# Assessing the Impact of Environmental Variables on Fruit Growth Dynamics and Developmental Physiology

**Mohsin Raza[1], Muhammad Atiq Ashraf[2], Muhammad Ateeq[2], Sahar Rashid[3], Talha Riaz[4], Burhan Khalid[5], Muhammad Asad Saleem[6], Hafiz Muhammad Usman[7], Iman Shafquat[1], Muhammad Sajid[7]***

[1] Institute of Horticultural Sciences, University of Agriculture Faisalabad, Pakistan
[2] National Key Laboratory for Germplasm Innovation and Utilization of Horticultural Crops, Huazhong Agricultural University, Wuhan, China
[3] Horticultural Research Institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan
[4] College of Food Science and Technology, Huazhong Agricultural University, Wuhan, China
[5] MOA Key Laboratory of Crops Ecophysiology and Farming System in the Middle of Yangtze River, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan, China
[6] Horticultural Research Station, Sahiwal, Pakistan
[7] Institute of Horticultural Biotechnology, College of Horticulture, Fujian Agriculture and Forestry University, Fuzhou, China
[8] Faculty of Veterinary Science, University of Agriculture Faisalabad

***Corresponding Author:** Muhammad Sajid
*Email: msajidkhan663@gmail.com

**Abstract**
Fruit growth and development are greatly influenced by environmental conditions. This phenomenon has been well-established for some time, and efforts have been made globally to investigate relationships and develop models and conditions to predict plant profitability. These efforts are ongoing, and this assessment includes some of the most recent ones. This study provides comprehensive information on the various meteorological variables that affect fruit physio morphological properties, such as light, temperature, humidity, and atmospheric gases.

**Keywords:** Environmental variables, Abiotic stress, Fruit, Physio morphological Properties, Relative Humidity

## Introduction

Fruits are integral to a healthy, well-balanced diet and are a source of several substances vital to human health (Pereira et al., 2022). The nutritional value of fruits has garnered attention recently due to their abundance of bioactive substances, fibers, health-promoting vitamins, minerals, and phytochemicals that can help prevent cardiovascular risks and cancer despite being low in calories. The body's absorption of beneficial nutrients and dietary fiber is enhanced while displacing high-energy foods like sweets and saturated fats on sufficient intake of fruits and vegetables (Vicente et al., 2022). Nonetheless, the environment significantly impacts the physical and physiological characteristics of fruits. Plant productivity changes due to environmental influences on vegetative growth and reproductive development (Li et al., 2020). A plant's development is always influenced more by its surroundings than geographical location. Plants restrict their growth and propagation if the weather or environment is unsuitable. The environmental factors that are the main causes of abiotic stress in plants are humidity, water, light, nutrition, and temperature (Muhammad et al., 2021). Throughout all phases of growth and development, the environment impacts plants. Plant production is influenced by a variety of environmental conditions, either separately or in combination, as they emerge from dormancy, begin vegetative development, and enter the reproductive period. This paper examines how environmental elements (such as humidity, light, atmosphere, and temperature) affect fruits' quality and physio-morphology development.

## Temperature

It is commonly known that plant physiological development and growth is controlled by temperature. Temperature is an important factor in plant development and yield, abrupt temperature spikes can negatively affect crop performance (Fahad et al., 2017). Growth chambers having temperatures of 45°C and 25°C, Roma and Ahmar varieties were grown to assess the effects of elemental sulfur treatment on their physiology and growth. 2-6 ppm sulfur was sprayed on plants forty-five days after seeding. Under both temperature conditions, the "Roma" cultivar plants that received six ppm sulfur showed the highest biomass values in their shoots and roots, followed by those that received four ppm. Sulfur had a salutary effect on tomato physiology, as substantiated by the maximum $CO_2$ indicator, rate of transpiration, rate of photosynthesis, and greenness indicator values (188.1 µmol spook $-1$,36.3 µmol $CO_2$ m $-2$ s $-1$,1.8 µmol $H_2O$ m $-2$ s $-1$, and 95 SPAD, independently) set up in shops of the" Roma" cultivar grown at 25 °C. also, in the leaves of both genotypes quantities of phosphorus, proline, and nitrogen were increased by sulfur at both temperatures. The variations observed between heatstressed shops treated with sulfur and those not treated suggest that sulfur may help alleviate heat stress. Overall, our findings point to 6 ppm of sulfur as the optimal lozenge for reducing heat stress and perfecting tomato shops' physiological, biochemical and morphological characteristics (Ali et al., 2021c).

An increase in the ideal temperature interferes with some physiological functions, which lowers plant yield. Plant germination, growth, and reproduction are all impacted by heat stress. The main source of damage to the stroma's carbon metabolism and the thylakoid lamellae's chemical signaling is high-temperature (Goraya et al., 2017). Due to damage from high temperatures, photosynthesis is more heat-sensitive than dark respiration and is inhibited before respiration is reduced (Almeselmani et al., 2012). Primary factor limiting development of plant is a decline in the photosynthetic rate, which disrupts mitochondrial activity. Control biomass formation and temperature increases reduce movement of cyclin dependent kinase enzyme (Kantharaj et al., 2022).

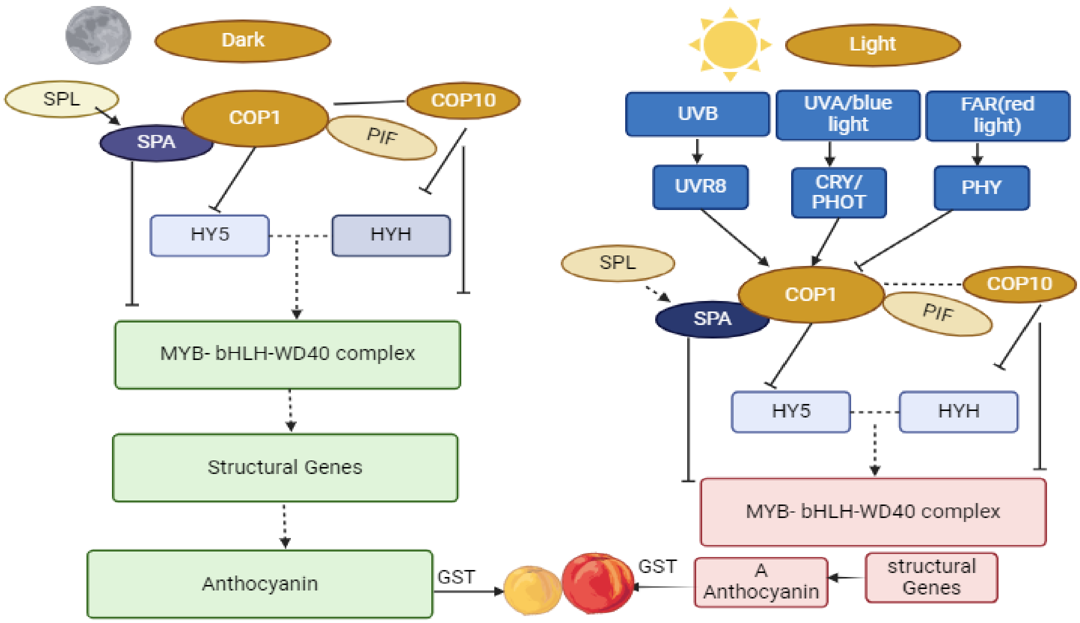


**Figure A.** A flowchart illustrating light-induced coloring of fruit peels

Carbohydrates generated in the leaves are necessary for the growth of fruits and flowers. Studies have investigated the connection between photosynthesis, fruit development, and the growing fruit crops' need for carbohydrates. The average fruit weight of the entire strawberry cyme was lower at 19°C (7.3 ± 0.3 g) than at 15°C (8.2 ± 0.4 g), indicating that temperature directly impacts the fruit and flowers rather than the cyme's structural integrity. With a rise in mean temperature from 15°C to 20°C to 25°C in glasshouses, strawberry fruit weight dropped. The fruit from the main flower weighed around 35 g, 20 g, and 11 g at each of the three temperatures (Kumakura and Shishido, 1994).

Fruit quality is also greatly impacted by temperature. It was noticed that total titratable acids in tomatoes increase under high temperatures (Vijayakumar et al., 2021). Effects of high temperatures on fruit growth and maturity include the control of the enzyme's acid invertase and sucrose synthase, and the distribution of sugars in tomato fruits. Lower sugar content was noted under high temperature in cherry tomatoes (Alsamir et al., 2021).

One important way that plants adapt to high temperatures is by producing heat shock proteins (HSPs). Heat shock genes (HSG) encode these proteins, which are necessary for maintaining or reestablishing equilibrium. HSPs contribute to the regulation of protein stability and function through their roles in protein translocation, assembly, folding, and denaturation. HSPs are involved in drought and salinity tolerance in addition to thermoregulation. They may be grouped as small HSPs, HSP70, HSP60, HSP100 and HSP90 (Wesner, 2005).

Heat stress disrupts protein homeostasis and modifies membrane fluidity (Kan and Lin, 2021). Plants respond to these changes by sending signals and transducing them, activating stress-responsive genes (HSP/HSF), free radical scavengers, antioxidant enzymes, and signaling molecules that aid in heat stress tolerance. Similarly, cold stress induces a variety of physiological and metabolic disturbances that reduce plant development. Plants become resistant to cold stress through the activation of transcription factors and genes that respond to cold via the stress-induced signal transduction pathway (Fig. B).

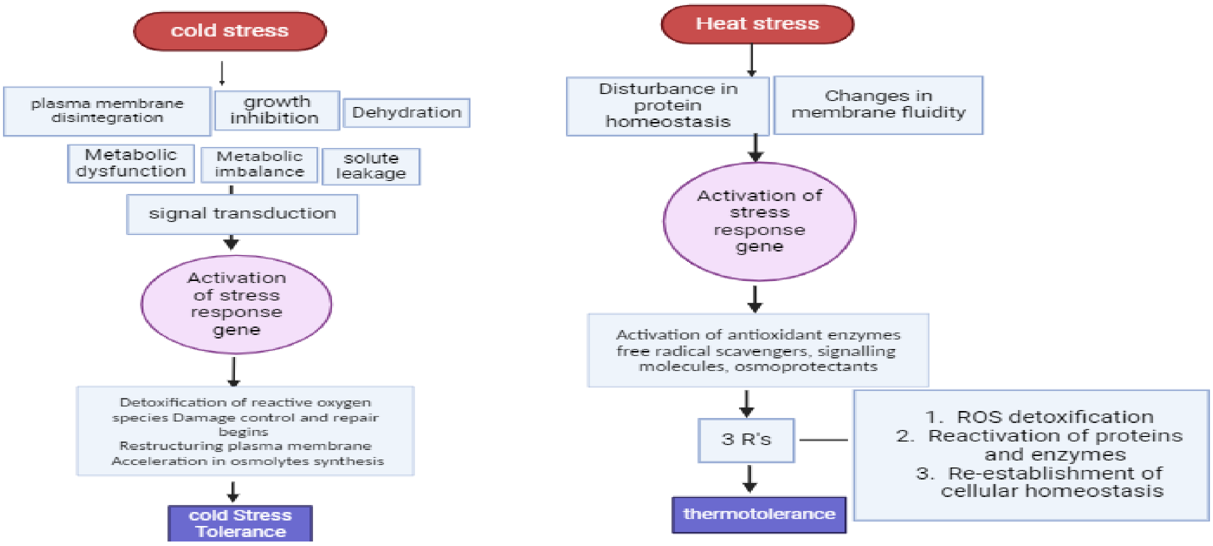


**Figure B.** Temperature stress-related Molecular Mechanism.

Fruit maturation times shortened during the first half of the season, most likely because of greater average temperature of the air. At 25°C fruits required 40 days to mature, 13°C required 90 days, and 19°C required 53 days (Van Ploeg and Heuvelink, 2005). Fruits' temperature sensitivity varied according to their developmental stage; those during their growth were less susceptible to temperature. Additionally, prolonged periods of high or low temperatures might prevent ripening. Apart from the adverse effects of elevated temperatures, low temperatures also impact plant production. Plant production may be affected by several mechanisms, including reduced photosynthetic activity, delayed guard cell activity in stomata, restricted growth initiation in the spring, and decreased membrane permeability on root surfaces (Zia et al., 2021). Plants suffer damage, such as winter injury, when temperatures drop below their tolerance levels. A layer of dirt or snow covering the plant's lower stem can shield it from winter damage. Temperature fluctuations can damage plants by freezing their cells and making them more susceptible to frost.

Because of low temperatures, all plants combat the formation of crystals in their tissues (Yadav et al., 2020). Certain plants have some degree of acclimation, while others have none. Shorter days with low temperatures may hasten the development of resistance in plants against high-temperature stress. Warm temperatures and abundant soil moisture can also slow down the hardiness process. Pests, diseases, and nutrient deficiencies are factors that cause plants to lose vigor by impeding the acclimation process of plant tissues (Fahad et al., 2022).

**Atmosphere**

An essential source of gases vital for plant development and survival is the atmosphere, encompassing $CO_2$ for photosynthesis and oxygen ($O_2$). Carbon absorption and $CO_2$ exchange, both driven by environmental conditions, influence plant dry matter production (Korner, 1991). Higher light intensity or longer light exposure directly correlates with dry matter production. Variations in photosynthetic capability, abrupt changes in temperature and moisture, and uneven nutrient delivery significantly contribute to decreased dry matter and yield in plants. Climate influences the absorption and transfer of carbon assimilates (Clark and York, 2005).

The atmosphere contains pollutants and toxins that severely impede plant development. Various human activities, such as industry, agriculture, traffic, and household chemical use, emit these pollutants and toxins into the atmosphere. Plants uptake these harmful compounds from soil, water, and the environment (Weldeslassie et al., 2018). Studies have demonstrated that (Ali et al., 2021d). Other detrimental pollutants include dust, tar fumes, hydrocarbons, nitrogen oxides ($NO_x$), and ammonia ($NH_3$). A broad assessment was conducted to determine plants of forest, agricultural, and ornamental plants susceptibility to chronic exposure to HF, SO2, NOx, and HC (Ullah et al., 2018).

**Light**

Photosynthesis, the process by which plants produce the chemical energy required for development, depends on light. The optimal amount of light is essential for a plant's life and development. Light also regulates many other plant activities, such as abscission, phototropism, mineral absorption, and the movement of stomatal guard cells, (Meena, 2021). Plant metabolic processes require a certain light spectrum. Maintaining this range may boost the functioning and growth of plants. The ability of plants to survive and grow will be compromised if the absence of these conditions. The quality and quantity of light influence gene expression and metabolism of plants. Thus, light interception is regarded as a key performance parameter for fruit growth; however, excessive light can reduce plant productivity by producing reactive oxygen species (ROS) through photooxidation. The phenological development of plants is also influenced by variations in day length (photoperiod), which function as a timer or trigger to initiate or stop the physiological or metabolic processes related to growth and blooming (Serrano-Bueno et al., 2021). The floral transition is a significant phenomenon controlled by light. The first stage in the reproductive phase is to distinguish between vegetative and reproductive primordia, which

impacts yield capability and bloom intensity. In this perspective, the most important element influencing production, particularly for perennial fruit crops, is the floral transition (Kalcsits et al., 2020).
The length of the daily light period impacts strawberry blossom development. Longer days often cause runners to emerge rather than flowers, whereas shorter light periods promote flower growth at the expense of runners (Parehwa, 2020). Research on the impact of seasonal change on papaya sex expression indicated that longer days encouraged the creation of female flowers (Olubode et al.). Transplanting strawberries beneath photo-selective nets delayed blossoming (Serra et al., 2020). A comparison was made between four different production systems: artificial light/irrigation; artificial light/irrigation/shade; artificial light and natural conditions and artificial light/shade. The results revealed that the number of fruits, blooms, and passion fruit yield increased by artificial light, with/without watering, artificial. Similarly, red raspberry blossoming was significantly hastened, and the quantity of leaves generated prior to blooming was reduced by night interruption, which consisted of three hours of light during a fourteen-hour daily dark phase. This blooming response was shown to be true and a unique photoperiodic impact (Ali et al., 2021d).
During photosynthesis, light energy is transformed into chemical energy. Three key stages of photosynthesis require light: capturing light from sunlight, converting carbon dioxide into carbohydrates, and reduction of the NADP into ATP (Wasilewska-Dębowska et al., 2022).
Exposure of apples to light triggers the formation of phenolic compounds (Ferreyra et al., 2021). Researchers discovered that light may activate genes such as flavanone 3-hydroxylase (F3H), chalcone synthase (CHS), and phenylalanine ammonia-lyase which are involved in flavonoid production (Kaur et al., 2021). Furthermore, some scientists have hypothesized that exposure to intense sunlight might alter the quantity and quality of flavonoids present (Zhang et al., 2022). Table 1 summarizes the various light treatments' contributions to enhancing fruit development, production, and quality.

**Table 1** Various treatments of light impact (photoperiod, shade, fruit bagging, etc.) on fruit development, quality, and growth.

| Crop | Application | Impact | Ref |
|---|---|---|---|
| *Mangifera indica* | Plastic bagging | The weight and glossiness of the fruit improved | (Ali et al., 2021a) |
| *Eriobotrya japonica* | Paper bagging | Fruit appearance improve | (Zhi et al., 2021) |
| *Litchi chinensis* | Cellophane bagging | Fruit appearance improve | (Lal, 2020) |
| *Malus domestica* | The outer grey inner red wrapping of two different layers of paper | Increased decaying less internal browning, and level of phenolic compounds reduced | (Ali et al., 2021a) |
| *Pyrus communis* | Wrapping of paper | Increase in anthocyanin and boost of MYB genes | (Ali et al., 2021a) |
| *Psidium guajava* | Packing in nylon | Defense against mechanical damage and pests | (Rajan et al., 2020) |
| *Phoenix dactylifera* | Packing in blue plastic | Rise in ripening rate | (Ali et al., 2021b) |
| *Averrhoa carambola* | Wrapping of paper | Increase of soluble solid and fruit size | (Kumar et al., 2021) |
| *Malus domestica* | Wax coated Outer yellow and inner red paper wrapping of two different layers of paper | Reduction of organic acid and sugar content and in red cultivars accumulation of Anthocyanin reduced | (Kumar et al., 2021) |
| *Fragaria ananassa* | Blue and red chromatin nets (photoselective) | Earlier flowering of no-shade control plants, while delayed flowering in transplants under photo-selective nets) | (Takeda) |
| *Fragaria ananassa* | 15, 13.5, and 12 h Different photoperiods for 49, 35, and 21d varying durations | Flowering, yield, and vegetative growth increased | (Rozbiany and Taha, 2023) |
| *Malus domestica* | Fruit Packing of Light-yellow color | Postharvest issues were reduced, and firmness improved | (Sharma and Sanikommu, 2018) |
| *Prunus persica* | Wrapping of orange paper | fruit pulp color improves | (Ma et al., 2021) |
| *Malus domestica* | Grey outside, yellow inside, and yellow inside, newspaper outside, wrapping of two different layers of paper | Little reduction in size and mass, Improved fruit skin | |
| *Malus domestica* | Double-layered brown and red paper packing | Granny Smith exhibits stronger red/pink pigmentation following bag removal. | (Ali et al., 2021a) |

**Water/ Relative Humidity**

All living things require water as a necessity. Both excess and deficiency of water can cause stress in plants. Water availability is the most critical factor limiting plant life and development. When the plant's surface rate of respiration increases than the rate of root's water absorption leads to subpar plant development water deficit occurs (Jagota et al., 2024). Water shortage negatively impacts plants' ability to photosynthesize. Plants develop more slowly when subjected to prolonged water stress. To adapt to various biotic and abiotic stressors, plants have evolved several intricate biochemical and physiological adaptations. Water stress lowers the water potential in leaves, modifies stomatal opening, down-regulates genes involved in photosynthesis, and decreases CO2 availability. Similar effects occur under mild stress (Shanker et al., 2022). Plant productivity and available soil moisture are positively correlated. A drop in available soil moisture causes plants to become less photosynthetically active.

Plants cultivated under moisture stress, after initially being established on soil enhanced with water, showed slowed growth in roots and leaves. Water stress significantly negatively impacted long-term development and productivity (Auler et al., 2022). Under moderate stress, plant leaves showed reduced growth, but photosynthetic activity did not change. CO2 assimilation is not restricted in crops with a high leaf area index whereas producing a crop with a low leaf area index limits the amount of CO2 that can be assimilated.

Prolonged stress of water harms shoot development, causing shorter internodes and smaller leaves. Additionally, certain physiological growth characteristics, such as new leaf emergence rate, rate of germination, size of leaf, expansion rate, and impact the overall dry matter produced (Hsiao and Xu, 2000). Younger leaves function well, while older leaves gradually lose their ability to expand the photosynthetic area and quickly close their stomata. Reproductive and vegetative growth is affected by water scarcity during the formation of buds. The number of fruits, leaves, and flowers is regulated by moisture stress during bud formation and development. Seed size, shoot length, fruit percentage, and leaf size are affected by moisture stress.

An experiment was done to investigate the impact of environmental factors on the growth of the loquat scab (*Fusicladium eriobotryae*). Ideal temperatures between 10 and 20°C were noted for *Fusicladium eriobotryae* germination and prolonging the wetness period increased disease severity. The highest fungal growth occurred during a 24-hour wetness period while reducing the moisture period led to decreased fungal germination (Ali et al., 2021d).

Fruit growth slows at the early stage, slows down at the mature stage, and accelerates at the rapid expansion stage with a single growth apex. Dropping of fruit and fruit bulk can be caused by drought by reduced Drought can cause late-stage fruit dropping and reduced fruit bulk by decreasing the quantity and size of cells, whereas soil water content is crucial for early fruit growth. Fruit size is influenced by carbon metabolism, cell division, and development inside the fruit, all of which are related to water and carbohydrate fluxes (Brizzolara et al., 2020). The ontogenetic program of fruit controlled these processes in response to the environment. One critical aspect of improving fruit quality and yield is managing soil water. Water scarcity generally slows the growth of various fruit species, resulting in fruit with higher sugar and acid content that mature faster but yield fewer marketable fruits. In many species, such as tomatoes and melons (*Cucumis melo* L.), cell division, which usually occurs during a brief stage of fruit development and does not significantly increase tissue volume, strongly affects the final fruit size (Monforte et al., 2013). The impact of low water content on fruit tissue cell division has been studied in only a few cases. Depending on the timing of treatment, *Vitis vinifera L.* fruit showed adverse or no effects. Except under extreme stress, no impacts were observed in olives (*Olea europaea* L.) or pear fruit (Ripoll et al., 2014). Carbon starvation resulting from severe water deprivation has been found to negatively affect cell division in tomato fruit, both at tissue and gene levels.

In various plants such as litchi, grapes, figs, and pome fruits, etc major pre-harvest splitting and cracking issues have been observed (Kaur et al., 2022). Citrus fruit splitting usually occurs when the skin has thinned, and the fruit has a high solute content (Huang et al., 2024). Fruits have internal turgor pressure, which increases in response to increased soil moisture from irrigation or heavy rainfall. The weakening of the cuticle resulting from prolonged fruit shrinkage and swelling, presumably as a result of the daily fluctuations in fruit turgor that take place under typical growing circumstances, can cause bell pepper fruit cuticular cracking. (Rodríguez et al., 2018). Interactions between soil moisture, rootstock, and climatic circumstances can cause anomalies in tree water status, resulting in significant alterations in fruit development rate and increased risk of splitting. Fruit cuticular cracks, which only appear in specific fruit loci, are linked to direct water uptake across the fruit skin, whereas side cracking in sweet cherry fruit is connected with the absorption of H20 through the vascular system of trees regardless of the plant material, crop load, and skin properties (Rodríguez et al., 2018).

In response to drought stress, plants activate various defense mechanisms to enhance their ability to withstand adverse environments (Ullah et al., 2018). Activating multiple genes and transcription factors leads to the involvement of these pathways in metabolism, improving stress tolerance. The response to drought stress involves various molecular and metabolic pathways (Fig. C). The involvement of regulatory transcription factors (TFs) and several genes was recently characterized, even if the mechanism of action of the bulk of genes linked to plant adaptation to drought stress has previously been established. Drought resistance mechanisms include recovery, avoidance, tolerance, and drought escape. The important physiological mechanism to avoid water stress is stromal control. (Kido et al., 2016). Osmoregulation and Osmo-protectants enable plants to withstand dehydration. When plants adjust their growth cycle to prevent the water deficit, it is called "drought escape." "Drought recovery" refers to a plant's ability to survive and thrive after experiencing drought stress (Rodríguez et al., 2018).

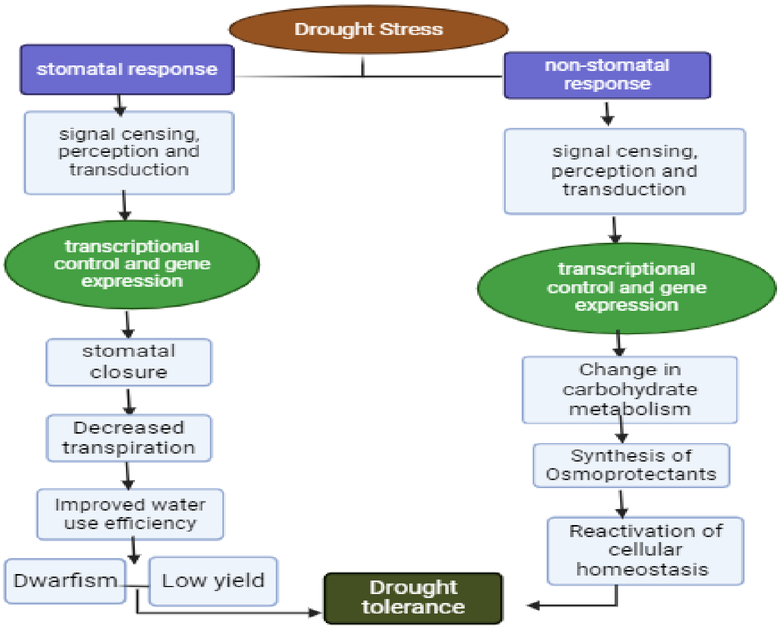


**Figure C.** Flowchart illustrating plants' response against drought stress

**Conclusion and Future Prospectives**

Environmental conditions primarily influence fruit growth and quality, serving as the main sources of abiotic stressors experienced by plants, which consequently affect fruit growth and quality. Stress tolerance resulting from diverse environmental influences is supported by specific systems. Given the existence of species-specific responses to climatic conditions, it is conceivable that climate reactions possess a genetic component, with various plant species exhibiting physiological responses to similar stimuli. Predicting the influence of change in climate on plant growth and production is difficult because of our limited information. Further research is necessary to investigate the molecular mechanisms through which plants respond to environmental stressors.

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