



Irregular Flowering Pattern in Papaya under Climate Change: Adverse Effects on Fruit Yield and Quality

*Swati Saha

ICAR–Indian Agricultural Research Institute, Regional Station, Pune, India

*Corresponding Author's email: swatisaha1980@gmail.com

Papaya (*Carica papaya* L.) is an economically important tropical fruit crop valued for its nutritional properties and year-round fruit availability under favourable growing conditions. The fruit is rich in vitamins A and C, minerals, dietary fibre and bioactive compounds. In India, papaya contributes significantly to commercial fruit production, nutritional security and farmers' livelihoods. However, increasing climatic variability has emerged as a major challenge to sustainable papaya cultivation because the crop is sensitive to changes in temperature, soil moisture, rainfall, humidity and light availability. Climate change is associated with increasing temperatures, heat waves, irregular rainfall, prolonged dry spells and extreme weather events. These conditions can influence plant growth, flowering, fruit set and fruit development. Tropical fruit crops are particularly vulnerable because their reproductive processes are closely linked to environmental conditions (Raju et al., 2024). In papaya, changes in flowering behaviour can affect the continuity of fruit production, marketable yield and fruit quality. Papaya differs from many seasonal fruit crops because it can flower and produce fruits continuously under suitable growing conditions. Consequently, environmental stress has affected successive flowering cycles and has created considerable variation in fruit production. Understanding the relationship between climatic conditions and flowering behavior, it is essential for developing climate-resilient production practices.

Normal Flowering Behaviour of Papaya

Papaya exhibits considerable diversity in floral expression (male, female or hermaphrodite flowers) depending on their genetic constitution. Female flowers generally develop into rounded fruits following successful pollination, whereas hermaphrodite flowers commonly produce elongated fruits preferred in many commercial markets. Male plants primarily produce pollen and generally do not contribute substantially to commercial fruit production. Under favourable conditions, papaya produces flowers continuously as new leaves develop along the main stem. The number and type of flowers, their position on the stem and their successful conversion into fruits determine the productivity of individual plants. However, flowering behaviour is influenced by both genetic and environmental factors. Temperature, seasonal conditions and plant physiological status can affect floral development and sex expression (Awada, 1958; Ramos et al., 2011). Floral abnormalities such as carpellody and pentandry can interfere with normal fruit formation. Carpellody involves abnormal development of female reproductive structures, while pentandry is associated with changes in floral organ development. These abnormalities may result in misshapen fruits and reduced commercial acceptability (Moreira et al., 2019).

Climate Change and Factors Affecting Flowering

Rising temperature and heat stress

Temperature is one of the most important environmental factors influencing papaya flowering. Continuous exposure to excessively high temperatures can adversely affect

reproductive development and sex expression in papaya. Relationships between minimum temperature, growth rate and sex expression and also seasonal and genetic influences on sex expression in segregating papaya populations was reported by Awada (1958) and (Ramos et al., 2011). Under unfavourable thermal conditions, hermaphrodite plants may produce flowers with poorly developed female reproductive structures or other abnormalities. Such flowers may fail to set fruits, leading to gaps in the fruit-bearing pattern along the stem. High temperature can also increase evaporative demand and intensify water stress, particularly when irrigation is inadequate. These combined effects may reduce reproductive success and contribute to irregular fruit production.

Low temperature and temperature fluctuations

Being a tropical crop, exposure to relatively low temperatures also affects floral development. Seasonal changes in temperature may alter sex expression and increase the occurrence of certain floral abnormalities in susceptible genotypes. Floral abnormalities can affect fruit shape, symmetry and marketability. Fruits developing from abnormal flowers may exhibit grooves, irregular surfaces or flattened cat-face appearances. Sudden fluctuations between warm days and cooler nights may further influence plant physiological processes. However, the expression of floral abnormalities cannot be attributed to temperature alone because genetic constitution, seasonal conditions and plant health also play important roles.

Irregular rainfall and water stress

Changing rainfall patterns can expose papaya plants to alternating periods of drought and excessive soil moisture. Even when total seasonal rainfall is adequate, its uneven distribution may produce prolonged dry spells followed by heavy rainfall. Water deficit can reduce plant water status, restrict stomatal conductance and limit photosynthesis. These changes may affect flower development, fruit retention and fruit growth. Research on papaya water relations and productivity has demonstrated the importance of appropriate water management for crop performance (Almeida et al., 2003). Water scarcity can also influence carbon assimilation, growth and yield, as reported by Eliemar et al., (2018). Conversely, excessive rainfall and waterlogging can reduce oxygen availability in the root zone, impair root function and restrict nutrient uptake. Prolonged waterlogging may also increase the risk of root diseases. Both drought and excessive soil moisture can therefore create unfavourable conditions for sustained flowering and fruit development.

Humidity, wind and light availability

Relative humidity influences transpiration and plant water balance. High humidity accompanied by prolonged rainfall may favour disease development, whereas low humidity combined with high temperatures can increase evaporative demand and water stress. Strong winds may damage leaves, cause mechanical injury and increase the risk of lodging. Since healthy leaves are essential for photosynthesis, extensive foliage damage can reduce the supply of assimilates required for reproductive development and fruit growth. Similarly, prolonged cloudy conditions and reduced sunshine may decrease photosynthetic activity and carbohydrate accumulation. These factors may affect fruit retention and development, particularly when plants are simultaneously experiencing heat or water stress. The effects of climatic variables on tropical fruit production are often interactive rather than independent (Raju et al., 2024).

Mechanisms Responsible for Irregular Flowering

Irregular flowering in papaya can arise from interactions among genetic, physiological and environmental factors. One important mechanism is altered floral sex expression. Under unfavourable environmental conditions, plants may produce a greater proportion of flowers that do not develop into marketable fruits. Seasonal and genetic influences on sex expression have been documented in papaya (Ramos et al., 2011). A second mechanism is the development of abnormal flowers. Changes in floral organ development may interfere with fertilization and fruit formation. The occurrence of floral abnormalities is therefore an important trait to assess in papaya improvement programmes (Moreira et al., 2019). Third, climatic stress may reduce successful fruit set and retention. Even when flowers appear

normal, inadequate water availability, high evaporative demand or other physiological stresses can adversely affect subsequent fruit development. Finally, prolonged stress may reduce photosynthesis and the availability of carbohydrates required for flower development and fruit growth. Thus, irregular flowering should be evaluated through systematic observations of flower type, flowering frequency, fruit set and fruit retention alongside weather and soil-moisture records.

Adverse Effects on Fruit Yield

Reduced flower production and fruit set

The most immediate consequence of irregular flowering is a reduction in the number of flowers that successfully develop into fruits. Changes in sex expression, floral abnormalities and stress during reproductive development may reduce the number of productive flowers. Consequently, fewer fruits are formed, and the number of fruit-bearing sites along the stem may decline (Ramos et al., 2011; Moreira et al., 2019).

Increased fruit abortion and fruit drop

Environmental stress during early fruit development can contribute to poor fruit retention. Water deficit, impaired root function and reduced assimilate availability may interfere with fruit growth and survival. The importance of maintaining suitable water relations for papaya growth and productivity has been demonstrated by Almeida et al. (2003).

Reduced fruit number and fruit size

Irregular flowering may reduce the total number of fruits produced per plant. Stress during fruit development can also restrict fruit growth by limiting water uptake and photosynthetic activity. The resulting changes in fruit number and size depend on the timing and severity of stress, genotype and crop management. Because fruit yield is determined by the combined effects of fruit number and average fruit weight, simultaneous reductions in these components can substantially lower total productivity. Studies on papaya water relations emphasise the importance of maintaining favourable growing conditions for achieving satisfactory crop performance (Almeida et al., 2003).

Uneven harvesting and lower marketable yield

Papaya is valued for continuous harvesting. Irregular flowering creates uneven fruit development and maturity along the stem, making harvesting less predictable. Periods of poor fruit set may be followed by concentrated harvesting periods, complicating labour management, grading, packing and marketing. For commercial growers, the consequences include reduced marketable yield, inconsistent fruit size and greater uncertainty in farm income. Floral abnormalities can further reduce commercial acceptability because fruits with irregular shapes may be rejected in quality-conscious markets (Moreira et al., 2019).

Effects on Fruit Quality

Fruit shape and external appearance

Floral abnormalities can produce misshapen fruits with grooves, irregular surfaces or asymmetrical development. These characteristics reduce visual appeal and may lower market value. The occurrence and quantification of floral abnormalities have been investigated in papaya breeding populations (Moreira et al., 2019).

Soluble solids and sweetness

Fruit sweetness depends on sugar accumulation, maturity and the physiological condition of the plant. Climatic stress can affect photosynthesis and the supply of assimilates to developing fruits, potentially contributing to variations in total soluble solids (TSS), commonly measured in °Brix. However, the response is not always uniform. Mild water stress may sometimes increase measured soluble solids through concentration effects, whereas severe stress may restrict fruit development and carbohydrate accumulation. Therefore, the effects of climate on sweetness should be established through measurements of fruit quality rather than inferred from weather conditions alone.

Flesh colour and nutritional composition

Characteristics like pulp colour, carotenoid concentration, vitamin content, firmness, aroma and acidity depend on genotype, fruit maturity, environmental conditions and postharvest handling influence nutritional composition and quality attributes across cultivars.

Shelf life and postharvest losses

Irregular fruit development may result in greater variation in fruit size, maturity and ripening behaviour. This variation complicates harvesting and postharvest handling. Fruits with abnormal shapes may face rejection during grading, while fruits harvested at inconsistent maturity stages may differ in ripening and storage behaviour. Consequently, climate-related reproductive disturbances can affect not only production but also postharvest quality, marketing efficiency and profitability.

Management Strategies under Changing Climatic Conditions**Development of climate-resilient cultivars**

The development and cultivation of genotypes that maintain stable flowering, fruit set and fruit quality under fluctuating environmental conditions should be a priority. Breeding programmes should evaluate sex expression, floral abnormalities, fruit retention, yield and quality across seasons and locations. The importance of evaluating floral abnormalities in papaya improvement programmes has been demonstrated by Moreira et al. (2019). Seasonal and genetic effects on sex expression should also be considered when selecting stable and productive genotypes (Ramos et al., 2011).

Efficient irrigation and drainage management

Drip irrigation, mulching and appropriate irrigation scheduling can help maintain relatively stable soil moisture. Irrigation should be adjusted according to soil type, rainfall, crop stage and evaporative demand. Maintaining suitable water availability is important for papaya growth and productivity (Almeida et al., 2003). Equally important is effective drainage during heavy rainfall. Raised planting beds, suitable drainage channels and avoidance of prolonged ponding can help reduce root-zone stress.

Balanced nutrition and soil management

Balanced fertilization based on soil testing supports healthy vegetative growth and reproductive development. Nutrient deficiencies and excessive fertiliser application should be avoided. Organic matter management and mulching can improve soil structure and water retention. Maintaining healthy foliage is essential for photosynthesis and fruit development. Appropriate plant protection and the prevention of unnecessary leaf injury help sustain the source of assimilates required for reproductive growth.

Adjustment of planting time

Where feasible, planting schedules may be adjusted to reduce the coincidence of peak flowering with periods of extreme heat or recurring moisture stress. However, suitable planting windows vary by region, cultivar and local climatic conditions. Recommendations should therefore be based on local weather records and multi-season field observations.

Climate monitoring and phenological recording

Systematic recording of maximum and minimum temperature, rainfall, relative humidity, sunshine duration and soil moisture can help identify associations between weather and flowering abnormalities. Researchers should record flower type, flowering frequency, abnormal flower incidence, fruit set, fruit drop, fruit number, fruit weight and quality attributes. Such observations can support the identification of genotypes with stable reproductive performance and help develop location-specific management recommendations. Papaya phenology and sex expression provide useful traits for crop improvement and adaptation research (Ramos et al., 2011; Moreira et al., 2019).

Conclusion

Irregular flowering in papaya is an important concern under increasing climatic variability. Temperature fluctuations, irregular rainfall, drought, water logging and other environmental stresses can affect floral development, sex expression, and fruit set and fruit retention. These

disturbances may reduce fruit number, increase abortion, and create gaps in fruit-bearing patterns and lower marketable yield. Floral abnormalities can also reduce fruit shape uniformity and commercial acceptability. The extent of damage depends on genotype, developmental stage, stress intensity, duration and management practices. Therefore, climate change should be considered an important risk factor rather than the sole explanation for every flowering abnormality. Developing climate-resilient cultivars, improving irrigation and drainage, maintaining balanced nutrition and systematically monitoring flowering and fruit development are important strategies for sustainable papaya production. Coordinated research and extension support will be essential to improve reproductive stability, protect fruit quality and strengthen the resilience of papaya cultivation under changing climatic conditions.

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