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REVIEW ARTICLE

Climate change impacts on the agriculture sector of Khyber Pakhtunkhwa: a comprehensive review with comparative regional analysis

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Abstract

Climate change presents pressing challenges to Pakistan's environmental and socio economic, systems with the province of Khyber Pakhtunkhwa (KP) emerging as one of the most vulnerable regions. Scientific assessments indicate that climate-induced hazards such as riverine and urban flooding, glacial lake outburst floods (GLOFs), prolonged heatwaves, droughts, and the spread of vector-borne diseases, are projected to intensify in frequency and severity in the coming decades. In response to these emerging threats, Adaptation strategies are designed to minimize exposure and vulnerability of both human and ecological systems, while mitigation efforts focus on curbing greenhouse gas emissions through sustainable practices and technological innovation. Khyber Pakhtunkhwa (KP), a predominantly agrarian province of Pakistan, is increasingly vulnerable to the multifaceted impacts of climate change. This comprehensive review synthesizes historical climate trends and the growing frequency of extreme weather events-such as floods, droughts, hailstorms, heatwaves, and erratic rainfall-and their detrimental effects on agriculture. Using meteorological data, published studies, and government reports, the paper highlights region-specific vulnerabilities, including rising temperatures, pest and disease outbreaks, and shifts in cropping calendars. Graphical analyses and evidence-based assessments underscore the scale of agricultural losses and livelihood disruptions across KP's diverse agro-ecological zones. The review further compares these findings with trends in other provinces of Pakistan and neighboring countries like India, Afghanistan, and Iran, providing a broader regional perspective on climate impacts and adaptation practices. The paper concludes with a set of targeted recommendations, including climate-smart agriculture, adaptive crop zoning, efficient water use, and integrated pest management strategies, aimed at enhancing resilience and sustainability in the province's agriculture sector.

Keywords: Climate change and agriculture; extreme weather events; climate-smart agriculture; pest outbreaks; adaptation strategies

Introduction

Agriculture remains a cornerstone of Khyber Pakhtunkhwa's (KP) economy, contributing significantly to the province's economic and social fabric. Engaging over 40% of the labor force, agriculture is not only the primary livelihood for a large portion of the population but also a vital sector for ensuring food security and poverty alleviation in the region (GoKP, 2020). In terms of its contribution to the provincial Gross Domestic Product (GDP), agriculture accounts for roughly 20%, with smallholder farming systems being the dominant structure of land use. These smallholder farms are primarily engaged in the cultivation of staple crops such as wheat, maize, rice, and various fruits and vegetables. Despite its importance, the sector faces numerous challenges, with climate change emerging as one of the most significant threats to its sustainability and productivity.

In recent decades, climate change has had a profound impact on the agro-ecological landscape of KP, making the region increasingly vulnerable to extreme weather events. These include intense and frequent floods, such as those experienced in 2010 and 2022, as well as prolonged droughts, sudden hailstorms, and more frequent heatwaves. Alongside these, rising temperatures are becoming a critical concern for agriculture in KP, directly affecting crop productivity, soil health, and the availability of essential resources like water. A report by the Intergovernmental Panel on Climate Change (IPCC, 2021) has highlighted the significant role of rising temperatures in exacerbating agricultural risks, with particular emphasis on the vulnerability of developing regions like KP. According to Rasul et al. (2012), the average temperature in KP has risen by approximately 0.6°C since the 1960s, with a more pronounced rate of warming observed in the past two decades. This increase in temperature has been accompanied by erratic rainfall patterns and heightened climate variability, which in turn affect the sowing and harvesting periods of key crops. The onset of rains is often unpredictable, and severe rainfall events can lead to flash floods, damaging crops and reducing yields. Additionally, hailstorms during critical growth stages of crops have led to substantial losses, further threatening the food security of the region. The effects of these climatic shifts are not only environmental but also socio-economic. KP's agricultural sector is characterized by a high level of socio-economic dependence on farming, with many rural households reliant on agriculture for both subsistence and income. However, the capacity of farmers to adapt to these changing climatic conditions is limited, due to a lack of resources, knowledge, and access to adaptive technologies. As a result, the agricultural sector in KP remains highly susceptible to climate-related risks, with little resilience to the escalating challenges posed by climate change. The province's vulnerability is compounded by the physical risks associated with extreme weather events, such as soil erosion, water scarcity, and crop failure. Moreover, the socio-economic impacts of climate change exacerbate existing inequalities within rural communities, where smallholder farmers are often the most affected due to their limited access to insurance, modern technologies, or alternative livelihoods. This makes it increasingly important to implement strategies that not only mitigate the effects of climate change on agriculture but also enhance the adaptive capacity of local farmers. Climate change is an urgent and growing challenge for the agricultural sector in Khyber Pakhtunkhwa. Its impacts are multifaceted, affecting not only crop yields and agricultural productivity but also the socio-economic well-being of rural communities. Understanding the nature of these risks and developing adaptive strategies are critical to securing the future of agriculture in the region and ensuring food security for the growing population.

Review Methodology

Past Climate Trends and Historical Damages in Khyber Pakhtunkhwa (KP)

Khyber Pakhtunkhwa (KP), Located in the northwestern region of Pakistan, is characterized by remarkable topographical diversity. The northern, northwestern, and eastern areas of the province are home to some of the world's most prominent mountain ranges, including the Hindu Kush, Himalayas, and Karakoram. In contrast, the southern parts of KP are defined by expansive plains and central valleys, which support extensive agricultural activities and rangelands. The province experiences a wide range of climatic conditions due to its varied geography (Table 1). The northern districts endure harsh winters with substantial snowfall, cooler summers, and significant rainfall, while the southern regions experience relatively mild winters, warmer temperatures, and moderate precipitation. Chitral, situated at the highest elevation in the province, records some of the coldest winter temperatures and contains numerous glaciers. Meanwhile, Dera Ismail Khan (D.I. Khan), located in the far south, benefits from a milder winter climate and favorable conditions for crop cultivation and grazing, making it a hub for agriculture and pastoral activities.a province located in the north-western part of Pakistan, has experienced significant climatic shocks in the past few decades (Fig 1).

Table 1: Categorization of Land Use/Land Cover in KP Province

Land Use	Area (ha)	Area (%)
Water	73,254	0.72
Forest/Tree-Cover	842,415	8.28
Crops	1,177,143	11.57
Built-Up Area	605,359	5.95
Bare Ground	1,031,654	10.14
Snow/Ice	371,355	3.65
Rangeland	6,072,920	59.69

Source: ESRI Land Use-Land Cover Classification, 2021

These extreme weather events have caused devastating impacts on agriculture, livelihoods, and infrastructure, underscoring the growing vulnerability of the region to climate change.

Figure 1: Geographical Map of Khyber Pakhtunkhwa Province, Pakistan

Climate Hazards in Khyber Pakhtunkhwa

Climate change continues to exert profound effects across various regions of the globe. The Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report (AR6, 2021), underscores the intricate links between climate change and its widespread consequences for both natural ecosystems and human societies. Growing scientific consensus attributes shifts in weather patterns, accelerated glacial retreat, the occurrence of Glacial Lake Outburst Floods (GLOFs), disruptions in hydrological systems, alterations in species migration, and changes in agricultural productivity directly to climate variability. These changes increasingly jeopardize traditional food production systems. The report also projects a significant rise in the frequency and duration of heatwaves across Asia, coupled with a decline in cold days and nights, and a corresponding increase in warmer extremes. These developments highlight the ongoing destabilization of ecological systems and reaffirm the interconnectedness and vulnerability of human life to environmental fluctuations (IPCC, 2021).

In recent years, the effects of climate change have become more pronounced, evident in the warming of the atmosphere and oceans, rising sea levels, and the heightened concentration of greenhouse gases. There is now overwhelming evidence confirming the reality and progression of climate change. Moreover, its impacts have amplified the severity of natural hazards. Increasing episodes of intense rainfall and elevated surface temperatures are altering long-standing weather patterns, making climate-related disasters more frequent and destructive, particularly in already vulnerable regions. Natural hazards—such as earthquakes, floods, droughts, landslides, hurricanes, and volcanic eruptions—pose significant risks, especially in geographies with limited adaptive capacities. Without adequate risk reduction strategies, mitigation efforts, and adaptive responses, these hazards can escalate into full-blown disasters. In Khyber Pakhtunkhwa (KP), the risks associated with climate change are particularly acute. The province faces a wide array of climate-induced threats, including glacial melt, drought, flooding, GLOFs, strong winds, avalanches, landslides, locust infestations, dengue outbreaks, and smog. Data from the National Disaster Management Plan (NDMP, 2012) identifies district-level vulnerabilities across KP. However, these risks demand updated assessments based on simulation modeling and forward-looking projections to guide policy and preparedness efforts more effectively.

The 2010 Catastrophic Floods

Khyber Pakhtunkhwa is home to a complex network of rivers, many of which eventually merge with the Indus River that flows through the province. The prominent rivers traversing the region include the Indus, Kabul, Swat, Kurram, and Gomal rivers. Collectively, the Indus River system and its tributaries carry an estimated annual flow of 154 million acre-feet (MAF) of water. This volume comprises approximately 145 MAF from the northwestern rivers such as the Indus, Jhelum, and Kabul, along with several smaller tributaries and around 9 MAF from the eastern rivers, mainly the Ravi and Sutlej (EPA, Government of Khyber Pakhtunkhwa). One of the most catastrophic climate-related events in recent history, the 2010 floods, affected over 1.6 million people in KP and caused severe damage to the region's agricultural landscape. The floods submerged approximately 0.7 million hectares of farmland, including staple crops like wheat, maize, and rice, as well as fruit orchards (NDMA, 2011). The extensive damage to crops, livestock, and infrastructure left communities struggling to recover, with many households unable to rebuild their livelihoods in the short term. The floods also washed away topsoil, reducing the productivity of affected lands for years to come (Ali et al., 2012). Due to the extensive river systems and mountainous terrain, the Khyber Pakhtunkhwa region is highly susceptible to flash flooding during the monsoon season. Over the past decade, flood frequency has significantly increased, with heavy precipitation events occurring almost annually. In 2007, Kohistan was severely affected by flooding caused by intense rainfall and glacial meltwater. The situation escalated in 2010, when Khyber Pakhtunkhwa experienced its worst flood in recent history, resulting in the displacement of hundreds of thousands of people and extensive damage to infrastructure. In the subsequent years 2011 through 2015 the region continued to witness recurrent flooding, albeit with varying intensities (Fig 2). These repetitive flood events compounded the challenges of recovery, as rehabilitation from previous disasters remained incomplete, thereby increasing both the human and economic toll. In 2010, data from OCHA reported that approximately 4.7 million individuals were impacted by flooding in Khyber Pakhtunkhwa. One of the most catastrophic glacial lake outburst flood (GLOF) events occurred in 2015, severely affecting around 321,644 people in Chitral and resulting in the loss of 1,200 acres of standing crops (PDMA, 2015). In recent years, additional destructive GLOF incidents have been recorded in the Golen Gol and Reshun Valleys. The Himalayan moist temperate forest zones, located at elevations ranging from 1,525 to 3,660 meters, remain particularly vulnerable to recurring flood risks. Due to the ongoing impacts of climate change, these regions particularly the lower Kaghan Valley, Galiat, and southern Kohistan are expected to witness more frequent and intense precipitation events. As such, implementing strategic mitigation and adaptation measures is essential to reduce the risk and impact of future floods in Khyber Pakhtunkhwa.

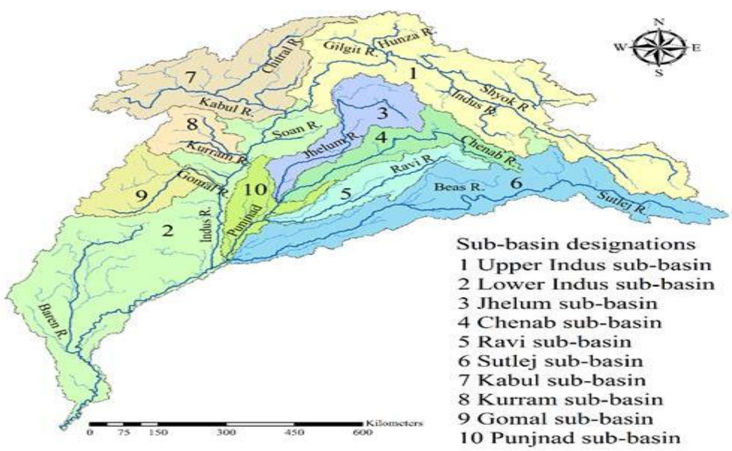

Figure 2: River system of Indus Basin (Mukhopadhyay and Khan,2016)

The 2015 Heatwave

In 2015, a severe heatwave swept through the lowland districts of KP, particularly Dera Ismail Khan (D.I. Khan), where temperatures exceeded 45°C for several consecutive days. This extreme heat led to a significant reduction in wheat yields by 15-20%, particularly in areas dependent on rain-fed agriculture. The heatwave exacerbated water scarcity and negatively impacted both crop productivity and livestock health, leading to financial losses for farmers (Khattak et al., 2017).

Hailstorms (2017-2021)

Between 2017 and 2021, KP experienced a series of hailstorms that caused extensive damage to fruit orchards, especially in the Swat, Dir, and Charsadda districts. These storms destroyed standing fruit crops such as apples, peaches, and plums, as well as vegetables, leading to significant economic losses for smallholder farmers. The increasing frequency of hailstorms during critical flowering and fruit-setting periods has raised concerns about the resilience of the province's horticulture sector to such extreme weather events (Raza et al., 2020).

Drought Periods (2002-2005 and 2016-2020)

KP has also been affected by recurring droughts, with two notable drought periods in recent history: one from 2002 to 2005 and another from 2016 to 2020. These droughts, particularly in the southern districts of KP such as D.I. Khan, Bannu, and Tank, have led to the failure of rabi (winter) crops like wheat and barley, resulting in food insecurity and livestock losses (Fig 3). Water shortages during these dry periods have further exacerbated the situation, with farmers facing difficulties in accessing sufficient irrigation for their crops. The prolonged dry spells have also led to the depletion of water tables and a reduction in the recharge rates of groundwater sources (Hussain et al., 2021). Droughts in the southern parts of Khyber Pakhtunkhwa are more common as compared to the northern parts. The central valley plain, Piedmont plain and Suleiman Piedmont are areas dedicated mostly to agriculture. The total cultivated area in Khyber Pakhtunkhwa is about 1.65 million ha. This signifies the magnitude of impact of a drought on food security in the province.

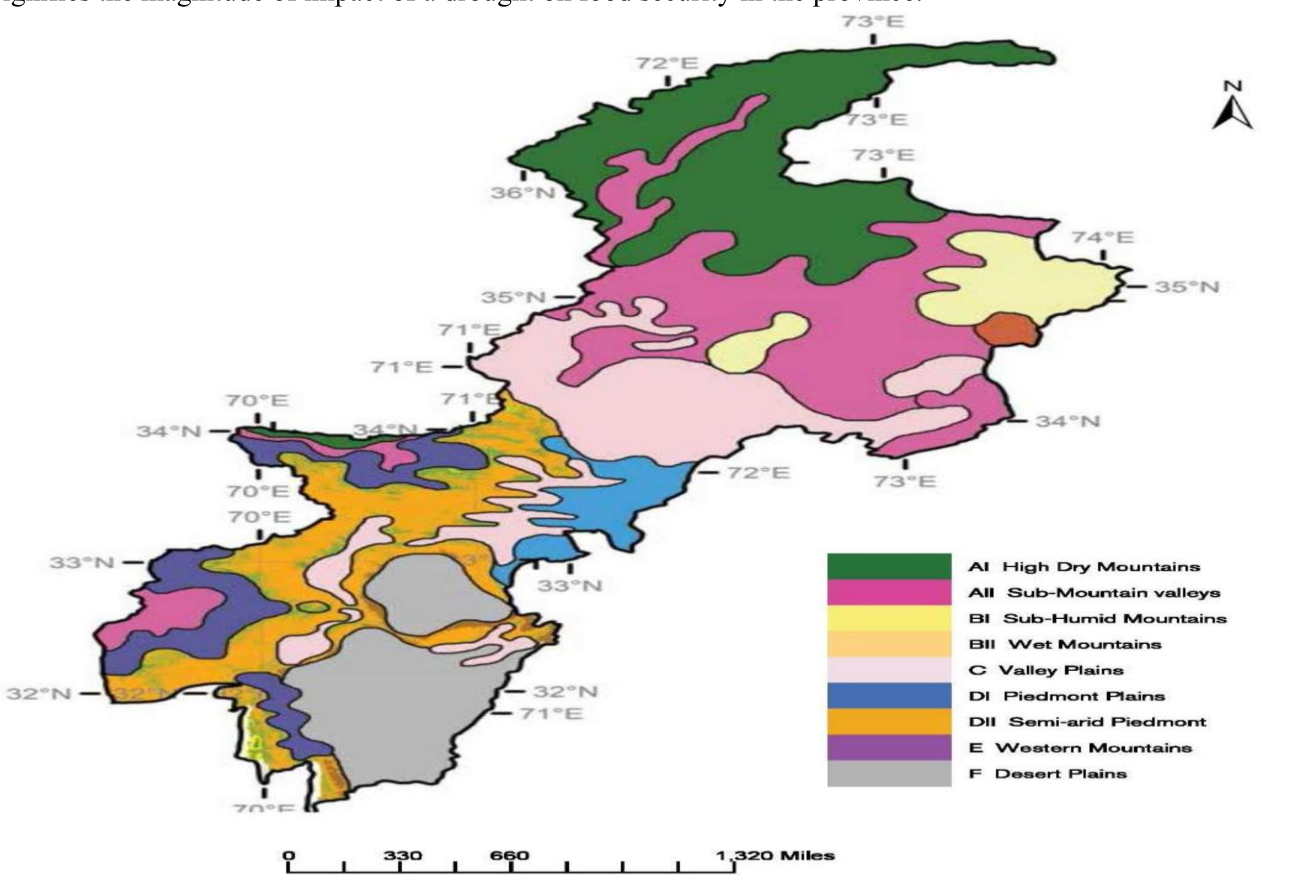

Figure 3. Distinct Agro-Ecological Regions Across Khyber Pakhtunkhwa Province (Data Source: Nizami et al., 2020)

With rising temperatures and decrease in rainfall in dry regions, particularly in southern parts, are most likely going to be water stressed region in the coming years. The climate ranges from warm and sub-humid in valley plains to hot and arid southern parts. Dera Ismail Khan is the area which will be most prone to droughts. Although, drought is a less common hazard compared to floods, the implications on food security cannot be ignored. Deserts in southern parts like Karak, Lakki Marwat and DI Khan may expand in case of prolonged droughts.

The southern parts of the province receive less rainfall and higher temperatures in the summer and drier winters (Fig 4). Climate forecasts predict that dry regions will get drier and wet regions will get wetter. As these areas are drier especially during the winter and hot during the summers there is an expected increase in average temperatures in the summer. These high temperatures may be optimal for some crops to cultivate but high temperatures will increase evapotranspiration which in turn increases the demand of crops for water. Therefore, the quantity and availability of groundwater and irrigation water will be vital in determining water stress in the area.

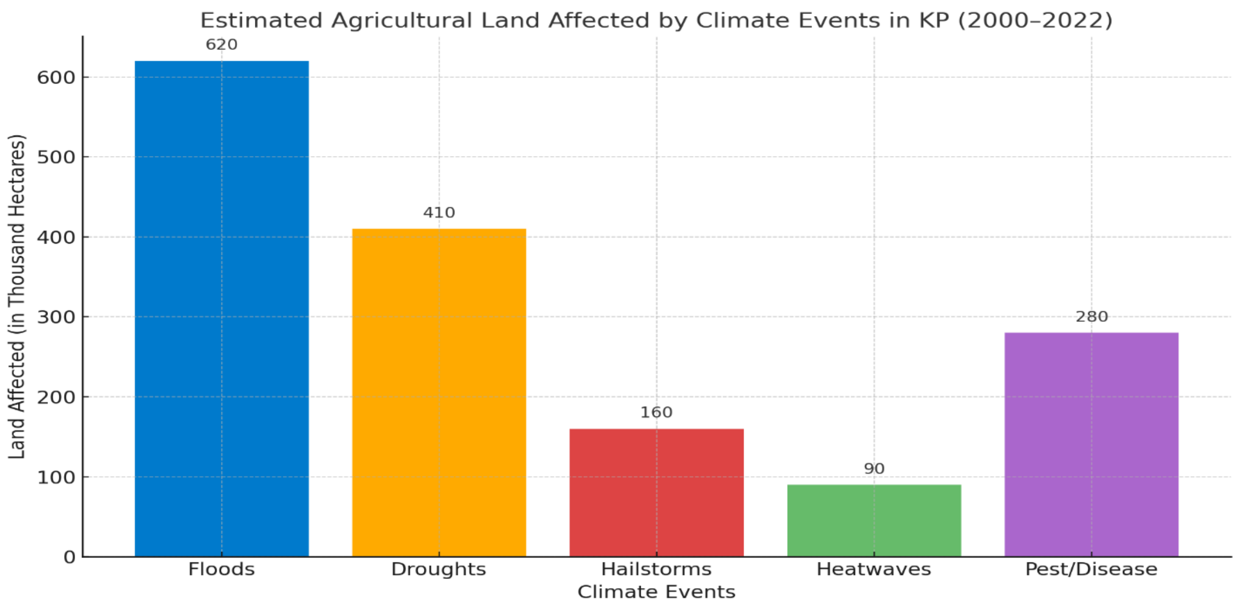

Figure 4: Agricultural land affected by different climate events in KP (2000-2022)

This figure illustrates the hectares per year of agricultural land affected by various climate events such as floods, droughts, hailstorms, heatwaves, and rainfall anomalies. The graph highlights the increasing frequency of extreme weather events over the past two decades, reflecting the growing vulnerability of the agricultural sector in KP.

Temperature Rise and its Impact on Agriculture

The rising temperatures in KP are altering the growing seasons for key crops, resulting in reduced productivity and increased pressure on water resources. Research has shown that higher summer temperatures, particularly in districts like Charsadda and Mardan, have shortened the growing seasons for crops like wheat and maize, leading to yield reductions of 10-15% (GOP-MinFA, 2020). The early grain filling due to warmer temperatures reduces the time available for crops to reach full maturity, negatively impacting overall yields.
In horticulture, particularly in the cooler regions of KP, warmer winters have disrupted fruit-setting in crops like apples, peaches, and plums. These crops, which typically require cold temperatures for proper dormancy and subsequent flowering, have seen a decline in fruit-setting due to the warmer-than-normal winter temperatures. As a result, the productivity of fruit orchards in regions like Swat and Abbottabad has been compromised (Shah et al., 2018).

Erratic Rainfall and Flash Flooding

The variability in rainfall patterns in KP has led to both prolonged droughts and devastating flash floods. In the spring, irregular rainfall patterns often result in water deficits that hinder maize sowing, one of the key crops in the region. On the other hand, summer rainfall can be erratic, leading to flash floods that cause soil erosion, wash away seeds, and damage infrastructure.

For example, flash floods in Upper Kohistan and Malakand in 2022 resulted in landslides that destroyed vegetable terraces, leading to the displacement of farming families and a loss of agricultural production. Flash floods are especially problematic in mountainous areas, where steep slopes increase the risk of landslides and erosion (Javed et al., 2022).

Drought and Water Scarcity

KP's agriculture, particularly in areas like D.I. Khan, Bannu, and Tank, is heavily dependent on rain-fed irrigation systems. However, chronic drought conditions, exacerbated by lower-than-normal snowfall and reduced rainfall, are leading to significant water shortages. The FAO’s drought risk map (2022) highlights southern KP as one of the most climate-vulnerable regions in Pakistan, with low rainfall and rising temperatures causing a steady decline in available water resources. As groundwater levels drop, small-scale farmers who rely on tube wells face increasing costs, as the electricity required to pump water becomes unaffordable (FAO, 2022).

Hailstorms and Heatwaves

Hailstorms have become an increasingly frequent occurrence in KP, particularly in the spring and pre-harvest periods. These storms, which affect regions such as Swabi, Haripur, and Dir, have caused considerable damage to wheat fields and fruit orchards. In addition, heatwaves during the summer months, especially from May to June, have led to crop stress, including flower abortion in crops like tomato and capsicum. In 2021, Peshawar experienced a heatwave where temperatures exceeded 45°C, resulting in severe damage to vegetable crops (Saeed et al., 2021).

Pest and Disease Incidence in a Changing Climate

Climate change is contributing to the intensification of pest and disease pressures in KP, altering the epidemiology of various plant diseases. Warmer temperatures and increased humidity are favorable conditions for pests like fruit flies, armyworms, and whiteflies, which are emerging earlier in the growing season and in greater numbers. For example, tomato leaf curl virus and maize stalk borer are spreading to regions where they were not previously a significant concern (Ali et al., 2019).

In fruit crops like apples and peaches, fungal diseases such as powdery mildew and fire blight are becoming more prevalent, particularly in the cooler districts of Swat, Mansehra, and Chitral. These diseases thrive under the increasingly warm and moist conditions created by climate change, posing a significant threat to the province’s fruit industry (Yousaf et al., 2020).

Vulnerability Across Agro-Ecological Zones

KP is home to diverse agro-ecological zones, each facing unique vulnerabilities due to climate change:

Mountainous Zones (Swat, Chitral, Dir): These areas are prone to glacial lake outburst floods (GLOFs), late frosts, and the resurgence of pests that thrive in the changing climate (Khan et al., 2020).

Central Plains (Mardan, Charsadda, Swabi): These zones are primarily affected by erratic rainfall, rising pest populations, and shorter growing seasons due to increased temperatures (Raza et al., 2020).
Southern Semi-Arid Zone (D.I. Khan, Tank, Bannu): These regions are highly vulnerable to drought due to their dependence on rain-fed agriculture, low soil organic matter, and limited water resources. As temperatures rise and precipitation becomes more erratic, the vulnerability of these areas is further compounded (Iqbal et al., 2021).

Comparative Analysis: Other Provinces and Neighboring Countries9.1 Punjab and Sindh

Punjab: Punjab, as Pakistan's agricultural heartland, is experiencing similar climatic pressures to Khyber Pakhtunkhwa (KP) but with distinct challenges (Table 2). The temperature increase in Punjab over the last five decades is approximately 1.2°C, slightly higher than KP's rate of warming (Pakistan Meteorological Department [PMD], 2023). This increase in temperature has been particularly detrimental to crops like wheat, rice, and cotton, which are highly sensitive to heat stress. For instance, prolonged heatwaves during critical flowering and grain-filling stages have reduced wheat and rice yields by up to 15-20% (Hassan et al., 2022).
Additionally, water scarcity is a pressing issue in Punjab, linked to the declining flow of the Indus River, which is exacerbated by reduced snowmelt from the Himalayas due to climate change. Water shortages have led to inefficient irrigation practices, impacting both crop yield and soil health. Groundwater depletion is another issue, with farmers increasingly relying on tube wells, contributing to rising salinity levels and diminishing agricultural productivity.

Sindh: Sindh's agricultural sector faces several climate-induced challenges, most notably recurring floods, sea intrusion in coastal districts, and salinity problems (Table 2). The province's coastal areas have seen significant damage due to seawater intrusion, which has destroyed large swathes of farmland. A 2021 study by WWF-Pakistan revealed that over 15% of the cropped area in Sindh's coastal zones was lost due to saltwater encroachment, exacerbated by rising sea levels and climate change (WWF-Pakistan, 2021). Flooding events, such as the 2010 super floods, have become more frequent and intense, damaging crops, infrastructure, and homes.
These changes in the climate are reshaping agriculture in Sindh, reducing yields of major crops like rice, wheat, and cotton, and leading to significant socio-economic displacement. In response, Sindh has been focusing on adaptive strategies like salt-tolerant crop varieties and improving flood-resilience infrastructure.

Baluchistan: Baluchistan, Pakistan's most arid province, faces some of the harshest climate conditions in the country, with limited rainfall and insufficient irrigation infrastructure (Table 2). The province has been severely affected by prolonged droughts, especially between 1999-2003 and 2016-2020. These droughts have led to significant losses in agriculture, particularly in fruit orchards in regions like Quetta, Pishin, and Zhob. Apple and grape production, which are among the region's key agricultural outputs, dropped by 30-50% during peak drought years (Pakistan Agricultural Research Council [PARC], 2018).

Pest and disease outbreaks, similar to those seen in KP, have also become more prevalent, with mealybugs and fruit flies damaging crops. The lack of sufficient water resources and a reliance on rainfall-based agriculture further increases the vulnerability of the province to future climate-related stresses.

Gilgit-Baltistan and AJK: Gilgit-Baltistan (GB) and Azad Jammu and Kashmir (AJK) share similar climate-induced challenges to those seen in the mountainous regions of KP, particularly in areas like Upper Kohistan and Swat (Table 2). Glacial retreat and the risk of Glacial Lake Outburst Floods (GLOFs) are significant threats to agriculture in these regions. The IPCC (2021) notes that glacial melting in the Himalayas, including the Karakoram range in GB, is occurring at one of the fastest rates globally, threatening water supplies that are crucial for seasonal agricultural activities.

In GB and AJK, the combined risks of GLOFs, landslides, and altered water availability are affecting crop production, particularly in areas reliant on snowmelt for irrigation. Changes in temperature patterns and precipitation levels have led to shifting growing seasons, which complicates traditional agricultural practices.

India: In India, several states face similar agricultural vulnerabilities due to climate change, with Punjab, Haryana, and Maharashtra being particularly affected (Table 2). Climate-induced temperature increases have led to reduced wheat and rice yields, with up to 15% losses projected by 2050 due to thermal stress (Indian Council of Agricultural Research [ICAR], 2020). Heatwaves during critical stages of crop growth, particularly during flowering and grain filling, have reduced yields, similar to trends observed in Pakistan.

Additionally, changes in pest dynamics have led to the spread of invasive species, such as the Fall Armyworm, which has severely impacted maize production in northern India. In response, India has launched the National Mission for Sustainable Agriculture, which focuses on developing climate-resilient crop varieties, enhancing water-use efficiency, and promoting soil health management practices to combat these stresses.

Afghanistan and Iran

Afghanistan: Afghanistan is facing a convergence of climate challenges, including severe droughts, erratic rainfall patterns, and soil degradation. Between 2018 and 2022, the country experienced widespread droughts that affected over 22 provinces and caused a 40% reduction in wheat production (Food and Agriculture Organization [FAO], 2022). This drought, along with deteriorating soil fertility, has led to widespread food insecurity, especially in rural areas dependent on rainfed agriculture (Table 2). Additionally, water-sharing tensions between Afghanistan and Pakistan, particularly in regions like Khyber Pakhtunkhwa, are intensifying as both countries face water scarcity exacerbated by climate change. Afghanistan's agricultural sector is struggling to adapt, with reduced crop productivity, particularly in wheat and maize, which are staple crops for the population.

Iran: Iran's agricultural sector is also feeling the effects of climate change, with a 20% decline in agricultural output observed in arid provinces like Sistan and Kerman due to rising temperatures and aquifer depletion (United Nations Development Programme [UNDP], 2020). The country's agriculture is heavily dependent on irrigation from underground aquifers, but over-extraction has led to a severe water crisis (Table 2). This crisis, combined with rising temperatures and heatwaves, has significantly reduced agricultural productivity, particularly in crops like wheat, barley, and fruits.

Iran has responded by promoting drought-tolerant crop varieties and investing in more efficient irrigation systems, such as drip irrigation and water conservation technologies. These measures are aimed at increasing resilience to both short-term droughts and long-term climate shifts.

Table 2. Regional Comparative Climate Risk Indicators, Crop Losses, and Adaptation Strategies

Region/Province	Avg. Temp Rise (°C)	Major Threats	Crop Loss Range (%)	Key Adaptations
KP (Pakistan)	0.6-1.1	Floods, drought, pests	20-30 (wheat/maize)	CSA, IPM, water reservoirs
Punjab (Pak)	1.2	Heatwaves, water scarcity	10-20 (wheat/rice)	HTVs, drip irrigation
Sindh (Pak)	1	Sea intrusion, salinity	15-25 (rice/sugarcane)	Coastal mangroves, raised beds
Baluchistan (Pak)	1.3	Drought, pests	30-50 (fruits)	Solar pumps, drought crops
India (Punjab)	1.5	Heat stress, pests	15-20 (rice/wheat)	Resilient seeds, NMSA
Afghanistan	1.4	Drought, soil degradation	25-40 (wheat)	FAO drought relief, IPM
Iran	1.8	Heat, groundwater loss	20-35 (barley, dates)	Drip systems, crop zoning

**CSA: Climate Smart Agriculture*
***IPM: Integrated Pest management,*
****HTV: Heat-Tolerant Varieties*
*****NMSA: National Mission for Sustainable Agriculture*

Source: IPCC, FAO, PMD, WWF-Pakistan, Rasul et al. (2012), and PARC (2018). Climate Change and Its Impact on Agriculture in Pakistan and Neighboring Regions: Trends, Threats, and Adaptation Strategies. Various Reports and Publications on Climate Change and Agriculture, including Pakistan Meteorological Department (PMD), Worldwide Fund for Nature (WWF-Pakistan), Food and Agriculture Organization (FAO), Pakistan Agricultural Research Council (PARC), and relevant academic studies.

Policy Implications and Recommendations

To strengthen the adaptive capacity of KP's agriculture sector in the face of climate change, the following strategic recommendations are proposed:

Strengthening Climate-Smart Agriculture (CSA)

To enhance agricultural resilience to climate change, it is essential to promote climate-smart agriculture (CSA) practices that improve productivity while reducing emissions and enhancing resilience to extreme weather. This includes promoting climate-resilient crop varieties that are drought-tolerant, heat-resistant, or pest-resistant, which can help ensure consistent yields in the face of changing conditions. Agroforestry practices, where trees are integrated into agricultural systems, can enhance biodiversity, improve soil health, and provide additional income sources for farmers. Conservation tillage practices, such as minimum tillage or no-till farming, help preserve soil moisture and prevent erosion, making agriculture more resilient to droughts. Organic amendments, such as compost or green manure, can improve soil structure, increase water retention, and reduce dependency on synthetic fertilizers, which may be less effective in changing climatic conditions. Strengthening the link between research and extension services is crucial to effectively disseminate CSA technologies at the grassroots level, ensuring that farmers have the knowledge and support they need to adopt these practices.

Physiological and Morphological Impacts of Climate Change

Climate change exerts profound effects on crop growth and development by altering physiological and morphological traits. Imran (2018a) emphasized that increasing temperatures, irregular rainfall, and shifting climatic regimes pose direct threats to agronomy as the foundation of food and fiber systems, thereby destabilizing food security. Similarly, Imran (2018b) highlighted how these climatic fluctuations disrupt physiological processes such as photosynthesis, respiration, and reproductive development, while also impairing morphological traits including leaf expansion, stem thickness, and panicle development. Earlier evidence from Imran (2017b) further reinforced that climate change is a critical reality undermining agricultural productivity worldwide, a challenge particularly severe in regions like Khyber Pakhtunkhwa (KPK), where staple crops such as wheat, maize, and rice are highly vulnerable to thermal and moisture stress.

Soil, Water, and Resource Challenges

In addition to crop-level impacts, climate change poses grave risks to water and soil resources. Imran (2018a,b) reported that global warming and erratic precipitation intensify soil degradation, reduce water availability, and threaten long-term food security, particularly in semi-arid and mountainous regions of Pakistan. These findings are highly relevant to KPK, where agriculture depends heavily on erratic rainfall and limited irrigation infrastructure. Water scarcity, coupled with declining soil fertility, exacerbates farmers' vulnerability, making adaptation strategies essential for sustaining productivity.

Greenhouse Gas Emissions and Traditional Practices

Agricultural practices themselves can worsen climate change through greenhouse gas (GHG) emissions. Imran et al. (2017a) demonstrated that traditional rice farming significantly accelerates methane (CH_4) and nitrous oxide (N_2O) emissions, both of which are potent GHGs contributing to climate instability. This insight is particularly relevant to KPK's rice-producing valleys, where conventional flooding methods dominate. Such practices not only exacerbate climate change but also create feedback loops, further intensifying risks to local agricultural productivity.

Adaptation Strategies and Crop Management

Adaptation of crop management practices offers pathways to reduce vulnerability and build resilience. Imran et al. (2025a,b) stressed the importance of integrating adaptive strategies such as crop diversification, conservation tillage, optimized irrigation scheduling, and altered sowing dates. These approaches can buffer crops against temperature extremes and water stress. For KPK, with its smallholder-dominated farming system and fragile agroecosystems, such low-cost and knowledge-based practices are critical for addressing the challenges of climate variability.

Technological Innovations and Microclimate Engineering

Recent advancements in agricultural engineering provide new opportunities for climate change mitigation at the field scale. Imran et al. (2025a) demonstrated that rotor-induced wind wall systems enhance rice leaf morphometric traits, yield, and agronomic performance by engineering favorable microclimates. Similarly, Imran et al. (2025b) reported that rotor wind field simulations can effectively regulate microclimate dynamics, mitigate heat stress, and sustain rice productivity across growth stages and diurnal variations. While these studies are primarily focused on rice systems in China, their implications extend to regions like KPK, where controlled airflow and microclimate management could serve as innovative tools for sustaining crop performance under rising temperatures.

Comparative Regional Insights

The evidence from Pakistan and other regions underscores that climate change impacts are multi-dimensional, affecting crop physiology, natural resources, and farming practices. While global findings emphasize the urgency of adaptive strategies, KPK faces unique vulnerabilities due to its complex topography, dependence on rain-fed farming, and limited adaptive capacity. Comparative insights suggest that a hybrid approach—combining traditional adaptation strategies with innovative technologies such as microclimate engineering—can provide a sustainable framework for enhancing agricultural resilience in KPK.

Adaptive Crop Zoning

As climate conditions evolve, it is important to update crop zoning maps based on new climatic normal and available water resources. Adaptive crop zoning ensures that crops are suited to the changing environmental conditions, thus optimizing productivity. This includes introducing alternative crops and crop varieties that are more resilient to drought, heat, or pests in specific agro-ecological zones. For instance, in areas where traditional crops like wheat or rice may no longer perform well due to temperature increases or water shortages, crops like drought-tolerant legumes or climate-adapted maize could be introduced. Additionally, crop rotation practices can be incorporated to enhance soil health and reduce pest and disease buildup. The updated zoning system would help optimize land use, reduce crop failure risks, and ensure more sustainable agricultural practices.

Integrated Water Resource Management

Water scarcity is one of the most pressing challenges posed by climate change, especially in rainfed areas of regions like Khyber Pakhtunkhwa (KP). To address this, it is essential to promote integrated water resource management (IWRM) approaches that enhance water efficiency and ensure equitable water distribution. High-efficiency irrigation systems such as drip and sprinkler irrigation allow water to be applied directly to the roots, minimizing wastage and ensuring crops receive the required moisture. In rainfed areas, rainwater harvesting systems can capture and store rainwater during wet periods for use during dry spells. The introduction of solar-powered tubewells can provide sustainable water access in off-grid areas while reducing reliance on fossil fuels. Small check dams in hilly or mountainous areas can help capture runoff water, recharge groundwater, and mitigate flooding. These practices not only conserve water but also enhance agricultural productivity and support climate resilience.

Early Warning and ICT-based Advisory Systems

Early warning systems that provide timely information on weather patterns, pest outbreaks, and disease threats are vital for reducing agricultural risks in climate-vulnerable areas. Establishing farmer-centric early warning systems that are tailored to the specific needs of farmers can significantly improve crop management decisions. These systems can be supported by mobile-based platforms, where farmers receive real-time climate information, pest alerts, and disease management advice directly on their phones. These ICT-based systems can help farmers take timely actions such as adjusting sowing dates, applying pest control measures, or preparing for extreme weather events. Additionally, climate information services can provide long-term forecasts that allow farmers to plan for future growing seasons, enabling them to adapt to changing weather conditions.

Institutional Capacity Building

The effectiveness of climate adaptation strategies in agriculture depends on the capacity of institutions involved in agricultural development. Training agricultural officers, Model Farm Service Centre (MFSC) staff, and farmer's organizations in climate risk assessment and sustainable land and water management practices is crucial. By building institutional capacity, these stakeholders can better identify climate risks, evaluate impacts on agricultural production, and implement appropriate adaptation measures. Training should also focus on disseminating knowledge about CSA practices, irrigation techniques, and soil conservation methods, ensuring that local institutions can effectively support farmers in adopting climate-resilient practices.

Regional Collaboration

Climate change knows no borders, and the impacts on agriculture and water resources are often transboundary. Therefore, fostering cross-border cooperation with neighboring countries such as Afghanistan and Iran is essential for addressing shared challenges like water management, pest control, and seed security. Regional collaboration can lead to more coordinated approaches to transboundary water management, including the fair allocation of shared water resources. Joint pest surveillance efforts can help mitigate the spread of invasive species across borders, while collaboration on seed security can ensure access to climate-resilient seeds in times of crisis. Establishing regional climate change frameworks can provide a platform for sharing knowledge, resources, and best practices to strengthen the adaptive capacity of all involved regions.

Policy Mainstreaming

For long-term resilience, it is crucial to integrate climate resilience into agricultural policies, land-use planning, and rural development programs. Climate-smart agricultural practices need to be incorporated into government policies to ensure they are supported at a higher level. This includes setting regulations that promote water conservation, soil health, and biodiversity while encouraging private-sector investments in climate-smart infrastructure and technologies. Public-private partnerships can play a key role in fostering innovation and scaling up climate-resilient practices. These partnerships can also provide financial support for farmers to adopt new technologies and improve their adaptive capacity. Policy mainstreaming will ensure that climate adaptation is not just an isolated initiative but an integral part of agricultural and rural development strategies.

Conclusion

Climate change poses a significant and multifaceted threat to agriculture in Khyber Pakhtunkhwa (KP), with challenges such as flooding, droughts, temperature rise, pest outbreaks, and water scarcity becoming increasingly prevalent. These issues are not confined to KP alone but are shared by neighboring provinces in

Pakistan and countries like India, Afghanistan, and Iran. Punjab and Sindh face similar risks, with rising temperatures, heatwaves, and water shortages affecting crop yields, while Baluchistan struggles with prolonged droughts and limited irrigation infrastructure. In neighboring countries like India and Afghanistan, pests are emerging earlier and spreading across borders, exacerbating crop losses. Climate-induced floods, such as those in KP in 2010 and 2022, have similarly affected other regions, highlighting the need for regional cooperation in managing water resources and pest control. To address these challenges, KP must adopt integrated climate-smart agricultural practices, such as promoting drought-resistant crops, improving water-use efficiency, and enhancing soil health. Drawing lessons from neighboring regions and strengthening institutional frameworks for coordinated climate adaptation, including transboundary cooperation, will be essential to ensuring long-term agricultural resilience and food security.

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