TRENDS IN ANIMAL AND PLANT SCIENCES
https://doi.org/10.62324/TAPS/2026.008
www.trendsaps.com; editor@trendsaps.com
E-ISSN: 3006-0559; P-ISSN: 3006-0540

REVIEW ARTICLE

Producing Nutritious and Aromatic Mangoes under Climatic Change Challenges and Solutions

Abdul Razzaq[1,2] and Abdul Wahab[2*]

[1]Tropical Crops Genetic Resources Institute, Chinese Academy of Tropical Agricultural Sciences, Haikou, China
[2]Institute of Molecular Biology and Biotechnology, The University of Lahore, Lahore
***Corresponding author:** wahabgul777@gmail.com

Article History: 26-022 Received: 11 Jan 2026 Revised: 23 Feb 2026 Accepted: 25 Feb 2026

ABSTRACT

Regarded as the King of Fruits, the mango is a very important tropical crop with immense cultural, economic, and nutritional importance worldwide. But their cultivation is becoming more challenging due to climate change, which exacerbates abiotic stresses like heat waves, drought, irregular rainfall, and rising CO_2. This results in lower yields, nutritional degradation, and loss of aroma. Reactive oxygen species (ROS) buildup, lipid peroxidation, soil nutrient depletion, and reduced levels of vitamin C, carotenoids, phenolics, and minerals are some of the physiological and biochemical effects of high temperatures. Fruit quality and market value are further threatened by altered flowering patterns, early harvesting, and greater susceptibility to pests and diseases, such as fruit flies, powdery mildew, and anthracnose. Today, integrated pest management, precision irrigation, mulching, shade nets, breeding, biotechnology (like CRISPR-based genome editing), and advanced postharvest technologies like edible coatings and controlled atmosphere storage are some of the mitigation strategies used to preserve nutrients and aroma. New technologies that offer creative answers for stress management, illness prediction, and quality preservation include ohmic heating, omics techniques, nanotechnology, and AI-driven predictive modeling. Mango production, nutritional integrity, and livelihoods must be preserved in the face of changing climatic concerns through the use of sustainable agronomic techniques, policy interventions, and technology.

Key words: Adaptability, imperishable, alleviation, harvesting, resistant, mango fertility.

INTRODUCTION

One of the most significant tropical fruits in the world is the mango, referred to as the ''KING OF FRUITS'', the most significant Asian fruit is the mango (*Mangifera indica*). Its importance extends beyond the fields of agriculture, culture, nutrition, and economics. One important fruit crop that makes a substantial economic contribution to many nations is the mango. It is a foreign exchange earner since it is widely exported in addition to being farmed for local consumption. The *Anacardiaceae* family, of which the mango is a member, has several dangerous and lethal plants. It smells good, is incredibly nutritious, and has the ideal ratio of sweetness to acidity. (Lebaka *et al.,* 2021). Since mangos are climacteric fruits, they may experience noticeable ripening-related changes in color, flavor, and scent prior to or following harvest. The global mango industry supports millions of jobs in various sectors, including marketing, transportation, processing, packing, harvesting, and farming. Both fresh and processed mangoes, such as juices, jams, purees, pickles, dried mango slices, and frozen goods, are available for purchase. In addition to non-nutrient substances like organic acids, dietary fibers, polyphenols, carotenoids, and other pigments, mango fruits are abundant in nutrients, including carbs, fatty acids, vitamins, and minerals. Mango fruit pulp has an energy content ranging from 60 to 90Kcal per 100 g. Green, immature mangos and mature, ripe mangos demand varying quantities of the main carbohydrate. Sugars (glucose, fructose, and sucrose) and cellulose, hemicellulose, pectin, and bounce are all abundant in ripe mango fruit. The most important and prevalent polyphenols, ascorbic acid, riboflavin, thiamine, niacin, and carotenoids, together with phenolic acids (ferulic acid, coumaric acid, and hydroxybenzoic acid), are among the primary bioactive composites found in mango fruits (Yahia et al., 2023). The presence of colored acids, such as citric, malic, oxalic, succinic, and other organic acids,

Cite This Article as: Razzaq A, Wahab A, 2026. Producing nutritious and aromatic mangoes under climatic change challenges and solutions. Trends in Animal and Plant Sciences 7: 60-73. https://doi.org/10.62324/TAPS/2026.008

gives callow mangos their sour flavor; diminishing sugar and malic acid, a significant acid source, give grew mangos their sweet flavor. The high concentration of β-carotene and other phytochemicals in mangoes can help prevent leukemia and the spread of malignancies in the bone, colon, and prostate. Mangos include a variety of macro and micronutrients. Mango pulp contains salutary fiber, proteins, amino acids, lipids, carbohydrates (16 – 18), and organic acids, among other macronutrients. Also, the pulp contains trace quantities of calcium, phosphorus, iron, and vitamins C and A, among other minerals. The pulp, peel, and kernel (occasionally known as the seed) shown in fig.1 are the three primary factors of a mango fruit. The fleshy, comestible portion of the mango that's generally eaten is called pulp (see Figure 1).

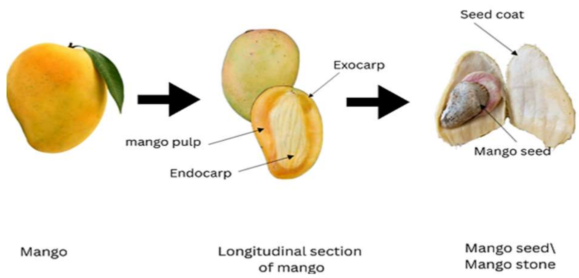

Fig. 1: Morphological structure of mango (Mangifera indica). The entire fruit (left) has three layers: the outer layer is the exocarp (skin), while the other two are edible. Longitudinal section (middle) has layers of pulp and endocarp, which is a protective tissue. The stone of a mango (right) has its seed embedded in fibrous seed coats.

Phenolic compound

Phenolic acids and polyphenols are two types of phenolic chemicals, which are significant secondary metabolites. These are mainly found in conjunction with sugar moieties, attached to one or more phenolic groups, or as derivatives of ester or methyl-ester. Figure 2 demonstrates the different antioxidant components of mangoes.

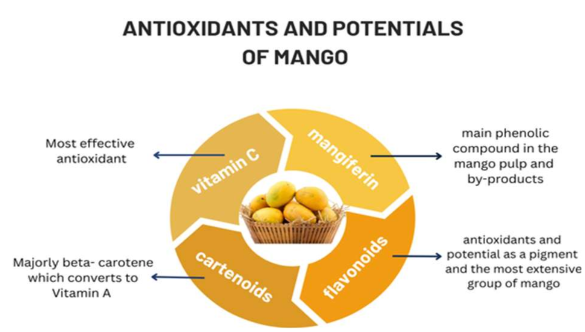

Fig. 2: Antioxidant and bioactive properties of mango. In this case, Vitamin C is illustrated with a strong oxidizing capacity to represent highly effective oxygen species. Carotenoids, particularly β-carotene, with antioxidant activity, act as Vitamin A progenitors. Mangiferin is pointed out as a chief phenolic compound in mango pulp. Flavonoids encompass the largest class of phytochemicals from mango.

Phenolic acids

Phenolic acids are one of the significant secondary metabolites and help in disease protection, and are crucial in managing human health. Phenolic acids that are hydroxycinnamic and hydroxybenzoic derivatives can be set up in the pulp either free or attached to quinic acid, glucose, or both. The hydroxybenzoic acid group is made up of gallic, syringic, vanillic, and protocatechuic acids, whereas the hydroxycinnamic group is substantially composed of p- coumaric, ferulic, chlorogenic, and caffeic acids. Mango variety, civilization position, and development stage all affect the kind and amount of phenolic acid. Ferulic acid (33.75 mg) is the most abundant acid in the mango pulp of most types, with lower quantities of caffeic acid (0.25–0.10 mg), vanillic (0.57–1.63 mg), gallic (0.93–2.98 mg), chlorogenic (0.96–6.20 mg), and protocatechuic (0.77 mg) per 100 g of fresh fruit weight. On the other hand, Ataulfo mango pulp contains chlorogenic acid as the main constituent (90%), followed by gallic (4%), and vanillic with protocatechuic acid at 30% and 56%, respectively, at the final ripe stage (Sapin *et al.,* 2021).

Climate change impact

Agriculture is one of the numerous sectors that climate change impacts since it's a global, multifaceted ecological issue. Climate change and global warming are the results of mortal exertion, adding greenhouse gas emissions. Depending on the region, climate change can have positive, negative, or neutral impacts. Climate is still a major factor in determining a community's farming ability and categorizing regions for growing particular commodities. Changes in temperature, precipitation, atmospheric CO_2 concentration, drought, soil, and soil salinity are only a few of the effects of climate variability. The consequences of climate change on mango farming are extensive for both the growers and the economy at large, as it may affect the productivity of an interdependent industry whose raw materials are mango fruit, eco-friendly for livelihood is hinged on mango production, and most importantly, the populace that cherishes the sweet fruit. The vegetative phonological phases of mangos are primarily controlled by temperature and rainfall; for instance, a mango tree's vegetative growth is optimally suited for temperatures between 20°C and 29°C and below 15°C, which encourages flowering; temperatures between 20°C and 28°C significantly affect leaf size, which may be related to dry matter moving to the root during elevated CO_2 periods. (Antwi-Boasiako *et al.,* 2024). When the temperature rises, mangoes react differently from annual crops. Under the conditions of drought and flooding, mango trees suffer from stunted development. Mango flowering depends on both the dry and cold seasons, with wet seasons favoring emissions from vegetative flow. Mango tree growth chamber experiments verify that low nighttime temperatures of 8 to 15°C, combined with daytime temperatures below 20°C causing flowering as soon as shoot initiation occurs. Mango can endure a broad spectrum of temperatures starting at 0°C. up to 48°C, without experiencing negative effects. However, being subjected to low Exposing the plant to temperatures for more than 6 hours can be fatal. Generally, most types, unless currently growing, when cold weather hits they, can endure 1-2°C, as long as this temperature does not last for over a couple of hours. Young trees experiencing strong growth sustain severe injuries at 0°C. Cool temperatures under 17°C result in abnormal and nonviable pollen grains. The prevaculate phase of meiosis during Microsporogenesis seems to be particularly sensitive to temperature variations. Under 10°C. Low temperatures also negatively impact germination and pollen tube development, which is entirely suppressed at temperatures below 15°C.

Effect of Temperature on Mango

Mango phenophase timing variations could have significant economic ramifications because to their likely direct effects on yield. Ages of surprisingly low temperatures can destroy the crop by affecting fruit set and flowering. In virtually every producing region, temperature has a significant impact on the mango's growth cycle, unfolding time and frequence, fruit development, flavor, and appearance. While inflorescence emergence comes shortly after the region's coldest winter season, growth required relatively higher temperature settings.

Impact of Climate Change on Mango Phenology

Phenology refers to the development of a plant through distinct stages and the distribution of resources among various plant parts. Such a pattern relies on the length of the developmental phase and the environment. Mango phenological patterns are greatly affected by the environment. When life-cycle processes like crop maturity and flowering occur have just lately been taken into consideration for studies on how the climate affects various crops. Mangoes are being affected by changes in the environment and exhibit both early and delayed blossoming. Rainfall and air temperature are two of the most crucial elements influencing a region's climate their suitability for mango cultivation. As temperatures increase and fall and the rainy and dry seasons begin, the sequence of seasonal shifts is either accelerated or delayed. Decreased production quality and quantity are thus anticipated as a result of climate change's impact on phenological patterns and, in turn, vegetative and reproductive processes. (Makhmale, *et al.,* 2016).

Effect of Rainfall on Mango

Reduced pollination effort and sluggish fruit set may result from heavy rainfall during the pre-flowering and blooming seasons. Ripe mango fruits' quality and aesthetics might be adversely affected by changes in rainfall patterns. Pests are encouraged by unseasonal rainfall, which also reduces fruit production. Mangoes grow in areas that are warm to hot during fruiting, have low rainfall, and have low relative humidity during flowering, fruit setting, and harvest. Mangos can withstand a broad. Anthracnose can pose a significant threat to mango agriculture in humid, high-temperature tropical regions that range from warm temperate to tropical. Tropical Fruit Tree Species and Climate Change 75 settings with rainfall. (Rajan, *et al.,* 2012). Mangos can be grown in regions with annual rainfall above 250 mm with minimal irrigation. The majority of locations where mangos are grown have a wide range of yearly rainfall. Without any water logging. Rainfall during flowering has a negative impact on fruit output, development, and set. Heavy and prolonged rainfall causes excessive vegetative growth and flower drop in several parts of southern Thailand and India, figure 3 shows different abiotic factors effecting on mango growth and development. In the wettest month of the time, extremely little downfall (lower than 40 mm) could be a constraint for marketable product. Some significant mango- growing regions, similar as India's Konkan region, have considerable monthly downfall but also dry spells, which are essential for healthy fruit development and flowery induction.

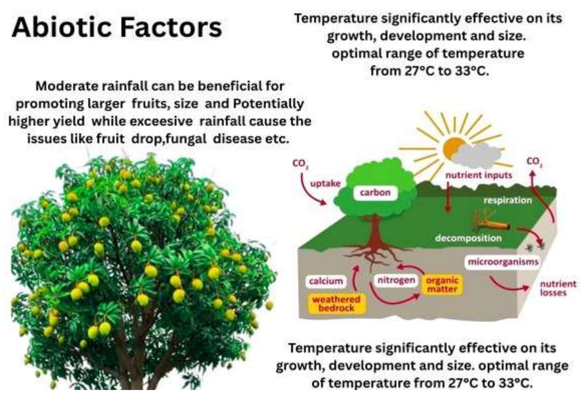

Fig. 3: Some of the most basic factors that affect the development and productivity of mango plants are rainfall, temperature, soil nutrients, and carbon. Adequate rainfall is required for proper vegetative development, larger fruit, and increased productivity. Temperature acts as an important controlling factor for the development of mango plants and fruit development. The optimum temperature for fruit development and plant growth is 27°C and 33°C, respectively. Soil nutrients and carbon assimilation act as a controlling factor for plant development.

Scope/Diversities

Mangoes are quite perishable; maintaining their newness and market value requires applicable storehouse conditions. Mango's shelf life can be increased by showing ripening and reducing the danger of disease by keeping them between (10–13°C) and (85–90%) humidity. The mango's nutritional rates and mouthwatering flavor make it the third most important fruit in the tropics. The fruit's climactic nature makes it largely perishable, lowering its quality and shelf life. Fruit preservation, one of the most important ways to meet mortal salutary requirements, is to maintain quality and reduce losses during the postharvest process. As time passes, due to some reasons like environmental problems and other climatic pattern the nutrient efficiency in mango will decline gradually.

Nutrient Density Declined

Mango is not only valued for its rich flavor or aroma but also for its nutritional profile, which includes important vitamins (like A and C), minerals (like potassium and magnesium), dietary fibers, and potent antioxidants (like beta-carotene and polyphenols), in addition to rich flavor or aroma. The nutrient viscosity of the mango (Mangifera *indica L*.), a fruit high in nutrients, can drop because of several pre-harvest (agronomic, environmental) and post-harvest conditions. Nutrient viscosity is the quantum of vital vitamins, minerals, antioxidants, and other bioactive substances in a fruit per unit weight. The fruit's flavor, nutritive value, and shelf life all drop when these factors are lowered. Some of the essential nutrients that might dwindle are:

1. **Vitamin C:** Particularly vulnerable to oxidation, heat, and light.
2. **Carotenoids (vitamin A precursor):** Erode as a result of sustained exposure to heat and sun.
3. **Phenolic Composites & Antioxidants:** lowered during ages of extreme heat stress of failure'.
4. **Sugars (sucrose, fructose, glucose):** May drop if the tree gets water stress when its fruit is growing.
5. **Minerals (potassium, calcium, magnesium):** unstable fertilization or inadequate soil nutrients can affect the scarcities.

Mangoes are still a nutrient- thick fruit, but their health advantages might not be as strong as they formerly were, especially when it comes to commercially developed and more accessible kinds. It's advised to eat seasonal and locally grown mangoes to maintain nutrient density, immaculately from granges that value biodiversity and soil health through organic or regenerative farming ways (Orr, R *et al.,* 2023).

Aroma loss under stress

One of the most important aspects of the mango fruit that contributes significantly to its appeal is its aroma. Further than 285 unpredictable chemicals have been found in mangoes, including aldehydes, alcohols, lactones, sesquiterpenes, monoterpenes (similar to 3-carene and limonene), and alcohols. These notes inclusively give the fruit its distinct scent hand. However, a number of stressors, including postharvest handling stress, controlled atmosphere (CA) storage, and cold storage (chilling injury), drastically lower the synthesis and release of these fragrance components, leading to scent loss.

Causes of Aroma Loss under Stress

Mangoes are sensitive when the temperature drops below 10°C. Chilling damage from prolonged exposure results in: 1) Damage to the cell membrane, 2) Pathway disruption for volatile biosynthesis, 3) Crucial aroma volatiles similar to myrcene, α- terpinolene, ans 3- careen are declining (Silué, Y. *et al.,* 2022). To increase shelf life, CA storehouses uses high attention to carbon dioxide (CO_2) and low concentration of oxygen (O_2). However, this suppresses: 1) Ethylene production and respiration are both necessary for the development of scent, 2) Terpene synthase and alcohol acetyltransferase (AAT) are examples of enzymes that reduce terpenes and esters (Lalel, H *et al.,* 2022). Improper postharvest treatment and damage might cause stress reactions and ethylene imbalance, and oxidative stress decreases the production of secondary metabolites linked to aroma (Singh *et al.,* 2025).

Climate change effect

Heat stress

Reduced yields, photosynthesis, growth, and changes in biomass distribution are all predicted by recent studies on how high temperatures affect the characteristics of numerous plant species. Additionally, flowering, physiology, fruit quality, and disease susceptibility can all be impacted by temperature. As a result, many crops are now at risk from rising temperatures (Hamdani *et al*., 2024). A complex process, mango flowering has been the subject of much research. The climate (air temperature, photoperiod, and rainfall) and the plant itself (mango cultivar, nutritional status, photoassimilates, enzyme activity, and plant hormones) are among the many factors that affect it. Although several of these processes can be changed to provide plants adequate flowering in terms of branch ratio, panicle emission, and flowering uniformity, they all work in concert (Cavalcante *et al*., 2022). Particularly in arid and semiarid areas, high solar radiation that damages crops surpass fruit trees' natural defenses, resulting in significant financial losses. Fruits exposed to the west, where radiation strikes them perpendicularly, are more likely to sustain harm when the environment and plants have lost moisture. With the worst damage occurring during dry seasons in crops that have few leaves in that area of the plant and are vulnerable to high temperatures and radiation. The risk of sunburn for fruits has more than doubled in recent decades, therefore harm is anticipated to rise with worldwide warming (FISCHER *et al*., 2022). Because organic acids are destroyed and liberated during heating, pasteurization of mango puree results in a lower sugar content and a higher acidity. As a result, pasteurized items' nutritional makeup and sensory attributes were impacted. Degradation of amylase and invertase activity was linked to extended exposure to lower temperatures and air velocities during oven drying. This could be explained by increased heat exposure or oxidation, product accumulation, and other physicochemical changes in dried mangoes. The sugar content of the dried plum fruits of the cultivars under investigation was impacted by drying temperatures of 70 °C and 90 °C. Varietal features, however, conditioned the degree of the modifications, which included an increase in invertase and a decrease in total sugars and sucrose content. An inventive processing method called vacuum frying has been used to preserve nutrients, improve organoleptic qualities, and create nutritious snacks with little to no acrylamide formation (Chin *et al*., 2024).

Water scarcity

Particularly in arid and semi-arid areas, water scarcity is a major stressor influencing mango cultivation. Mango trees need regular, sufficient irrigation, especially during important growth phases like fruit development, flowering, and fruit set. Poor flowering, higher fruit drop, smaller fruit, and decreased yield can all result from inadequate water. Additionally, prolonged dry conditions hinder photosynthesis and nutrient uptake, which erodes the general health of the tree. Commonly advised methods to lessen the consequences of water scarcity include mulching, drip irrigation, rainwater collection, and choosing drought-tolerant rootstocks. All things considered, mangos are a good target to help manage agricultural water scarcity. Therefore, this study's goal was to lower irrigation water use in mango cultivation and assess how SDI affected the crop's quality and output (Lipan *et al*., 2021). Volatiles are released either passively or actively by the bacteria as a normal metabolic process throughout their growth and development. The volatiles are classified chemically into alkenes, ketones, alcoholic drinks, terpenes, benzenoides, and pyrazines. (Janamatti *et al*., 2022). Removing volatile components from mangos, whether as a result of postharvest processing or natural causes like dehydration, significantly reduces the fruit's flavor, aroma, and overall quality. It is volatile substances like alcohols, terpenes (including myrcene and limonene), esters, and aldehydes that give mangos their unique fruity and flowery aroma.

Elevated CO_2

Higher CO_2 has a beneficial effect on photosynthesis; this benefit can be offset by rising temperatures. In addition to causing plants to grow and develop more quickly, higher temperatures may postpone the onset of winter growth stoppage for perennial plants (KS *et al*., 2024). Within fruit storage packages, low oxygen and high carbon dioxide levels are created, which can prevent the growth of germs, lower fruit respiration rates, postpone postharvest metabolic rates, and minimize nutritional loss (Wei *et al*., 2021). Mango fruit's sweetness can be greatly impacted by altered carbohydrate metabolism brought on by elevated CO_2 levels and water constraint. Internal CO_2 accumulation results from stomatal closure, which restricts gas exchange under drought stress. This increased CO_2 can interfere with normal enzymatic processes that break down and synthesize carbohydrates, including those that control the breakdown of starch and the buildup of sugar. Because of this, there may be less or an imbalance in the conversion of starch to simple sugars like glucose, fructose, and sucrose, which results in lower sugar concentrations and less sweetness in the fruit. Both customer choice and fruit quality are adversely affected by these metabolic changes, as shown in figure 4, which describes the different factors i.e; heat stress, water scarcity, elevated CO_2 etc shows the various impacts on crops due to climate change.

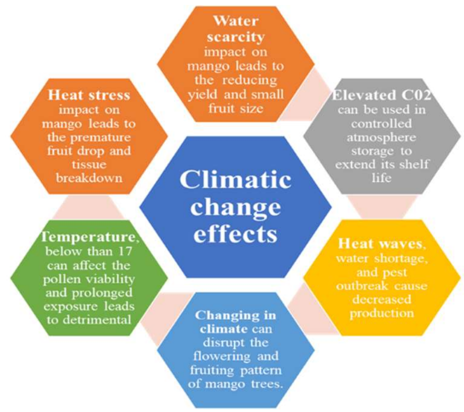

Fig. 4: Demonstrates how climate change factors of heat stress, water shortage, high temperature, and CO_2 concentration can affect the development of crops. It is affecting yield, floral and fruit development, and post-harvest qualities.

Nutritional Degradation

Food quality has drastically declined over the past 60 years, and a wide range of vital minerals and nutraceutical compounds found in essential fruits, vegetables, and food crops have also decreased. The use of high-yielding cultivars and crops, chaotic mineral nutrient application, the preference for less nutritious cultivars and crops, and agronomic problems related to the transition from natural to chemical farming have all been identified as potential causes of the global decline in food nutritional quality (Bhardwaj *et al.,* 2024). The fruit's nutritional profile indicates that it is a good source of organic acids (OA), minerals, vitamins, protein (0.36%), fat (0.3%), and carbohydrates (16%). From the fruit, nearly 13 vitamins have been identified. Because of increased oxidative damage and metabolic disturbances, fruits under drought stress frequently see a large drop in their carotenoid and vitamin C (ascorbic acid) content. Reactive oxygen species (ROS) are produced in excess during drought, which eliminates vitamin C, a crucial antioxidant. High temperatures and lipid peroxidation speed up the breakdown of these substances, especially for lipid-soluble carotenoids. While mild drought may cause some fruits, such as tomatoes, to exhibit higher levels of lycopene, severe water scarcity typically results in significant losses in both vitamin C and carotenoids.

Soil Nutrient Loss

Nutrients can be lost in a number of ways. Soluble nutrients like potassium and nitrate can be lost in runoff and drainage water, while less soluble minerals like phosphorus are more likely to be lost as sediments move through eroding soil and runoff water. Insignificant loss by wind erosion, which disrupts the ratio of organic matter, clay, and silt in the soil and lowers fertility (Meena *et al.,* 2017). Fruit production is severely hampered by soil erosion and ineffective fertilizer use, which results in lower yields, lower-quality fruit, and less nutritional value, fig. 5. shows different factors shows the impact on mango yield loss. While excessive or unbalanced fertilizer use leads to nutrient loss, soil acidification, and disturbed microbial communities, intensive agricultural methods, monocropping, and poor nutrient management deplete the soil of vital minerals. Key minerals like potassium, phosphorus, and micronutrients are depleted by constant fruit picking, and soil structure is weakened by erosion and organic matter loss, which lowers the soil's ability to retain water.

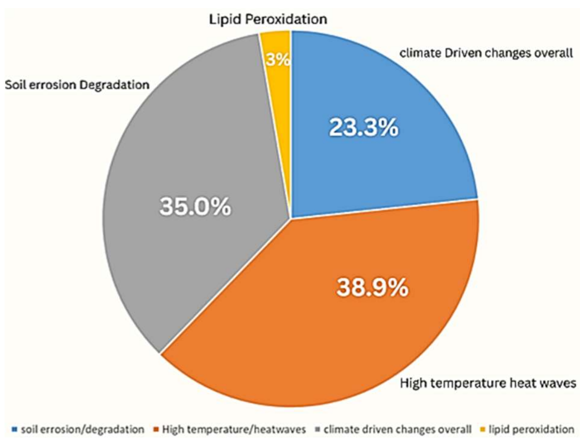

Fig. 5: The various factors demonstrate the impact of the loss of yield in mango production. Heat stress and heat waves cause the fall of fruit and reduced production, while the impact of water scarcity leads to reduced yield and reduced sizes. Temperature and rainfall affect the flowering, fruiting, and growth, while high CO_2 has a negligible impact.

Aroma and Flavor Loss

A wide range of low molecular weight compounds, including volatile fatty acids, phenols, lactones, aldehydes, ketones, monoterpenes, sesquiterpenes, esters, and carotenoids, contribute to the scent. Environmental and genetic factors affect the concentration and composition of aromatic volatiles in mango fruit. Seven cultivars have been discovered to differ in the content of monoterpenes, including limonene, trans-cis-ocimene, and β-myrcene. Additionally, 84 VOCs were found in 27 mango cultivars in the previous research, demonstrating the qualitative and quantitative abundance of volatiles (Dar *et al*., 2023). Additionally, a dense fruit arrangement can cause terpenoids to degrade, lessen the production of chemicals from the lipoxygenase pathway response, and lessen the mango's flavor and scent. Aldehydes, alcohols, esters, ketones, terpenes, and hundreds of other chemicals have previously been found together with the volatiles of several mango cultivars. The smell of each volatile organic compound (VOC) varies. Through cumulative, synergistic, and masking actions, their ratios, concentrations, and combinations give the fruit its distinct fragrance characteristics. After 48 hours of ripening, terpenes are the most prevalent fragrant substance in Kent mangoes, followed by esters and other compounds. However, other cultivars need to be examined to better understand the dynamic changes in volatile organic compounds (Xie *et al*., 2023).

Premature harvesting

Fruit harvests must be harvested at the ideal stage of maturity to guarantee quality, a longer shelf life, and market value. Finding the ideal time of fruit maturation becomes much more important, particularly for climacteric fruits, whose maturity is accompanied by a sharp rise in ethylene production and respiration rate. While late harvesting causes internal disintegration because of the quick changes in biochemical components, early picking produces fruits of suboptimal quality (Kishore *et al*., 2024). Mango flavor and overall quality are frequently sacrificed when mangoes are harvested too early to increase shelf life. Because the ripening process on the tree is essential for the accumulation of sugars, volatiles, and bioactive compounds, mangoes may not develop their distinctive sweetness, flavor, and texture if they are harvested before they reach full maturity. Early harvesting lowers the chance of spoiling during storage and transportation, but it also degrades the quality of the food, resulting in a bland or starchy flavor and lower customer satisfaction.

Disease and Pest Pressure

Climate-linked disease surges

Mango illnesses are on the rise due to climate change, which poses a severe danger to quality and output, especially in important growing regions like Pakistan. Mango trees are more susceptible to pests and diseases as a result of the disruption of their natural growth cycle caused by erratic weather patterns, which include extended winters, early and severe heatwaves, and unexpected rainfall. Due to rising humidity and temperature swings, diseases including anthracnose and powdery mildew have grown increasingly common. Additionally, pest infestations have gotten worse, harming fruit, flowers, and buds. These include black hoppers, thrips, and bark beetles, which are associated with mango wilt. *Oidium Mangifera* poses-caused powdery mildew, one of the fungal diseases that poses the biggest threat to mango production, causing total yield losses in various mango-growing regions across the world. The main targets of powdery mildew are young fruits, mango clusters, and leaves of extremely vulnerable mango cultivars. Because of the harm it causes, it also promotes the growth of anthracnose (Iqbal *et al*., 2024). Before and after harvest, mangoes are severely harmed by the global illness known as mango anthracnose disease (MAD). Low fruit output and quality are the results of the disease's damage to the affected mango trees. In poorly maintained orchards with favorable conditions for the disease's propagation, MAD can result in a 100% yield loss. Nearly every area that produces the crop is affected by the illness, and because of the significant financial losses it causes, there is a plethora of research on postharvest losses (Dofuor *et al*., 2023). About 25 °C is the ideal temperature for anthracnose infection. Rain, fog, dampness, or too much dew can all affect anthracnose-related injuries. while flowering, severe bloom blight is caused by extended wet weather during flowering. Within 12 hours, a relative humidity of 95% or more is essential for C. gloeosporioides infection and development in mango fruit. Ripe fruits and damaged tissues have a quicker progression of the illness (Paudel *et al*., 2022).

Climate-Driven Pathogen Evolution

Mango tree aerial sections can be harmed by the anthracnose (blossom blight) pathogen, which develops conidia on twigs, leaves, and other parts that are spread by raindrop splashing. The most vulnerable area to this disease is the inflorescence; the minimum temperature has a negative relationship with the severity of anthracnose. Flower infections are the most damaging and reduce production among mango illnesses. The disease's most dangerous symptom is floral deformity, which results in significant losses each year (Hammad *et al*., 2025). Numerous pathogenic strains have developed fungicide resistance as a result of the extensive and frequent use of specific chemical fungicides, and fungicide residues have polluted the environment and injured aquatic and soil species. Although endophytic fungi are environmentally benign and efficient biocontrol agents against a variety of bacterial and fungal diseases, little is known about the endophytic fungi that are linked to mangos. Table 1 in the following demonstrates various pest diseases associated with their vectors and climatic factors that trigger the microbial growth. In order to prevent bacterial and fungal infections in the field, it is helpful to look at the variety of endophytic fungi linked to mangos and to screen for antagonistic strains. Investigating the endophytic fungi linked to mangos and screening endophytic strains with potential for biocontrol were the objectives of this study (Yang *et al*., 2023).

Pest proliferation

The fast growth of insect, mite, and other organism populations that harm fruit crops is referred to as pest proliferation in fruits. An increase in insect infestations has been caused by a number of factors, including monoculture practices, climate change, and excessive pesticide use. In addition to extending breeding seasons, warmer temperatures and changing rainfall patterns also facilitate the migration of pests into new areas. This has led to an increase in the frequency and difficulty of controlling pests such as borers, mealybugs, aphids, and fruit flies. Economic losses, decreased fruit output and quality, and a greater reliance on chemical control methods—which can further upset ecological balance and harm beneficial insects—are the results of this. The use of integrated pest management (IPM) techniques is becoming more and more important in the fight against this problem. There are 462 insect species and 26 nematode species known to attack mangoes worldwide. Several insect predators have been identified that affect mango trees, including fruit flies like Bactrocera dorsalis, mealy bugs like *Drosicha mangiferae* (Green), and hoppers like *Idioscopus clypealis* (Lethierry) and *Amritodus atkinsoni* (Lethierry) (Arya *et al*., 2024). Depending on the climate and mango variety, the pest's harm is always different. Mango plants' shoots, twigs, leaves, branches, and fruits are among the several places where this sucking insect pest is found. The pest is seen on all plant parts, including leaves, twigs, and fruits, when it is prevalent in mango crops. The female WMS are attracted to the scents emitted by ripening fruits, which is why they are so prevalent on the fruit during this period. However, because of their biochemical makeup, ripened mangoes that are sweeter, less acidic, and more viscous could be more appealing than immature ones (Raza *et al*., 2023). Every cultivated plant experiences attack from a considerable number of insect pests throughout its life cycle, and the mango tree is no exception. Some examples include fruit flies, mango mealy bugs, thrips, aphids, scale insects, tree borers, mango stone weevils, and mango hoppers. Nevertheless, the main pests of mango comprise the fruit flies, mango stone weevil, tree borers, and mango hopper (Aboagye *et al*., 2022).

Current mitigation strategies

Present mitigation strategies in fruit cultivation concentrate on the management of climate stress, pests, diseases, and postharvest losses. Important methods comprise drip irrigation, mulching, and shade nets for regulating water and temperature; integrated pest management (IPM) and disease-resistant varieties to address biotic stress; as well as postharvest techniques such as cold storage and modified atmosphere packaging to prolong shelf life. The application of biofertilizers, organic amendments, and digital tools contributes to sustainable and resilient fruit production.

Breeding and biotechnology

Over the years, mango breeding has faced various challenges. These challenges are mainly due to a lack of understanding about how certain traits are inherited, the high levels of heterozygosity found in cultivars, and the low number of successful hybrid offspring produced from crossbreeding (Bura *et al*., 2023) Mango breeding programs have encountered considerable difficulties because of specific intrinsic traits of the plant species, which are; A prolonged juvenile phase. High heterozygosity levels, which result in hybridization that cannot be predicted. Each fruit contains just a single seed. A significant fruit drop rate leads to low retention of cross-pollinated fruits. Many cultivars exhibit polyembryony. The considerable land area required for a significant assessment of hybrid progeny.

Heat stress adversely affects numerous plant organs across different fruit crops, such as leaves, stems, branches, flowers, fruits, seeds, and roots. This is manifested through processes like leaf aging and dropping, sunburn, suppression of shoot and root development, and changes in fruit color. Initial consequences of high-temperature (heat) damage comprise the hindrance of protein synthesis, breakdown of proteins, enzyme inactivation, compromised membrane integrity, and increased lipid membrane fluidity. Under osmotic stress, the secondary effects of heat injury include partial protein unfolding, aggregation of proteins, oxidative stress, increased fluidity of lipid membranes, and inhibition of respiration and photosynthesis, among others. Heat stress can lead to the generation of reactive oxygen species (ROS), but antioxidants like anthocyanins can mitigate this effect and help maintain cellular osmotic homeostasis, allowing plants to adapt to changing environmental conditions, such as rising temperatures (Panigrahy *et al*., 2025). A primary aim of mango breeding initiatives is to develop commercial cultivars and rootstocks that exhibit enhanced drought tolerance. Research has pinpointed certain mango cultivars that can maintain optimal photosynthesis levels for extended durations compared to those with lesser drought resistance following water deprivation (Perera-Castro *et al*., 2023).

CRISPR-Enhanced Mango Quality

By removing the need for significant backcrossing and selection, genome editing offers a superior alternative to conventional breeding methods and an efficient way to introduce precise alterations in plants. It is likely that the regulations for genome-edited crops will be simpler than those for GMOs, due to the absence of transgenes in edited crops. Genome editing platforms can be used to investigate gene function and regulatory mechanisms by creating mutant crops, making them outstanding tools for crop enhancement. Genome editing tools allow for the removal of unwanted chromosomal DNA, the insertion of new coding sequences, and the activation or downregulation of advantageous genes. The effectiveness of the CRISPR/Cas9 genome editing system is increasing in various dicotyledonous and monocotyledonous species. This approach holds significant promise for enhancing the qualities of fruit in tropical fruit crops (Mathiazhagan *et al*., 2021). Due to developments in genetic engineering, the CRISPR/Cas9 technology has emerged as a flexible tool for genome editing. The usefulness of CRISPR as a means to induce mutations at targeted genomic loci could be harnessed to enhance the agronomic traits and nutritional value of fruit crops. The DNA-free CRISPR system operates without the incorporation of any external DNA elements; As a result, it can reduce the regulatory challenges linked to transgenic crops and facilitate their acceptance. The successful establishment of CRISPR/Cas9 based genome editing in various fruit crops, including mango, apple, kiwi, orange, and banana, has demonstrated its applicability and usefulness (Kaur *et al*., 2020).

Agronomic practices

In cultural and agronomic strategies, the purpose of both cultural and agronomic strategies is to change the environment in order to lower prevalence. Several effective practices for controlling the white mango scale insect have been identified and recommended across the impacted countries. The first and foremost strategy for managing crop pests and diseases is to practice appropriate field and variety selection, specifically choosing mango varieties Another significant practice involves adopting a better density of mango trees (Otieno *et al*., 2021). The findings from different reports suggested that the adoption of improved agronomic practices, including pest management and disease control, could lead to a significant enhancement of mango yields in Siaya County. Marketing channels showed that farmers supplying factories and those selling at farm gate markets attained similar sales, suggesting that both routes can be viable with appropriate support (Beatrice *et al*.,2025).

Precision irrigation to manage water stress

Since the 1980s, precision agriculture has relied on remote sensing techniques, with initial images sourced from satellites and more recently from unmanned aerial vehicles (UAVs). The spectral data produced can aid in the effective administration of irrigation and enhance the physiological condition of various crop plants. UAVs are low-cost and more frequently utilized across various agricultural sectors because of their versatility, adaptability, and ease of movement. UAV-based techniques are particularly effective for evaluating water stress in crops, which can enhance crop management and increase yields (Sillero-Medina *et al*., 2025). Satellite remote sensing has developed into a useful instrument for agricultural water management, offering global coverage with relatively high spatial resolution and the ability to monitor vegetation health and water status across extensive areas. Vegetation indices obtained from satellite images, including the for assessing the health and stress levels of vegetation, the normalized differences in vegetation index (NDVI), Soil-Adjusted Vegetation Index (SAVI), and Normalized Difference Water Index (NDWI) are widely used. (Torres-Quezada *et al*., 2025).

Mulching and shade nets to reduce thermal stress

Shade nets consist of plastic threads (typically high-density polyethylene) that are woven or knitted together to create a regular porous geometric structure, permitting the passage of fluids (both gases and liquids). Nets are primarily used to shield cultivated plant species from a variety of natural calamities, including hail, torrential rain, snow, strong winds, excessive sunlight, birds, and more recently, insects (via anti-insect nets). Anti-insect nets resemble anti-hail nets, but they vary in mesh size and application method. Because solar radiation is essential for plant life, the effect of nets on its quality and quantity is vital. Generally, the radiation spectrum pertinent to plants spans from 280 to 800 nm, encompassing UV-B (280–320 nm), UV-A/B (300–400 nm), photosynthetically active radiation (PAR, 400–700 nm), and far-red radiation (TC, 700–800 nm). (Vuković *et al*., 2022). Mulching reduces transpiration and maintains a cool canopy. Straw, a reflective organic mulch with low density, diminishes surface radiation and helps retain moisture. Shading cloth offers partial shade by diminishing advected heat and the total incoming radiation (Tandel *et al*., 2025). Mulching can increase soil moisture content and lessen water evaporation from the soil. Under drought conditions, reducing canopy transpiration through heavy summer pruning can mitigate the adverse effects of water stress on fruit growth. To promote fruit growth in arid conditions, another effective approach is to apply heavy thinning of fruits. Net shading is another gardening technique that can reduce water requirements. A further noteworthy water-conserving innovation known as "cocoon" has demonstrated its effectiveness in enhancing seedling survival rates across the globe for fruit tree species like mango (Devin *et al*.,2023).

Post-Harvest Innovations

A number of strategies have been suggested to tackle the difficulties associated with postharvest management of mangoes. Such practices encompass pre-harvest methods like effective orchard management, harvesting at the right maturity stage, and reducing physical damage during harvest. Postharvest treatments like hot water treatment, controlled atmospheric storage, modified atmospheric storage, gamma irradiation, and the use of edible coatings have demonstrated promising outcomes in delaying ripening and maintaining fruit quality. Additionally, natural and synthetic ripening inhibitors like 1-MCP (1-methylcyclopropene) have been investigated to extend the shelf life of mangoes (Singh *et al*., 2025). The field of post-harvest technology embodies a multidisciplinary synthesis of agro-technological engineering, biochemical preservation strategies, and mechanized post-harvest logistics. This synthesis is carefully designed to reduce organoleptic and physicochemical degradation after harvest (Ahmed *et al*., 2025).

Edible coatings to preserve aroma and nutrients

One of the methods devised for prolonging fruits' shelf life is to apply edible coatings to them. The edible coating, which is safe to consume, creates a thin layer that shields the fruits from oxygen, moisture, and microbes. Edible coatings can effectively manage the browning, unpleasant odor and taste, and microbial activity of fruits and vegetables. The primary advantage of employing edible coatings is the possibility of integrating certain active components into the polymer matrix for consumption alongside food. This can enhance safety and potentially improve nutritional and sensory qualities. Mangoes coated with 10% Arabic gum and 1% chitosan were able to reduce mass loss, respiration rate, ethylene production, changes in soluble solid concentration (SSC), decay incidence (DI), and maintain firmness. This demonstrates engrave application as a natural prerogative is a straightforward and efficient method brisk delay for 28 days at a relative humidity of 80% without the application of fungicides (Handojo *et al*., 2022). Compared to synthetic materials, edible coatings provide various benefits, including being environmentally friendly and biodegradable. Some edible coatings can improve food appearance and nutritional quality, and delay or prevent the growth of pathogenic and spoilage microorganisms through various mechanisms. They serve as a barrier against water vapor and gas transport, helping to mitigate the effects of controlled atmosphere storage (Elsayed *et al*., 2022). Edible coatings represent a promising post-harvest technique shows in fig 6 such as high-Pressure Processing, ultrasonic technique, Edible Packaging, for preserving the aroma and nutrients of mangoes. They create a semi-permeable barrier that slows respiration and moisture loss, aiding in the retention of volatile aroma compounds and essential nutrients such as vitamin C and β-carotene. Natural coatings like chitosan, aloe vera, and starch often enhanced with essential oils provide antimicrobial protection that prolongs shelf life while preserving flavor and nutritional quality.

Controlled atmosphere storage for flavor retention

Controlled atmosphere storage has also been utilized to alleviate chilling injury. This technique, akin to modified atmosphere packaging, involves introducing mango fruits into a storage room where the gas composition has been altered to contain low levels of oxygen. This is said to lower ethylene production, respiration rate, and ripening speed. Storage in a controlled atmosphere (2% O_2 and 6% CO_2) at 13°C was regarded as an effective method for prolonging the shelf-life of mangoes and preserving their high quality, while a gas mixture of 2% O_2 and 2% CO_2 proved more effective for retaining the aroma compounds in ripe mangoes (Le *et al*., 2022). several aspects underscore the importance of innovative methods for postharvest management, such as controlled atmosphere storage, refined cooling systems, and packaging that minimizes decay and preserves fruit quality. Methods like hydro-cooling and the application of edible coatings made from natural materials are investigated for how well they extend freshness and reduce chemical use. It is emphasized that processing mangoes into products such as dried slices, purees, and drinks can add value, improve economic returns, and decrease postharvest losses (Rehman *et al*., 2025). some study aimed to investigate the impact of various postharvest treatments using oxalic acid (OA) and salicylic acid (SA) on the quality characteristics and postharvest shelf life of temperate-grown apricot varieties stored under controlled atmosphere (CA) conditions. Following each treatment, the samples were kept for 30 days in a controlled atmosphere (CA) store at 0 °C, with a relative humidity of 90 ± 5%, and gas concentrations of 5% oxygen and 15% carbon dioxide. Results indicated that both OA and SA treatments had a significant impact ($p \leq 0.05$) on retaining the total soluble solids, titratable acidity, color profile, ascorbic acid content, and total phenolic content of apricot varieties, while also positively affecting antioxidant activity and texture compared to the control (Batool *et al*., 2022) (see Figure 6).

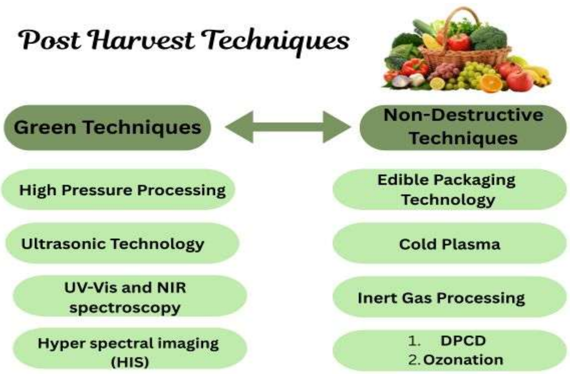

Fig. 6: The post-harvest technologies applied reduce the number of wastes and ensure their physical and nutritional qualities. These post-harvest technologies are provided by modern technologies. This technology reduces the wastes that are produced during the processing of this produce and ensures that their qualities are maintained. It is applied using the green, non-destructive technologies.

Emerging Technologies

Emerging technologies provide scalable and sustainable disease management strategies that connect traditional practices with modern solutions (Naqvi *et al*., 2025). Ohmic heating (OH) is a developing technology that could be used for pasteurizing and inactivating enzymes in mango pulp (Barrón-García *et al*., 2021). Ohmic heating is a rapid and uniform heating method that uses electrical current to generate heat within the food itself, as shown in Figure 7. that the ohmic and other useful techniques are used for different improvements in the crops regarding any difficulty, specifically stress control. In mango processing, it helps retain nutrients, flavor, color, and aroma while effectively reducing microbial load. This energy-efficient technique is ideal for pasteurization and pulp extraction, preserving the quality of mango-based products with minimal nutrient loss.

Omics Approaches

Genomics, metabolomics, transcriptomics, and proteomics are omics-based biotechnological approaches that are essential for interpreting the processes involved in mango fruit ripening and understanding postharvest physiology. This knowledge allows mango researchers to explore the effects and efficacy of different postharvest technologies (Zahid *et al*., 2022). Transcriptomics, the examination of gene expression patterns and RNA levels in biological samples, has greatly enhanced our comprehension of the molecular mechanisms underlying various biological processes in mango, such as fruit growth, ripening, and responses to biotic and abiotic stress. Among these processes, the transcriptome-level response of mango to several abiotic stimuli has been well studied. According to transcription profiling of mango, the transcript levels of many C_2H_2-type zinc finger proteins are increased in response to various abiotic stress factors, such as cold, salinity, drought, osmotic stress, and oxidative stress (Muthuramalingam *et al*., 2023). It became feasible to identify and quantify transcripts, including non-coding RNAs, associated with sugar metabolism, fruit development and ripening, shelf life, and the biotic and abiotic stress affecting fruit quality. The use of genomic-assisted breeding techniques like genome-wide association (GWAS), genomic selection (GS), and genetic modifications through CRISPR/Cas9 and transgenics has made it possible to study gene function and create cultivars with desirable fruit traits, thus overcoming the limitations of lengthy breeding cycles (Mathiazhagan *et al*., 2021). Utilizing transcriptome and metabolome analyses, several studies sought to clarify how low-temperature storage affects the production of volatile organic compounds (VOCs), flavonoids, and sucrose, as well as the breakdown of organic acids in mango (Cong *et al*., 2025). Metabolites can be categorized into products of both the primary and secondary metabolisms. In fruits, central primary metabolites such as sugars, sugar alcohols, organic acids, amino acids, and fatty acids are essential for fruit taste and serve as precursors for secondary metabolites like volatile, phenylpropanoid, and terpenoid compounds that contribute to the color, aroma, and nutritional properties of fruits. In particular, the primary pigments, flavonoids and carotenoids, are crucial to the fruit's appearance and thus to how consumers perceive its quality (Romero *et al*., 2021).

Nano-Technologies

Nanotechnology is environmentally friendly and shows promise compared to traditional methods for treating fungal diseases. While various nanoparticles exhibit antifungal potential for managing plant fungal diseases, the use of nanotechnology in plant disease management remains limited (Shahbaz *et al*., 2025). Nanotechnology has recently highlighted its importance in managing post-harvest disease, notably as an effective antimicrobial agent in food processing, storage, and transportation (Mahmoud *et al*., 2024). Fruit farmers' reliance on chemical fertilizers while neglecting or minimally using organic alternatives leads to numerous issues. These include a decrease in soil organic matter, soil acidification, element imbalances, ecosystem degradation, reduced element availability, and heightened environmental pollution. On the other hand, Organic fertilization significantly boosts soil organic carbon, cation exchange capacity, and microbial activity, which is crucial for enhancing soil health and properties and promoting the sustainability of agroecosystems. Moreover, it improves the physical characteristics of the soil by decreasing its bulk density, optimizing porosity, enhancing water retention, restoring degraded arid soils, and improving soil structure and stability while effectively mitigating environmental pollution. Moreover, organic fertilization enhances tree growth and yield by improving soil fertility and plant nutrition (Mosa *et al*., 2024). Nano fertilizers arise as groundbreaking approaches to transform nutrient management, boost crop yield, and foster environmental sustainability. Compared to conventional fertilizers, nano fertilizers enhance nutrient use efficiency, reduce the need for fertilizers, and lessen environmental pollution by employing nano-sized materials for controlled and targeted nutrient release (Patra *et al*., 2025). In biosensing applications, nano biosensors have demonstrated a high level of sensitivity and reliability compared to traditional sensors, which face numerous detection limitations. The Many studies examine the present situation of biosensors and nano sensors used in fruit quality control and handling. The purpose of these sensors is to evaluate aspects like maturity indices, freshness, contaminants, allergens, microorganisms, and toxicants. The need for rapid screening, counterfeit detection, and tracking has led to the development of innovative and intelligent fruit packaging solutions, thanks to real-time monitoring of fruit quality (Khedr *et al*., 2024). Nano sensors utilize a variety of sensing mechanisms to detect and convert the target stimulus into observable signals. These mechanisms may be based on optical, electrical, magnetic, thermal, or mechanical principles (Dixit *et al*., 2025).

AI and predictive Modeling

AI technology assists farmers in obtaining high-quality crops, with its core concept revolving around flexibility, reliability, rapid performance, and applicability. By automating processes or tasks that previously necessitated human skill, AI technology enhances enterprise performance and productivity. AI can comprehend data on an unprecedented scale, surpassing human capability; this proficiency can offer significant benefits in agriculture (Hassoon *et al*., 2022). Numerous studies underline the necessity of identifying the best harvest time according to the climacteric peak and quality changes during storage to guarantee that mangoes fulfill consumer expectations and optimize their quality and shelf life (Kailaku *et al*., 2023). To identify the best harvest time for peak mango flavor, it is necessary to combine physiological, biochemical, and environmental indicators to predict optimal harvest windows. The main indicators comprise total soluble solids (TSS), titratable acidity, sugar-acid ratio, firmness, color, and the buildup of volatile organic compounds (VOCs) that contribute to aroma and flavor. Tools such as near-infrared (NIR) spectroscopy, electronic noses, and machine learning models are being utilized more and more for the prediction of flavor maturity through non-destructive measurements. Moreover, environmental data like temperature, precipitation, and sunlight exposure are taken into account due to their considerable impact on flavor development. Growers can more accurately predict harvest timing by integrating these data sources, thereby ensuring optimal flavor quality, particularly important for export and premium markets. Recent researches place a strong emphasis on proactive management through predictive disease modeling utilizing artificial intelligence and accurate climate data. For these measures to be utilized successfully, policy backing, capacity building, and farmer awareness must all be strengthened (Abdurrehman *et al*., 2025). To predict outbreaks of diseases like anthracnose and powdery mildew, disease prediction models in mangos employ climate data, including temperature, humidity, rainfall, and leaf wetness. Regression models and machine learning are two examples of the techniques that these systems use to analyze weather patterns and predict high-risk periods. This allows for prompt preventive measures and lowers crop losses (see Figure 7).

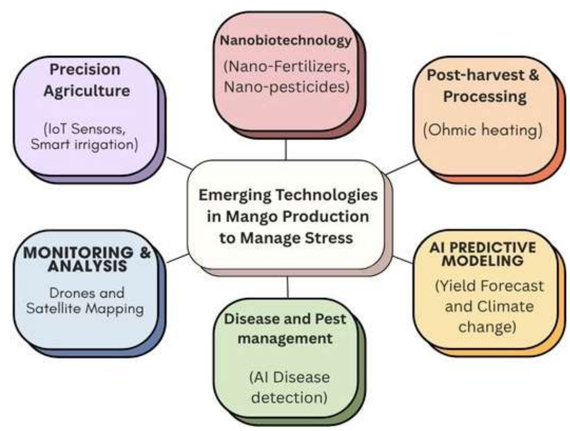

Fig. 7: Several of the emerging technologies already used in mango farming can also be applied for stress management in mango. The emerging technologies for managing stress in a mango tree include Precision farming, Application of nanobiotech, Application of artificial intelligence in control and management of diseases, Application of technology in monitoring through drone or satellite images, Application of artificial intelligence in predictive modeling, and improvement in post-harvest handling.

Policy and Socioeconomics considerations

Different trade regulations and variations in global demand expose the industry to risks that must be removed for long-term profitability and growth. Even though the government has worked hard to improve export conditions with programs like expanding market access and implementing Good Agricultural Practices (GAP), these efforts are not only still in their infancy but have also not been able to completely address current obstacles. From the stage of production to processing and export, agribusiness projects have the potential to significantly boost the economic effect of the mango industry. Better market connections, enhanced processing techniques, and effective postharvest management could boost farmers' earnings and make it easier for them to integrate into global value chains (Barmon *et al*., 2025). For sustainable urban planning and decision-making, it is essential to comprehend the social and economic effects on nearby populations impacted by the conversion of orchards into urban areas. We can ensure a peaceful coexistence between urbanization and the preservation of essential agricultural resources by promoting well-informed policies and methods that strike a balance between urban expansion and agricultural land preservation (Hassan *et al*., 2024). Smallholder agriculture's socio-ecological and economic aspects highlight how difficult it is to develop and implement these policies in a variety of cultural and environmental contexts (Yusof *et al*., 2025). Non-Forest Timber Products' (NTFPs') economic potential and impact on rural development and livelihood have made them a hot topic for national and international policy discussions. Job creation and economic growth will result from well-managed NTFPs, which will also enhance the standard of living in these rural communities (Shidiki *et al*., 2021).

Conclusions

"Climate change poses a significant problem for mango growth, as it influences their phenological, productive, nutritional, and fragrance properties in the context of rising temperatures, water shortages, rainfall anomalies, and growing CO_2 concentrations." To overcome these problems associated with growth, there is a need for an integrated approach toward making them resistant to climate change, and this should include, in view of crop improvement, things like climate change-resistant mango varieties, best practices in agronomic and soil management, state-of-the-art post-harvest technology, and emerging solutions that could include things like biotechnology, omic solutions, nanotechnology, and AI technology that not only solve growth-related issues, maintaining a qualifying product, but also solve other post-harvest issues.

Declarations

Funding: This research article did not receive any financial support from any agency/institution.

Conflicts of Interest: All authors declare that they have no conflicts of interest.

Data Availability: The data collected for this article are included in the article.

Ethics Statement: No prior study was conducted on live animals/humans; thus, it did not require any ethical approval.

Author's Contributions: AR and AW wrote the initial draft. Review and editing were performed by AR. All authors approved the final version of the manuscript.

Generative AI Statements: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

Publisher's Note: All claims stated in this article are exclusively those of the authors and do not necessarily represent those of their affiliated organizations those of the publisher, the editors, and the reviewers. Any product that may be evaluated/assessed in this article or claimed by its manufacturer is not guaranteed or endorsed by the publisher/editors.

REFERENCES

Lebaka, V. R., Wee, Y. J., Ye, W., & Korivi, M. (2021). Nutritional composition and bioactive compounds in three different parts of mango fruit. *International journal of environmental research and public health*, *18*(2), 741.

Yahia, E. M., de Jesús Ornelas-Paz, J., Brecht, J. K., García-Solís, P., & Celis, M. E. M. (2023). The contribution of mango fruit (Mangifera indica L.) to human nutrition and health. *Arabian Journal of Chemistry*, *16*(7), 104860.

Sapin, A. B., Alaon, M. K. N., Tambalo, F. M. Z., Perez, R. H., & Gaylon, A. (2021). Evaluation of the bioactivities of natural phenolics from mango (Mangifera indica Linn) leaves for cosmetic industry applications. *Philipp. J. Sci*, *150*, 397-406.

Antwi-Boasiako, A., Amponsah, P., Opoku, J. A., Coulibaly, D., & Mintah, P. (2024). Increasing Mango Production Efficiency under the Fast-Changing Climate. In *Abiotic Stress in Crop Plants-Ecophysiological Responses and Molecular Approaches*. IntechOpen.

Makhmale, S., Bhutada, P., Yadav, L., & Yadav, B. K. (2016). Impact of climate change on phenology of mango-the case study. *Ecology, Environment and Conservation*, *22*(9), S127-S132.

Orr, R., Ibell, P. T., Wilkie, J., Wright, C., & Bally, I. S. (2023). Competition regulates mango fruiting above a floral density threshold. *Scientia Horticulturae*, *321*, 112241.

Silué, Y., Nindjin, C., Cissé, M., Kouamé, K. A., Mbéguié-A-Mbéguié, D., Lopez-Lauri, F., & Tano, K. (2022). Hexanal application reduces postharvest losses of mango (Mangifera indica L. variety" Kent") over cold storage whilst maintaining fruit quality. *Postharvest Biology and Technology*, *189*, 111930.

Lalel, H. J. D., Singh, Z., & Tan, S. C. (2002, August). Elevated levels of CO_2 in controlled atmosphere storage affects shelf life, fruit quality and aroma volatiles of mango. In *XXVI International Horticultural Congress: Issues and Advances in Postharvest Horticulture 628* (pp. 407-413).

Singh, A. K., Rawat, M., Mani, G., Gautam, R., Raj, R., Shah, I., ... & Kumar, V. (2025). Postharvest Physiology of Mango Crops: Understanding Ripening, Quality, and Storage Strategies. *Applied Fruit Science*, *67*(2), 1-14.

Hamdani, A., Bouda, S., Hssaini, L., Adiba, A., Kouighat, M., & Razouk, R. (2024). The effect of heat stress on yield, growth, physiology and fruit quality in Japanese plum 'Angelino'. *Vegetos*, *37*(3), 1061-1070.

Cavalcante, I. H. L. (2022). Mango flowering-factors involved in the natural environment and associated management techniques for commercial crops.

FISCHER, G., ORDUZ-RODRÍGUEZ, J. O., & DO, C. V. T. Sunburn disorder in tropical and subtropical fruits. A review El desorden del golpe de sol en frutos tropicales y subtropicales. Una revisión.

Chin, L., Servent, A., Hor, S., Mith, H., & Bugaud, C. (2024). Predictive models for estimating the sugar content and organic acids in processed mangoes based on the initial content. *International Journal of Food Science and Technology*, *59*(12), 9547-9558.

Lipan, L., Carbonell-Pedro, A. A., Cárceles Rodríguez, B., Durán-Zuazo, V. H., Franco Tarifa, D., García-Tejero, I. F., ... & Hernández, F. (2021). Can sustained deficit irrigation save water and meet the quality characteristics of mango?. *Agriculture*, *11*(5), 448.

Janamatti, A. T., Kumar, A., Kaur, C., Gogoi, R., Varghese, E., & Kumar, S. (2022). Fumigation by bacterial volatile 2, 5-dimethylpyrazine enhances anthracnose resistance and shelf life of mango. *European Journal of Plant Pathology*, *164*(2), 209-227.

KS, S., Laxman, R. H., Geetha, G. A., Rashmi, K., & Kannan, S. (2024). Growth and physiological response of mango (Mangifera indica L.) cv. Alphonso under elevated CO. *J. Hortic. Sci*, *19*, 1.

Wei, S., Mei, J., & Xie, J. (2021). Effects of different carbon dioxide-modified atmosphere packaging and low-temperature storage at 13 C on the quality and metabolism in mango (Mangifera indica L.). *Agriculture*, *11*(7), 636.

Bhardwaj, R. L., Parashar, A., Parewa, H. P., & Vyas, L. (2024). An alarming decline in the nutritional quality of foods: The biggest challenge for future generations' health. *Foods*, *13*(6), 877.

Meena, N. K., Gautam, R., Tiwari, P., & Sharma, P. (2017). Nutrient losses in soil due to erosion. *Journal of Pharmacognosy and Phytochemistry*, *1*(0), 0.

Dar, M. S., Dholakia, B. B., Punekar, S. A., Gupta, V. S., & Giri, A. P. (2023). Volatile profiles of mango (Mangifera indica L.) fruits from natural accessions and cultivated alphonso. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, *93*(3), 659-667.

Xie, H., Meng, L., Guo, Y., Xiao, H., Jiang, L., Zhang, Z., ... & Shi, X. (2023). Effects of volatile flavour compound variations on the varying aroma of mangoes 'Tainong'and 'Hongyu'during storage. *Molecules*, *28*(9), 3693.

Kishore, K., Kumar, D., Srivastava, K. K., Dwivedi, S. K., Mishra, D., Singh, A., ... & Kumar, D. (2024). Evaluation of mango fruit quality in relation to harvest time in the subtropical region of India. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *52*(4), 14157-14157.

Iqbal, S., Atiq, M., Fayyaz, M., Zakria, M., Rajput, N. A., Kachelo, G. A., ... & Mehmood, A. (2024). Powdery mildew of mango: current status, perspective and emerging tools for management. *Agricultural Sciences Journal*, *6*(1), 92-101.

Dofuor, A. K., Quartey, N. K. A., Osabutey, A. F., Antwi-Agyakwa, A. K., Asante, K., Boateng, B. O., ... & Ninsin, K. D. (2023). Mango anthracnose disease: the current situation and direction for future research. *Frontiers in Microbiology*, *14*, 1168203.

Paudel, A., Poudel, P., Yogi, M., Bhattarai, A., & Yadav, P. K. (2022). Insights on the mango anthracnose and its management. *J. Plant Pathol. Res*, *4*, 81-90.

Hammad, H. M., Tariq, T., Saeed, S., Malik, M. T., Siddique, H. F., Jawad, R., ... & Farooque, A. A. (2025). Impact of Climatic Variables on Fruit Bearing Behavior and Disease Incidence in Commercial Mango Cultivars in a Semi-arid Region. *Applied Fruit Science*, *67*(4), 272.

Yang, E. F., Karunarathna, S. C., Tibpromma, S., Stephenson, S. L., Promputtha, I., Elgorban, A. M., ... & Chomnunti, P. (2023). Endophytic fungi associated with mango show in vitro antagonism against bacterial and fungal pathogens. *Agronomy*, *13*(1), 169.

Arya, A., Kumar, R., Chauhan, S., Kumar, N., & Ahad, I. (2024). Seasonal Incidence and Effect of Abiotic Factors on Mango Leaf Hopper (Amritodus atkinsoni L.) Population on Different Cultivars of Mango in Eastern Uttar Pradesh, India. *Journal of Advances in Biology & Biotechnology*, *27*(6), 563-573.

Raza, S. T., Khan, A. H., Hameed, A., Muhammad, N., Grewal, A. G., Malik, M. T., ... & Iqbal, A. (2023). A review on white mango scale biology, ecology, distribution and management. *Agriculture*, *13*(9), 1770.

Aboagye, E. N. G. (2022). *On Farm And Post-Harvest Management Of Mango Stone Weevil (Sternochetus mangiferae F.)* (Doctoral dissertation, University Of Ghana).

Bura, S., Jasrotia, A., Sharma, S., Sharma, A., & Tutlani, A. (2023). Recent advances in breeding of mango (Mangifera indica): a review. *Int J Environ Climate Change.*, *13*, 521-38.

Panigrahy, M., Priyadarshi Paikaray, K., Bhusan, L. P., & Dash, S. (2025). Tolerance Mechanisms and Management Strategies to Combat Heat Stress in Fruit Crops. *Applied Fruit Science*, *67*(4), 265.

Perera-Castro, A. V., Hernández, B., Grajal-Martín, M. J., & González-Rodríguez, Á. M. (2023). Assessment of drought stress tolerance of Mangifera indica L. autotetraploids. *Agronomy*, *13*(1), 277.

Mathiazhagan, M., Chidambara, B., Hunashikatti, L. R., & Ravishankar, K. V. (2021). Genomic approaches for improvement of tropical fruits: fruit quality, shelf life and nutrient content. *Genes*, *12*(12), 1881.

Kaur, N., Awasthi, P., & Tiwari, S. (2020). Fruit crops improvement using CRISPR/Cas9 system. In *Genome engineering via CRISPR-Cas9 system* (pp. 131-145). Academic Press.

Otieno, H. M. (2021). A review of white mango scale (Aulacaspis Tubercularis Newstead; Hemiptera: Diaspididae) in Sub-Saharan Africa: Distribution, impact and management strategies. *Pak. J. Agric. Res*, *34*, 227-238.

Beatrice, O. P., Thomas, R., & Leo, O. (2025). Mango (Magnifera indica) Farming as Influenced by Agronomic and Marketing Channels in Siaya County, Kenya. *Asian Journal of Agricultural and Horticultural Research*, *12*(3), 54-64.

Sillero-Medina, J. A., González-Pérez, J., Hueso-González, P., González-Fernández, J. J., Hormaza-Urroz, J. I., & Ruiz-Sinoga, J. D. (2025). Effect of different deficit irrigation regimens on soil moisture, production parameters of mango (Mangifera indica L.), and spectral vegetation indices in the Mediterranean region of Southern Spain. *Remote Sensing Applications: Society and Environment*, *37*, 101415.

Torres-Quezada, E., Fuentes-Peñailillo, F., Gutter, K., Rondón, F., Marmolejos, J. M., Maurer, W., & Bisono, A. (2025). Remote Sensing and Soil Moisture Sensors for Irrigation Management in Avocado Orchards: A Practical Approach for Water Stress Assessment in Remote Agricultural Areas. *Remote Sensing*, *17*(4), 708.

Vuković, M., Jurić, S., Maslov Bandić, L., Levaj, B., Fu, D. Q., & Jemrić, T. (2022). Sustainable food production: Innovative netting concepts and their mode of action on fruit crops. *Sustainability*, *14*(15), 9264.

Tandel, Y. N., Zala, V. R., & Koti, S. (2025). Impact of High-Temperature on Growth and Development of Fruit Crops. In *Growth and Development in Plants and Their Medicinal and Environmental Impact*. IntechOpen.

Devin, S. R., Prudencio, Á. S., Mahdavi, S. M. E., Rubio, M., Martínez-García, P. J., & Martínez-Gómez, P. (2023). Orchard management and incorporation of biochemical and molecular strategies for improving drought tolerance in fruit tree crops. *Plants*, *12*(4), 773.

Singh, A. K., Rawat, M., Mani, G., Gautam, R., Raj, R., Shah, I., ... & Kumar, V. (2025). Postharvest Physiology of Mango Crops: Understanding Ripening, Quality, and Storage Strategies. *Applied Fruit Science*, *67*(2), 1-14.

Ahmed, A., Mahmud, M. N., & Muniza, N. T. (2025). Post-harvest technology and food processing innovations: Prospects and challenges in Bangladesh. *IJCS*, *13*(2), 93-103.

Handojo, L. A., Shofinita, D., Evelina, G., & Nasution, A. N. (2022, February). Edible coating development to extend shelf life of mangoes (Mangivera indica L.). In *IOP Conference Series: Earth and Environmental Science* (Vol. 980, No. 1, p. 012046). IOP Publishing.

Elsayed, N., Hassan, A. A. M., Abdelaziz, S. M., Abdeldaym, E. A., & Darwish, O. S. (2022). Effect of whey protein edible coating incorporated with mango peel extract on postharvest quality, bioactive compounds and shelf life of broccoli. *Horticulturae*, *8*(9), 770.

Le, T. D., Viet Nguyen, T., Muoi, N. V., Toan, H. T., Lan, N. M., & Pham, T. N. (2022). Supply chain management of Mango (Mangifera indica L.) fruit: A review with a focus on product quality during postharvest. *Frontiers in Sustainable Food Systems*, *5*, 799431.

Rehman, R. N. U., Ali, S., Naz, S., Chen, W., Kalsoom, T., & Khan, M. A. (2025). Climate-Smart Postharvest Management and Value Addition of Mangoes. In *Climate Change and Mango Production* (pp. 269-285). Springer, Cham.

Batool, M., Bashir, O., Amin, T., Wani, S. M., Masoodi, F. A., Jan, N., ... & Gul, A. (2022). Effect of oxalic acid and salicylic acid treatments on the post-harvest life of temperate grown apricot varieties (Prunus armeniaca) during controlled atmosphere storage. *Food Science and Technology International*, *28*(7), 557-569.

Naqvi, S. A. H., Abbas, A., & Ahmad, M. (2025). Innovative Technologies for Surveillance and Management of Mango Tree Diseases and Disorders in a Changing Climate. In *Climate Change and Mango Production* (pp. 819-846). Springer, Cham.

Barrón-García, O. Y., Gaytán-Martínez, M., Ramírez-Jiménez, A. K., Luzardo-Ocampo, I., Velazquez, G., & Morales-Sánchez, E. (2021). Physicochemical characterization and polyphenol oxidase inactivation of Ataulfo mango pulp pasteurized by conventional and ohmic heating processes. *Lwt*, *143*, 111113.

Zahid, G., Aka Kaçar, Y., Shimira, F., Iftikhar, S., & Nadeem, M. A. (2022). Recent progress in omics and biotechnological approaches for improved mango cultivars in Pakistan. *Genetic Resources and Crop Evolution*, *69*(6), 2047-2065.

Muthuramalingam, P., Muthamil, S., Shilpha, J., Venkatramanan, V., Priya, A., Kim, J., ... & Shin, H. (2023). Molecular insights into Abiotic stresses in Mango. *Plants*, *12*(10), 1939.

Mathiazhagan, M., Chidambara, B., Hunashikatti, L. R., & Ravishankar, K. V. (2021). Genomic approaches for improvement of tropical fruits: fruit quality, shelf life and nutrient content. *Genes*, *12*(12), 1881.

Cong, H., Huo, T., Huang, X., Chen, Y., Bai, Y., Luo, H., ... & Qiao, F. (2025). Transcriptome and metabolome analysis of low-temperature storage on fruit quality deterioration of mangoes. *Turkish Journal of Agriculture and Forestry*, *49*(1), 141-152.

Romero, H., Pott, D. M., Vallarino, J. G., & Osorio, S. (2021). Metabolomics-based evaluation of crop quality changes as a consequence of climate change. *Metabolites*, *11*(7), 461.

Shahbaz, M., Seelan, J. S. S., Abasi, F., Fatima, N., Mehak, A., Raza, M. U., ... &Proćków, J. (2025). Nanotechnology for controlling mango malformation: a promising approach. *Journal of Biomolecular Structure and Dynamics*, *43*(5), 2610-2630.

Mahmoud, G. A. E., & Gaber, S. H. (2024). Nanotechnology applications in postharvest disease management. In *Recent Advances in Postharvest Technologies, Volume 2: Postharvest Applications* (pp. 225-245). Cham: Springer Nature Switzerland.

Mosa, W. F., Al-Saif, A. M., Sas-Paszt, L., Górnik, K., & Eladly, R. M. (2024). Effect of the Combined Application of Compost with the Spraying of Some Nano Fertilizers on the Performance of Mango. *Sustainability (2071-1050)*, *16*(23).

Patra, A. K., & Coumar M, V. (2025). Nanotechnology in Agriculture: Harnessing Nanofertilizers for Sustainable Global Food Security. In *Nanofertilizers in Agriculture* (pp. 21-36). Singapore: Springer Nature Singapore.

Khedr, E. H., & Al-Khayri, J. M. (2024). Biosensors and nanosensors for determination of harvest quality parameters and fruit handling processes monitoring. In *Innovative Methods in Horticultural Crop Improvement: Biosensors and Nanosensors* (pp. 143-190). Cham: Springer Nature Switzerland.

Dixit, A., Sonwal, S., Upadhyay, A., Bajpai, V. K., Huh, Y. S., & Shukla, S. (2025). Development and characterization of gold nanoparticle-based colorimetric sensing assay functionalized with L-cysteine for the detection of calcium carbide in ripened mango and banana fruits. *Heliyon*, *11*(4).

Hassoon, I. M. (2022). Classification and diseases identification of mango based on artificial intelligence: A review. *Journal of Al-Qadisiyah for computer science and mathematics*, *14*(4), Page-39.

Kailaku, S., Arkeman, Y., Purwanto, Y. A., & Udin, F. Respiration and Maturity Assessment of Mango (Mangifera Indica Cv. Arumanis) for Long-Distance Transportation Planning in Indonesia. *Available at SSRN 4408014*.

Abdurrehman, Mansoor, T., Hamza, M., Malik, M. T., Hakim, F., Waheed, A., ... & Subhani, M. N. (2025). Mitigation Strategies and Options Forward for the Management of Mango Malformation Disease Under Changing Climate Scenarios. In *Climate Change and Mango Production: Potential Adaptation and Mitigation Options* (pp. 713-737). Cham: Springer Nature Switzerland.