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From orchard to table: Understanding climate change impacts on mango production in India: A review

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Abstract
Mango (*Mangifera indica* L.) is a renowned horticultural cash crop prized globally for its taste, aroma, and nutritional benefits. However, climate change poses significant challenges to mango production. This review synthesizes the impacts of climate variability on mango growth, fruit development, and phenology, drawing on scientific literature. Fluctuations in temperature, rainfall patterns, and extreme weather events influence mango cultivation, affecting flowering, fruit set, and quality. Climate-induced changes disrupt traditional phenological patterns, impacting pollination, fruit development, and harvest. Elevated temperatures lead to premature flowering, irregular fruit set, and post-harvest quality degradation. Additionally, rainfall variability affects pollinator activity and fruit set. Understanding mango phenology under changing climate conditions is crucial for sustainable cultivation. Studies suggest that mango trees exhibit plasticity, offering resilience against adverse conditions. Nevertheless, adaptation strategies are essential for mitigating climate impacts on mango production. Future research should focus on cultivar-specific responses and adaptation measures to ensure the resilience of mango cultivation in the face of climate change.

Keywords: Mango, climate change, phenology, fruit development, temperature fluctuations, rainfall variability

Introduction
Mango (*Mangifera indica* L.) is a popular horticultural cash crop in numerous tropical and subtropical regions, with its fruit highly valued by consumers worldwide due to its exceptional taste, alluring aroma, nutritional benefits, and medicinal properties [1, 2]. The fruit has been grown for at least 4000 years, with more than 1000 varieties developing during this time. Different fruit crops are affected differently by changes in climate, especially when it comes to increasing temperatures, increased atmospheric CO2 levels, and warmer winter nights [3]. Climate change will pose serious obstacles to agriculture in general and mango production in particular soon. Given that atmospheric CO2 contributes significantly to changes in temperature and is necessary for basic plant processes like photosynthesis, it is imperative that we take climate change in agriculture into account. Mangos are a seasonal delicacy that are widely grown and consumed in tropical and subtropical countries due to their economic and nutritional benefits. The system that produces mangos is, regrettably, challenged by several problems, including changing climatic circumstances. The timing of recurring events in plants' lives and their relationships to their surroundings, known as phenology, has garnered increasing attention considering climate change. Worldwide. Phenological monitoring has therefore become an immensely valuable instrument for assessing the effects of climate change. Numerous biological processes and ecosystems have been impacted by the present climate shift [4]. One of the oldest recognized markers of climate change is phenological phenomena, whose frequency of reporting increases yearly [5-7]. Plant blooming phenology is a complicated characteristic that depends on a range of climatic factors, tree age, shoot maturity, and the genetic makeup of specific kinds [8, 9]. Through significant disruptions to the timing of fruit, seed, and flower availability, the predicted changes in environmental cues have the potential to alter tree phenology. These disruptions could have a domino effect on the distribution, fitness, and population dynamics of dependent invertebrate and vertebrate fauna, such as birds, bats, and primates [10].

Tropical regions that have traditionally had high temperatures will suffer from climate change. Mangoes are a heat-tolerant crop, while growing well in humid, semiarid subtropics and monsoonal tropical regions. However, in the event of extreme heat, drought, or evaporative demands, this crop's potential output capacity will be diminished. Because they are a seasonal fruit crop, mangos react differently to temperature variations than do their annual counterparts [11]. Mangoes can withstand extremely dry conditions because they are a perennial crop, which can greatly increase productivity in subsequent growing seasons. In an annual crop farm, survival is virtually worthless if a stress-induced delay in output leads to a total loss of yield [12].

Climate variability's effect on mango growth

Impact of Rainfall

Climatic occurrences such as unpredictable weather patterns, excessive precipitation, inundations, extended periods of aridity, and droughts disrupt agricultural operations, impacting seasonal produce like mango cultivation. Precipitation levels play a pivotal role in influencing plant growth and the development of flowers and fruits. Mango plants thrive within a rainfall range of 1,000 to 2,500 mm annually, accompanied by a dry spell lasting 4 to 6 months each year. In instances of insufficient rainfall, mango farming necessitates irrigation. However, during the flowering and fruiting stages, mango trees do not require excessive moisture, as heightened rainfall can impede fruit formation and promote disease susceptibility instead. Unpredictable rainfall in the lead-up to and during blooming might result in reduced pollinator activity and poor fruit set. A significant amount of the crop might be destroyed by storms during the final stages of fruit maturation due to the shifting climate. Ripe mango fruits can have a negative impact on their look and quality due to changes in rainfall patterns. Unseasonal rains can promote bugs, which reduce fruit production. Mangoes grow best in warm to hot areas with low relative humidity, little rainfall, and flowering, fruit setting, and harvesting periods. Mangos grow well in a variety of temperatures, from warm temperate to tropical, although in humid, high-rainfall areas, anthracnose can pose a significant threat to mango agriculture [13]. Regions experiencing seasonal rainfall exceeding 100 mm are preferred for mango cultivation due to the inhibition of vegetative growth during dry periods. Both the amount and distribution of rainfall play crucial roles in mango production. While mango trees naturally thrive in regions with rainfall ranging from as low as 250 mm to as high as 3000 mm, the timing of rainfall during fruit development and ripening stages is paramount. In areas with high rainfall, mature fruits are susceptible to diseases like anthracnose, resulting in unsightly blackening of the peel. Mango cultivation can rely on minimal irrigation in regions where annual rainfall exceeds 250 mm, typically avoiding waterlogged conditions. Mango cultivation spans regions with diverse annual rainfall ranges, provided there is no waterlogging. Rainfall during the flowering stage negatively impacts fruit set, development, and yield, particularly evident in specific areas of Southern Thailand and India where excessive rainfall leads to vigorous vegetative growth and flower drop. However, certain regional cultivars exhibit resistance to these effects. Mango trees demonstrate robust performance in arid regions of Thailand and Southern India. Consequently, varietal disparities exist in their adaptability to wet and dry conditions, with fruits exhibiting enhanced coloration and reduced disease susceptibility in environments characterized by comparatively drier air during flowering, fruit set and development.

The effects of intense heat and cold waves

There have been reports of major damage caused by hot and cold waves to a number of fruit plantations. Temperature seems to affect perennial crops like mangos in terms of blossoming. When temperatures rise, the phenology of flowering is influenced by the vegetative bias of mangos. This inclination becomes more pronounced. In late emerging panicles, a higher percentage of hermaphrodite flowers was connected with higher temperatures [14–16]. Mango panicles are susceptible to dehydration during peak bloom periods, which are defined as temperatures above 35 °C with continuous sunshine, low relative humidity (49%), and high transpiration. Heat stress causes twig death and leaf blistering in both bearing and non-bearing mango trees. Mangoes are experiencing a number of noteworthy effects from the changing environment, such as delayed or early flowering, numerous reproductive flushes, uneven fruit set, varying fruit maturity, and the conversion of reproductive buds into vegetative ones [17]. When high temperatures and moisture stress are present, apples, apricots, and cherries are more vulnerable to sunburn and cracking. Premature mango ripening, as well as fruit cracking and burning in litchi, are caused by temperature increases around the period of fruit maturity [18]. In a warm environment, pollen can thrive, while cold temperatures might disrupt both pollen formation and the ability of the pollen tube to reach the ovule [19]. Although mangos have demonstrated both self- and cross-pollination capabilities, there have been varied reports globally regarding the effectiveness of cross-pollination methods [20]. Pollen grains experience deformities and become nonviable when subjected to temperatures lower than 17 °C. Temperatures below 10 °C have a significant impact on the meiotic precalculated phase, which is the first stage of microsporogenesis. In addition, low temperatures have a negative impact on the process of pollen tube germination and growth, and growth is totally halted when temperatures drop below 15 °C [21]. Mango fruit development initiates during the flowering stage, necessitating favorable conditions such as moderate temperatures and adequate humidity. Nevertheless, sudden temperature fluctuations-such as heatwaves or unexpected cold spells-can disrupt flower development and reduce successful pollination rates [17]. Consequently, fruit quality suffers, leading to irregular fruit set." The quality of mangoes during post-harvest processing is still being impacted by changes in temperature and weather conditions. Elevated temperatures expedite the deterioration of fruit during storage and transportation, leading to heightened decay rates and reduced market value [22]. Conversely, employing cold storage techniques can prolong shelf life; however, if temperatures dip below the critical threshold, it can result in chilling injury.

Influence of climatic factors on fruit development and it's quality

Fruiting and flowering phases are important for crops that can be influenced by the surrounding environment. Changing environmental conditions might hinder the fertilisation of natural product crops and the blossoming patterns of fruit sets through reduced pollinator activity and unsuitable dust conditions. Precipitation throughout the flowering period washes away the pollen residue that occurs when there is minimal or no fruit production [23]. The unseasonal downpours and heavy dew attack during the blooming season in Gujarat were responsible for 80% to 90% of the mango production misfortune [24]. These factors also increased the rate of dingy moulid and fi ne buildup in mangos and decreased the organic product setting. Parmar *et al*. [25] found that warm evenings in December, which occur during the flower induction period, had a detrimental impact on flowering in mangoes, thus leading to a decrease in crop output. Consequently, there was a substantial decrease in the yield of mangoes. Elevated temperatures will expedite the growth of mangoes, inevitably impacting their development. The recent 1.5 °C warming during the winter season in Australia has led to a decrease in the expected development time frame for mangoes by 12-16 days (7%-8%) [26]. High temperatures can also have a considerable impact on the quality of organic products due to the mixing of optional ingredients caused by pressure, some of which have great nutritional value. The intricacy of coloured varieties is further enhanced by higher luminosity [27]. Increasing the temperature can improve the quality of natural products as high levels of light can induce stress. Moreover, it has the potential to greatly impact the dimensions of organic substances while promoting the process of photosynthesis [28]. The acceptability of mango tree blossoms is mostly influenced by chilly climatic conditions. Consequently, increasing temperatures will impede enlistment. However, increasing temperatures will intensify the effectiveness of dust and the formation of natural products in regions with extremely cold temperatures during the blossoming process. In addition, temperature has an impact on the size of inflorescences [29] and the quantity of flowers per inflorescence [12]. The recruitment of botanical species is also dependent on the accessibility of fully developed leaves to sunlight, and increased levels of light intensity may have a beneficial effect on the flowering of mango trees. In India, the difficulty in fruit setting was not caused by the early flowering period, but rather by the environmental variations that impacted mango blossoming. During March, the daytime temperatures were conducive for flower knotting, but the trees experienced a sudden temperature spike, causing significant damage to a large portion of pollen grains. Consequently, there was a decline in fruit set rates and the loss of some embryos formed during the previous period. Subsequently, temperatures improved during the day with some cold spells at midnight. When nighttime temperatures dropped below 12 °C, cell division halted, resulting in abnormal fetal growth and atrophy.

From blossom to harvest: Climate change's effect on mango phenology: Climate change may affect plant phenology, and several studies have used blooming time as a visual indication of plant phenology. Beyond serving as a means of reproduction, flowering is an essential process for angiosperm survival under stressful conditions. Based on research conducted at ICAR-CISH, Lucknow (subtropics), the current study collects and analyzes phenological data using the BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) scale, which was previously created for mango [30, 31]. The stages of formation and expansion of mango flower buds are described in the observation that was made. Over a two-year period (2018–2020), the impact of meteorological conditions on the phenology of mango flowers was observed. The primary causes of the cultivars' genetic diversity in panicle length and width are their interactions with the physicochemical environment, most especially the shoot's physiological parameters, and their genetic makeup [32]. Other researchers carefully corroborated this finding as well [33, 34]. Prasad and his colleague [35] noted that panicle development and subsequent flowering intensity may be stimulated by increased glucose levels during the pre-flowering period. Additionally, we found in our research that Amrapali had greater levels of carbohydrates (data not published), which related to both the length of the panicle and the intensity of the flowers. Across all parent mango cultivars, it was generally found that the percentage of hermaphrodite flowers in early emerging panicles was lower than that of late emerged panicles. The lesser number of hermaphrodite flowers in early emerged flowers may be attributed to the fact that cool weather during inflorescence contributes to the fewer perfect flowers [36, 37]. In our study, we observed a higher number of hermaphrodite flowers in late variety *viz*. Chausa and Amrapali. A similar line of the result was obtained by Geeta and her coworkers [38]. It is reported that low temperatures (10–15 °C or below 15 °C) during flowering increased the proportion of staminate flowers while high temperatures increased hermaphrodite flowers [38, 39]. The current data strongly agree with Singh *et al*.'s findings [37]. They found that panicles that emerge in the middle and end of the flowering season provide a higher quality of flawless blooms than panicles that break early. The findings suggest that temperature has a direct correlation with the frequency of hermaphrodite flowers. Genetic variations may be the cause of the variance in the fruit set. The viability of pollen, its availability, pollinator insect populations, self- and cross-compatibility of a cultivar and with other cultivars, as well as an off-year for specific plants, all affect a cultivar's capacity to produce fruit [40]. Fruit set is a varietal trait that depends on several variables, including the timing of blooming, the sex like rain and hail.

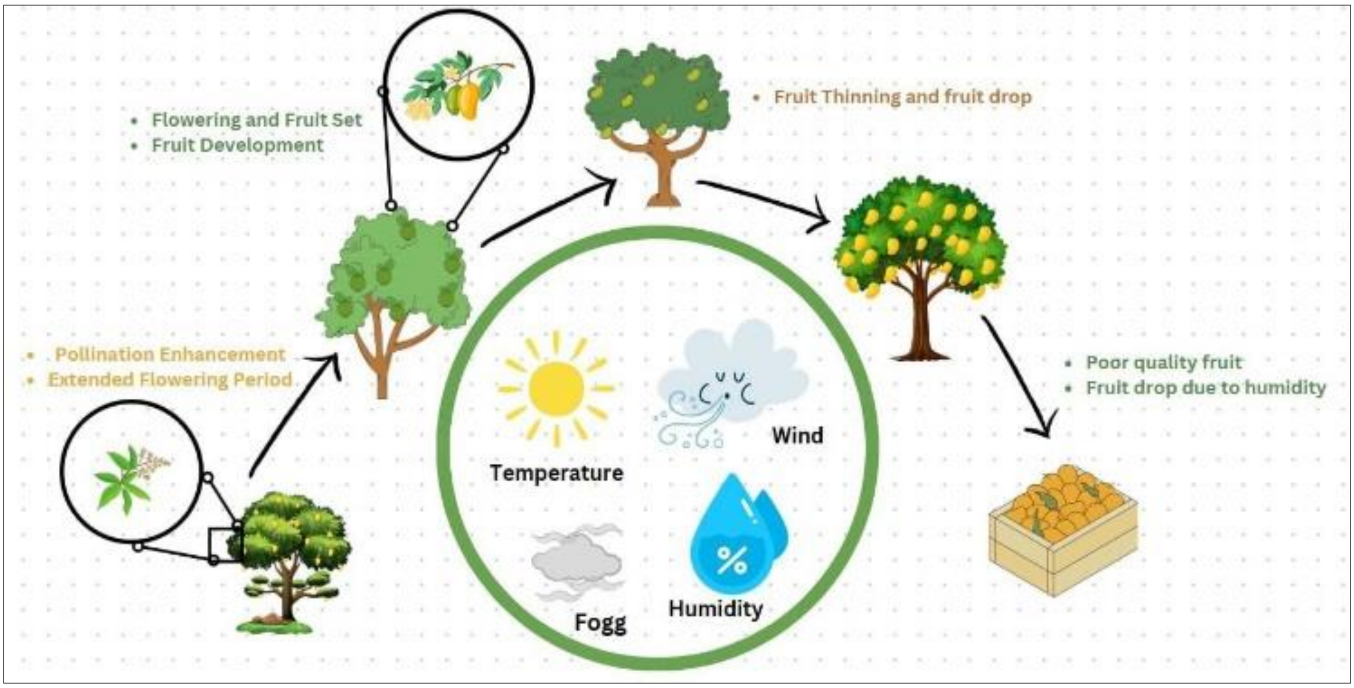

Fig 1: Stand spatial structure

Many plant species exhibit enhanced flowering in response to temperature, sunshine (photoperiod), autonomous variables, or a combination of these [41], indicating that environmental cues in addition to genetic ones are responsible for inducing this occurrence. Climate change and its potential impacts on mango cultivation and output were evaluated by Normand *et al*. [42]. They projected a slightly warmer and drier environment in the Caribbean islands, which would likely result in less floral induction, and a warmer and wetter temperature in South Asia compared to the mean climate of the final 20 years of the 20th century.

During the winter, the plant is visibly dormant for almost three months [33]. Mango buds that are in a dormant state are non-differentiated, with a halted apical meristem and a series of preformed nodes. The commitment of the bud to grow into a floral shoot is referred to as floral induction. Mature leaves, active growth, and inductive temperatures during the initial phases of shoot development are the three components of flower induction [43]. Floral induction (BS stage), according to meteorological data analysis, requires relatively lower maximum and lowest temperatures than previous phases. For blooming induction, an average maximum temperature of 20 °C and an average lowest temperature of 5 °C were noted. Furthermore, a gradual rise in both day and nighttime temperatures was necessary for the BS stage transition.

According to research by Naphrom *et al*. [44], mango flower development requires a chilly temperature of about 15°C. Pérez-Barraza and colleagues [45] found that nighttime temperatures of around 15 ºC promoted the onset of floral bud development in a trial involving the mango cultivar Ataulfo. Rangare and their colleagues [46] discovered a related avenue of inquiry. Our discovery is substantially supported by the previously cited findings of Naphrom *et al*. [44], Pérez–Barraza *et al*. [45], and Rangare *et al*. [46]. According to different research by Naphrom *et al*. [44], the main phytohormone levels in the leaves and shoots of mango trees may be the cause of climactic conditions that influence flower initiation. Furthermore, genotypes affect how a mango responds to environmental cues like temperature during blooming [47]. Though the exact mechanism is unknown, humidity may influence blooming phenology, especially as a secondary trigger [48].

In our investigation, we also found that blooming intensity and Hmax had a positive association, although Hmin and Hmax showed a negative correlation. Future research needs to investigate the possibility that humidity played a role in the early blooming seen in Primack *et al*.' study [49]. Regardless of the cultivation site, photoperiod, or sunshine, is another significant environmental cue that influences the induction of blooming in mango trees. Nonetheless, as shown by the varying dates of blossoming in various parts of the world, mango trees were more sensitive to changes in temperature than to photoperiods [47, 50]. This is due to the lack of knowledge on its role in the process. Inflorescences are often released during mango flowering on branches that receive higher light exposure or on the outside margins of the plant canopy. As a result, exposure to sunshine matters, particularly for regular blooming and the quantity of panicles that each plant produces. We found in this study that there was a positive correlation between floral intensity and sunlight. Mango leaves require sunshine to blossom in unfavourable inductive settings, according to Davenport [51].

Branches exposed to full daylight generate reproductive branches, but branches exposed to lesser light intensities typically develop vegetative branches. The rate of photosynthesis has always been positively associated with sunshine. Because of this, more sunshine may lead to a rise in biomass, or the creation of carbohydrates, through the fixing of atmospheric carbon. According to Pongsomboon *et al*. [52], high carbohydrate levels cause mangos to blossom. Furthermore, Mouco *et al*. [53] emphasized that the activities taking place during the plant phenological cycle are dependent on the quantity of carbon fixed in this process and its subsequent distribution to various plant organs. Furthermore, Das *et al*. [54] found that the mango cultivar "Amrapali" can sustain carbohydrate contents above the threshold for ideal source-to-sink transfers during a typical flowering year; in contrast, other cultivars cannot sustain high carbohydrate levels and as a result, their flowering is hampered. Through the creation of water stress/non-stress conditions, the evaporation rate also affects the blooming phenomena. In the current investigation, we found that blooming intensity was positively impacted by a greater evaporation rate. Mango mature leaves are the source of the floral stimulation, and it has been shown that young leaves prevent buds from initiating flowers [55]. Water stress may limit the development of new leaves and raise the percentage of mature, inductive leaves, which in turn enhances the trees' susceptibility to the warm tropical climate's slightly inductive temperatures [56]. Another research by JiShen *et al.* [57] on the subtropical fruit crop Litchi chinensis, which is experiencing alternative bearing issues, found that water stress followed by cold temperature resulted in early floral induction.

Conclusion

Due to the geographical and seasonal unpredictability of future climate conditions, it is not possible to accurately forecast the impact of climate change on the development and productivity of mango trees in their existing cultivation areas. Various cultivars may elicit diverse reactions as well. However, they are often unfavourable and observe a rise in mango production in areas with severe climatic conditions. There are multiple reasons to be optimistic about the future of mango production and agriculture. These species have significant adaptability in response to their surroundings. Mangos possess physiological mechanisms that allow them to adjust and thrive in diverse and demanding environments. The substantial genetic diversity provides several advantages for the transfer of traditional or modern breeding technique and for determining how to adapt to climate change.

The climatic conditions required for the growth and production of mango trees are to some extent compatible with the impacts of global climate change, including drought and high temperatures.

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