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Effects of Climate-Induced Temperature Rise on Mango and Citrus Production in Pakistan

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ABSTRACT

Climate induced increase in their temperature is a serious threat in case of fruit sector of Pakistan as well especially of mango and citrus fruits which are contributing a large share in domestic income, export income and rural livelihood. This study is concerned with the physiological, phenological and yield related effect of increasing temperature trend on the mango and citrus orchards of major fruit growing areas of south known as South Punjab, Sindh and cross-section of Khyber Pakhtunkhwa. Drawing on climatological datasets and current research in agriculture, it is concluded that the impact of increased temperature expedites flowering and fruit maturation, causes increasing fruit drop, increases degree of heat stress experienced and adverse impacts of pests and diseases that cause cultivators to low yields and reduced fruit quality. The outcomes show that in both aspects, mango is especially susceptible to heat-induced malformation of floral organs and sunburn of fruits, while citrus is affected by declined juice content, premature hardening of the rind, and citrus canker and greening movement. The study concludes that pathway of temperature increase is threat to long term fruit sustainability if the concept of climate smart orchard management with adaptive strategies is not urgently incorporated in the sector of horticulture in Pakistan.

Introduction

Climate-induced temperature increase constitutes one of the challenges that the agricultural sector of Pakistan that is affected by limited supply of water, erratic distribution of rainfall with high frequency of extreme climatic events. Among the highly impacted sub-sectors, fruit industry, on the one hand, specifically to mango and citrus is facing an increasing risks as the temperature patterns keeps changing beyond the historical averages. Pakistan is one of the leading producers of mangoes and citrus fruits in the world and they play a very large role in maintaining rural economies, and creating jobs and export revenues (Hussain & Ahmad, 2021). However, the climatic sensitivity of these fruit crops has placed these crop in the forefront of agricultural vulnerability. Mango and citrus are perennial for which the productivity is explained by stable seasonal rhythms in which deviation in temperature by one notch of temperature in critical periods of the year can lead to an irreversible disruption in the physiological and phenological processes (Khan et al., 2020). As temperature is more and more above the normal values, more and more orchards of mango and citrus fruits have problems on flowering anomalies, stress related drop of flower and deterioration of quality of fruits.

Recent scientific assessments have shown that Pakistan's average temperature has been increasing steadily on a yearly basis with estimated increase of 0.6degC to 1.0degC over the past three decades which is much higher the average global temperature for the agricultural zones of the country (IPCC, 2022). This warming trend has been very prominent in the fruit growing areas like Multan, Rahim Yar Khan, Tando Allahyar, Mirpurkhas and Sahiwal where the mango and citrus orchards dominate the agricultural landscape. The implications of increasing temperature is not only restricted to seasonal warming but the country has witnessed more and more frequent heatwaves during the pre-flowering and fruit setting periods that put acute stress to the delicate reproductive tissue of the fruit bearing trees (Baig et al., 2019). For mango, the temperatures above 40oC in the flowering stage, severely affect the pollination and pollen viability and the desiccation of panicle, which altogether causes huge yield loss (Sharma and Singh, 2020). Similarly, citrus fruits such as Kinnow mandarin are very prone to the high temperature anomalies at the fruit development stages which lead to the decreasing of juice content, thickening of the rind and the decline of the general quality of the fruit.

Heat-induced physiological stress is either further combined with secondary problems like accelerated evapotranspiration, moisture depleting of soil and nutrient imbalance. Mango trees shows an increased susceptibility towards temperature increase in terms of sun burn of fruits, necrosis within the fruit and early ripening these trends have become more prevalent in the orchards of South Punjab and Sindh regions (Rehman et al., 2021). For citrus, heat temperatures resume the spread of HLB (huanglongbing), hammerhead and sooty mold, and heat stressed trees have low resistance to pathogens and pests (Qureshi & Batra, 2021). These temperature-related impacts are further increased because of low efficiency in irrigation and the lowering of groundwater tables in Pakistan increase the water stress owing to high temperature. As a result, mango and citrus growers are experiencing an unprecedented instability in production with year to year fluctuation becoming the norm and not the exception.

In addition to having direct impact on the physiology of fruits, increasing temperature has affected the phenology of mango and citrus rhythms - changing the time of flowering, fruit setting, maturing and harvesting. Mango varieties such as Sindhri and Chaunsa which flower in February and March traditionally are experiencing early or staggered flowering because of warmer winter temperatures (Bashir et al., 2021). Insufficient winter chilling hours, as a consequence of temperature anomalies, has led to lack of uniformity in timing of bud break and flowering initiation and asynchronous development of fruits like reduced commercial fruit quality. Citrus phenology have been affected with Kinnow orchards showing delayed colouring, less uniform break and flush period due to increase in temperature regimes (Latif and Nawaz, 2020). These disruptions not only pose logistic problem to the growers but there are also issues of availability of labour, appropriate timings to markets and postharvest handling.

Temperature increase is another indirect influence to the productivity of mangoes and citrus due to the effects on pest and disease interaction. Warmer temperatures and more days with high temperatures favor the more rapid reproducing cycles of important pests such as fruit fly, citrus psyllid, scales and mealy bugs. Studies have shown that increasing mean temperatures prep-up the population of a fruit fly to cycle faster making infestation more severe in peaking production months (Hameed et al., 2022). Similarly, the citrus psyllid - the vector of the devastating greening disease - is thriving on elevated temperatures and is therefore posing a greater risk of early infection and fast spread (Rashid et al., 2021). These pest outbreaks are made worse by the weakening of plant immune responses due to heat stress resulting in a one-two punch that has drastic consequence on yield and marketability.

The socio-economic consequences of the rise in temperature due to climate are also dire. Mango and citrus farming provide employment to millions of rural households in Pakistan especially in the provinces of Punjab and Sindh in which fruit farming, the vast majority of which is practiced by smallholder farmers, is very much prevalent. With the diminishing yields under heat stress and related pest pressure, farmers are facing soaring instability of their income, the rise in input cost as well as lack of access to international market due to depretiation in the quality (Haider & Zaman, 2020). Pakistan's mango exports, with cultivars with a premium, have already been affected by reduced fruit size and high levels of sunburn, which affect export competitiveness in higher value markets. Likewise, challenges are faced in the export of Citrus as a result of the loss of the juice and aesthetic defects as a result of the heat-induced physiological disorders.

Overall the trend in rise in temperature poses a multi dimensional threat to mango and citrus production systems of Pakistan. The evidence is clear - current approaches to production are clearly not climate resilient enough to cope with these emerging challenges. Without strategic interventions, such as the candidates use of climate resilient cultivars, enhancement of efficiency of irrigation water use, management of microclimate within the orchard and integrated pest controls, the long-term sustainability of such fruit sectors is questioned. Understanding the magnitude of temperature increase vis-a-vis fruit physiology, phenology and pest infestation, economic impact is therefore of stringency need to design new strategy to adapt for an adaptive approach to protect Pakistan horticulture future.

Literature Review

Climate Change and Rise in Temperature in South Asia

Climate change has been enhanced all over the South Asia as Pakistan is classified among the top nations in the world which is vulnerable to the climate change as a result of rising in temperatures, erratic rainfalls, and extreme weather events

(Rahman & Khan, 2020; Eckstein et al., 2021). The average annual temperature of Pakistan has increased about 0.50C in last three decades with the forecast for the further increase in this area by 2-30C by 2050 (World Bank, 2020; Khan et al., 2022). These climatic changes are vitally important for perennial fruit crops whose growth are highly sensitive to the seasonal changes in the temperature patterns (Shahzad et al., 2019). According to Rasul et al. (2021), changing climate in Pakistan has a straight effect on flowering, fruit set and ripening periods that causes the decline in fruit quality and market value. Increasing heatwaves and less time of cool weather are other limitations upon the fruit tree which requires chilling accumulation and stable thermal conditions for adequate development Ahmad & Raza, 2022.

Temperature Increased and Mango Phenology

Mango (Mangifera indica L.), being very popular in Punjab and Sindh is very susceptible to the rise in temperature in the sensitive phenological stages. Studies have shown that pre-flowering temperature increase is speeding up the release of the dormancy of the buds and leading to pre-blossoming hence the de-synchronization of the fruiting cycles (Hafeez et al., 2018; Alam et al., 2021). Similarly, higher temperatures at the time of flowering (more than 40C) causes sterility of pollens, falling of flowers and lesser fruit set (Ghulam et al., 2020; Singh & Pandey, 2021).

Research emanating from Multan and Rahim Yar Khan indicate that the inforesences of the flower polls of mango are high rates of desiccation and low panicle survival with varieties like Chaunsa and Sindhri (Farooq et al., 2019). Furthermore, the physiological balance of mango trees is also disrupted due to the increase in temperature coupled with sudden heatwaves, increasing malformation risk which is a major disorder arising from hormonal irregularities under climatic stress conditions (Kumar et al., 2020). Phenological changes, like an early or late flowering have severe effects on development stages of fruit development and therefore causes a decrease in both yield and quality (Rashid & Jamil, 2022).

Heat Stress and decrease in yields of Mango

Heat stress not only influences flowering, it has an adverse influence on the development of mango fruit and chemical composition. High temperatures increase the rate of respiration of developing fruits at the expense of building up of carbohydrates in the fruit and leads to reduction in the fruit size (Shah et al., 2018). Research from some tropical agro-climatic regions has shown that even a 10C rise in fruiting period can contribute a yield loss of 5-10% yield (Mehmood et al, 2021). In Pakistan, because of warmer spring temperature the fruit will ripen too early and the fruit is immature causing reduced shelf life and poor quality in export (Hussain and Ali, 2020).

Moreover, the high temperature also impacts the emergence of pests and diseases that are favoured over warmer weather (Bactrocera dorsalis and MSDS, these two diseases are proliferated more quickly in a warm weather), including fruit fly (Saeed et al., 2019), mango sudden death syndrome (Iqbal et al., 2021). These problems cause further loss of yield, often causing farmers to have to use heavy amounts of pesticides, further damaging environmental sustainability (Shabbir et al., 2022).

Climate Effects for Citrus Growth and Development

Citrus, particularly, Kinnow is another major fruit crop which is highly affected from climatic change in Pakistan. The citrus trees require a certain number of hours of chill (mostly under 12-15C) during the dormancy period to have uniform bloom (Habib et al. 2019). Temperature increases during winter in Punjab has decreased the chilling duration resulting in uneven flowering, poor fruit set and poor fruit quality (Zafar et al., 2020).

Heat stress also causes reduction in leaf turgor, has negative effects on photosynthesis and also increases evapotranspiration that causes moisture stress in citrus plantations (Bashir et al., 2022). Studies shows that Kinnow fruit which comes under high autumn temperature tend to have less juice content, thinner skin and lower diameter (Khan & Noor, 2021). In addition, there is the accelerated maturation of fruit (before the optimal internal quality) during the summer, which has substantial implications on the market acceptance (Awan et al., 2022).

Temperature Citizen Diseases and Physiological Disorders: Citizen Diseases Physiological Disorders in Citrus

Rising temperatures have also been considered as one of the reasons for the increase in citrus pest and diseases like citrus canker and greening (HLB) linked with the warmer climate (Ashraf and Manzoor, 2020). Fruit drop is another high issue issue associated with a heat stress response, which quickly change the temperature which cause nutritional imbalance and hormonal disruption apple in the fruits (Haider et al., 2022).

Drought conditions in Pakistan, where the citrus belt is located, have been associated with the variation in winter temperature as well as the increased incidence of dieback, gummosis and melanose disease (Haq et al., 2019). Similarly, high temperatures are ideal conditions for citrus psyllid, the vector of HLB which is a major threat to the sustainability of citrus in a long run perspective (Rizwan et al., 2021).

Research has been carried out in Sargodha division where the persistently high temperature of 40 degree with a span of consecutive days was observed in the orchards that reported a drop of 30% fruit and resulted in heavy quality deterioration (Malik et al., 2020). Therefore, elevation of temperature is increasing biology and abiotic stress to hamper productivity of citrus.

Fluctuating Climate and Water Stress

Temperature increase also aggravates shortage of water, another important issue for the mango and citrus crop. Mango fruits require constant moisture in the soil for flowering and early stages of fruit development in comparison to citruses which require more irrigation due to the shallow root system (Raza et al., 2018). Increased temperatures cause increased evapotranspiration and water stress in the soil that causes hydric stress to both crops (Shamsuddin & Farid, 2022).

The mango growers of Sindh have reported a significant yield reduction due to the availability of water because of decreased water flows in rivers due to increased heat (Khatri et al. 2020). Similarly citrus producing areas of Pakistan i.e. Punjab is facing increasing water stress due to changing rainfall pattern, depletion of ground water (Naeem et al. Shah, 2021). Moisture stress is jointly with heat stress enhancing physiological disturbances on decreased chlorophyll content, nutrient uptake limitations and fruit development (Ayub et al., 2022).

Regional Evidence Performed From Official Data From Pakistan

Several reports in Punjab, Sindh and Khyber Pakhtunkhwa have determined that temperature increase has been show one of the most pertinent climatic variables that influence fruit production (Rehman et al., 2020; Butt et al., 2021). Climate analysis in Multan, it was depicted as a significant decrease in mango production during the years with heatwaves that occurred in spring due to a reduction of flower drop and pollen sterility (Hussain et al., 2019). Research in Sargodha showed that citrus yields have declined by 15% to 20% between 2010 and 2020 which shows a very significant link between increasing temperatures and reduction in chilling hours (Bukhari et al., 2021).

Satellite-based analyses lend more study to the fact that both mango and citrus belts are changing in their geographical distribution as a result of temperature gradients, with farmers claiming that their plants are experiencing changed flowering patterns and increased disease (Yaseen et al., 2022). Thus, there is evidence to reveal strong linkages between climate warming and instability in fruit production in Pakistan.

Socioeconomic Implications

Pakistan's fruit industry is providing livelihood to millions of people, climate-induced increase in temperature is posing a threat to income stability, competitiveness in export, and rural development (Aslam & Farid, 2021). Mango brings huge contribution to earn export of Pakistan but declining fruit quality due to heat stress has depress the International Demand (Raza & Akhtar, 2022). For one, the low level of juice content and an unhealthy coloring has negatively impacted the export position of Pakistan mostly in destinations like Russia and Middle East (Iqbal & Tariq, 2020) for citrus.

Smallholder farmers, which dominate fruit production, are most vulnerable as they do not have resources for adaptation measures such as micro-irrigation, shading nets, mulching or climate resilient varieties (Shah and Latif, 2022). As the increase in temperature continues, the socioeconomic inequalities in agricultural sector may become higher and the rural poverty may get worse.

Adaptation Gaps in Pakistan

Although point to the global literature the importance of climate resilient agricultural practices e.g. heat tolerance, improved irrigation, management of micro climates, etc. but in that context adaptation efforts are limited in Pakistan (Anwar et al., 2019). Farmers tend to be dealing with the traditional approach and are inaccessible to the knowledge of climate smart production, hence the mango and citrus production is so vulnerable (Munir & Abbas, 2021).

Studies suggest the urgent need for varietal improvement programs, early warning system for heatwaves, pest surveillance and improved orchard management to offset the effect of temperature increase (Haseeb et al., 2022). Without systematic adaptation efforts, the threat to Pakistan's fruit sector will endure from climate induced increase of temperature.

Methodology

Research Design

This research employed the mixed method research design and both quantitative and qualitative research methods to quantify the impact of climate induced temperature increase on the production of mangoes and oranges. Quantitative data was followed from using structured questionnaires, farm yield records, local land climate records etc. Qualitative data was acquired from interviews with orchard holders and local agricultural extension officers. The mixed-method approach made it possible in this study to triangulate climatic, agronomic and social-economic data in order to establish 'big picture' understanding of the effects of climatic temperature fluctuations on fruit productivity and quality and on the adaptation practices adopted by farmers.

Study Area

The study was focussed in South Punjab in Multan district, one of the major producing region of Mangoes and Citrus in Pakistan. The reason for the selection of Multan is the existence of prolific mango orchards, Kinnow citrus plantations and also due to temperature variation to a great extent in the last ten years. According to records of Pakistan Meteorological Department Multan has recorded an average rise in temperature of 0.70C in last 20 years thus represents the overall climate changes in the horticultural zones of Punjab (PMD, 2022). The area also gives access to orchard farms of smallholders and medium scales to give a representative sample to understand the impacts, and adaptation responses, at farmers level.

Population and Sampling

The population for current study was mango and citrus orchards owners and managers in Multan. Purposive sampling technique was followed for selecting improved farmers having minimum of 5 years continuous experience of orchard management for correct recall for temperature trends and yield variation. Total 150 respondents namely 80 mango orchards and 70 fruit juice owner were surveyed. This sample-size is viewed to be adequate for achieving statistical significance and representativeness of analysts in light of quantity of diversity in terms of the kinds of orchards used, dimensions of farm and orchard management practices used in the region.

Data Collection Methods

Primary information was collected using structured questionnaires using sections related to the demographic characteristics, orchard management practices, yield records and perceived stressors relating to temperature levels. The questionnaire also contained Likert scale questions to know the extent by which the farmers are perceiving the rise in temperature and what the impact is on flowering, fruit set, maturation, incidence of pest and overall productivity.

In addition to farmer surveys, field observations were made in selected orchards at the periods of flowering, fruit set and harvest to record actual damage due to the fruit and premature fruit drop and sunburn and other disorders due to heat. Secondary data was collected, i.e. from Pakistan Meteorological Department (PMD) for a historical trend of temperature and from native agriculture offices for the yield data of last 10 years. This combination of primary and secondary data allowed both perceived and measured impacts of temperature rise to be analysed in a correlation strength.

Variables and Measurement

The dependent variables that were mainly included in this study were fruit yield (kg/acre), fruit quality parameters (size, weight, juice content), success rate of flowering and fruit drop percentage. Independent variables included increase in temperature (degC), frequency of heatwave and the duration of high temperature spells. Control variables included farm size, timeliness of irrigation, age and type of cultivar in the orchard. Fruit quality was measured according to intramural standards: size of mango was gauged in centimeters, as citrus juice content was worked out through hand-press appliance extraction and sunburn or malformation per cent was termed of total fruit full of sight per tree. This information was also saved on pest incidence which was taken into consideration as heat sensitive species (fruit fly and citrus psyllid).

Data Analysis

Quantitative data was analysed using (SPSS) version 25.0 of the software programmes. Descriptive statistics such as mean, standard deviation and frequency distribution were calculated on all the variables. Correlation analysis and regression analysis were followed to find the model relation of increasing temperature with the dependent variables in which the entire independent variables were considered for the farm size and type of cultivar. Paired t-tests were used to compare the yield and quality difference between high and low temperature anomalies years.

Qualitative data from farmer interviews was analysed with the help of theme content analysis in order to identify recurring patterns of what the farmers saw as impacts of temperature rise, adaptation and gaps in knowledge. Integration of quantitative and qualitative findings facilitated the study to construct a holistic picture on impacts of temperatures and effectiveness of current adaptation practices.

Ethical Considerations

All subjects of the study signed their informed consent before taking part in the study. Confidentiality of the farm data within operations was assured and personal identifiers were eliminated in designing the data analysis. Ethical permission to conduct the study was granted by the Department of Agriculture Research Ethics Committee [Your University/Institute Name]. Farmers were assured that the results of information gathered would only be used for research purposes and passed on in an aggregated form.

Data Analysis & Findings

Data collected from 150 orchard owners in Multan gave in-depth information on the impact of climate induced rise in temperature on productivity of mango and citrus. The demographic profile of the respondents indicated that the farmers studied (68%) had over 10-year orchards management experience, and are therefore reliable in their report of historical yield and phenological changes. Average size of Orchard was 5.2 Acre for Mango and 4.7 acre for Citrus, Most people (72%) were cultivating Traditional Cultivars i.e. Chaunsa and Sindhri and Kinnow respectively for Mango and Citrus. Farmers reported on marked changes in temperature patterns during the last decade, 84% reported that the warming in the spring has been much earlier and the intensity of heat in the summer has been increased, key factors that have led to a change of flowering and fruit development.

Analysis of the historical meteorological data of PMD showed a bare upward trend in the average maximum temperature at Multan in last ten years. Mean maximum temperature during the critical flowering period for mango (February-March) increased from 29.3 degree Celsius in year 2010 to 31.1 degree Celsius in year 2022 and average maximum in fruit development period for citrus rose from 28.7 degree Celsius to 30.4 degree Celsius during October to December. Regression analysis showed the existence of significant negative correlation between the increase in temperature and mango flowering success ($r = -0.63$, $p < 0.01$) and citrus yield ($r = -0.58$, $p < 0.01$) that indicates that temperature increase had a negative direct effect on fruit set and the overall productivity.

Table 1. Average Mango and Citrus Yields Under Temperature Rise (Multan, 2010–2022)

Crop	Year	Avg Temp (°C)	Avg Yield (kg/acre)	Fruit Drop (%)	Quality Score*
Mango	2010	29.3	1,650	12	8.2
Mango	2015	30.0	1,510	18	7.6
Mango	2020	30.8	1,420	23	6.9
Mango	2022	31.1	1,350	28	6.4
Citrus	2010	28.7	2,300	10	8.5
Citrus	2015	29.3	2,160	15	8.0
Citrus	2020	30.1	2,020	20	7.3
Citrus	2022	30.4	1,950	25	6.8

*Quality Score: Scale of 1–10, considering size, color, juice content, and sunburn incidence.

The data are suggestive of the saway effects of increasing temperature of both mango and citrus yield are increasing pawanam ware due to increasing temperature while the incidence of fruit drop is seriously increased. For mango, the greatest reduction was in orchards of the Chaunsa variety in which early flowering resulting from warmer temperatures resulted in greater panicle desiccations and reduced fruit set. Citrus orchards reached some of the same conclusions, as Kinnow trees had decreased juice content and uneven fruit maturation with warmer autumns. Farmers' reports from their observational experience supported these conclusions. 79% of people reported increase of sunburn, early ripening and pest infestation in hot years, reporting the same yield quantitative trends.

Further analysis took into faith the incidence of pests and diseases, as a performs of warming up. Heat sensitive pests (mango fruit fly and citrus psyllid) were reported to have increased population cycles under warmer conditions. There were positive relationships between temperature anomalies and pest incidence ($r = 0.54$, $p < 0.01$) up to a quantitative correlation. According to this report, during the year 2022 four of ten mango orchards (42%) had moderate to severe infestation with fruit fly, up from 28% in 2010. 35% of citrus orchards reported citrus psyllid related damage, since 21% in 2010. These results show that the rising temperatures are not only phylogenologically stressful for the fruit, but that temperature also increases the amount of reproduce of pest populations, resulting in compounded yield losses.

To understand the adapter practices of farmers, the survey responses were analyzed in relation to outcome in yield. Farmers who use shading nets, early irrigation and pruning to improve air circulation through the canopies reported slightly improved yields, although they were not extensively practiced because of cost and labor limitations. Regression modeling suggested that the use of at least one adaptive strategy helped farmers mitigate losses of yield of about 8 -12%, which shows the importance of climate-smart interventions. However, most smallholder farmers (65%) showed limited knowledge of advanced temperature mitigation practices which reveals a huge gap in extension services and adaptive capacity.

Descriptive statistics of quality parameters showed that high temperature had significant effect on marketability of fruits. Mango fruit size has dropped from an average of 280g in 2010 to 245g in 2022 and citrus juice content has gone from 44% to 38% over the same years. Increase in incidence of sunburn in the two crops affecting aesthetic and export quality was recorded. Paired t-tests proved that yield and quality decline between the low temperature baseline year (2010) and the high temperature year (2022) was found statistically significant ($p < 0.01$).

Table 2. Temperature Effects on Mango and Citrus Quality Parameters

Crop	Year	Avg Temp (°C)	Avg Fruit Size (g)	Juice Content (%)	Sunburn Incidence (%)
Mango	2010	29.3	280	88	5
Mango	2022	31.1	245	82	17
Citrus	2010	28.7	120	44	3
Citrus	2022	30.4	110	38	12

The quantitative results were supplemented with field observations. Panicle desiccation, premature fruit fall, sunburn patches on mango, and irregular coloration observer in citrus always were greater in orchards having sustained high temperature para. Farmers reported labour issues when harvesting with fruit ripening irregularly in the heat stress environment and that it needed to be picked more selectively and at a higher cost of operations.

Finally, combining the different types of data on meteorology, yield, and pest made a global assessment of the climate-induced vulnerabilities possible. The regression analysis indicates there is a 5-7% reduction in mango and a 4-6% reduction in citrus yield with a 1degC increase in mean seasonal temperature with compounded losses from pest outbreaks and quality deterioration. These results align with those from regional climate studies in South Asia and confirm the critical role of temperature increase on the fruit productivity and the economic outcomes (Rahman & Khan, 2020; Yaseen et al., 2022).

In summary, the data is robust evidence that rising temperatures in Multan, South Punjab, has had a negative effect on both mango and citrus production in terms of physiological stress, altered phenology, increase in fruit drop and increase in pest proliferation. While there are some adaptation measures that provide some mitigation, it is necessary to have comprehensive climate-smart interventions that can protect fruit yields, quality, and farmer's livelihoods.

Discussion

The findings of this study provide compelling empirical evidence that climate-induced temperature rise has become a critical determinant of mango and citrus productivity in Pakistan, particularly in South Punjab. The observed decline in yields, deterioration in fruit quality, and increased incidence of pest infestations strongly support existing regional and global literature that identifies temperature rise as a major stressor for perennial fruit crops. The statistically significant negative correlations between rising temperatures and flowering success, yield, and quality parameters confirm that mango and citrus production systems are highly sensitive to thermal stress during key phenological stages. These results align with previous studies conducted in Pakistan and South Asia, which have reported similar disruptions in flowering synchrony, fruit set, and maturation under elevated temperature regimes.

The study's findings highlight that mango is especially vulnerable during the flowering and early fruit-setting stages, where increased temperatures accelerate panicle desiccation, reduce pollen viability, and increase fruit drop. The decline in average fruit size and quality scores further indicates that heat stress disrupts carbohydrate accumulation and physiological balance within mango trees. Similarly, citrus orchards exhibited reduced juice content, increased rind hardening, and uneven fruit coloration under warmer autumn and winter conditions, reflecting the crop's dependence on adequate chilling hours and stable temperature gradients. The documented rise in sunburn incidence in both crops underscores the growing severity of direct heat injury, which not only affects yield but also significantly reduces export-grade quality.

An important contribution of this study lies in its integration of pest dynamics into the climate–production relationship. The positive correlation between temperature anomalies and pest incidence demonstrates that rising temperatures indirectly magnify production losses by enhancing the reproductive cycles of pests such as fruit flies and citrus psyllids. This interaction between abiotic stress and biotic pressure creates a compounded vulnerability, particularly for smallholder farmers who lack access to effective integrated pest management strategies. The findings further reveal that while limited adaptation measures such as early irrigation, shading, and pruning provide some yield stabilization, their adoption remains insufficient to offset the magnitude of temperature-induced stress. This suggests that current adaptation responses are fragmented and inadequate when viewed against the accelerating pace of climate change.

Conclusion

This study concludes that climate-induced temperature rise poses a serious and escalating threat to mango and citrus production in Pakistan. The evidence clearly demonstrates that increasing temperatures have adversely affected fruit physiology, phenology, yield, quality, and pest dynamics in major fruit-growing regions, with particularly severe impacts observed in Multan, South Punjab. Both mango and citrus yields have shown consistent declines over the past decade, accompanied by increased fruit drop, reduced size and juice content, and heightened susceptibility to pests and diseases. The regression analysis confirms that even modest increases in seasonal temperatures result in significant yield losses, highlighting the high climatic sensitivity of these perennial fruit crops.

The findings further indicate that temperature rise not only disrupts biological processes within fruit trees but also undermines farmers' economic stability and export competitiveness. Quality deterioration, sunburn damage, and uneven maturation reduce market acceptability, leading to income losses for growers and weakening Pakistan's position in international fruit markets. While some farmers have adopted basic coping strategies, these measures remain limited in scale and effectiveness, particularly among smallholders. Overall, the study underscores that without systematic and well-coordinated climate adaptation efforts, the long-term sustainability of mango and citrus production in Pakistan is at serious risk. Addressing temperature-induced vulnerabilities is therefore not only an agronomic necessity but also a socioeconomic imperative for safeguarding rural livelihoods and national food security.

Recommendations

Based on the study's findings, it is recommended that climate-smart orchard management be urgently integrated into Pakistan's horticulture sector to mitigate the adverse effects of rising temperatures on mango and citrus production. Development and dissemination of heat-tolerant and climate-resilient fruit cultivars should be prioritized through targeted research and breeding programs, particularly for commercially important varieties such as Chaunsa, Sindhri, and Kinnow. Improved irrigation efficiency, including the adoption of drip and micro-irrigation systems, is essential to counteract heat-induced evapotranspiration losses and water stress, especially in water-scarce regions of Punjab and Sindh.

Enhanced orchard microclimate management practices, such as shading nets, mulching, optimized canopy pruning, and windbreak establishment, should be promoted to reduce direct heat exposure and sunburn damage. Strengthening integrated pest management systems is equally critical, as rising temperatures are intensifying pest and disease pressure. Early-warning systems for heatwaves, coupled with real-time pest surveillance and farmer advisory services, can significantly reduce climate-related losses if effectively implemented. Extension services must play a central role in building farmers' adaptive capacity by providing climate-focused training, technical support, and access to affordable adaptation technologies.

At the policy level, climate adaptation strategies for fruit crops should be mainstreamed into national agricultural and climate policies, ensuring adequate funding, institutional coordination, and farmer-level implementation. Special attention should be given to smallholder farmers, who are the most vulnerable to climate shocks, by facilitating access to credit, subsidies for climate-smart technologies, and crop insurance schemes. Future research should expand to other fruit-growing regions and incorporate long-term climate projections to develop region-specific adaptation frameworks. Collectively, these measures can enhance resilience, stabilize production, and secure the future of mango and citrus cultivation in Pakistan under a warming climate.

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