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ORIGINAL ARTICLE

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Remote sensing assessment of climate variability impact on cotton crop in Faisalabad, Sahiwal, and Pakpattan

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ABSTRACT

Agriculture is the backbone of Pakistan's economy and the patterns of cropping hold a significant position in agriculture. Climatic changes threaten Agriculture worldwide year to year, especially in developing countries like Pakistan. The productivity of agriculture is directly influenced by climatic factors such as increases in high temperature, heavy rainwater, precipitation, floods and deficiency of irrigation, etc. Climate patterns decrease global temperatures by 2.9 to 5.5°C by 2060, and crop production is at high risk of these trends. Extreme temperatures negatively control crop phenology, leading to reductions in crop yields. Changes in the rainy season and temperature affect cotton production and threaten the stability of cotton production and quality in Pakistan. This study employed a quantitative research design and is based on a time-series analysis. Climate data from 2000-2015, including rainfall, maximum temperature, and minimum temperature, was collected from the Pakistan Meteorological Department. The statistical analysis revealed that all climate variables significantly impact cotton productivity in Pakistan. Rainfall and maximum temperature showed a positive correlation with cotton yields, while minimum temperature exhibited a negative impact. The findings conclude that climatic variability plays a critical role in influencing cotton production, underscoring the need for adaptive measures to mitigate these effects in Punjab, Pakistan.

KEYWORDS

Agriculture; Climate change; Cotton production; Hydrogen-Ion Concentration

ARTICLE HISTORY

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Introduction

Cotton farming primarily takes place during the monsoon season, from May to August, known as the Kharif period. It is also cultivated on a minor scale between February and April. The major cotton-growing areas are the provinces of Punjab and Sindh, where the climate is considered by high temperatures and low seasonal rainfall. As climate change is a danger to water resources it also risks the production of food and fiber [1]. Farming cost, sowing cost, seed, fertilizer, pesticide, and irrigation are the important variables in the production of cotton [2]. Though cotton is not a high-water consuming crop low public attentiveness and technical inability make Pakistan more prone to climate change. Plant safety and irrigation are the most important variables which affect the cost of cotton production. Pakistan is the fourth-largest producer of cotton in the world and 80% of its total production arises from Punjab. The use of unauthorized and illegal seeds has greatly impacted cotton production, leading to a notable decline in output. Cotton is very well grown on a range of soil having pH levels in-between 6-8 [3]. Thoughtful, friable, well-irrigated, and productive soil is useful for cotton production. Sandy, saline, or drenched soils are not suitable for the production of cotton crops. The depth of soil must not be under 20-25 cm.

Climate change is characterized by rising temperature, erratic and lower rainfall—declined frequency but with greater intensity, changing seasons, and occurrence of extreme events—floods and droughts [4]. The study inspects the influence of climate change on the production of cotton in Pakistan using the district-level disintegrated data of yield, area, fertilizer, and climate variables (temperature and precipitation) from 2000-2015. Fifteen years moving average of each climate variable is used. The production function approach is used to examine the bond between crop yield and climate change. This tactic takes all the explanatory variables as exogenous so the chance of endogeneity may also be minimalized. Climate-related factors i.e. mean temperature, precipitation, and their quadratic terms were analyzed. The findings validate a very significant influence of precipitation and temperature on cotton production. In addition to this, physical factors including land area, use of fertilizer, the P/NPK ratio (the percentage of nitrogen (N), phosphorus (P) and potassium (K) that the fertilizer contains), and technology have positive and high important effects [5]. These outcomes suggest that educating farmers on the balanced use of fertilizers and raising awareness about climate change could serve as practical and actionable measures to alleviate the negative effects of climate change to a manageable degree.

Due to climate change, cotton production faces momentous challenges, mainly from heat stress, which is a main issue in the cotton-growing regions of Punjab, Pakistan [6]. Familiarizing with these climatic shifts is serious to sustaining cotton yields. This research anticipated establishing a reliable cotton crop model based on climate and crop

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management data to create an adaptation strategy for cotton farming in the context of climate change. Data were collected from cotton-cultivating areas in Punjab, specifically Bahawalpur and Khanewal. Using field data, the model was calibrated and validated and run using the CSM–CROPGRO (Cropping System Model), part of the DSSAT (Decision Support System for Agro Technology Transfer).

In developing countries, rising temperatures, floods, melting glaciers and climate variability threaten agriculture [6]. By 2060, it is predicted by the global climate models that the temperature rise of 2.9 to 5.5°C [7]. These alarming trends pose a significant risk to crop production [8]. 30 years of agrometeorological data have been used in this study using multiple crop modeling tools to evaluate the impact of high temperatures on cotton production [9]. In China, rising temperatures are directed to earlier planting and shifts in other growth stages, such as the emergence of leaves, flowering, and boll opening, by several days [10]. Likewise, warming trends caused harvest times to shift earlier by an average of 2.16 days, with variations in delays during the 1970s, 1980s, and 1990s [11].

This study aims to highlight the understanding of climate-related risks and susceptibilities that are affecting cotton farmers in the semi-arid regions of Pakistan. Cotton production is badly affected by climate change, particularly in water-scarce areas, the study focuses on two semi-arid districts in Punjab, which contribute about 80% of the country's total cotton production [12]. Climate indicators such as temperature, rainfall, and extreme weather events have been analyzed with a qualitative and quantitative approach to assess the challenges faced by these farmers [11]. Due to better financial capacity, the larger landholders are less vulnerable to climate change, to mitigate adverse effects like crop damage. Country wise, adaptive capacity, including access to resources, diversified income, and meteorological information, plays a critical role in reducing household vulnerability, irrespective of land size.

Globally, Pakistan is the fourth largest cotton producer, and the cultivation area along the Indus River covers nearly three million hectares [13]. Cotton is not only vigorous for fiber production but also for cottonseed oil, a weighty contributor to the national edible oil industry. Despite its agricultural focus, Pakistan fights to meet its edible oil demand, with internal production far below the required levels. Genetically modified (Bt) cotton, presented to reduce losses from pests, now accounts for over 95% of the cotton cultivated [14]. However, challenges persist, mainly in non-traditional cotton zones with lower pest pressure, and in areas facing extreme water scarcity and heat stress. Almost 1.7 million individuals are involved in cotton farming in Pakistan, striving to improve fiber quality and yield. The cottonseed oil industry also faces a need for further refinement to produce healthier cooking oil alternatives.

Globally, climate change poses a weighty threat to agriculture, particularly in developing nations like Pakistan [15,16]. Climatic factors such as rising temperatures, irregular rainfall, flooding, and water scarcity directly influence agricultural productivity. Research indicates that global temperatures may decline by 2.9 to 5.5°C by 2060, putting crop yields, including cotton, at serious risk [17]. Extreme heat and changes in rainfall patterns disrupt cotton growth, affecting both production stability and quality. Cotton farmers in Pakistan are increasingly focused on improving fiber and lint yield, while also contributing 18.8% to the country's edible oil needs from cottonseed oil. Strengthening the cotton oil industry to produce vegetable cooking oil, without the necessity for hydrogenation, is a rising priority.

Background of study

Cotton, a pivotal cash crop in Pakistan, significantly contributes to the country's economy [13]. Its cultivation, however, has faced considerable challenges due to external pressures like climate change, biotic, and abiotic stresses, leading to noteworthy fiscal losses [18]. To address these challenges, meet the growing demands of both local and export markets, sustainable cotton production has become imperious. Historically, cotton production in Pakistan has been inclined by various climate factors, including temperature, rainfall, and extreme weather events [19]. The crop contributes for approximately 5.2% of the country's agricultural sector and contributes 1.0% to its gross domestic product (GDP). While cotton production faded with significant fluctuations in the past, mainly during the 2015-16 floods, it has remained a vibrant component of the Pakistani economy [20,21]. The cotton industry in Pakistan has confronted several challenges, including pest attacks, climatic variations, and price instability [7]. While the introduction of Bt cotton has mitigated the issue of pest attacks, climate change remains a considerable threat [22]. Rising temperatures, increased evapotranspiration, and water scarcity have badly exaggerated cotton productivity [3]. Despite these challenges, cotton production in Pakistan offers significant economic opportunities. It serves as a vital raw material for the textile industry, a major contributor to the country's GDP. The government has also been enthusiastically supporting small and marginalized farmers through many initiatives.

As of the 2019-20 marketing year, Pakistan's cotton production was assessed at 8.0 million 480-pound bales [23]. The crop's worth in the textile industry, tied with government support, has fueled optimism for future growth. The accessibility of sufficient water and certified seeds is expected to play a critical role in enhancing cotton production. To further strengthen the cotton industry, Pakistan has implemented various strategies, including promoting bio-engineered cotton varieties, improving textile mill operations, and increasing exports. The government has also taken steps to tackle challenges such as price variabilities and ensure adequate support for farmers. Table 1 shows cotton zones in Punjab province categorized with percentage of cotton production.

Table 1. Cotton zones in province of Punjab, Pakistan.

Area specified	Districts	Production level %
Core	Multan, Khanewal, vehan, lodhran, Bahawalpur, D.G khan	91.0
Non - core	Sahiwal, T.T Singh, Jhang	8.50
Marginal	Bhakar, Gujrat, Kasur, Sialkot	0.78

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Study Area

Faisalabad

Faisalabad as shown in figure 1 previously well-known as Lyallpur named after the founder of the city is the third most populated city in Pakistan after Karachi and Lahore correspondingly and the second-largest in the eastern province of Punjab [24]. Faisalabad, once one of the earliest planned cities in British India, has progressed into a lively and diverse urban center. It has since been upgraded to city district status. The entire Faisalabad District spans 5,856 km² (2,261 square miles), while the Faisalabad Development Authority (FDA) oversees an area of 1,280 km² (490 square miles). Faisalabad has grown to become a major industrial and distribution center because of its central location in the region and connecting roads, rails, and air transportation. Faisalabad is often called the "Manchester of Pakistan" because of its dynamic textile industry. In 2013, its GDP (PPP) was estimated at $43 billion, with projections suggesting it could reach $87 billion by 2025, reflecting an average growth rate of 5.7%. The city plays very important role in the economy of Punjab, and contributes more than 10% to the province's GDP and contributes around $20.5 billion annually, with agriculture and industry continuing to be vital sectors driving its economic development.

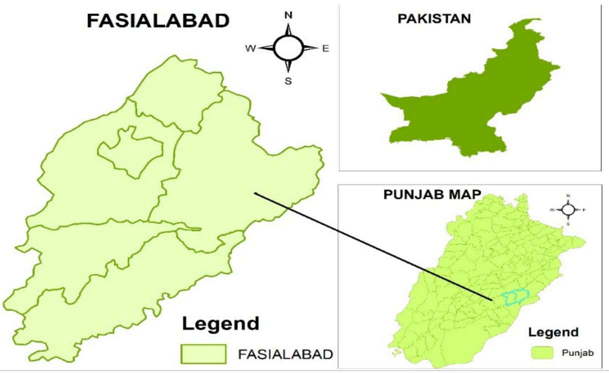

Figure 1. Administrative map of District Faisalabad

Pakpattan

Pakpattan as shown in figure 2 often mentioned as Pākpattan Sharif is the capital city of District Pakpattan District, located in Punjab province of Pakistan. Sahiwal is the 48th most populous city in Pakistan as per the 2017 census.

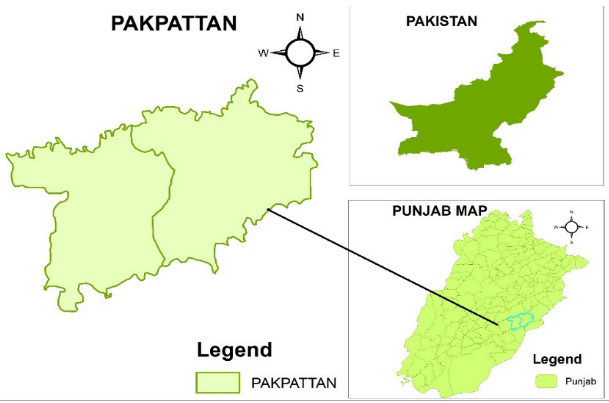

Figure 2. Administrative map of district Pakpattan

Sahiwal

Previously known as Montgomery, Sahiwal District as shown in figure 3 is located in the Punjab province of Pakistan. As of 1998, the district had a population of 1,843,194, with 16.27% living in urban areas. Since 2008, Sahiwal District, along with Okara and Pakpattan, has formed part of the Sahiwal Division. The city of Sahiwal serves as the administrative center for both the district and division.

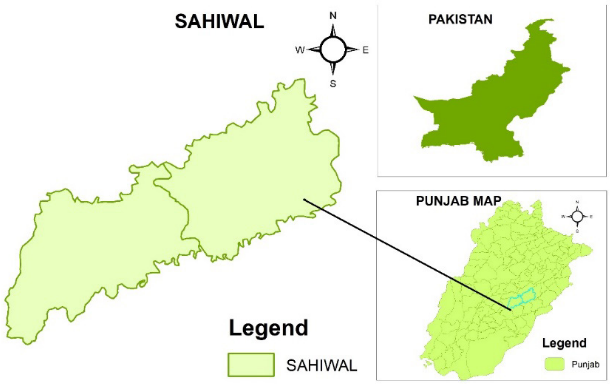

Figure 3. Map of Sahiwal

Materials and Methods

Data Source

Agricultural crop data for the period between 2000 and 2015 was sourced from the Pakistan Agriculture Department (PAD). During this same time, meteorological information such as rainfall and temperature was collected from the Pakistan Meteorological Department.

Landsat 7

Landsat 7, launched on April 15, 1999, is the seventh satellite of the Landsat program. Its primary objective is to provide updated, cloud-free satellite imagery. Managed by the United States Geological Survey (USGS), Landsat 7 data is collected and distributed by USGS. The NASA World Wide project enables 3D visualizations of images from Landsat 7 and other satellites, allowing users to view them from different perspectives.

NDVI

The Normalized Difference Vegetation Index (NDVI) ranges on a scale from -1 to +1, without set boundaries for definite land types. Negative values typically reflect water bodies, while values nearing +1 reflect areas of dense vegetation. Values around zero often direct regions with minimal vegetation, such as urban areas. NDVI is one of the most widespread indices in remote sensing, derived from the Near-Infrared (NIR) and red light bands.

The Normalized Difference Vegetation Index (NDVI) is a widely used remote sensing index to measure vegetation health, density, and coverage. The formula for NDVI is:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Where:

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- NIR (Near-Infrared Reflectance): This refers to the amount of light in the near-infrared spectrum that is reflected by vegetation. Healthy vegetation reflects a large amount of NIR light due to its internal cell structure.
- Red (Red Reflectance): This refers to the amount of light in the red spectrum that is reflected by vegetation. Healthy vegetation absorbs a significant amount of red light during photosynthesis.

Evapotranspiration

Evapotranspiration (ET) describes the combination of evaporation and plant transpiration. As the sun warms the Earth's surface, water evaporates from soil and water bodies, and plants release moisture into the atmosphere through transpiration. This joint process is called evapotranspiration.

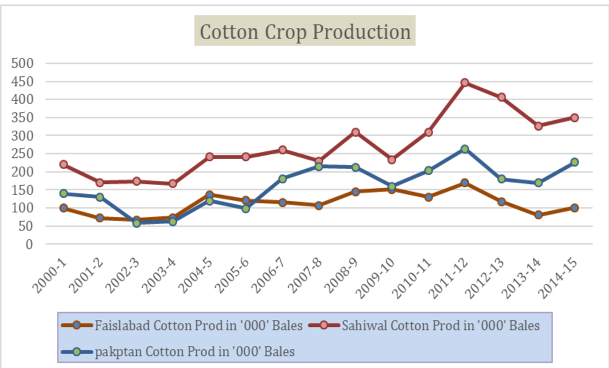
Results, Discussions and Recommendations

Cotton production data

Table 2 shows annual cotton production from 2001 to 2015 in Faisalabad, Sahiwal and Pakpattan districts of Punjab, Pakistan.

Table 2. Cotton production data in Faisalabad, Pakpattan, and Sahiwal districts per year (in '000 bales)

Year	Faisalabad Cotton Prod in '000' Bales	Sahiwal Cotton Prod in '000' Bales	Pakpattan Cotton Prod in '000' Bales
2000-1	100.04	219.92	139.61
2001-2	72.15	170.76	130.08
2002-3	66.73	173.59	58.76
2003-4	73.24	167.41	63.02
2004-5	136.64	241.47	119.82
2005-6	120.64	240.8	98.44
2006-7	115.37	260.41	181.53
2007-8	106.52	229.65	215.08
2008-9	144.71	309.86	212.48
2009-10	151.21	233.57	159.99
2010-11	130.04	309.51	203.05
2011-12	169.76	445.83	263.66
2012-13	117.27	405.87	180.07
2013-14	80.55	327.05	169.19
2014-15	100.24	350.21	226.05



This graph shows the highest and lowest production in between 2000 to 2015. The highest production value is 450 (thousands of bales) in 2011-12 which is in Sahiwal and lowest production value is 50 (thousands of bales) which is in Pakpattan in year 2002-03.

Temperature analysis

Below map shows average temperature in district Faisalabad, Pakpattan and Sahiwal in year 2000, 2005, 2010 and 2015. The dataset was evaluated to determine the daily, monthly, and yearly averages, as well as the maximum and minimum temperatures. These results were then used for in-depth trend analysis. Microsoft Excel facilitated the analysis of trends, while ArcGIS was applied for spatial interpolation, enabling a geographical visualization of temperature changes (Figure 4).

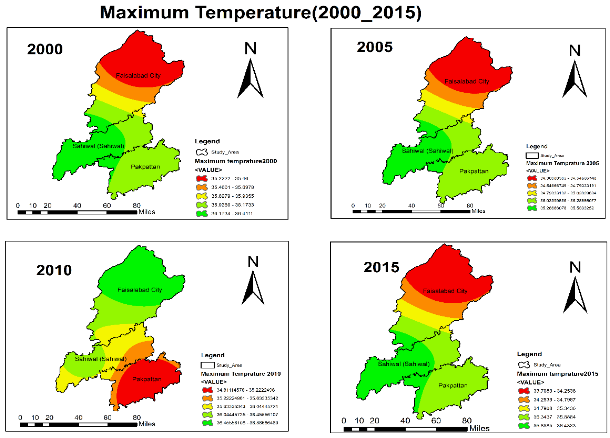


Figure 4. Average temperature distribution in Faisalabad, Pakpattan, and Sahiwal districts for the years 2000, 2005, 2010, and 2015, derived from processed meteorological data.

Precipitation data analysis

Below map shows average rainfall in district Faisalabad, Pakpattan and Sahiwal in year 2000, 2005, 2010 and 2015. The data consists of mean monthly and annual sum of precipitation in millimeters (mm). Daily rainfall data from 2000 to 2015 collected from fixed meteorological stations of the Pakistan Meteorological Department were used in this study. Average, daily, monthly and yearly rainfall data have been derived from this dataset and have been used for further trend analysis (Figure 5).

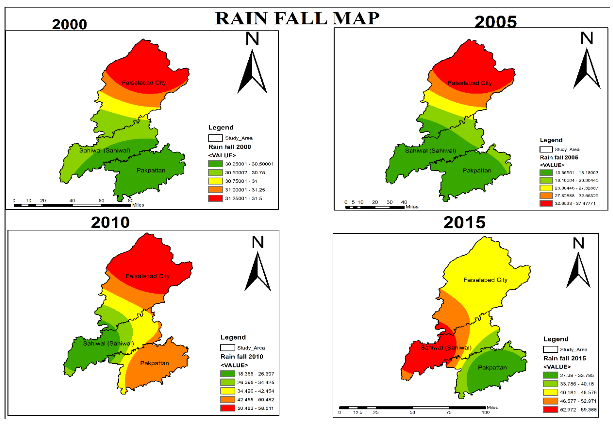


Figure 5. Average rainfall distribution in Faisalabad, Pakpattan, and Sahiwal districts for the years 2000, 2005, 2010, and 2015, based on mean monthly and annual precipitation data (in millimeters)

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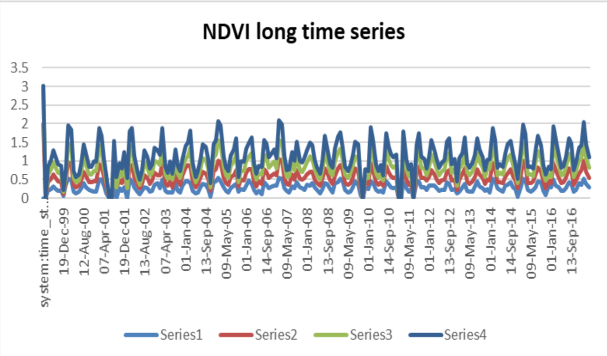
NDVI analysis

Long-term monitoring of vegetation through traditional ground methods is Due to the large area of arid regions, it is particularly problematic in arid and semi-arid regions. Therefore, remote sensing technology propose is to collect high-level information about the field Spatial and temporal resolution, more specifically the infrared part of the spectrum provides a direct monitoring method Vegetation from space. The normalized vegetation index (NDVI) is Usually used for this purpose. Several indices for analyzing satellite imagery have been developed, including the Normalized Difference Vegetation Index (NDVI). NDVI link the reflectivity of the red area and NIR to vegetation parameters such as canopy cover, leaf area index and total chlorophyll concentration. The NIR and red regions of the spectrum are highly correlated with plant parameters, such as plant height, plant density, and plant percentage cover. Initially, NDVI was used to estimate green biomass, but then it was used to assess crop health Normalized Difference Vegetation Index (NDVI) is often recognized as a good indicator of vegetation productivity. Understanding climatic influences, in particular precipitation and temperature, on NDVI enables prediction of productivity changes under variegated climatic scenarios. We examined temporal and spatial responses of remotely sensed NDVI to precipitation and temperature during period (2000-2015) in Faisalabad Pakpattan Sahiwal. During the growing season from May to July, NDVI values were derived from Landsat imagery. Precipitation plays a significant role in influencing NDVI, which is directly related to vegetation productivity. When analyzed at an appropriate spatial scale, a clear and consistent relationship emerges between precipitation levels, cotton growth, and NDVI patterns.

NDVI Graph Between (2000-2015)



Annual cotton yield in districts Faisalabad, Pakpattan and Sahiwal between 2000 to 2015

In Faisalabad, cotton productivity was significantly influenced by climate variability, as indicated by a strong correlation between climate variables and cotton yield. Rainfall showed a positive impact on cotton production, with higher precipitation leading to increased yields. Maximum temperature also positively affected cotton productivity, suggesting that the cotton crop in Faisalabad benefits from warmer conditions. However, minimum temperature exhibited a negative impact on yield, indicating that lower nighttime temperatures may hinder cotton growth.

Similar to Faisalabad, Sahiwal's cotton productivity was impacted by climatic factors. Rainfall and maximum temperature both had positive effects on cotton yield, aligning with the trends observed in Faisalabad. The negative impact of minimum temperature was also consistent, suggesting a regional pattern where lower nighttime temperatures adversely affect cotton production.

In Pakpattan, the results mirrored those of Faisalabad and Sahiwal. Rainfall and maximum temperature were positively correlated with cotton yields, while minimum temperature had a negative correlation. The consistency across all three districts suggests that climatic factors have a uniform impact on cotton productivity in these regions (Figure 6).

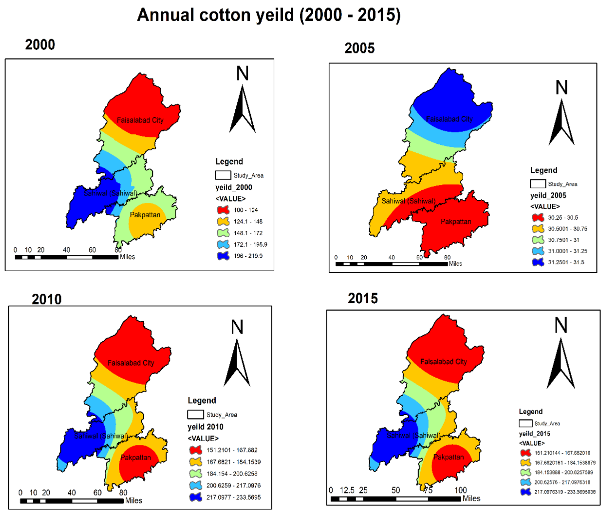


Figure 6. Cotton productivity trends in Faisalabad, Sahiwal, and Pakpattan districts for the years 2000, 2005, 2010, and 2015. The cotton yield was measured in '000 bales.

Discussions

The analysis of climate variables (rainfall, maximum temperature, and minimum temperature) over 15 years (2000-2015) reveals that climate variability significantly affects cotton productivity in Faisalabad, Sahiwal, and Pakpattan. The positive correlation between rainfall and cotton yield indicates that adequate precipitation is crucial for optimal cotton growth. This is particularly relevant in the context of Punjab, where irrigation practices play a vital role in agriculture.

The positive impact of maximum temperature suggests that cotton crops in these regions thrive in warmer conditions. This finding aligns with the general understanding that cotton is a heat-tolerant crop that benefits from higher temperatures. However, the negative impact of minimum temperature underscores the sensitivity of cotton to lower nighttime temperatures, which can impede growth and reduce yields.

These valuable findings are consistent with previous research demonstrating that climate variability, predominantly changes in temperature and precipitation patterns, significantly affects agricultural productivity. The observed trends in Faisalabad, Sahiwal, and Pakpattan highlight the importance of understanding regional climatic impacts to develop targeted strategies for enhancing cotton production.

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Recommendation

1. Improved Irrigation Practices: Given the positive impact of rainfall on cotton yields, enhancing irrigation practices can help mitigate the effects of inadequate precipitation. Implementing efficient irrigation systems and water management strategies will support cotton production during dry spells.
2. Heat-Tolerant Cotton Varieties: Developing and promoting the use of heat-tolerant cotton varieties can help leverage the positive effects of higher maximum temperatures. These varieties should be resilient to heat stress and capable of maintaining high yields under warmer conditions.
3. Temperature Management: To address the negative impact of lower nighttime temperatures, adopting practices such as row covers or mulching can help maintain optimal temperature conditions for cotton growth. Additionally, selecting planting dates that avoid periods of low nighttime temperatures can improve yields.
4. Climate-Smart Agriculture: Encouraging the adoption of climate-smart agricultural practices will help farmers adapt to climate variability. This includes using weather forecasting tools, adjusting planting schedules, and implementing soil conservation techniques to enhance resilience against climate change.
5. Policy Support: Policymakers should focus on creating supportive policies that facilitate access to climate-resilient technologies and resources for farmers. Subsidies for irrigation equipment, research funding for developing heat-tolerant cotton varieties, and educational programs on climate-smart practices can significantly benefit cotton producers.

Disclosure Statement

No potential conflict of interest was reported by the author.

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