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Review

Climate Change as an Existential Threat to Tropical Fruit Crop Production—A Review

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Abstract: Climate change is an emerging threat to global food and nutritional security. The tropical fruits such as mango, bananas, passionfruit, custard apples, and papaya are highly sensitive to weather changes especially; changes of monsoon onset and elevated temperature are influencing crop growth and production. There is a need for more specific studies concerning individual crops and regional variations. Long-term effects and interactions of weather parameters and increased concentration of greenhouse gases, especially carbon dioxide, with phenological stages of the plant, pests, and diseases remain understudied, while adaptation strategies require further exploration for comprehensive understanding and effective mitigation. Few researchers have addressed the issues on the effect of climate change on tropical fruits. This paper focuses on the impact of abiotic (temperature, rainfall, humidity, wind speed, evaporation, carbon dioxide concentration) and biotic (pest and pathogens dynamics) factors affecting the fruit crop ecosystem. These factors influence flowering, pollination, fruit set, fruit yield and quality. This review paper will help develop adaptive strategies, policy interventions and technological innovations aimed at mitigating the adverse effects of climate change on tropical fruit production and safeguarding global food and nutritional security.

Keywords: fruit quality; pest and pathogen dynamics; phenology; pollination; weather; yield

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1. Introduction

Climate change represents one of the most pressing challenges of our time, with profound implications for multiple facets of human life, particularly agriculture. Tropical regions are more vulnerable to climate change than other parts of the world because of their relatively small temperature ranges, high reliance on ecosystem services and natural resources and the poor socioeconomic status of the people [1]. Recently, rainfall patterns in the tropics have become highly irregular with increased frequency and intensity leading to flash floods, while at the same time there have been absences of rainfall for prolonged periods causing droughts [2]. According to the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report, the global surface temperature is expected to rise by 2.5 °C to 4 °C in 2100, with the most likely estimate being around 3 °C [3]. The frequency and intensity of heat waves have increased in recent decades, with severe impacts from multi-day heat waves that are accompanied by warm nighttime temperatures and high relative humidity [4,5]. Rise in temperature and heat waves cause increased thermally induced morbidity and mortality of species [3]. Carbon dioxide (CO_2) concentration in the atmosphere is expected to reach 550–800 ppm by 2100, which may accelerate global warming and the rise in temperature across the globe [6]. Fruit production, a significant activity in tropical areas, has not received much attention in the comprehensive assessment of climate change impacts and adaptation research [7].

Tropical fruit crops are grown in the region between the Tropic of Cancer (23° (27) N latitude) and the Tropic of Capricorn (23° (27) S latitude). Unlike subtropical crops, tropical crops are extremely sensitive to frost. The average mean temperature of the coldest month should be higher than 50 °F (10 °C) for the growth and development of tropical fruits [8]. Tropical crops include 2700 species of fruits belonging to families like *Anacardiaceae* (mango), *Musaceae* (banana), *Sapindaceae* (rambutan), *Passifloraceae* (passion fruit), *Bromeliaceae* (pineapple), and *Annonaceae* (custard apple, soursop, sugar apple) [9]. They are vital components of both local diets and international markets, providing essential nutrients and economic opportunities for millions of people in tropical regions. Nearly 99% of tropical fruit production is concentrated in Asia and Latin America and a smaller share in African countries. Tropical fruits are the third most important fruit group, contributing to 3% of world agricultural food exports with an average export unit value of more than USD 1000 per tonne. It is estimated that 11 million tonnes of tropical fruits were exported in 2023 and the export volume of tropical fruits shows the fastest average annual growth among other internationally traded food commodities. European countries are the major importers of tropical fruits, consuming 50% of the world's exports [10]. However, their cultivation is intricately linked to climatic conditions, making them highly susceptible to the effects of a changing climate. The production and quality can be significantly affected by any departure from the ideal conditions. The interplay of changed temperatures, different fruit growth stages, suitability of various species and cultivars, increased CO_2 levels, limited water availability, pollinators, pests, diseases and management practices has shown to have a significant influence and will heavily influence tropical fruit production [7].

In this review, we delve into the ecological impacts of climate change on tropical fruit crop ecosystems, exploring how shifts in temperature, precipitation, CO_2 concentration and weather patterns influence crop phenology, water availability, pollination dynamics, pest and disease outbreaks, crop yields, fruit quality and supply chain networks. Ultimately, this comprehensive review seeks to inform policymakers, agricultural practitioners, researchers and stakeholders about the urgent need for adaptation and mitigation strategies to safeguard tropical fruit crop ecosystems against the existential threat of climate change.

2. Methodology

Databases like Scopus, ScienceDirect, Springer, Centre for Agriculture and Bioscience International (CABI), and Google Scholar were used for collection of literature (Table 1). The PRISMA diagram (Figure 1) depicts the systematic review process followed while preparing this review article. BioRender (Science Suite Inc., Toronto, Canada) and Canva (Canva Pty Ltd., Sydney, Australia) softwares were used to prepare figures and illustrations in this review.

Table 1. Inclusion and exclusion criteria.

Sl. No.	Article Characteristics	Included	Excluded
1	Study area	Articles from agricultural and biological sciences	Articles from study areas other than agricultural and biological sciences
2	Study population	Tropical fruit crops	Crops other than tropical fruits
3	Document type	Research articles, review papers, and book chapters	Conference papers, preprints, note, letter, short survey
4	Language	English	Languages other than English
5	Year of publishing	2000 to 2024	Article older than 2000

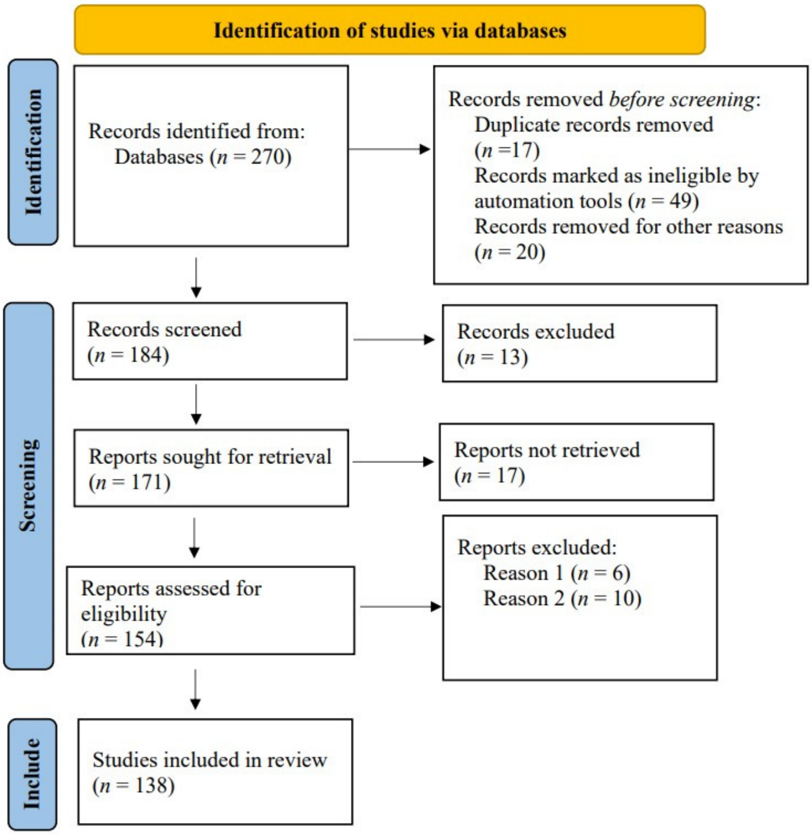

Figure 1. PRISMA flow diagram.

3. Abiotic Factors Affecting Tropical Fruit Ecosystem

Abiotic factors are the non-living components of an ecosystem that influence the living organisms within it. In a tropical fruit ecosystem, several abiotic factors such as temperature, rainfall, humidity, wind speed, evaporation and changes in atmospheric CO_2 level play a crucial role in determining the growth, geographical distribution and health of fruit-bearing plants.

3.1. Impact of Temperature Variations on Tropical Fruit Crops

Temperature plays an important role in tropical fruit crop growth, development, and yield [11]. Plants experience two types of temperature stress: high-temperature stress and low-temperature stress [12]. The cardinal temperatures of some tropical fruits are depicted in Table 2, which includes the minimum, maximum, and optimum temperature requirements of each species. Generally, tropical fruit crops thrive best in temperatures ranging from 24 °C to 30 °C, but their growth is adversely affected by temperatures below 10 °C or above 42 °C [7].

Table 2. Cardinal temperature requirements of tropical fruits.

Fruits	Minimum Threshold Temperature (°C)	Optimum Temperature Range (°C)	Maximum Threshold Temperature (°C)	References
Mango (*Mangifera indica*)	10	24–30	42	[7,13]
Banana (*Musa* sp.)	10	25–35	38	[14,15]
Guava (*Psidium guajava*)	10	23–28	51.2	[16,17]

Table 2. *Cont.*

Fruits	Minimum Threshold Temperature (°C)	Optimum Temperature Range (°C)	Maximum Threshold Temperature (°C)	References
Papaya (*Carica papaya*)	20	21–33	35	[18,19]
Custard apple (*Annona squamosa*)	11	21–30	38	[20,21]
Watermelon (*Citrullus lanatus*)	18	22–30	35	[22,23]
Jack fruit (*Artocarpus heterophyllus*)	5	22–35	35	[24,25]
Sapota (*Manikara zapota*)	10	16–38	43	[26,27]
Pineapple (*Ananas comosus*)	10	20–30	35	[28,29]
Aonla (*Emblica officinalis*)	4	20–34	43	[30,31]
Carambola (*Averrhoa carambola*)	15	21–32	30	[7,32]
Passion fruit (*Passiflora edulis*)	1–2	20–30	30	[33,34]
Mangosteen (*Garcinia mangostana*)	20	25–35	35	[7,35]
Rambutan (*Nephelium lappaceum*)	10	22–30	40	[36,37]

3.1.1. High Temperature Stress

High temperature stress is said to occur when the ambient temperature rises above a threshold limit for a sufficient period such that it causes irreversible damage to plant growth and development [38]. The response of plants to high temperature stress depends on the degree of rise in temperature, duration and crop characteristics. Plants undergo morphological, anatomical, phenological and physiological changes when exposed to high temperature stress [39]. The morphological changes are initially manifested as scorching and sunburn on all plant parts followed by senescence and abscission of leaves, stunted growth and damage and discolouration of fruit [40]. The anatomical changes include reduction in cell size, bigger xylem vessels in both the root and the shoot, as well as higher stomatal and trichomatous densities [41]. High temperature damages thylakoid membranes, decreases the number of photosynthetic pigments, affects the performance of photosystem II and alters the carbon metabolism of stroma and photochemical reactions of thylakoid lamellae, in turn, resulting in reduced photosynthetic rate in plants [42,43]. High temperature affects all the stages of the plant right from germination, growth and development, reproduction, yield and quality of the fruits as depicted in Figure 2. Seed germination is inhibited due to abscisic acid (ABA) production in heat-stressed plants. The reproductive stage is significantly impacted by heat stress, leading to reduced flower bud formation, sterility of male and female organs, reduced pollen germination and pollen tube growth, alterations in stigma and style positions, disturbed fertilization and embryo abortion [44]. The physiological response of plants to high temperature stress involves overproduction of reactive oxygen species (ROS) such as singlet oxygen ($^1O_2$), superoxide (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals (OH^-) resulting in oxidative stress in plants causing damage to cell membrane, protein denaturation and DNA fragmentation [45]. During certain plant stages, especially seed germination, embryogenesis, microsporogenesis and fruit maturity, heat shock proteins (HSPs) are expressed when a plant is subjected to high temperatures. This serves to preserve the stability of the cell membrane and shields the plant against protein denaturation [39].

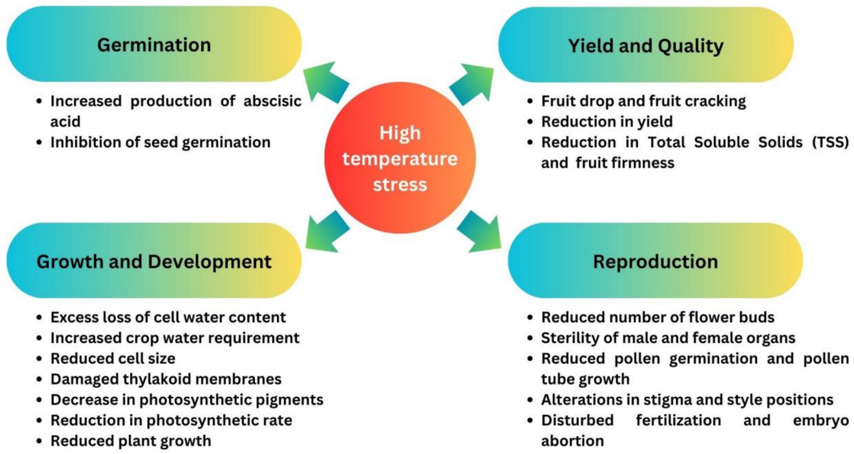

Figure 2. Effect of high temperature stress on different phenological stages of fruit crops.

In recent decades, an increase in the frequency and intensity of heat waves and droughts was reported in the tropical region. Nath et al., opined that the rise in temperature by 1 °C may alter the geographical distribution and potential area of cultivation of tropical fruits. For example, an increase in temperature by 1 °C reduced the area suitable for the *Dussaheri* variety of mango, while *Alphonso* became confined to the *Ratnagiri* area of Maharashtra state in India [7]. However, if the temperature increases by 10 °C, the crop water requirement rises by 50% [12]. High temperature delays flowering, resulting in a pseudo-setting called clustering in mango. Heat stress during the panicle development stage enhances rapid growth, resulting in a reduced number of effective days for pollination, pollen desiccation and poor pollinator activities, leading to poor fruit set. Warm night conditions result in the conversion of flower buds into vegetative buds [14,46]. In traditional guava-growing regions, higher summer temperatures result in suppressed blossom bud differentiation and a prolonged growth period [14]. If the temperature goes below 23 °C and above 27 °C during the flowering stage of guava, it reduces the fruit set [16]. A temperature above 38 °C causes growth cessation and leaf burn in bananas [47]. Leaf emergence in bananas depends on the health of the crop and climate. In summer, 4–5 leaves are produced, whereas in winter only half a leaf is produced.

Temperature also affects the orientation of leaves in bananas; low temperature results in upright leaves, whereas high temperature results in horizontal leaves [48]. When the temperature increases by 1 °C, there will be a shift in the area of cultivation of bananas by 200–300 km in mid-latitudes [14]. In papaya, at higher temperatures, there is a tendency for bisexual cultivars to produce male flowers with poorly developed female parts; in addition, the net photosynthetic rate also decreases above 30 °C [47]. In annona, poor pollination occurs under high temperatures (30 °C) and low humidity (30%) with effective pollination at 25 °C temperature and 80% relative humidity. Pollen germination and pollen tube growth are also reduced under high temperatures [47,49]. Rise in leaf temperature, reduced stomatal conductance and leaf vapor pressure deficit occur in annona due to high temperature and irradiance. Hence, photosynthesis and shoot growth are affected [50]. Figure 3 represents the effect of high temperatures on major tropical fruits such as mango, guava, banana, annona and papaya.

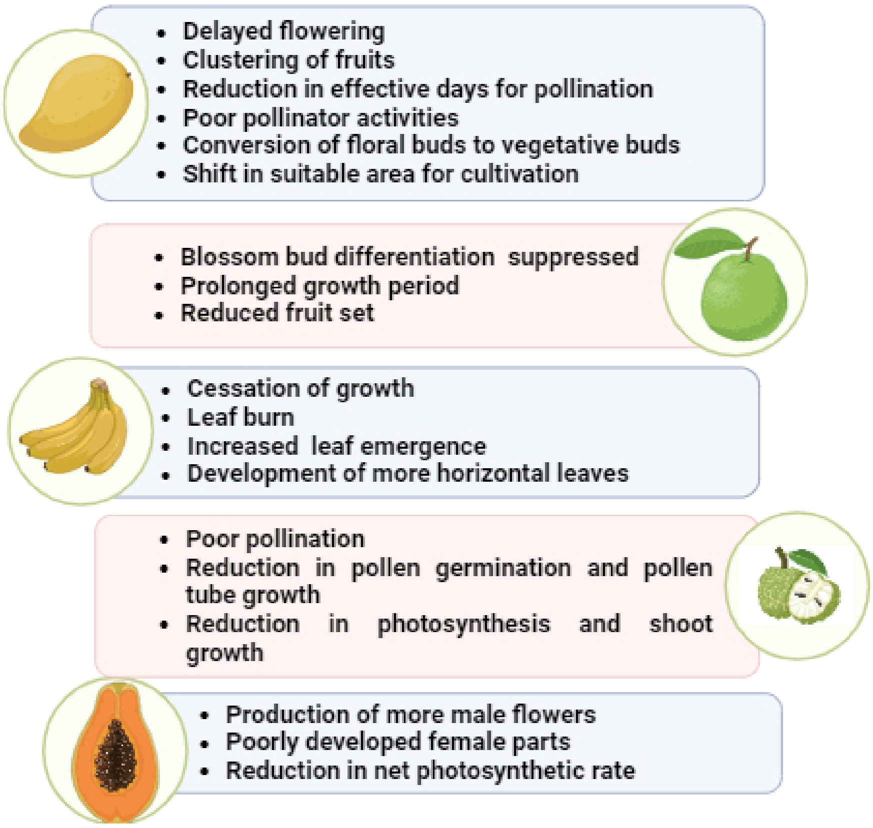

Figure 3. Effects of high-temperature stress on major tropical fruits.

3.1.2. Low Temperature Stress

Injuries due to low temperature or cold stress in plants are of two types: chilling injury and freezing injury. Chilling injury occurs at temperature range of 0–15 °C, it will not cause ice crystal formation in plant tissues. The chilling injury cause damage to cell membrane, reduces uptake function of roots leading to water balance disorders, lowers photosynthetic rate and retards plant growth. Freezing injury occurs at a temperature below 0 °C, with ice crystal formation in plant tissues. The ice crystal formation can be intercellular (when temperature falls gradually) or intracellular (when there is a sudden fall in temperature), latter one directly affects the cell metabolism and hence more dangerous. These injuries further lead to suffocation and heaving, ultimately affecting yield of the crop. Tropical and subtropical plants are more susceptible to low temperatures than temperate plants due to the lack of cold acclimatization [12,51]. The impact of low temperatures on tropical fruit crops, in general, is illustrated in Figure 4. Dinesh and Reddy reported that temperature less than 20 °C for mangosteen trees leads to slow growth and lower numbers of flowers [46]. When the temperature drops below 10 °C, bananas may develop the 'choke throat' disorder, which adversely affects the emergence of leaves and inflorescence, leading to poor fruit development [47]. In annona, anthesis time is delayed by one hour when the temperature decreases from 25 °C to 15 °C [49]. Low temperatures in the range of 4–11 °C combined with high humidity and cloudy weather delay panicle emergence in mango. Early flowering and poor fruit set in mangoes occur as a result of low night temperatures, whereas low day temperatures result in a greater proportion of male flowers and poor pollinator activities, which causes poor fruit set [14]. In addition, low temperatures can lead to flower deformation, loss of pollen viability, reduced number of perfect flowers, and ovule abortion, leading to the development of parthenocarpic fruit and malformation of fruits in mango [52,53].

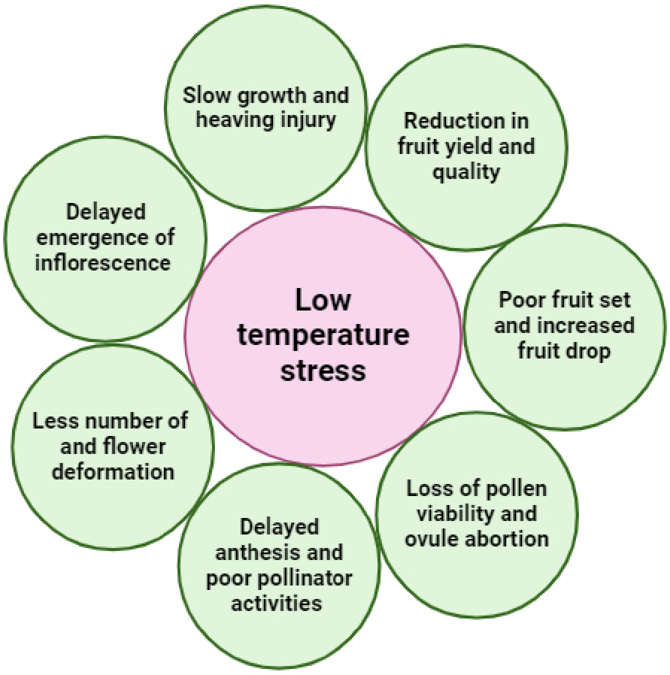

Figure 4. Effects of low-temperature stress on major tropical fruits.

3.2. Impact of Erratic Rainfall Pattern on Growth and Development of Tropical Fruit Crops

Rainfall variability due to climate change can lead to water shortages, decreased crop yields, increased pest pressure and even the total failure of crop stands [54]. Table 3 represents the optimum rainfall requirement and maximum altitude level up to which some of the important tropical crops could be grown without severe impacts on yield.

Table 3. Optimum rainfall and maximum altitude for the growth of important tropical fruits.

Fruits	Optimum Rainfall (mm)	Maximum Elevation from Mean Sea Level (m)	References
Mango	400–3600	1200	[52,55]
Banana	1200	2000	[56]
Guava	1000–2000	1500	[14,16]
Papaya	1200	2395	[57,58]
Annona	1500	1500	[59]
Passion fruit	1000–1500	2000	[60]
Pineapple	760–1000	1000	[28]
Aonla	630–800	1800	[31]
Carambola	1800	1200	[61]
Rambutan	2000–5000	700	[36]

Mango is basically drought tolerant and can withstand occasional flooding. The crop prefers even distribution of rainfall for flowering and fruit set. Heavy rain accompanied by high humidity and temperature variations induces more vegetative flushes, leading to alteration in flowering and delay in panicle emergence and fruit set [52]. In India, heavy rains during the flowering time of mango washed out pollen grains accompanied by poor pollinator activities, leading to poor pollination and fruit set [62]. Heavy rainfall causes the blackening of mango fruits [46]. Water stress during the first 4-6 weeks will affect fruit development and also cause fruit drop in mango. The summer rains during the pre-monsoon period will lead to early flowering in guava when grown as a winter crop [14].

In papaya, drought leads to rapid shedding of leaves and poor fruit set. Flooding causes chlorosis and abscission of leaves, followed by death of the leaves due to root rot [58].

Hail is a form of precipitation of small ice pieces with size ranging from 5 to 50 mm usually. Hailstorms lead to heavy defoliation, peeling of bark, flower and fruit drop, fruit cracking and in severe cases lodging or uprooting of trees may also occur. Among tropical fruit crops, banana and papaya are severely affected, nearly 50% damage to plants were reported for these fruit crops in India [63].

3.3. Effect of Relative Humidity, Wind Speed, and Evaporation on the Growth and Yield of Tropical Fruits

Meteorological parameters like relative humidity (RH), wind speed, and evaporation play crucial roles in the growth and yield of tropical fruits. Research indicates that different humidity levels have a substantial effect on the growth of plants, with increased humidity levels positively impacting both photosynthesis and water regulation [64]. But low temperature combined with high humidity favors the occurrence of plant diseases. Germination rates were low under high-temperature conditions (30 °C) and high humidity (90% RH), as well as under low-temperature conditions (15 °C) and low humidity (40% RH) in annonas [49]. During guava flowering, low relative humidity results in the abortion of flowers, decreases fruit set and raises fruit drop rates. Additionally, it diminishes fruit size and quality [16].

Wind leads to increased stomatal transpiration, speeds up the drying of leaf surfaces, making them vulnerable to pest and disease infestations [65]. The accelerated transpiration rate results in wilting and stunted growth. Mango yields decrease if strong winds occur during the flowering and early fruiting stages. Papaya trees are fragile and require shelter from strong winds, as strong winds can lead to uprooting. Even if uprooting does not happen, strong winds can still cause significant damage to the large leaves, resulting in the shedding of flowers and fruits. Banana plants are uprooted when the wind speed exceeds 80 km/h. In such areas, people prefer the *Dwarf Cavendish* types. Wind speeds ranging from 18 to 30 km/h cause the splitting of leaf lamina and this reduces bunch yield. High-speed hot winds during the summer months shred and desiccate the leaves, significantly reducing photosynthetic efficiency when the leaves are torn into 10 cm wide strips [66]. The wind, in combination with rain, assists in spreading primary inoculums, leading to the increased spread of plant diseases.

Papaya growth and yield are positively influenced by higher evaporation-replenishment rates, resulting in improved relative water content, transpiration rate, plant height, stem girth, fruit number and yield when using drip irrigation [67]. Furthermore, tropical fruits like bananas and avocados have high water needs because of their increased evapotranspiration rates. This highlights the significance of employing efficient irrigation methods to maximize water usage and improve crop yield [68].

3.4. Influence of Rising Carbon Dioxide (CO_2) Levels on Tropical Fruit Production

The primary cause of global warming is the rise in carbon dioxide levels and it is projected that by the year 2100, the concentration of CO_2 will reach 600–700 parts per million (ppm). Studies conducted in Columbia proved that elevated CO_2 has a positive impact on fruit trees like citrus, papaya, dragon fruit, grapevine and strawberry, causing increased photosynthesis, efficient use of water, growth and greater biomass. Under elevated levels of CO_2, C_3 plants exhibit an increase in growth rate by 30% [6]. Sugar accumulation in fruits is enhanced by higher levels of CO_2, leading to improved weight and size as well as biochemical aspects of the fruit [69].

The reaction of plant species to increased CO_2 levels might not only depend on their photosynthetic capacity and ability to distribute nutrients to different parts of the plant, but also on how effectively they can transport assimilates to the areas where they are needed. This suggests that certain species, varieties or rootstocks with narrow vessels (such as many dwarf fruit tree rootstocks) may struggle to move the excess carbohydrates produced under elevated CO_2 to the appropriate areas, making them susceptible to feedback inhibition of photosynthesis [70]. Researchers have identified positive [71–73] and negative effects [74–76] of elevated CO_2 levels on fruit crops as illustrated in Figure 5. The higher photosynthetic rates are primarily responsible for increased availability of carbohydrates in the apical meristem region leading to increased cell division. Higher CO_2 levels cause the cell wall to loosen up and become more extensible, which eventually results in bigger cells. The increased internodal length, high root and shoot growth, increased tree height and fruit biomass as mentioned in Figure 5. would all result from high cell division and larger cell size. It is anticipated that higher CO_2 levels will cause leaf area of tree species to increase by 14%, producing larger leaves [77,78]. The stomatal density and stomatal conductance are expected to decrease leading to reduced transpiration rates [79]. Reduced transpiration would affect the mass flow mechanism resulting in decreased nutrient absorption and transportation in plants [74,80].

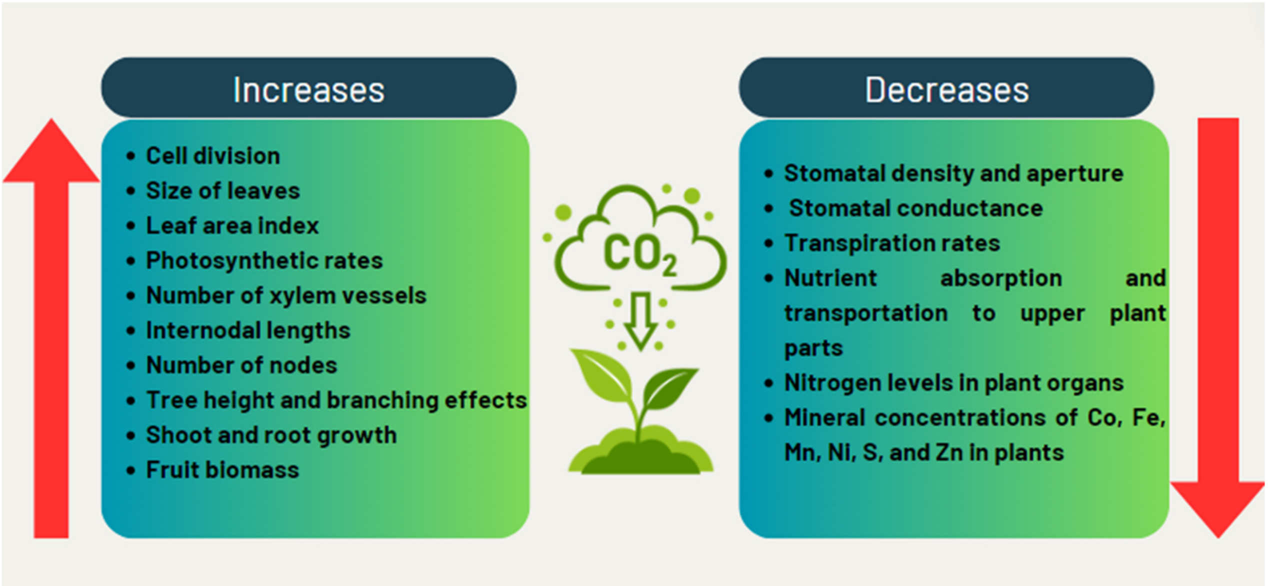

Figure 5. Responses of fruit crops to elevated CO_2 levels in the atmosphere.

3.5. Impact of Environmental Factors on the Behavior of Pollinators and Pollination of Tropical Fruit Crops

Crop production in the tropics will be significantly affected with a reduction in the population of pollinating insects due to climate change [11]. There will be a reduction in pollinator population by 61% with an increase in temperature. The potential threat to crop yield in 2050 due to declines in insect pollinator numbers, relative to overall production in a specific area, is most pronounced in the tropical areas of Sub-Saharan Africa, South America and Southeast Asia. Cocoa is considered to be at the greatest risk among crops, especially in Africa, followed by mango (especially in India) and watermelon (particularly in China) [81]. In mango temperatures, more than 32 °C caused a reduction in the activity of the honey bee pollinators (*Apis florea*) while dipteran pollinators were not affected (*Chrysomya megacephala*) [82]. Nitidulid beetles are the pollinators of annona flowers; in the absence of these pollinators, a 25% reduction in fruit set was observed. The natural occurrence of nitidulid beetles was favored by high soil temperatures (range: 20–30 °C), but was adversely affected by rainfall greater than 5 mm/day [83]. Climate change not only affects pollination activities but also pollen dehiscence, pollen tube growth and synchrony of male and female organs. In annonas, pollen is discharged in the afternoon between 3 and 6 pm, the temperature at that time should be greater than22 °C and relative humidity above 80%; if the temperature is less than 22 °C, pollen dehiscence will not occur [83].

3.6. Climate Change Impact on Biochemical Aspects and Quality of Tropical Fruit Crops

High quality standards are essential for securing a competitive price in the export market [84]. The changing climate leads to changes in the total soluble solids (TSSs), titrable acidity and content of ascorbic acid in the fruit, as well as fruit's color, flavor and firmness. Exposure of mango to high temperatures along with intense solar radiation results in scalds, which makes the fruits unmarketable [14]. In addition, exposure to high UV-B radiation reduces yield and quality of mangoes [85].

The total soluble solids (TSSs), fruit firmness, and percentage dry mass in guava all show a negative correlation with temperature [86]. The development of anthocyanin pigments, which give a red color to the pericarp of Guava, requires a night temperature of 8–10 °C or even lower. Better-quality guava fruits will come from cooler nights rather than warmer ones [14]. Rise in temperature above 26.7 °C reduces pulp firmness and changes the color of the skin in banana [87]. Guava fruit that has experienced heavy rainfall becomes watery, loses firmness, TSS, titrable acidity, ascorbic acid content and may also crack and drop [16,88]. In annona, low humidity (<60% RH) and low temperature (<13 °C) in the months prior to fruit maturity can exacerbate fruit-skin russeting and postpone fruit maturity [89].

4. Biotic Factors Affecting Tropical Fruit Ecosystem

4.1. Impact of Climate Change on Pest Population Dynamics of Tropical Crops

A changing climate directly affects pest reproduction, development, survival and dispersal and indirectly affects natural enemies, predators, competitors, vectors and mutualists [90]. Temperature is the most important parameter affecting insect physiology since their metabolism doubles when temperatures increase by 10 °C [91]. In tropical regions, however, a decrease in growth rate will occur because temperatures in this region have already reached the optimum level for pest development. If the temperature rises further, then growth and development will decrease [92]. Climate change results in a rise in temperature, uneven precipitation and an increase in CO_2 concentration, affecting insect population dynamics, geographical distribution, growth and development, abundance, etc., as illustrated in Figure 6 [93].

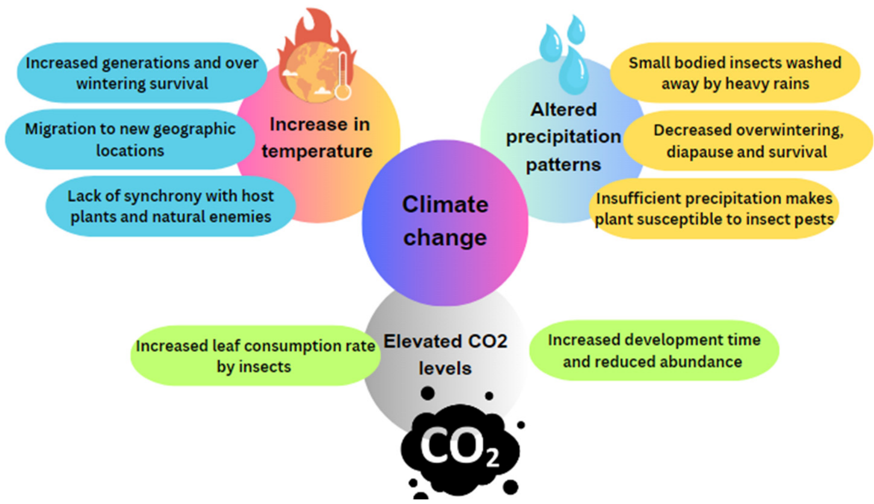

Figure 6. Responses of insects under climate change scenario.

In the tropics, rainfall frequency has decreased but the intensity has increased, affecting overwintering, diapause and insect survival. Heavy rainfall also affects the flying and reproduction of insects [94]. In addition, insect eggs, larvae and small-bodied insects like aphids, mites, jassids, whiteflies, etc., will be washed away due to heavy rain [95]. Reduced rainfall will lead to drought, making the plant susceptible to insect pests [96].

Mango hoppers cause damage to leaves, inflorescence and fruits by sucking sap from plant tissues. Leaf hoppers transmit viruses while they are sucking sap from the plants. The optimum temperature for leaf hopper growth and development is 15–35 °C and a decline in hopper population was observed when the temperature goes above 35 °C [97]. High humidity and unseasonal rains increase the attack of mango hoppers, leading to heavy flower and fruit shedding [98]. Cloudy weather with high relative humidity favors the multiplication of hoppers [99]. The population of hoppers decrease with an increase in wind speed [100].

In mango, thrips attack is seen on leaves, flowers and fruits. Female thrips lay eggs on any non-woody structures like stems, leaves, flowers and fruits. The optimum temperature for the multiplication of eggs by female thrips is 25–30 °C [101]. Fruit fly attack occurs during the fruit-ripening stage of mango. The rate of development of fruit flies increases when the temperature rises from 20 to 35 °C [102]. Mango fruit fly attacks increase with an increase in temperature up to 28 °C but after that, they decrease. Heavy rainfall along with fruit fly attacks will accelerate the yield loss [103].

The aphid (*Pentalonia nigronervosa*) transmits Banana Bunchy Top Virus (BBTV) more efficiently at 25 °C and 30 °C as compared to 20 °C [104]. It is reported that aphids are not able to recognize alarm pheromones properly under high-temperature conditions, which makes them more susceptible to predators and parasitoids [105]. High temperatures along with high humidity favor whitefly population buildup [106]. Based on a study conducted on 1100 insect species, the rise in temperature would lead to the extinction of 15–37% of species by 2050 [107].

4.2. Diseases of Tropical Fruit Crops in the Context of Climate Change

A plant disease is a dynamic process in which a host and a pathogen intimately related to the environment are mutually influenced, resulting in morphological and physiological changes [108]. In phytopathology, the environment encompasses temperature, humidity, precipitation and ultraviolet (UV) radiation, along with water, air and soil [109]. Among the environmental parameters, temperature and humidity are important parameters which favour the development of plant disease. Climate change can lead to the emergence of a pre-existing pathogen as a major disease, allow the introduction of new pathogens, alter the stage and rate of development of the prevailing disease, cause changes in the physiology of host–pathogen interactions and even affect host resistance, making the plant more susceptible to the pathogen [110].

4.2.1. Fungal Diseases

Fungal diseases like downy mildews, powdery mildews, anthracnose, phytophthora rot and leaf blight that affect horticultural crops are weather-driven [14]. Rise in temperatures, especially night temperatures and milder winters, have increased the winter survival of pathogens, shortened pathogen life cycles and increased sporulation and infectiousness of foliar fungi [111]. In general, during warmer and drier summers fungal infection tends to decrease, but some pathogens like *Podosphaera*, *Sphaerotheca*, *Uncinula* and *Ustilago*. thrive in such conditions. High temperature and drought stress will increase vascular wilt diseases caused by *Fusarium*, *Verticillium* and *Ganoderma* in annual and perennial crops [112]. Severe summers will cause early infection and longer epidemics in the case of air and seed-borne pathogens like *Pernospora* and *Puccinia* but the survival of soil-borne fungi will be impacted by reduced soil moisture [14].

The prevalence of weather parameters like temperature in the range of 25–30 °C, a greater number of rainy days, low sunshine hours and a relative humidity of over 90% for a prolonged period leads to the development of *Phytopthora* infections in crops. On the other hand, increased temperatures, less precipitation and extended drought periods can reduce the incidence of *Phytophthora* infections. Temperature in the range of 10–22 °C along with high relative humidity favors the occurrence of powdery mildew disease. However, the development of pathogen-causing powdery mildew disease will be inhibited by temperatures below 9–10 °C and above 34–35 °C [14].

A major fungal disease of tropical fruit crops is anthracnose, which affects all the phenological stages of the crop. This disease is aggravated under high relative humidity growth rate and tends to increase with humidity and temperature conditions [113–115]. Rain splashes disperse the spores of anthracnose disease [115]. In mango, anthracnose disease affects leaves, inflorescence and fruits. This disease will lead to twig dieback, defoliation and dropping of flowers and fruit in soursop. Heavy rain causes leaching of the fruit's protective layer, making it susceptible to blackening disorder and post-harvest diseases in mango [46]. Climate change affects the disease dynamics of two major diseases, banana black sigatoka (*Mycosphaerella fijiensis*) and Panama wilt or Fusarium wilt (*Fusarium oxysporum* f. sp. *cubense*). The changes in relative humidity may reduce the spatial distribution of black sigatoka because the pathogen survival is negatively affected below 70% relative humidity [116,117]. Panama wilt is positively correlated with increased temperature and water stress [118]. Pineapple fusariosis (*Fusarium subglutinans* f. sp. *ananas*) disease incidence decreases when temperature rises above 35 °C [119]. The temperature in the range of 23–27 °C and heavy rainfall increases the severity of black spot disease caused by *Asperisporium caricae* in papaya [120].

4.2.2. Bacterial Diseases

Bacterial diseases generally affect the yield and quality of tropical fruits. Common bacterial diseases in tropical fruits are bacterial wilt and bacterial canker of stone fruits. The bacterium *Pseudomonas syringe* pv. *morsprunorum* causes bacterial canker and gummosis of stone fruits. This bacterium attacks trunks, branches, shoots, spurs, blossoms, dormant buds, leaves and even fruits. The dispersal and infection of pathogens are facilitated by frequent rainfall, high humidity, cool temperatures and wind. Rainfall in the orchard during the growing season ensures the spread of disease. Typically, autumn and winter are when the trunk and branches are impacted [14].

Bacterial blight of pomegranate is caused by *Xanthomonas axonopodis* pv. *punicae*, which attacks all the above-ground parts, including fruits, causing the splitting of fruits. High temperature, low humidity and rainfall favour disease development. The increase in day temperature (38.6 °C) and afternoon RH of 30.4% along with cloudy weather and intermittent rainfall favour the initiation and further spread [121]. Wind-splashed rains increase the disease spread from healthy plants to unhealthy plants.

4.2.3. Viral Diseases

Pineapple mealybug wilt-associated virus (PMWaV-1, PMWaV-2 and PMWaV-3) causes mealybug wilt disease, prevalent in all pineapple-growing areas. The vectors of the disease are *Dysmicoccus brevipes* and *Dysmicoccus neobrevipes*, commonly known as pineapple mealy bugs. *Dysmicoccus brevipes* also acts as a vector of banana streak virus (BSV) in Uganda, which causes banana streak disease [122]. Studies suggest that the vector population increases with the temperature rise; hence, the incidence of pineapple mealybug wilt and banana streak disease may increase in the future [25,123]. The incidence of papaya ring spot virus transmitted by aphids is more severe when the temperature is in the range of 26–31 °C, increasing temperature favors the spread of the disease [27].

5. Prospects: Adaptation and Mitigation Strategies in Tropical Fruit Production

A combination of adaptation and mitigation strategies is necessary for better outcomes. Even if emissions were completely halted, the adverse effects of climate change would persist for years [124].

Orchard establishment: Due to changing climate scenarios, tropical regions may experience a northward shift in agroclimatic zones in the northern hemisphere and a southward shift in the southern hemisphere in the future [125]. Hence, identification of potential areas for orchard establishment could be done using climate suitability models. The suitable areas for establishment of mango and guava orchards in India were mapped using models developed using algorithms like rule set prediction (GARP), maximum entropy (MAXENT) and bio-climate (BIOCLIM) [126].

Variety development: Breeding techniques could be adopted to develop varieties that can endure both biotic and abiotic stresses like high temperature, drought, salinity, pest and diseases. For example, in regions with limited water resources, varieties like Arka sahan (Annona) and ruby (pomegranate), that can withstand droughts show great potential. Mango cultivars that are monoembryonic are best suited for areas with well-defined winter season, while coastal regions benefit from polyembryonic varieties [7]. In vegetatively propagated plants virus infection is a major issue. Certified virus-free plants could be used to avoid the spread of graft-transmissible diseases [127,128].

Management practices: Pruning for canopy management shapes young plants and increases leaf and fruit exposure, leading to enhanced fruit yield and quality. Innovative techniques like fruit bagging could be adopted to prevent fruit drop at early stages and avoid physiological disorders. Bagging of mango fruits at the marble stage using brown paper or newspaper improved fruit retention and reduced the occurrence of spongy tissue [129]. The use of prgmen bags to cover pomegranate fruits helped decrease fruit cracking and sunburn issues [130]. Nets could be used to provide shade and protect fruits from birds, insects and hail. The abiotic stress tolerance could be imparted by the exogeneous application of plant growth regulators like cytokinins, abscisic acid, salicylic acid, jasmonic acid and proline [131,132].

Soil and water conservation: Mulching and microsite modification using fillers improves the water-holding capacity of soils. Reuse of wastewater and solid waste in agriculture, along with implementing water-harvesting technologies, is advisable. Conservation techniques such as levelling, constructing bunds, bench terracing, etc., need to be implemented, as well as effective management of irrigation water through the use of drip systems in growing bananas, papayas, pomegranates, mangoes and sapotas [65]. Transformation of degraded lands and barren areas into tropical fruit orchards can serve as a significant carbon-sequestration tool. Over a year, perennial crops can store 320 to 1100 kg of soil carbon per hectare, while annual crops can store 0 to 450 kg; additionally, perennial crops tend to yield better than annual crops in hotter conditions [133].

Microclimate modifications: Modifications to the microclimate can be utilized to mitigate extreme weather events. Overcoming heat and cold stress is possible by utilizing methods such as overhead irrigation, sprinklers and shade nets. The use of mulch enhances soil microclimate, microbial activity and soil health. Plastic mulch resulted in higher yields for papaya (64.24%), mango (45.23%), banana (33.95%), ber (27.06%), guava (25.93%), pineapple (14.63%), and litchi (12.61%) compared to no mulch [134]. Antitranspirants can be used to reduce water loss through transpiration and temperature on leaf and fruit surfaces. The use of antitranspirant chitosan at a concentration of 2% resulted in significantly higher average finger weight, average hand weight and bunch weight in bananas compared to the other treatments [135]. Using terra alba in treatment improves the quality of pomegranate fruits by lowering fruit and leaf temperature compared to the control, as reported by [136]. Kaolin is also key in preventing sunburn in pomegranate fruits [137]. Windbreaks or shelter belts alter the microclimate and soil of orchards, offering shelter for pollinating insects and guarding against wind erosion and natural disasters. Fruit plant mortality due to frost is lower in orchards with wind breaks (2.97 to 30.81%) compared to those without (up to 91.43%) [138].

Pest and disease control: Integrated pest and disease management along with choice of tolerant cultivars will help to ensure good yield and avoid economic losses.

6. Conclusions

Tropical fruit ecosystems are threatened by rising temperatures, shifting precipitation and unprecedented extreme weather events. The changing climate plays a crucial role right from seed germination, growth and development, flowering, fruiting, occurrence of pests and diseases, production, productivity and nutritional quality in tropical fruit crops. Adoption of proper adaptation and mitigation measures is the only possible way to overcome these challenges. The existing strategies include proper site selection for orchard establishment, development of tolerant varieties using breeding techniques, proper tree/canopy management, adoption of microclimate modifications and pest and disease control measures. Though the existing technologies are capable of minimizing short-term negative effects, thorough research is required in this field to overcome long-term impacts of climate change on tropical fruit production. Hence, in future, research and development should focus in developing advanced technologies that are economically viable and user-friendly for stakeholders.

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