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Impact of Climate Change on Phenology, Productivity, and Water Use Efficiency of Major Cereal Crops in Pakistan

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ABSTRACT

Pakistan, ranked among the top ten climate-vulnerable nations, faces severe socioeconomic threats from rising temperatures (0.5–1.0 °C increase since 1960), erratic precipitation, and extreme events, profoundly impacting its agriculture sector (24% GDP contribution, 37.4% employment). This review synthesizes the effects on major cereals wheat, rice, and maize focusing on phenological shifts (e.g., shortened growth cycles by 5–15 days), productivity declines (projected 10–20% by 2050), and altered water-use efficiency (WUE) amid water scarcity affecting 80% of arable land. Elevated CO_2 enhances photosynthesis but is offset by heat stress reducing grain filling; drought exacerbates WUE reductions (10–30%) via stomatal closure and biomass loss. Regional variations highlight Indus Basin vulnerabilities, with glacial melt disrupting irrigation. Adaptation strategies climate-smart varieties, precision irrigation, and diversified cropping offer mitigation, potentially stabilizing yields and WUE. Projections indicate 15–25% GDP losses without intervention, underscoring the need for integrated policies to bolster rural resilience and food security in this climate hotspot.

Keywords: Climate Change, Pakistan, Cereal Crops, Phenology, Productivity, Water-Use Efficiency, Wheat, Rice, Maize, Heat Stress, Drought, Co_2 Elevation, Indus Basin, Adaptation Strategies, Food Security

Introduction

The existential challenge of the twenty-first century is manifest in the intensifying volatility of global climate systems, placing Pakistan at a critical crossroads of environmental vulnerability and economic stability (Rashid et al., 2025). Ranking consistently among the top ten countries most affected by climate-induced disasters, Pakistan faces a multi-dimensional threat to its agricultural sector, which remains the cornerstone of its national economy (Ishaque et al., 2024). The sector contributes approximately 24 percent to the national Gross Domestic Product (GDP) and provides a livelihood for nearly 37.4 percent of the total labor force, underscoring that any disruption in crop cycles translates directly into broader socio-economic fragility (Ministry of National Food Security and Research, 2024; Hussain & Bangash, 2017). The core of this agricultural system is the Indus River Basin, a vast hydrological network that serves as a lifeline for over 240 million people, yet it is increasingly compromised by shifting thermal and precipitation regimes (Shafeeque et al., 2023).

Historical data confirms that the mean annual temperature across Pakistan has risen significantly over the past six decades, with a marked acceleration observed since the 1990s (World Meteorological Organization, 2023). This warming is not uniform; rather, it exhibits complex regional variations that disrupt the synchronized biological clocks of major cereal crops including wheat, rice, and maize (Shahzad et al., 2025). The agricultural landscape is defined by two primary cropping seasons: 'Kharif' (April–

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June to October–December) and 'Rabi' (October–December to April–May). Both seasons are increasingly besieged by climate extremes, ranging from catastrophic monsoon floods that ravaged over 450,000 acres of crops in 2022 to intense rainfall events in 2025 (World Weather Attribution, 2025).

The convergence of rising temperatures, erratic rainfall, and elevated atmospheric carbon dioxide (CO2) levels creates a complex physiological environment for cereal crops. While CO2 fertilization can theoretically enhance growth in C3 plants like wheat and rice, concurrent thermal stress often negates these gains by inducing grain abortion and shortening the grain-filling duration (Bhattacharya, 2025). Understanding specific impacts on phenology, productivity, and Water Use Efficiency (WUE) is paramount for developing climate-resilient strategies to safeguard national food security (Khan et al., 2024). The interactions between climatic drivers and crop responses are complex and multidimensional. Figure 1 presents a conceptual framework summarizing how climate change influences phenology, productivity, and water-use efficiency of major cereal crops in Pakistan.

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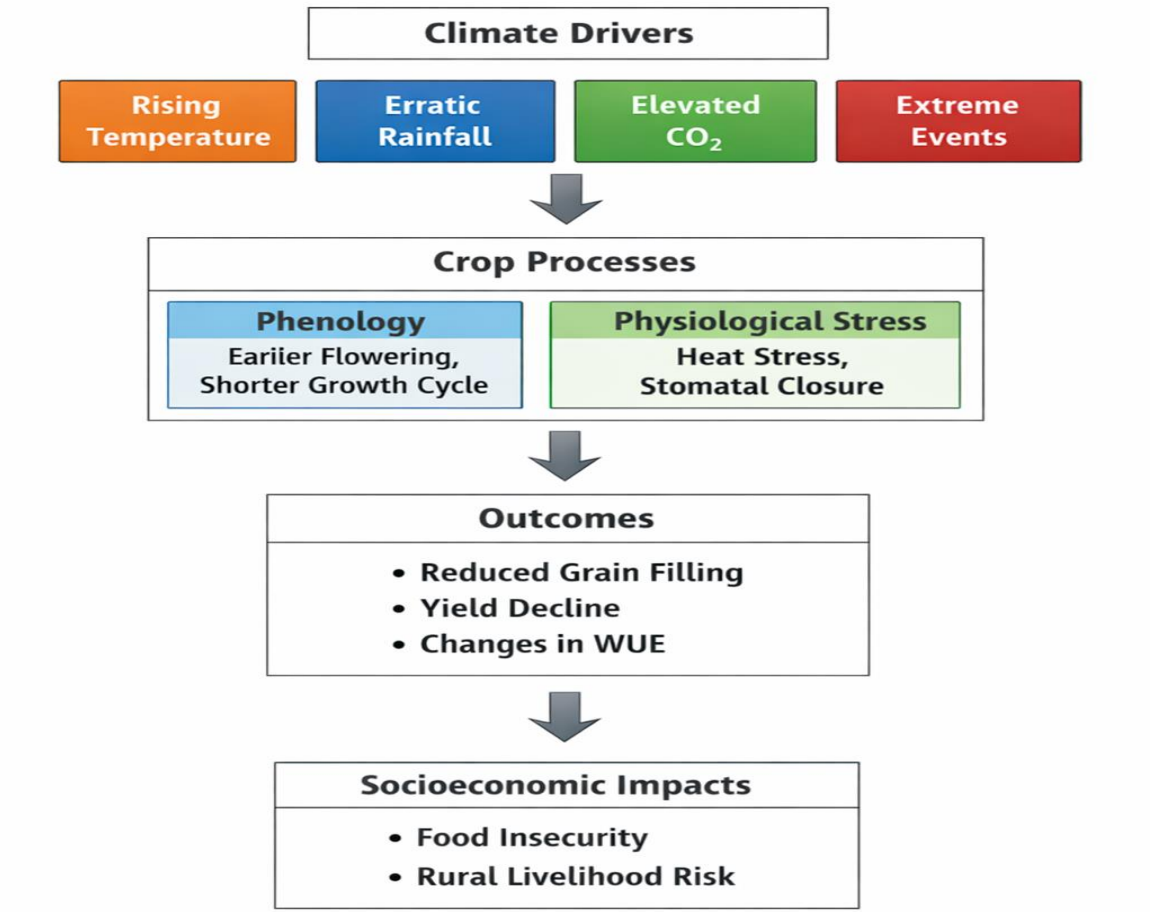
Figure 1: Conceptual Framework: Climate Change Impacts on Phenology, Productivity, and Water Use Efficiency of Cereal Crops



Climatological Transformations and Extreme Events

The trajectory of climate change in Pakistan is characterized by an increase in the frequency and intensity of extreme meteorological events. Between 1999 and 2018, the country endured 152 severe weather events, resulting in an economic toll of 3.8 billion USD (Eco Justice, 2024). More recently, the historic rainfall of 2022 and the intense monsoon floods of 2025 have highlighted acute vulnerability, with 30-day maximum rainfall events becoming approximately 22 percent more intense due to global warming (Jackson, 2025).

Shifting Temperature and Precipitation Regimes

Analysis of meteorological time series data (1981–2020) reveals significant increases in hot days, warm nights, and extreme precipitation events. The decadal variation in temperature shows a distinct upward trend, particularly in the maximum and minimum annual temperatures (Khan et al., 2018).

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Table 1. Decadal Changes in Meteorological Variables in Pakistan

Meteorological Variable	Decadal Rate of Change	2023 Observed Mean
Maximum Annual Temperature	+0.12 to +0.29 degrees Celsius	30.23 degrees Celsius
Minimum Annual Temperature	+0.10 to +0.37 degrees Celsius	16.36 degrees Celsius
Mean Annual Temperature	Accelerated rise since 2000	23.31 degrees Celsius
Monsoon Precipitation	High inter-annual variability	16 percent above average

Sources: Khan et al. (2018); WMO (2023)

In the Potwar Plateau, a semi-arid region critical for rain-fed agriculture, the Rabi season precipitation has exhibited a decreasing trend of -20.47 mm per decade (Naz et al., 2024). This volatility is mirrored in the Indus Basin, where the normal flow has plummeted to 40 percent of historical levels due to climate change, largely because the melting of Himalayan glaciers is becoming increasingly unpredictable (Shah et al., 2020).

Recent Flooding and Rainfall Deficits

The 2025 monsoon rainfall in northern Pakistan led to flash floods that killed 300 people and damaged over 1,600 houses, strained the agricultural infrastructure, and necessitated adaptation investments estimated at 152 billion USD by 2030 (Ali, 2024). Conversely, between September 2024 and January 2025, Pakistan experienced an almost 40 percent rainfall deficit, which hit Sindh, Balochistan, and Punjab hardest, causing severe crop losses in arid areas (Hussain et al., 2024).

Impact of Climate Change on Crop Phenology

Crop phenology refers to the timing of developmental stages, primarily driven by the accumulation of thermal units, measured as Growing Degree Days (GDD). Rising temperatures accelerate these processes, leading to a compression of the growing season and reduced time for biomass accumulation (Abbas et al., 2017).

Shortening of the Wheat and Maize Developmental Cycles

Wheat and maize are exceptionally sensitive to temperature shifts during their reproductive phases. Simulation models like the Agricultural Production Systems sIMulator (APSIM) have quantified these shifts under future scenarios (Banerjee et al., 2024).

Wheat Phenology: Emergence is predicted earlier by 7–9 days, anthesis by 8–10 days, and maturity by 2–6 days (Chauhdary et al., 2025).

Maize Phenology: Spring maize maturity is projected to advance by 16–24 days, while autumn maize maturity may advance by 8–19 days (Xiao et al., 2018).

High temperatures during the grain-filling phase (exceeding 30 degrees Celsius) lead to premature senescence, resulting in shriveled kernels and lower test weights (George

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al., 2024).

Phenological Variability in Rice

For rice in Punjab, sowing and transplanting stages have advanced by 6 to 8 days per decade, while actual maturity dates have advanced by approximately 6.4 days per decade. A portion of this impact has been mitigated through the adoption of new cultivars with higher thermal time requirements (Manhas, 2021).

Agricultural Productivity and Yield Dynamics

The relationship between climatic variables and productivity is characterized by non-linearity and regional specificity. Research reveals an "inverted U-shaped" relationship between temperature and yield, where warming boost production initially but triggers a collapse beyond critical thresholds (Namri et al., 2026).

Projections for Cereal Yield Losses

Simulations for the near future (2025–2065) project average yield reductions of 11.5 percent for wheat, 11.8 percent for spring maize, and 11.0 percent for autumn maize. In Punjab, a 2 degrees Celsius temperature rise is projected to reduce wheat yields by 1 to 4 percent and rice yields by 3 to 17 percent (Rahman et al., 2018).

In Balochistan, a 1 percent increase in temperature initially boosts maize production due to its tropical origin, but further increases lead to a 2.563 percent decline for every subsequent 1 percent rise. During the 2024–25 season, a combination of heatwaves and irregular rainfall caused a 13.5 percent drop in the production of major crops across Pakistan (Jan Alam, 2025).

Biotic Stresses and Soil Degradation

Climate change acts as a force multiplier for biotic stresses, expanding the range of pests and diseases. Higher temperatures and erratic rains increase susceptibility to leaf and stem rust in wheat and bacterial blights in rice (Naz et al., 2024). Simultaneously, high temperatures exacerbate salinity and erosion, reducing the overall fertility of the Indus Basin (Concave Agri, 2024).

Water Use Efficiency and Evapotranspiration Trends

Water Use Efficiency is defined as the ratio of grain yield to the total water consumed via evapotranspiration (ET). Rising temperatures increase potential ET, thereby raising Crop Water Requirements (CWR) (Shafeeque et al., 2023).

Rising Crop Water Requirements

By the end of the century, CWR is projected to rise significantly under high-emission scenarios.

Kharif Season: CWR increase of 8 to 14 percent

Rabi Season: CWR increase of 12 to 15 percent.

This increased demand is creating a "water gap," where the demand-supply gap in arid and semi-arid zones is expected to widen by up to 32 percent for the Rabi season by

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2100 (Alotaibi et al., 2023).

Carbon Dioxide Fertilization and Physiological Buffers

Elevated atmospheric CO2 concentrations can decrease stomatal conductance, potentially improving WUE by allowing plants to assimilate more carbon with less water loss (Bhattacharya, 2025).

Rice and Wheat: WUE is positively correlated with CO2 but negatively correlated with temperature

Mechanism: CO2 levels below 600 ppm can increase WUE in C3 crops like wheat and rice by 40 to 50 percent. However, this fertilization effect often fails to protect grain yield from heat-induced abortion during anthesis (Sabagh et al., 2021).

Redefining Pakistan's Agro-Ecological Zones (AEZ)

The Pakistan Agricultural Research Council (PARC) redefined the country's agro-ecological zones in 2024 to reflect the contemporary impacts of climate change, utilizing precise topography and hydrology data (Pakistan Agricultural Research Council, 2024).

Table 2. Redefined 10 Agro-Ecological Zones and Potential Commodities

Zone Name	Extent (M.ha)	Key Potential Crops
Northern Dry Mountains	8.00	High-value fruits, vegetables, fish
Temperate Mountains	5.13	Sustainable livestock, high-value fruits
Rainfed Plateau	2.61	Wheat, maize, pulses (Rain-fed)
Northern Irrigated Plain	9.82	Wheat, rice, maize, cotton
Southern Irrigated Plain	5.04	Rice, wheat, sugarcane, sunflower
Western Dry Mountains	16.60	Rangeland, livestock
Western Dry Plateau	12.51	Drought-resistant varieties
Piedmont Plain	6.43	Targeted climate-smart crops
Sandy Desert	12.17	Olives, dates, bio-saline agriculture
Coastal Zone	8.60	Fish, livestock, tropical fruits

Policy Response and the National Water Policy 2018

The National Water Policy (NWP) 2018 sets strategic priorities to address the imminent water crisis, aiming for a 20 percent improvement in agricultural water use efficiency by 2030 through the "More Crop per Drop" strategy (Mumtaz et al., 2019).

Implementation Status and Challenges

Implementation remains hampered by structural and economic constraints. Federal priorities remain focused on infrastructure, with 66 percent of the water sector budget allocated to large dams and surface storage, while on-farm water management receive only 8 percent (Food and Agriculture Organization [FAO], 2024). Furthermore, irrigation water is heavily subsidized, costing the government between 0.81 and 1.07

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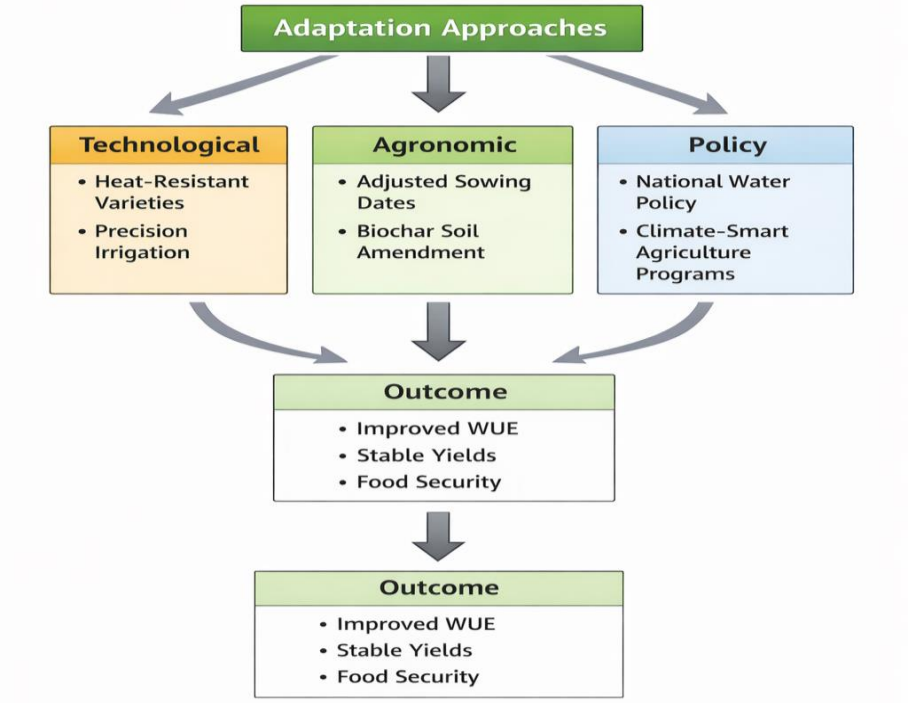
percent of GDP annually, which disincentivizes the adoption of water-saving technologies (Abedullah & Ali, 2024).

Adaptation Strategies for a Climate-Resilient Future

Transitioning to Climate-Smart Agriculture (CSA) is imperative to mitigate losses (Hellin et al., 203). Multiple technological, agronomic, and policy interventions are required to reduce climate risks to agriculture. Figure 2 summarizes the key climate-smart adaptation strategies that can enhance resilience of cereal production systems in Pakistan.

Figure 2: Climate-Smart Adaptation Strategies for Sustainable Cereal Production



Technological and Agronomic Interventions

Heat-Resilient Varieties: PARC has initiated genomics-based variety development and speed breeding to produce cereal lines resistant to thermal stress, such as the 'Markaz-2019' wheat variety (PARC, 2020, 2024).

Precision Irrigation: Drip and sprinkler systems have shown significant promise, with drip irrigation enhancing maize WUE by 100 to 128 percent compared to furrow systems (Ahmad et al., 2024).

Soil Amendments: Biochar application can increase soil moisture retention by 9.2 percent and overall wheat WUE by 13.6 percent (Begna et al., 2025).

Management Adaptation

Shifting sowing dates is a low-cost, effective strategy. For instance, adjusting planting

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windows can significantly reduce exposure to terminal heat stress for wheat. Additionally, enhancing farmers' access to meteorological information and climate change knowledge (CCK) self-motivates the adoption of adaptation measures (Hussain et al., 2024).

Socio-Economic Implications and Food Security

The decline in cereal crop productivity has profound implications for national security. Between April and July 2025, 10 million people (20 percent of the rural population analyzed) were projected to experience acute food insecurity (IPC Phase 3 or above) (Integrated Food Security Phase Classification [IPC], 2024). Small farmers are particularly vulnerable, often trapped in cycles of poverty as they sell livestock or borrow to cope with climate shocks (Eichsteller et al., 2022).

Conclusions

Climate change imposes cascading socioeconomic burdens on Pakistan's rural livelihoods through disrupted phenology, diminished productivity, and impaired water-use efficiency in staple cereals, threatening national food security and economic stability. With projected yield losses of 10–20% by mid-century and escalating water deficits, the imperative for proactive adaptation via resilient cultivars, efficient irrigation technologies, and diversified systems is clear. Integrated policy frameworks, supported by research and extension, can mitigate these impacts, fostering sustainable agriculture resilient to thermal and hydrological extremes. Ultimately, addressing this crisis demands global cooperation on emissions reduction alongside localized strategies to safeguard Pakistan's agrarian base and prevent humanitarian escalations in vulnerable regions.

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