial and species-specific variations underscore the limitations of state-level analyses and the necessity of location-specific assessments to guide intervention design.

Fourth, adaptation strategies exist and demonstrate effectiveness when implemented, but adoption remains constrained by human capital limitations, institutional access barriers and policy environments that sometimes work at cross-purposes with adaptation objectives. Optimized planting dates enabled by digital advisory tools, crop diversification toward less water-demanding and more nutritionally dense alternatives and community-based innovations such as water chestnut cultivation and floating vegetable beds all offer pathways for maintaining productivity under changing conditions. The superior outcomes achieved by farmers employing multiple adaptation measures support integrated approaches that combine improved varieties, water management practices and livelihood diversification. However, realizing the potential of these strategies at scale requires supportive policy environments, including reformed incentive structures that currently favour water-intensive crops.

Fifth, community-based innovations emerging from farmer experimentation offer valuable models for adaptation that complement formal research systems. Water chestnut cultivation in submerged fields, floating vegetable beds constructed from locally available materials and community-based water monitoring systems all demonstrate the creative potential of farmer-led adaptation when supportive conditions exist. These grassroots innovations often emerge from women farmers whose contributions to adaptation remain underrecognized in formal accounts of agricultural innovation. Bridging the gap between scientific knowledge generation and farmer experimentation-creating spaces where farmers' insights and needs shape research priorities-represents a critical priority for accelerating adaptation.

The policy implications of these findings extend across multiple domains. Agricultural research systems must reorient priorities toward climate-resilient varieties and practices, with particular attention to prolonged submergence tolerance given the increasing frequency of waterlogging in inland areas. Currently, while submergence-tolerant varieties like Swarna-Sub1 and IR64-Sub1 survive flooding for about 14 days, farmers in waterlogged villages face submergence lasting months. This gap between available technologies and on-the-ground needs highlights the importance of research priority-setting processes that incorporate farmer perspectives and ground-level realities.

Extension systems require strengthening to deliver climate information and adaptation recommendations to farmers, supported by digital tools that enable location-specific advisories. The AgDay application's successful generation of planting date advisories for 200 farmers across six districts demonstrates the potential of information technology to support farmer decision-making, but scaling such innovations requires investment in institutional capacity and last-mile connectivity. Water management infrastructure investments must prioritize both supply-side enhancements such as improved irrigation efficiency and demand-side measures including incentives for water-saving crops, with recognition that groundwater depletion trends of 16 to 70 centimeters annually in some blocks cannot continue indefinitely.

The path forward requires moving beyond generic calls for adaptation toward detailed, location-specific strategies that recognize the diverse ways climate change manifests across West Bengal's varied landscapes. The Gangetic Plain region, with its combination of intensive agriculture, groundwater dependence and exposure to post-monsoon precipitation extremes, requires different interventions than the coastal saline zone where salinity intrusion and cyclone risk predominate, or the inland waterlogged areas where prolonged submergence challenges the very feasibility of paddy cultivation. Developing and implementing such spatially differentiated strategies demands institutional arrangements capable of coordinating across scales, from state-level policy frameworks to block-level implementation to community-level participation.

Ultimately, the climate challenge facing West Bengal's agriculture is not merely technical but deeply social and political. It involves questions of who bears the costs of climate impacts, who controls the resources needed for adaptation and whose knowledge counts in designing responses. The villages of Makaltala, where women farmers experiment with floating vegetable beds while awaiting improved rice varieties that can withstand months of submergence, exemplify both the urgency of adaptation and the creativity of community responses. Their experiences remind us that climate adaptation is not a problem to be solved once and for all but an ongoing process of learning, experimentation and adjustment as conditions continue to evolve. The goal of research and policy should be not to deliver final solutions but to support farmers' own adaptive capacities, enabling them to navigate an uncertain future with resilience and resourcefulness.

References

Chandran, M. A. S., Banerjee, S., Mukherjee, A., Nanda, M. K., & Niyogi, D. (2022). Evaluating the long-term impact of projected climate on rice-lentil-groundnut cropping system in Lower Gangetic Plain of India using crop simulation modelling. *International Journal of Biometeorology*, *66*(1), 55–69. https://doi.org/10.1007/s00484-021-02189-8

Government of India. (2022). *Agricultural Statistics at a Glance 2022*. Ministry of Agriculture and Farmers Welfare, Directorate of Economics & Statistics. https://desagri.gov.in/wp-content/uploads/2023/05/Agricultural-Statistics-at-a-Glance-2022.pdf

IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Kapuria, P., & Banerjee, S. (2023). Crop shifting for improved water use and nutritional productivity in the lower Indo-Gangetic plains of West Bengal. *ORF Occasional Paper No. 358*, Observer Research Foundation. https://www.orfonline.org/research/crop-shifting-for-improved-water-use-and-nutritional-productivity-in-the-lower-indo-gangetic-plains-of-west-bengal

Karim, F., Yu, Y., Kamruzzaman, M., Mandal, U. K., Zahan, T., Paul, P. L. C., & Mainuddin, M. (2024). Assessing changes in climate extremes using CMIP6 and its implications for agriculture in the Ganges Delta. *Journal of the Indian Society of Coastal Agricultural Research*, *42*(1), 1–14. https://epubs.icar.org.in/index.php/JISCAR/article/view/147069

Mali, S. S., Paul, A., Singh, D. K., Sarangi, A., Naik, S. K., & Das, D. K. (2024). Climate linked variations in blue and green water footprints of major vegetable crops cultivated in Eastern Gangetic Plains of India. *Journal of Agricultural Engineering*, *61*(3), 245–258. https://doi.org/10.52151/jae2024613.1854

Mukhopadhyay, P., & Puskur, R. (2025). Reimagining farming in Bengal's changing ecology: Bridging science and community solutions. *Down To Earth*. https://www.downtoearth.org.in/environment/reimagining-farming-in-bengals-changing-ecology-bridging-science-and-community-solutions

Munshi, S., Srivastava, A., Sohane, R. K., Yadav, A. K., Kumar, R., Veetill, P., Patil, V., Paneerselvam, Sherpa, S., & Kumar, V. (2024). In Eastern India, timely planting can mitigate climate change. *The Gurgaon Story*. http://thegurgaonstory.com/in-eastern-india-timely-planting-can-mitigate-climate-change/

Renault, D., & Wallender, W. W. (2000). Nutritional water productivity and diets. *Agricultural Water Management*, *45*(3), 275–296. https://doi.org/10.1016/S0378-3774(99)00107-9

Singha, C., Sahoo, S., Govind, A., Pradhan, B., Alrawashdeh, S., Aljohani, T. H., Almohamad, H., Islam, A. R. M. T., & Abdo, H. G. (2024). Impacts of hydroclimate change on climate-resilient agriculture at the river basin management. *Journal of Water and Climate Change, 15*(1), 209–232. https://doi.org/10.2166/wcc.2023.482