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Impacts of climate variability on fruit production: A comprehensive review

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ABSTRACT

Climate change poses a significant threat to the productivity and quality of fruit crops, often exerting a more severe impact than on annual field crops due to the limited adaptive capacity of perennial species. Its influence spans various stages of fruit crop growth and development, manifesting in adverse outcomes such as sunburn damage, inadequate pollination, delayed ripening, diminished pigmentation, reduced sugar accumulation, poor fruit set, compromised quality, lowered yield, and restricted panicle emergence, particularly under conditions of terminal heat stress and water scarcity. This comprehensive review investigates the multifaceted effects of climate variability including fluctuations in temperature, rainfall patterns, humidity levels, and evaporation rates on fruit crops across temperate, subtropical, and tropical agro-climatic zones. By exploring the complex interactions between climatic factors and physiological processes such as flowering behavior, this study provides in-depth insights into the underlying mechanisms governing climate-crop responses. A key challenge in synthesizing this information lies in the scarcity of long-term, crop-specific datasets and the high variability in regional microclimates and management practices, which limit the generalization of climate impacts across fruit species. Despite these constraints, the review makes significant contributions by consolidating scattered evidence, identifying vulnerable phenophases and highlighting crop-specific sensitivities to climatic stressors. It further emphasizes the urgency of implementing adaptive strategies and developing climate-resilient varieties to safeguard the growth, phenology, yield, and quality attributes of fruit crops under an increasingly unpredictable climate regime.

Keywords: *Climate change, temperature variability, relative humidity, rainfall, fruit crops, Phenology, Fruit set, Yield, Fruit quality, Physiological responses, Climate-resilient varieties.*

Introduction

India has been bestowed with a wide range of climate and physio-geographical conditions, and as such is most feasible for growing various kinds of horticultural crops such as fruits, vegetables, flowers, nuts, and spices, and plantation crops such as coco nut, cashew nuts, and cocoa (1). This diversity has positioned India as one of the leading countries in horticultural production, second only to China. In 2022–23, fruit production was estimated at 110.21 million tonnes, primarily due to increased yields of apple, banana, grapes, mango, and watermelon. This growth was accompanied by a 1.41% increase in cultivation area over 2021–22 (2). Despite this progress, India currently meets only 46% of its total fruit demand. While fruit production has significantly expanded over the past decade, driven by improved horticultural practices and growing consumer demand, a considerable gap remains between supply and consumption.

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This indicates the need for better alignment of production with market demand. Emerging challenges such as urbanization, water and soil contamination, limited water supply, extreme temperatures, irregular precipitation, and high humidity can negatively impact the growth, development, and quality of fruit crops. While studies directly linking climate change and horticulture remain limited, this review draws on available research, regional case studies, and related physiological and climatic evidence to highlight current knowledge and gaps. Horticultural crops are generally more vulnerable to climate fluctuations than arable crops (3). Climate change is altering growing conditions in traditional fruit-producing regions. *Localized microclimatic effects, such as restricted airflow coupled with increased humidity, can further influence plant growth and disease incidence, thereby reducing yield.* Temperature, humidity, and rainfall are key factors influencing plant phenology, with temperature playing a major role in overall plant growth and reproduction (4). According to IPCC assessments, fluctuations in global temperature and precipitation since 2010 show an accelerating trend (Fig. 1), underlining the urgency of assessing crop-specific vulnerabilities. Extreme temperatures can damage or even kill trees, while moderate fluctuations can impair reproductive development.

In summer, climate change affects photosynthesis and fruit quality, including sugar levels, acidity, firmness, and shelf life. In winter, inadequate chilling hours disrupt flowering and reduce yields in temperate fruits. Since fruit crop cultivation plays a vital role in nutrition, economy, and rural livelihoods, it is essential to understand their physiological responses and regional suitability. Developing climate-resilient fruit varieties is a key step toward adapting to current and future environmental challenges (5).

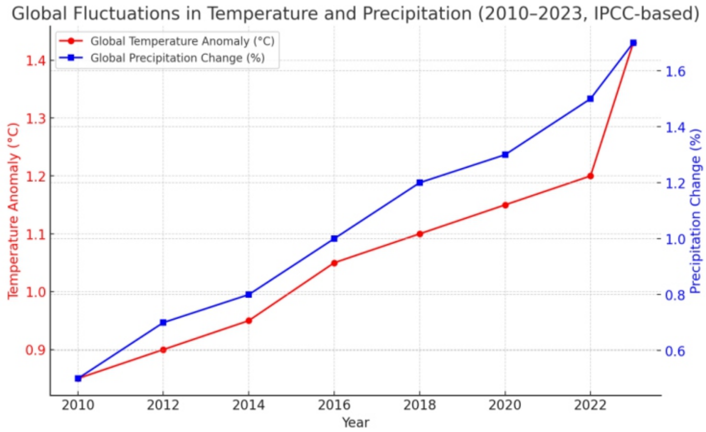

Fig 1: Global fluctuations in temperature and precipitation from 2010 to 2023 based on IPCC assessments

STUDIES ON THE EFFECT OF CLIMATE ON FRUIT CROPS

Climate variability significantly influences global food production, particularly in developing regions where fruit crop distribution is closely linked to climatic conditions. In recent decades, escalating temperatures and shifting climate patterns have raised international concern, with agriculture identified as a highly vulnerable sector. Since the late 1980s, notable changes in air temperature and its correlation with phenological shifts have been documented. This review synthesizes research on the effects of key climatic factors, temperature, chilling hours, and relative humidity on the growth, yield, and quality of various fruit crops, including Kinnow mandarin.

1. Impact of Temperature on Fruit Crops

Environmental variables, particularly temperature, are key factors that affect plant growth, development, and productivity.

a) Growth characteristics

According to (6) found that olive trees had greater trunk area, canopy volume, yield, and oil content in cooler, well-watered locations, concluding that lower temperatures and moderate rainfall enhance olive productivity. Recently, high-chilling apple cultivars like Royal Delicious have been replaced by low-chilling varieties and other fruits in Shimla's middle hills, with a shift away from potato and apple cultivation. Declining snowfall and apple production in Himachal Pradesh, dropping from 10.8 to 5.8 tons/ha, illustrate climate change impacts (7). 'Royal Empire' apple trees showed maximum fruit growth at 33/28°C early in the season, followed by optimal growth at 19/14°C in the next two weeks, while cooler temperatures later enhanced shoot growth as fruit size reached 27 mm (8). As reported by (9) reported that mulberry shoot growth ceased under short photoperiods, but temperatures above 24°C activated growth. He observed that temperature both controlled mulberry shoot growth and determined the potential rate of shoot elongation, which occurred at maximum growth activity under optimal conditions.

As stated in (10), the higher spring temperatures advanced kiwifruit flowering, summer heat reduced fruit growth and dry matter, while warmer late autumn increased growth but lowered soluble solids and delayed maturity, with 17°C being optimal for maximum fruit growth. Kadir (11) used the four European wine grape cultivars (Semillon, Pinot Noir, Chardonnay and Cabernet Sauvignon) and one American winegrape cultivar (Cynthiana) in three temperature regimes in growth chamber set at 20/15 °C, 30/25 °C, or 40/35 °C, for 16/8 h day/night to determine the influence of temperatures on vine growth and development and noticed that under high temperature shoot growth, the European wine grape cultivars showed continued shoot growth, while American cultivars ceased growth. Vegetative components such as shoot wood and root biomass slightly increased ($0.01 < 0.05$) with increasing temperature (12).

A report in (13) found that peach shoot growth peaked 45 days after full bloom, with fruit growth occurring under mild conditions. Results from (14) examined the phenological stages, flower characteristics, shoot growth, and flower bud differentiation of sweet cherry cultivars Hongdeng and Van in different climatic zones and reported that sweet cherry trees grown in subtropical monsoon climatic zones had earlier phenological stages and longer blooming durations than those grown in temperate climatic zones, whereas both cultivars showed more abnormal flowers under a subtropical monsoon climate. According to (15) observed that canopy temperature was negatively correlated with long, middle, and short shoots, shoot quantity, and leaf area. As reported in (16), high mid-day temperatures in subtropical citrus growing regions can lead to excessively high leaf temperatures and large leaf-to-air vapor pressure differences in sun-exposed leaves compared with shaded leaves. This heat stress reduced the net CO_2 assimilation and vegetative growth of fruit trees. According to the research reported in (17), the growing season for maple and lime was extended by 25.4 and 21.5 days, respectively; the length of the growing season of birch did not experience any statistical changes, and the entire growing period. Findings from (18) observed a 12–35% reduction in strawberry yield under elevated temperatures and CO_2, regardless of nitrogen levels. High temperature and humidity increased pest and disease incidence in fruit crops, with guava showing greater susceptibility to Bactrocera spp. and papaya to leaf curl virus. The study in (19) reported that rising temperatures would lead to more rapid growth in mango, shortening the time between vegetative flushes and delaying growth cessation in winter. High temperatures alter plant morphology, anatomy, and physiology, thereby affecting seed germination, plant development, flower shedding, pollen viability, gametic fertilization, fruit setting, fruit weight, size, and fruit quality (20). In contrast, low-chill crops like apricot, plum, and peach exhibited reduced productivity and decline under thermal stress (21).

b) Flowering

As reported in (22), elevated pre-blossom temperatures in apricots accelerated flowering but led to malformed flowers due to unsynchronized pistil development, resulting in reduced fruit set. The flowering of the Autumn Bliss cultivar of raspberry is significantly affected by temperature, and the rate of progress to flowering increases linearly to an optimum temperature of 24 °C and declines progressively at higher temperatures (23). Findings from (24) found associated declining apple yields in Kullu Valley with fluctuating climate during flowering, which shortened the bloom period by 4–7 days. A finding from (25) reported that under humid temperate mid-hills of Uttaranchal, peach cultivars differed in their time requirement to complete bud development ranging from 22 days (Early White Giant) to 26 days (Craw Ford's Early) from its appearance; thus, subsequent flowering occurred from 10^{th} March (Tessia Samisto) to 18^{th} March (Hales Early).

Results from (26) noticed increased floral intensity in sweet orange trees due to accumulated cool temperature hours (11–15 °C) by the combined effect on the number of sprouting buds with reproductive growth and the number of flowers per flowering bud. a finding from (27) found that higher temperatures accelerated pollen tube growth but reduced pollen germination in sweet cherry, with genotype-specific responses. According to (28), blooming in woody perennials (apple, grapes, and lilac) advanced by 2–8 days due to climate change.

Flowering and flower development are the major physiological phenomena in fruits, and most studies have focused on understanding the impacts of varying temperatures (29). As reported in (30), strawberry yield and flowering were influenced by chilling accumulation and diurnal temperature variation during crown development. Greater diurnal temperature differences 2–3 months before harvest reduced flowering time and enhanced yield, with 180 diurnal degree-days increasing yield by 30% in Saskatchewan-grown crowns compared to those from California. As finding in (31) reported that full flowering in cherry trees was strongly correlated with March mean temperatures, as flowering timing varied with temperature accumulation, modeled as an exponential function of temperature during February–March. Results from (32) found that cocoa flowering intensity was regulated by temperature and varied among the different clones. Result from (33) revealed that due to climate warming during the last decade, apple trees start flowering 4-5 days earlier than the April. According to (34), similar trends in berry crops, with bud break advancing 22–25 days and flowering 9–16 days in response to a 2 °C rise.

A report in (35) highlights that early springs and high temperatures accelerated plum trees's vegetative phenophases development. According to (36), earlier developing fruit trees (Japanese pear, peaches, and apricot) showed accelerated flowering and harvesting, whereas in prolonged developing fruit trees (apples, persimmons, grapes, and Satsuma mandarin), the flowering period accelerated, while the harvesting period was not affected. The results presented in (37) confirm that the peach cv. 'Cresthaven' showed variation in time from full bloom to harvest, which varied from 109 to 143 days in correlation with weather parameters. Decreases in global banana production are expected in most banana-growing areas below 500 m asl and, especially because of the sensitivity of the crop to high temperatures and drought during the flowering and fruit filling periods (38). In both bearing and non-bearing Mango trees, primary symptoms of heat stress include leaf scorching, twig dieback, increased frequency of reproductive flushes, variations in flowering phenology, reduced fruit set, transformation of reproductive buds into vegetative ones, alterations in fruit maturation, and other phenological changes (39).

Climate variability also plays a crucial role in regulating reproductive development and fruit set across a wide range of fruit and vegetable crops.

For instance, the results presented in (40) confirm that prolonged water logging in Cape gooseberry reduced flower and fruit production. As stated in (41), elevated temperatures promoted flower drop and sex alteration in papaya, while low temperatures induced flowering in mandarins. The number of cluster shoots increased with increasing temperature, but the number of flower cluster decreased (42). Findings from (43) reported that pollination and fertilization processes are most effective within an optimal temperature range of 20–25 °C for temperate fruit species, such as plums, apples, cherries, and pears. Data from (44) reported that insufficient chilling can hinder pollination in cross-pollinated fruits, such as pistachios and walnuts, resulting in reduced crop yields. For temperate fruits, such as plums, apples, cherries, and pears, the optimal temperature range for effective pollination and fertilization is between 20°C and 25°C.

(c) Fruit set

Findings in (45) show that advanced leafing, when overlapping with vigorous vegetative growth, impaired flower and fruitlet retention and increased fruit drop. according to (46) found that a 3 °C increase above the optimal 15 °C reduced fruit set in cherries. The study in (47) found that increased pre-blossom temperatures negatively impacted fruit set in apricots. Temperature-related issues such as poor synchronization with pollinators, formation of 'blind buds', erratic flowering, and reduced leaf quality during bloom contribute to poor fruit set globally (48).

A result from (27) found that even a moderate increase (1–3 °C) in average temperature due to elevated maximum temperatures (by 5–7 °C) significantly reduced fruit set in sweet cherry. Results from (49) found that the 'Toyonoka' cultivar had lower fruit set under 30/25 °C temperature, whereas fruit set in Nyoho was not affected by temperature regimes. A report in (50) highlights that lower fruit set and yield due to higher temperature during the pre-blooming and blooming period. The findings of (51) show that reported that 'Granada' was more affected by high temperature than 'Maciel' at blooming time, pollen grain production and fruit set stages. Climate change increasingly disrupts mango early and delayed blooms cause floral abnormalities and pseudo-setting, accelerated panicle development limits hermaphrodite-flower availability, and elevated heat induces pollen desiccation and reduced pollinator activity, collectively leading to poor fruit set (52). The study in (53) observed that fruit set in Kinnow mandarin was positively influenced by both maximum and minimum temperatures during the pre-flowering (K1) and early fruit set (K3) stages (r = 0.7243*, 0.734*, and 0.687*, 0.749*, respectively). However, low minimum temperatures during the fruit maturation stage (K4) negatively impacted fruit set (r= −0.6668*). Relative humidity was also influential, with positive correlations observed at K1 (r = 0.736* and 0.742%) and K4 stages (r = 0.811**). Further in (44) highlighted that extreme temperatures, particularly high heat, reduce pollinator populations, leading to poor fertilization and diminished fruit set.

(d) Fruit yield

Findings from (54) show that the Chandler strawberry cultivar had higher yield at 20/15°C compared to 30/25°C, suggesting a stronger source-to-sink relationship at cooler temperatures. Esitken *et al*. (55) also observed that increased night temperatures negatively impacted strawberry yield. The study in (56) linked temperature to strawberry production, noting that climate change could affect yield and crop cycle duration. According to (16) reported that high midday temperatures in sub-tropical citrus regions caused heat stress, reducing CO_2 assimilation and fruit yield. Findings from (18) show that elevated CO_2 and high temperatures reduced strawberry yield by 12% and 35%, respectively, with a detrimental effect at high temperatures despite improved yield at low temperatures. Findings from (57) observed warming trends in grape-growing regions in China, noting increased temperatures but stable precipitation. While yield was not significantly affected by warming, it was correlated with precipitation trends. The results presented in (21) confirm that high winter temperatures disrupted flowering and yield in pear trees due to inadequate chilling hours. As documented by (47), temperature positively influenced the yield of peach cv. Early Grande from full bloom to fruit maturity. Similarly, a research in (53) also reported that temperatures during the first fruit set to the maximum fruit set stage positively correlated with kinnow mandarin yield. Climate variability during flowering and fruiting particularly increased temperature and decreased humidity, led to reduced fruit set and lower yields of ber. However, early varieties like CAZRI Gola and Gola performed better under these stresses (58).

As stated in (59), found that longan yield suffered when rainfall during flowering exceeded approximately 63 mm. High temperatures (> 35 °C) during flower and early fruit development also reduced flowering and ovary growth. Additionally, drought conditions in critical phenophases impaired yield. As reported in (60), both maximum temperature and evaporation were strongly negatively correlated ($r = -0.84$ and -0.85) with minimum temperature showing a slight negative effect ($r = -0.14$). A regression model explained about 87 % of the variation in yield. According to the findings in (61) reported that strawberry yield showed negative correlations with maximum ($r = -0.63$) and minimum temperature ($r = -0.58$), as well as rainfall during late growth ($r = -0.49$). Optimal planting on September 30th achieved the highest yield (243.6 g plant^{-1}), highlighting the importance of aligning planting time with favorable temperature and precipitation regimes.

(e) Fruit maturity

The study in (62) observed that mango cultivars matured earlier at Rameshwar than at Vengurle, due to additional heat units (Degree Days) at Rameshwar. Warmer temperatures reduced the time from full bloom to maturity in figs (63), causing harvesting to start one month earlier in warmer areas. According to (64), peach and nectarine varieties, showing that low chilling varieties required fewer chilling hours and had a shorter harvest period. Finding from (65) reported that early maturity in grape cultivars like Chardonnay and Shiraz to higher temperatures, radiation, and vapor pressure deficit. As noted by (66), temperature and rainfall influence transitions between phenological stages, with higher temperatures during fruit development accelerating maturity and affecting both quality and yield.

According to (67), the high temperatures of the tropics induce fast development and production of large fruits that ripen quickly and remain marketable for a very short time, whereas in sub-tropical zones, the development of fruits slows in the winter and the fruit remains mature on the tree for longer before it is harvested and marketed. In (68), reported that the number of days for fruit growth and maturity of shogun (*Citrus reticulata* Blanco) at Yala was shorter than that at Pattani by about 14-21 days. Fruits are known to mature normally at temperatures as high as 35 °C, whereas higher temperatures beyond this block ripening process (69).

(f) Fruit quality

Climate is interrelated with citrus quality and quantity in the subtropical region, the fruit growth rate is rapid, but the fruit quality of oranges and mandarins is poor, with peel color typically green and the juice color a pale, light yellow (70). Size and appearance, soluble solids content, total sugar content, total acids content, and water content were greater, and sugar to acidity ratio and vitamin C content were lower in pear fruits collected from the low temperature regions than in the high temperature regions in China (71). According to (72), raising canopy air temperatures during the second stage of fruit growth in Satsuma mandarin resulted in lower titratable acidity, total acids, citrate, and malate levels compared with those in control fruit, and these lower levels were maintained until harvest.

During fruit development, when the temperature exceeds the optimum range of 13-27 °C with temperatures over 33 °C, there is a reduction in Brix (sugar content), acid content, and fruit size in citrus (73). A study in (74) reported that the strawberries grown at 18/12 °C had higher citric and ellagic acids, sugars, and total carbohydrates, while higher temperatures increased malic acid but reduced other organic acids and sugars. Maximum sucrose content was observed at 25/12 °C, with the lowest at 30/22 °C. According to (75), observed that Merlot and Cabernet Sauvignon grape varieties tended to produce greater berry weight and potential wine quality with an increase in temperature during the last two decades in France. In Navel oranges, the acidity content is affected by low temperatures leading to low TSS content (76).

Findings from (63) show that in the Kadota and Kennedy cultivars of fig, fruit weight per plant was more than 10 times higher, while the Larga de Burdeos cultivar of fig, although it was also more productive at El Palqui (warmer than other locations), showed somewhat less climatic effects. Data from (77) found that total soluble solids were significantly better in fruits harvested from the tree spaced at 6m^2 and in the upper part of the tree canopy and fruit quality was positively related to warm and dry weather in April and June, and to cool and wet weather in May, and Sardar guava fruit from the upper part of the canopy had lower acid content, whereas fruit harvested from middle and lower tree canopies had higher acidity. According to (78), kiwifruit fruit had low carbohydrate and vitamin C content at elevated temperatures.

The results presented in (79) confirmed that favorable climate conditions (higher rainfall and lower temperatures) during apple fruit development improved size, quality, and return bloom, while high temperatures and low rainfall negatively affected fruit size. According to (11) reported that grapevine anthocyanin synthesis, vital for color, was optimal at 15-20ºC, and extreme temperatures delayed ripening, affecting quality. As report in (80), temperature negatively affected grape development, particularly firmness, soluble solids, and dry weight, varying by cultivar. According to the results of (81), the aonla cv. NA 6 had the highest TSS content (19.30%), followed by Kanchan, with a TSS content of 14.90%. According to (82) reported that plums had a higher total soluble content under high temperatures during April and June.

According to the findings in (83) reported that peach cv. Flavorcrest, Elegant lady, and O' Henry under high early spring temperatures tended to decrease the size of the fruit. The marketability of red-colored apples is strongly influenced by temperature, as it affects the fruit pigmentation. Cross-sectional analysis of fruit tissues indicated that anthocyanin pigments accumulate more prominently in the upper layers of the skin and flesh under low temperature conditions. Cells exposed to temperatures of 20°C and 25°C demonstrated a higher intensity of red pigmentation compared to those exposed to 30°C (84). As shown in (85), the influence of temperature on fruit growth in olives and observed that the lower threshold temperature for fruit growth was 15 ºC with respect to fresh weight and 24ºC -26 ºC with respect to cross-sectional diameter, as the increase in the longitudinal diameter of the fruit was more rapid than the increase in the cross-sectional diameter and was more dependent on temperature. Results from (49) reported that Toyonoka and Nyoho of strawberry cultivars showed a reduction in fruit diameter at 30/25 °C temperature.

A study in (86) examined the effect of climate on the fruit quality of four low-chill peach cultivars (Florida Prince, Florida Glo, UF Gold, and Tropic Beauty) at three locations (north–central, central, and southwest Florida) and reported that peach cv. Florida Prince, Florida Glo, and Tropic Beauty had higher titratable acidity than the UF Gold peach cultivar. In (87), it was found that found that weather had no effect on fructose, glucose, and citric acid levels in Melalahti black currants, but these compounds in Mortti and Ola cultivars were positively correlated with temperatures in February and July and negatively correlated with days of 10-30% humidity from growth start to harvest. They also observed positive correlations between fructose and glucose, citric acid and fructose, and citric acid and glucose due to related metabolic pathways. Kadainou R-1 grapevines exposed to 25°C had lower titratable acidity and higher total soluble solids (TSS) compared to those at 20°C and 30°C (88). High temperatures (35/20°C) were found to have no effect on ascorbic acid content in pot-grown strawberries (89). It was also noted that Melalahti black currants had lower vitamin C content than Mortti and Ola cultivars, and that berries from southern Finland contained less malic acid and vitamin C than those from northern regions (87). In (90), it was observed that changes in temperature, precipitation, and season duration negatively impacted mango and sugarcane crops, shortening ripening periods and reducing size, weight, and production. Samany and Zaghloul date palms in different regions of Egypt were studied by (91) and found that temperature influenced fruit weight, bunch weight, and yield, with variations across locations. The findings of (36) show that reduced titratable acidity in various fruit crops under high temperatures.

Finding from (15) observed that titratable acidity in Fuji apples was negatively correlated with light intensity and temperature, but positively with humidity. A studies in (92) noted that high spring temperatures 30 days after bloom decreased fruit size in peaches. The results presented in (93) confirm that warmer temperatures led to earlier phenological events in grapevines, with an increase in sugar content at harvest. The study in (94) identified specific temperature and sunshine factors, such as the highest temperature in April and sunshine duration in July, that significantly influenced the sugar and acid content in Chardonnay grapes. In low land tropical areas, due to high respiration rates at warm temperatures, fruits do not accumulate high TSS, and the acidity of the fruit declines rapidly so that the soluble solid/acid ratio increases sharply, and the fruit quickly becomes insipid and dry (95). As reported by (16) that high mid-day temperatures in sub-tropical citrus growing regions can lead to excessively high leaf temperatures and large leaf-to-air vapor pressure differences in sun exposed leaves, leading to reduced CO_2 assimilation and poorer fruit quality. In (96), it was reported that yield was mainly influenced by mean maximum temperature, while precipitation and sunshine had lesser effects. They further observed that sugar content increased at absolute maturity, whereas acidity decreased at the same stage.

The transitions between different phenological stages, which depend on various environmental cues of temperature and rainfall, have implications for eventual fruit production, both in terms of quality and quantity, and higher temperatures at the fruit development stage speed up fruit size and quality **(66)**. Findings from (18) reported that elevated CO_2 increased the levels of dry matter, fructose, glucose, total sugar, and sweetness index per dry matter, but decreased fruit nitrogen content, total antioxidant capacity and all antioxidant compounds per dry matter in strawberry fruit.

A study in (97) found that at 20°C, orange juice had the highest vitamin C content (612.15), followed by grape (454.47), lemon (305.57), and lime (270.75) juices. As the temperature increased to 80°C, vitamin C levels decreased in all juices: orange (550.87), grape (380.16), lemon (248.85), and lime (222.58). They concluded that lower temperatures preserve vitamin C, while higher temperatures reduce its concentration, emphasizing the importance of storing fruit juices below room temperature to maintain vitamin C levels. In another study in (69) observed that the combined effect of elevated temperature and CO_2 levels contained more phenols and ascorbic acid. In (98), reported that excessive temperature and moisture stress adversely affect apple quality, leading to sunburn and fruit cracking. High temperatures alter plant morphology, anatomy and physiology, affecting seed germination, plant development, flower shedding, pollen viability, gametic fertilization, fruit setting, fruit weight, size, and fruit quality (20).

2 Impact of Relative Humidity and Rainfall/Precipitation on Fruit Crops

As study in (6), observed that olive tree trunk cross sectional area (TCA) and canopy volume possessed significantly high values at higher rainfall during pre-bloom periods. According to (99), reported that rainfall during a physiologically important period (flowering and maturation) tends to decrease crop production. Findings from (100) reported that among climatic factors, the rainfall in September and October had an obvious effect on the fruit soluble solids, content where less rainfall during this period increased the soluble solids.

A study in (101) examined the effects of varying humidity levels on Elsanta strawberries and found that high humidity (70-90%) reduced fruit set but increased fruit size and vegetative growth, resulting in lower yields. The effect of different humidity levels during flowering stage of Macadamia plants were examined and found that high humidity increased peroxidase and superoxide dismutase activity, improved pollen fertility, and accelerated fruit growth, leading to higher yield and quality (102). A study in (103) found that frequent rain reduced blueberry fruit set and yield, particularly in southern high bush varieties like Malennia, Star, and Southern Belle, with up to a 50% yield reduction in north Florida and southeast Georgia due to poor pollination. Mulching reduced soil water changes and increased fruit hardness and sugar content compared to the control (104). In (105), found that high soil temperature and light hours negatively impacted guava tree height, while relative humidity and rainfall positively influenced stem diameter and fruit size.

A study in (106), observed that apple fruit set was negatively impacted by relative humidity and rainfall during April-May and May-June, respectively. According to research reported in (107), rainfall during the sprouting phase improved yield, while September rainfall reduced it in ber. Further, low moisture adequacy and high atmospheric dryness during ripening improved yield and quality. A report in (108), noted a strong negative correlation between night temperature, February rainfall, and almond yield. A mild increases in relative humidity improved fruit set in date palm cultivars in the Gaza Strip, with Al Hayani showing the best fruit set across regions (109).

According to (110), rainfall significantly reduced pollen concentration in the atmosphere, with up to an 80% decline when daily rainfall exceeded 8 mm during olive flowering, disrupting pollination and fertilization. A study in (111) observed that after 105.5 mm of rainfall during fruit ripening, soluble solid content in Kurakatawase dropped from 10.6 to 9.6 °Brix, alongside a decrease in sucrose synthase activity and sucrose content. Finding from (32) revealed that flowering intensity was influenced by rainfall, with more flowers produced in May compared to January in cocoa clones, and clone T86/45 had the highest flower count of 415. Rainfall negatively affected the yield of black currant cultivars Ojebyn and Titania during the blossoming period (112).

According to (3), global warming could increase rainfall and atmospheric humidity, potentially fostering fungal diseases and insect pressures. Similarly, with higher temperatures and humidity, there could be increased pressure from insects and disease vectors (113). As stated in (114), humidity during flowering negatively impacted apricot yield, while rainfall had a positive effect. Result from (70) reported that citrus yield was positively related to maximum temperature, rainfall, and humidity, but negatively to minimum temperature in Nigeria. They concluded that climatic factors accounted for 70% of citrus yield variability. According to (37) reported that peach cv. 'Cresthaven' had higher soluble solid content (10.2 to 15.1%) when there was little rainfall before harvest and lower minimum temperatures during the growing season.

A study in (66), also reported that rains during fruiting periods may blacken fruits (in mango) or prevent desirable fruit coloration (in guava), reducing their quality and marketability. An increase in humidity can initiate unseasonal flowering. A study in (68), reported that decreases in rainfall and soil moisture in two areas, Yala and Pattani, affected fruit development, yield and quality. The quantity of fruit was better in Pattain than in Yala based on fruit diameter, fruit weight, peel, juice, and peels thickness; whereas the total soluble solids in Pattani were lower than in Yala. Furthermore, the rind in Pattani was greener than that in Yala.

According to (115) reported that extreme precipitation reduced aboveground net primary productivity (ANPP) at mesic sites (ecosystems with relatively moderate and well-balanced water availability) but enhanced it at xeric sites (ecosystems characterized by limited water availability and arid conditions), highlighting the critical role of plant-available water. Seasonal precipitation variability was found to influence ANPP, phenology, and reproductive development. In particular, reduced rainfall during spring or summer significantly lowered soil water content and constrained plant growth, whereas deficits in autumn or winter had minimal effects. Mandarin fruit production was strongly correlated with post-monsoon rainfall, while other fruits like mango and guava showed stronger correlations with pre-monsoon and south-west monsoon rainfall (116). As report in (117) noted that unseasonal rainfall during mango flowering could interfere with fruit set and development, leading to reduced yield and quality. Excessive rainfall promoted vegetative growth, flower loss, and pest infestations, while high rainfall made mangoes more susceptible to diseases like anthracnose. The findings of (53) found that rainfall during the fruit set to harvest stage negatively affected kinnow mandarin yield ($r = -0.919$), while maximum relative humidity during the same stage had a positive correlation with yield ($r = 0.883$). Evapotranspiration during flowering to fruit set and first to maximum fruit set stages was also positively related to kinnow mandarin yield ($r = 0.899$ and 0.833, respectively).

Uneven precipitation patterns or prolonged dry spells can significantly reduce crop yields, especially in rainfed agricultural areas, and inadequate drainage during periods of excessive rainfall depletes soil oxygen levels, thereby inhibiting the activity of beneficial microorganisms. These waterlogged conditions create a favorable environment for the proliferation of insect pests and diseases, ultimately diminishing crop productivity (118). According to (60), rainfall had a moderate positive correlation ($r = 0.63$), while maximum and minimum relative humidity showed very strong positive correlations ($r = 0.87$ and 0.84, respectively); thus, litchi yield was significantly influenced by weather parameters.

Table 1: Phenological Responses of Fruit Crops to Climatic Factors

Climatic Factor	Fruit Crop(s)	Phenological Change Observed	Source(s)
Temperature	Apple (Royal Empire, Fuji, Royal Delicious)	Decline in yield due to reduced chilling; flowering advanced 4–7 days; fruit size and pigmentation affected	24; 4; 33
	Cherry (Sweet, Hongdeng, Van)	High pre-blossom temp. → malformed flowers, poor fruit set; flowering advanced; fruit set declined by 3 °C rise	22; 13; 46
	Strawberry	Elevated temp. reduced yield 12–35%, smaller fruit, poor quality; anthocyanin synthesis optimal at 15–20 °C	18; 11
	Grapes (Chardonnay, Shiraz, etc.)	Higher temp. advanced maturity, reduced acidity, higher sugar; anthocyanin synthesis optimal at 15–20 °C	65; 11
	Mango	High temp. → leaf scorching, altered flowering, poor fruit set, early/delayed blooms, pollen desiccation	39; 19
	Citrus (Kinnow, Sweet Orange)	More intense flushing under warm/moist conditions; heat stress reduces CO_2 assimilation, fruit size, and yield	16
	Olive	Greater trunk area and oil yield in cooler climates	6
	Mulberry	Shoot growth ceased < 24 °C, activated > 24 °C	9
Relative Humidity	Strawberry	High RH (70–90%) → reduced fruit set, larger fruit, but lower yield	90
	Macadamia	High RH improved pollen fertility and fruit growth	91
	Apricot	Humidity during flowering reduced yield	114
	Citrus (Kinnow)	High RH positively correlated with fruit set and yield	53
	Ber	High temp & low RH during flowering decrease fruit set/yield; early varieties more tolerant	58

	Litchi	Yield increase with humidity & rainfall (r = 0.84–0.87); decrease with high temp & evaporation (R^2 =0.87)	60
Rainfall / Precipitation	Olive	Excess rainfall reduced pollen concentration, poor pollination	110
	Mango	Unseasonal rainfall → flower loss, pest incidence, anthracnose disease	117
	Guava	High rainfall reduced fruit coloration, lower quality	66
	Blueberry	Frequent rain reduced fruit set (up to 50%)	103
	Kinnow	Rainfall during fruit set–harvest reduced yield (r = –0.919)	53
	Apple	Yield negatively affected by rainfall during Apr–Jun	106
	Strawberry	Yield decrease with high temp & late rain; Sept 30 planting best (243.6 g $plant^{-1}$)	61

Strategies to overcome the effect of climate change

Adaptation refers to the process by which farmers mitigate the adverse effects of climate change by employing strategies to safeguard the environment from predicted impacts. Recognizing the effects of climate change and developing corresponding adaptation measures is crucial for sustaining the productivity and profitability of horticultural crops under shifting climatic conditions.

- Development of Climate-Resilient crops through breeding for abiotic stress tolerance, pest resistance, and photo thermal insensitivity.
- Sustainable Water Management through efficient irrigation, rainwater harvesting, and moisture conservation practices.
- Soil Health Management by improving fertility, preventing erosion, and enhancing carbon and moisture retention through organic practices.
- Improved Crop Management through adjusted planting dates, diversification, and integration of intercropping and agroforestry for climate resilience
- Advanced Pest and Disease Control through IPM, predictive monitoring, and use of biological and climate-adapted solutions.
- Improved Orchard design through windbreaks, climate-adapted rootstocks, and shading or cooling techniques.
- Adoption Precision agriculture using remote sensing, data-driven tools, and weather forecasting to optimize resource use and manage climate impacts.
- Agroecological Approaches integrating biodiversity, natural ecosystems, and sustainable grazing to boost ecological resilience.
- Policy support through subsidies, insurance schemes, and regulations to promote climate-smart agriculture and reduce emissions.
- Research and education focused on adaptive strategies, knowledge dissemination, and raising awareness of sustainable farming.
- Global and regional collaboration through resource sharing and participation in international climate initiatives

By implementing these strategies, agricultural systems can become more resilient, ensuring productivity and sustainability despite the challenges posed by climate change.

Future Scope

- Development of climate-resilient fruit crop varieties to withstand temperature extremes, drought, and humidity fluctuations.
- Adoption of advanced agronomic and water management practices to mitigate the adverse effects of climate change.
- Integration of precision agriculture tools and remote sensing for real-time monitoring of crop health and productivity.
- Modeling fruit crop responses under projected climate scenarios to guide policy and management decisions.
- Long-term studies on soil-plant-water interactions, pest, and disease dynamics under changing climatic conditions.
- Strategies to improve synchronization of flowering, fruit set, and harvest timing in response to climate variability.

Conclusion

Changing climatic parameters disrupt the normal growth and development pattern, alter flowering behavior, influence yield attributes and quality fruit production, and lead to changes in pest and disease incidence. In view of the potential impact of climate change, more emphasis must be placed on the identification and development of heat, drought, photothermal-insensitive, and climate-resilient crops, which are essential strategies to ensure sustainable horticultural production and address the challenges posed by changing climatic conditions. The selection of varieties for various agro-ecological areas and growing seasons as the current climate is not suitable for future climate conditions in the long term. Similarly, when planning the establishment of a systematic orchard, it is crucial to incorporate the planting of dense and tall windbreaks. Some cultural practices must follow and avoid to ensure compatibility with the evolving climatic conditions. Fruit development represents a long-term investment with limited opportunities for modification once an orchard is established. Therefore, climate adaptation strategies should prioritize the enhancement of existing technologies to optimize the production environment and, ensure suitability for both current and future climatic conditions.

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