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REVIEW ARTICLE

A comprehensive review on impact of climatic change on adaptability and mitigation in fruit crop

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Abstract

Global warming and climate change are among the most pressing challenges confronting humanity in the 21st century. Climate change will result in rising temperatures, changes in rainfall patterns and an increased occurrence of extreme weather events, such as heatwaves, cold spells, frost days, droughts and floods. The effects of climate change have recently become more evident, with rising temperatures, altered and irregular precipitation patterns and increased extreme weather events. These changes are directly impacting the maturity and development of fruit crops. Heat stress during flowering and fruit set can greatly reduce fruit production, while irregular rainfall may disrupt pollination and heighten the risk of pests and diseases. Furthermore, increased carbon dioxide levels can influence the quality characteristics of fruits. To maintain the ongoing production and sustainability of fruit crops, it is vital to enhance resilience. Focusing on developing new varieties that offer higher yield potential and resistance to various stresses, such as drought, flooding and salinity, is crucial for sustaining crop yields. Additionally, breeding programs should aim to enhance the germplasm of key tropical and subtropical fruit crops to improve heat stress tolerance. Recent advancements in genetic editing technologies present substantial opportunities for the agricultural sector, especially in enhancing fruit crop traits. These innovations can be precisely tailored to meet consumer preferences, which is crucial for driving commercial success. In this review, we strive to provide a comprehensive overview of the current understanding of this important topic, along with recommendations for future research.

Keywords

climate change; CRSIPR/cas9; gene editing techniques; global warming; temperature

Introduction

Climate change will likely have a major effect on water resources and the hydrological cycle, causing the rapid melting of polar ice caps, rising sea levels and shifts in global precipitation patterns. Climate change and food security are two of the most pressing global challenges today, closely linked. It may impact food availability, stability and sustainability by altering the productivity of agricultural systems (1). These transform how sustainable production is planned for in the long term. Crop yields are susceptible to climate variations and worsening food scarcity, which poses a significant challenge on a global scale (2). It can be intensified by human activities such as extensive fossil fuel use and deforestation, exacerbates biodiversity loss (3). Carbon dioxide (CO_2) emissions and climate change represent worldwide apprehensions (4). Furthermore, human-induced global warming stands out as the most alarming issue of the modern era (5). Fruit trees are recognized for their substantial contribution to lowering atmospheric carbon dioxide levels through carbon sequestration (6). Fruit trees are said to absorb significant amounts of atmospheric carbon due to their structural distinctions from annual crops (7). The impact of climate change is exacerbated by multiple stressors and a low capacity for adaptation, which stems from endemic poverty, complicated governance and institutional challenges, limited access to capital, markets, infrastructure and technology, ecosystem degradation, intricate disasters and conflicts (8, 9).

According to the Inter-governmental Panel on Climate Change, this has led to a rise in global mean sea level and extensive melting of snow and ice. These changes also include variations in ocean salinity, wind patterns and elements of extreme weather such as droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.

Methods

Data analysis

To assess the impact of environmental exposures, individual studies were analyzed. For each study, the absolute difference in outcome (yield or nutritional quality) between the baseline and exposure conditions was calculated. These differences were then converted into percentage changes for each study. The findings were subsequently categorized based on the type of environmental exposure (single or combined) and the specific crop (seeds) or crop group (fruits). To facilitate analysis, fruits were categorized into groups based on their shared dietary functions: berries (including grapes and strawberries), pome fruits (including apples and pears), cucurbits (including various melons), citrus fruits (including oranges and lemons), drupes (including peaches and apricots) and bromeliads (including pineapple). To account for the diverse environmental conditions encountered in both field and greenhouse studies, the data from these two experimental settings were combined for this analysis. A sensitivity analysis was conducted to confirm the consistency of findings across both study designs, revealing similar trends in both direction and magnitude of effects. To account for the clustered structure of the data (multiple experiments within each publication), the Huber-White (sandwich) estimator was employed to calculate means, treating each publication as an independent cluster. The impact on nutritional indicators was evaluated separately for each crop group and environmental exposure. Pooled analyses were conducted when a minimum of three publications provided precision estimates for the effect of a specific exposure on crop yield or nutritional quality. All data visualizations and statistical analyses were performed using Stata 15.0 (StataCorp, LLC, College Station, Texas, USA) (10).

Fruticulture leverages advanced models and algorithms to optimize fruit production

Fruit production technology has seen remarkable progress through the application of AI and machine learning in recent years. These technologies are now utilized for sophisticated modeling, image analysis and robotic systems (11). Predictive models, utilizing climate, soil and crop data, assist farmers in making informed decisions about irrigation, fertilization, pest control and management, thereby maximizing crop yields and quality (12). Fruit orchard data inputs commonly include weather, soil, management, tree characteristics, satellite data and historical records (13). Computer vision enables early disease detection and plant growth monitoring, while agricultural robotics automates processes like harvesting and sowing, improving efficiency and reducing labor (14, 15). These innovations are collectively reshaping agriculture towards greater precision, productivity and sustainability.

Data analysis, facilitated by models and algorithms, is reshaping fruit production practices (16). These tools are employed in various areas, including yield forecasting, precision agriculture, pest and disease detection, breeding programs, waste management and market analysis. While early models for perennial crops, such as TREEDYN (17), predated the widespread use of personal computers, modern research leverages AI-powered models on cloud platforms. Fruit tree models are primarily classified based on tree organs' structural, functional and process-related characteristics. This categorization results in three main types: Processed-Based Models (PBM), Functional Structural Plant Models (FSPM) and a combination of both (18). These models can also be categorized based on their data relationship with function or statistical properties, leading to the classification of empirical and mechanistic models (19). Each category offers distinct applications that address diverse aspects of crop management and optimization. Supervised learning algorithms, such as classification and regression models, are valuable tools for tasks like crop categorization and yield estimation. Common machine learning techniques utilized include support vector machines (SVM), decision trees and random forests and artificial neural networks (ANN).

Neural networks demonstrate superior performance in representing complex, non-linear relationships within agricultural data compared to previous techniques that rely on expert-driven feature engineering (20). Deep learning, a specialized type of neural network, leverages multiple layers to effectively extract intricate and abstract patterns from data (21). Decision trees and random forests excel at analyzing complex and noisy datasets. Our current research focus involves leveraging these models to enhance fruit production efficiency. This includes anticipating specific growth conditions and classifying detailed information, such as fruit quality and disease identification. Unsupervised algorithms, particularly clustering methods like K-means and hierarchical clustering, are valuable in this context. These algorithms effectively identify patterns and groupings within the data.

Impact of climate change on the temperature, water cycle and external parameters

This effect causes increased floral abortion and fruit droppings could arise from pollination problems caused by high temperatures. The fruit often ages more gradually and loses taste at these unusually elevated temps. Therefore, at high temperatures, fruit can additionally lose their color. Furthermore, fruit trees that experience are more experienced with various health problems. Fruit cracking, black spots on custard apples and spongy tissue in mangoes are a few examples. Elevated temperatures also affect the cooling requirements of stone fruits and pome, causing their dormancy to break earlier than typical. Mangos with soft tissue experience more severe soft tissue damage when the temperature rises above 40.5 °C. Nonetheless, mango trees can withstand brief periods of up to 48 °C, despite having a low tolerance for low temperatures (22).

More water is expected to be needed in most India's irrigation systems by 2025. Furthermore, compared to the scenario in which environmental change never happens, it is anticipated that worldwide net irrigation requirements will increase by roughly 3.5-5% by 2025 and 6-8% by 2075. According to projections, more water is expected to be needed in nearly every one of India's irrigation systems by 2025. The rapid pace of evaporation had an impact on the remaining 20%. The number of chill unit hours, which are essential for the production of apples, also decreased in these areas (23). Rainfall before the beginning of the season of monsoons is harmful to products including dates and grapevines and it can ruin the harvest entirely. Rainfall during the blooming season removes pollen from flower stigmas, which leads to a poor or non-existent fruit set. Unseasonal rain followed by a strong dew attack during the flowering season caused a significant 80-90% loss in Gujarat's mango crop. These unfavorable weather circumstances caused mango crops to experience decreased fruit set, enhanced fruit drop during the pea stage and an increased prevalence of powdery mildew and sooty Mold (24).

Effect of global warming on food security

Globally, a great deal of research is being done to determine how smallholder farmer's production and access to food may be impacted by climate change (25). However, no one knows how human-caused climate change may affect nearby residences or towns. Due to the difficulty in separating the contributions of climate change from the effects of natural weather variability and human activity (26). As the National Adaptation Programme of Action in Ethiopia (NAPAE) highlights, it is imperative to accurately evaluate the effects of climate change across socioeconomic sectors (27). It is still difficult to assess problems like agricultural effects, productivity, carbon effects, socioeconomic shifts and technological improvements (4). Crop growing seasons are reportedly impacted by climate change (28). Most of the farmers in Ethiopia are small-scale, rain-fed farmers, which makes them especially susceptible to fluctuations in the climate. Semi-arid and dry regions like Afar and Somalia are vulnerable to climate change, according to Ethiopia's regional vulnerability assessments (29). The lowland areas of both the Borena and Tigray regions are experiencing a protracted drought, despite the highlands and midlands of both regions experiencing high levels of agricultural productivity (30).

A spike in flood and drought frequency and intensity will negatively impact crop, animal and tree growth. The growing season will become shorter and less predictable due to climate change, which will affect how well or poorly crops perform. Food production will be severely hampered by climate change-related changes in hydrology and water stresses. Land yield reduction, desertification and soil salinization will drive large areas out of agriculture. It is estimated that by the 2080s, Africa's arid and semiarid landmass will have expanded by 5% to 8%, reducing the amount of suitable rain-fed area for cultivating cereals. Climate change will impact fish stocks and marine environments, creating greater challenges for older fishermen as they strive to sustain their essential sources of food and income for coastal residents. Climate change will exacerbate nutrition-related health problems in Africa, impacting the workforce essential for agricultural production and food supply. This, in turn, will have implications for other public health challenges, as a substantial portion of the population relies on agriculture for their livelihoods. Temperature and other climate changes could increase or alter the occurrence of pests and diseases, along with the levels of mycotoxins in food and animal feed crops.

Research suggests that pests - like aphids and weevil larvae - respond well to rising carbon dioxide (carbon dioxide) emissions and shifting weather patterns. The elevated danger for novel insect outbreaks is another effect of these changes in climatic factors. Extreme temperatures and increased CO_2 have been shown responsible for a 12% and 35% drop in yields of fruit in strawberries. At high levels of CO_2 and temperatures, fruit results decreased due to fewer inflorescences and smaller umbels during flower induction.

Effect of temperature

The global warming trend will become more pronounced as temperatures rise, leading to regular extreme heat regimes spreading into higher latitude regions. The growth and development of plants are significantly impacted by the rise in the earth's surface temperature, especially on land (31). Intense and frequent extreme weather events may also encourage the spread of diseases into new regions and they may adapt to infect different plant species and/or become more virulent (32). Temperature and the length of the development cycle will likely affect the crop's water demand, impacting its water status, especially in arid and semi-arid regions.

Climate change can cause blossom drop and the generation of malformed underdeveloped berries due to an increase in the frequency of significantly higher daytime and nighttime temperatures (31, 33). The substantial effect of temperature on fruit growth points to possible difficulties in production in the future. High temperatures, particularly when coupled with strong sunshine, can cause sunburn, uneven ripening, changed textures and a reduction in nutritional value. These effects will lower the fruits' overall taste together with appearance and lower their market value. Furthermore, the direct application of melatonin to plants or its inclusion in their nutrient regimen can improve their tolerance to temperature stress and aid in fruit development. Melatonin can boost antioxidant activity in fruits, resulting in enhanced shelf life and overall quality (34).

Freezing temperatures have the potential to cause harm to the membranes of cells, decrease the efficiency of scavenging enzymes, cause protein instability and delay the setting of fruit and flowering, all of which can obstruct fruit growth (35). Freezing temperatures can ultimately result in a decreased sugar content and a worse grade of flavor. Fruit growers can protect their crops from severe cold and freeze injury by using frost blankets, modifying the microclimate, selecting cold-hardy fruit cultivars, pruning their fruit crops with their plan and using PGRs with the value brassinosteroids and abscisic acids.

Extreme temperatures often impede fruit maturity and diminish overall fruit quality. The appropriate improvement of color in fruits. Moreover, such circumstances tend to improve the transmission of many different physiological disorders in fruit crops. Mango fruits have a spongy skin, which gets worse when the temperature rises beyond 40.5 °C. However, mango trees are capable of weathering temperatures as high as 48 °C for brief durations, however, they have limited endurance to cold temperatures. From sea level to as high as 2100 meters, citrus is grown. Nonetheless, a temperature range of 2 °C to 30 °C is thought to be best for growth. Citrus fruit trees can sustain deterioration from prolonged exposure to temperatures below 0 °C and their development is hampered by dips below 13 °C. Regarding its nutritional content, physical attributes and biochemical markers, the dragon fruit varies. Variables in the environment like temperature, humidity, light intensity and substance might represent the source of these changes.

Impact of light on fruit development, colour and flavour

The light interaction of these components controls physiological processes in the plant and affects fruit development, quality and yield in Fig. 1. The impact of light exposure on the quantity and/ or quality of certain fruits, such as grapes. Light has a major effect on the growth and development of fruit, affecting several aspects like intensity, length and quality. These essential metabolites also affect the fruit's taste and odor since elements like vitamin C are directly impacted by light availability. Moreover, light availability influences the production of secondary metabolites like anthocyanins, phenolic acids and carotenoids. Secondary metabolites are key in enhancing fruit quality by contributing to aroma, color and nutritional value, catering to consumer demand for high-quality produce. They also help protect fruits from environmental stress, particularly during postharvest storage. Light also influences the regulation of plant hormones, including auxins, cytokinins, gibberellins, abscisic acid and ethylene, which govern different stages of fruit development and ripening.

Importance of fruit trees to a sustainable environment

Planting fruit trees is essential for our future prosperity since they greatly preserve the world's natural balance (36). Planting trees and vegetation near highways and parking areas is an effective mitigation measure (37). In addition, vegetation helps reduce urban heat by offering shade and promoting evapotranspiration, as trees naturally cool the environment (38). It absorbs less heat and less radiation from areas directly exposed to the sun, for instance (39). Thereby planting deciduous trees or vines to the west of a building has been reported to be the most effective way to cool it, it is reported that shaded surfaces remain cooler by 11 to 25°C, especially if they shade the windows and part of the roof (40). Moreover, the diversity of crops is significantly increased by the comparative monoculture integration of fruit trees with other plant species, thereby enhancing the richness of certain species without affecting yields (41).

During the gas-exchanging process, the trees play a role in enhanced air quality and purification of the air (42). The process by which fruit trees use sunshine to change the gases carbon dioxide and water into oxygen and glucose is called photosynthesis (43). Fruit trees are subsequently essential to the global ecology, helping to regulate carbon dioxide and oxygen. Fruit trees may maintain multiple individuals at a time at about four feet tall because they release up to 15 tons of oxygen per acre and absorb 10-20 tons of carbon dioxide annually shown in table 1(44).

The plants can purify or filter the air by absorbing carbon dioxide and releasing fresh oxygen into the atmosphere. Foot-tall plants, such as apple trees, may support four people by absorbing 10-20 tonnes of carbon dioxide annually and releasing up to 15 tons of oxygen into the atmosphere per acre. The process of photosynthesis is the mechanism by which fruit trees use sunshine to change carbon dioxide and water into glucose and oxygen.

Adaptation of fruit trees to climate change

Plants exposed to environmental stress, trees adopt structural adaptations to cope, including reducing water loss by closing their

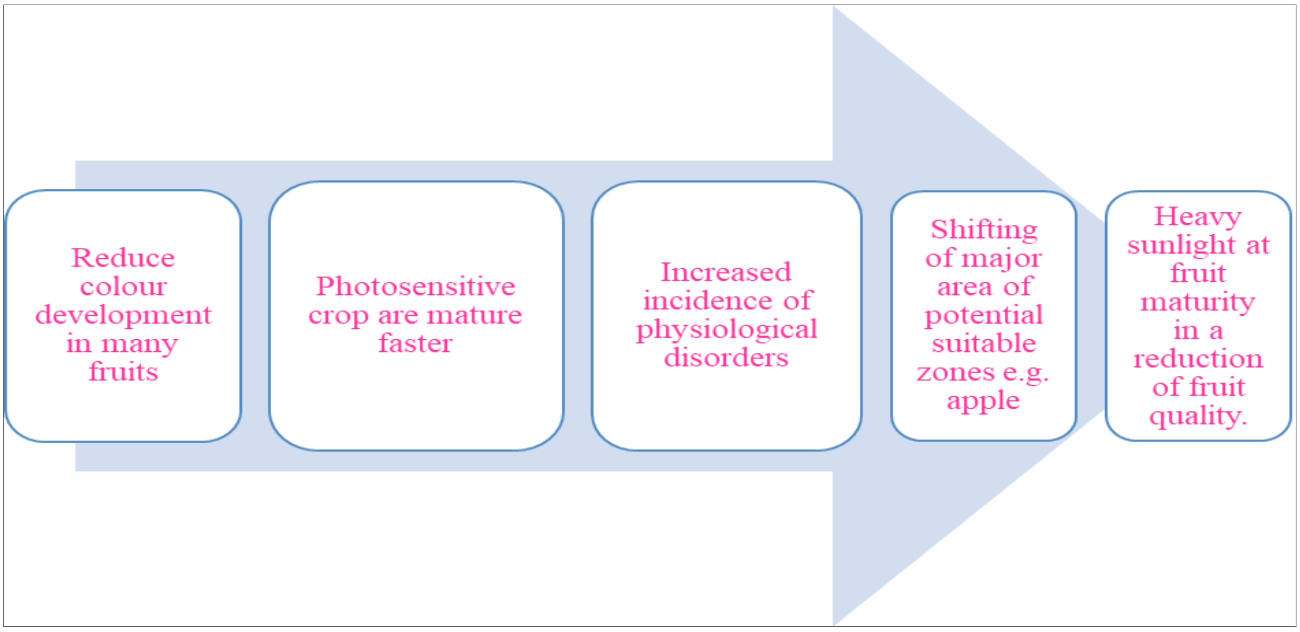

Fig. 1. Impact of light on fruit.

Table 1. Fruits are linked with certain carbon footprint values

Sl. No	Type of fruits	Mean value of carbon concentration	References
1.	Apples	0.24 kg (0.53 lbs)	(71)
2.	Apricot	0.16kg (0.36lb) CO_2 e/kg	
3.	Avocado	0.19 kg CO_2 e/kg	
4.	Banana	0.21 kg (0.48 lb) CO_2 e /kg	
5.	Blueberries	0.45kg (1lb) of CO_2 e/kg	
6.	Cherry	0.584 kg CO_2 e/kg	
7.	Dragon fruit	0.9 kg CO_2 e/kg	
8.	Grape	0.64 kg (1.42 lbs) CO_2 e/kg	
9.	Guava	0.15 kg CO_2 e/kg	
10.	Jack fruit	0.9 kg CO_2 e/kg	
11.	Kiwifruits	0.9 kg CO_2 e/kg	
12.	Lemons, Orange and Limes	0.3kg (0.66 lbs) CO_2 e/kg	(71)
13.	Mango	0.21 kg (0.46 lbs) CO_2 e/kg	
15.	Papaya	0.3kg (0.67lb) of CO_2 e/kg	
16.	Passion fruit	0.77 kg CO_2 e/kg	
17.	Peach	0.17kg (0.38lbs) CO_2 e/kg	
18.	Pear	0.34 kg CO_2 e/kg	
19.	Pineapple	0.09 kg (0.20 lb) CO_2 e/kg	
20.	Plum	0.4 kg (0.88 lbs) CO_2 e/kg	(71)
21.	Pomegranate	0.39kg (0.87lb) CO_2 e/kg	
22.	Raspberries (Aggregate fruit)	0.15kg (0.33lb) of CO_2 e/kg	
23.	Strawberry	0.39kg (0.88lb) CO_2 e/kg	

stomata. This response, a significant marker of drought stress, leads to a decline in the activity of photosynthetic enzymes such as ribulose-1,5-bisphosphate carboxylase/oxygenase (45). Moreover, under drought conditions, plants adapt by reducing the number of stomata to conserve water and better manage limited water resources. Maintaining orchard productivity under climate change and abiotic stresses requires several measures. Implementing appropriate agricultural practices, ensuring adequate nutrient supply, preserving soil moisture and utilizing drought and/or salinity-tolerant rootstocks are essential. Additionally, the external application of plant growth regulators can significantly contribute to sustaining fruit orchard production in challenging climatic conditions (46).

Physiologically adaptations

The stress process helps combat reactive oxygen species (ROS) and photoinhibition by elevating glucose, malate and proline levels, which support osmotic regulation. To adapt to drought, plants employ strategies such as drought escape, tolerance and avoidance, though these approaches often overlap and lack clear distinctions (30). For example, under drought and elevated temperature conditions, citrus trees, especially those grafted onto Cleopatra rootstock, enhance the biosynthesis of flavonoids to reduce oxidative damage.

Jasmonic acid (JA) biosynthesis is a key physiological mechanism that helps plants adapt to stressful conditions. JA is produced through the involvement of various plastids, cytoplasmic enzymes and peroxisomes. It plays a beneficial role in enhancing salt tolerance by regulating plant development under salinity stress. Applying JA as a foliar spray boosts the salinity tolerance of fruit trees, improves their vigor and enhances productivity (47).

Role of potassium in plant cell

Potassium (K^+) is a charge-balancing ion within plant cells and the cytosol. Maintaining potassium (K^+) homeostasis is essential for plants to tolerate stress effectively (48). The ability to retain potassium (K^+) in mesophyll cells is a key strategy for achieving salt tolerance, although different plants exhibit varying capacities for potassium retention (49).

Under stress conditions, potassium (K^+) balance in plant cells is disturbed, resulting in K^+ loss during soil salinity stress due to two main reasons, activation of caspase-like proteases and endonucleases. The inevitable sodium (Na^+) influx triggers abrupt membrane depolarization and interferes with transporting vital elements across the plasma membrane.

Providing plants with adequate potassium under saline conditions helps alleviate the harmful effects of salinity stress (50).

Cultivar selection and breeding

Trees have developed anatomical adaptations to withstand environmental stress. One such adaptation is the closure of stomata, which reduces water loss and is a key indicator of drought stress. This closure can lead to decreased activity of photosynthetic enzymes, such as Rubisco. Certain apple and grape varieties have been engineered to tolerate warmer temperatures. "Fuji" and "Tsugaru" apples have been modified to ripen more quickly. Newer cultivars, including "Kinshu", "Beniminori", "Morinokagayaki", "Shine-muscat", "Queen Nina", "Gross Krone" and "Rinka" have also been introduced. These new varieties offer enhanced color, reduced color-related problems and greater resistance to adverse weather conditions.

Japanese peach cultivars require long exposure to low temperatures to complete endo dormancy to achieve flower bud break. In contrast, some foreign peach cultivars require only a short chilling period to complete endodormancy. However, these cultivars generally lack the superior quality of Japanese varieties. To address this, a new peach cultivar, “Sakuhime,” which combines a low chilling requirement with excellent fruit quality, was developed by hybridizing foreign cultivars with Japanese ones (51).

Advanced crop improvement through genetic engineering and molecular techniques for selecting new varieties with desirable traits

Crop improvement focuses on enhancing both yield and quality. Although recent advancements in agricultural technology have boosted productivity, there is now a heightened emphasis on meeting consumer preferences for higher-quality produce. A variety of methods have been utilized to improve crop traits, such as conventional breeding, mutation breeding, molecular marker-assisted breeding and genetic engineering. Although genetically modified crops have shown success, concerns continue to exist regarding their health and environmental implications. Advances in genetic engineering and molecular techniques have significantly changed the landscape of plant breeding, allowing for the precise and efficient selection of varieties with targeted traits shown in Fig. 2.

Plant genetics has been precisely and particularly altered through gene editing using CRISPR/Cas9 (clustered regularly

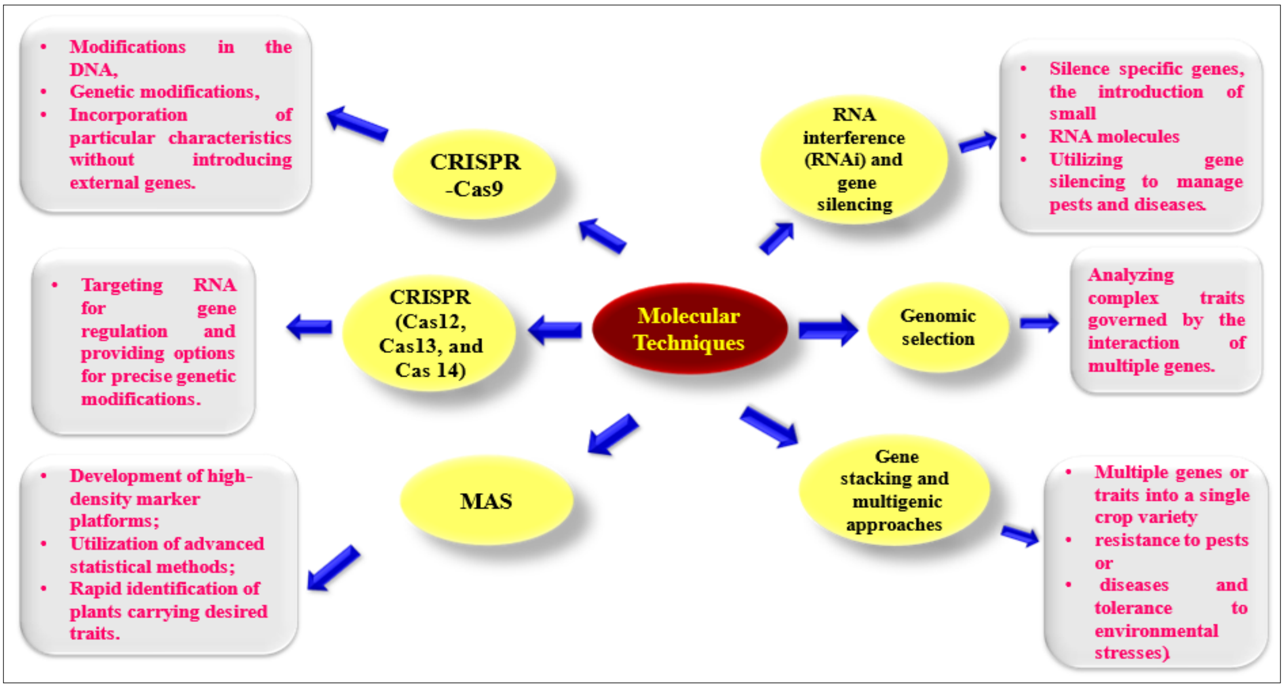

Fig. 2. Developments in genetic engineering and molecular techniques.

interspaced short palindromic repeats). These developments have changed the area of genetic manipulation. The efficiency and accuracy of these alterations have been improved further with current advances in CRISPR approaches, such as base editing and prime editing. This eliminates the requirement to introduce foreign genes to introduce particular features (52, 53). Technologies Using CRISPR-Cas with Cas9, various other systems using CRISPR-Cas have been studied and investigated with potential uses in the regulation of genes and editing of the genome, including Cas12, Cas13 and Cas14. These systems also provide other functions, including RNA (Cas13) targeting for gene regulation and alternate alternatives for precise genetic changes (54). High-throughput sequencing and omics technologies have grown affordable and widely available, enabling the thorough investigation of genomes, transcriptomes and proteomes on a massive scale. This allows for the quick discovery of genes linked to desired features. The selection of excellent breeding candidates is aided by this knowledge (55). Marker-assisted selection (MAS) is a breeding and selection methodology involving genetic markers related to genes or phenotypes. Modern statistical techniques and the development of high-density marker platforms have increased MAS's effectiveness, making it possible to identify plants with desired characteristics more quickly and accurately (56). Genomic selection refers to the process of evaluating the plant's effectiveness using its complete genome as opposed to specific indicators. Improvements in artificial intelligence and biological computation have improved the precision of genetic prediction models. This method helps with complicated features that are influenced by several genes (57). The fields of synthetic biology and gene synthesis, which entail the design and construction of novel biological components and apparatuses, have demonstrated increased efficiency and economy in the process of producing synthetic genes or pathways. This makes it possible to develop crops with unique features or to optimize already-existing pathways (58). Gene silence and RNA interference (RNAi) are two methods for downregulating or suppressing genes by inserting tiny RNA molecules. It is now a helpful instrument for directed gene silencing, especially for the management of illnesses and pests, mainly to improve delivery techniques and a better understanding of RNA interference mechanisms (59). Breeders may develop varieties of crops with resistance to several pests and diseases as well as tolerance to a range of environmental challenges by integrating multiple genes or traits into a single variety through gene stacking and multigenic techniques (60). The combined effect of these developments is the development of superior features in crops, addressing issues like higher yields, disease and pest resistance, improved stress tolerance and pleasing sensory attributes. Future developments in technology should bring about ever more advanced and focused methods of plant breeding.

Important endonucleases for gene editing aimed to improve crops' sensory traits and consumer acceptance

Enzymes known as specific to the sequence nucleases, or SSNs, add, remove, or modify sequences of DNA to generate mutations at specific sites (61). These SSNs, which may be classified into three categories (TALENs, ZFNs and CRISPR/Cas9), are widely employed in genome editing processes (62). According to present EU criteria, ZFNs, TALENs and plants that utilize methods for genome editing, including CRISPR, may not be classified as genetically modified organisms (GMOs). This could shift Europeans' attitudes toward GMOs and create new business prospects for improved fruit crops.

Editing genes using CRISPR/Cas9 innovation

Due to its great effectiveness and versatility in modifying the DNA in various organisms, the combination of CRISPR and Cas9 is a groundbreaking genome editing tool that has drawn much interest. Derived from the bacterial and archaeal adaptive immune systems. The CRISPR technique, which was initially developed by bacteria as a defence against viral infections, has been successful in editing the genomes of plants (63, 64) shown in Fig. 3.

The two main components of the CRISPR/ Cas9 system are the Cas9 nuclease and the guide RNA (gRNA). The

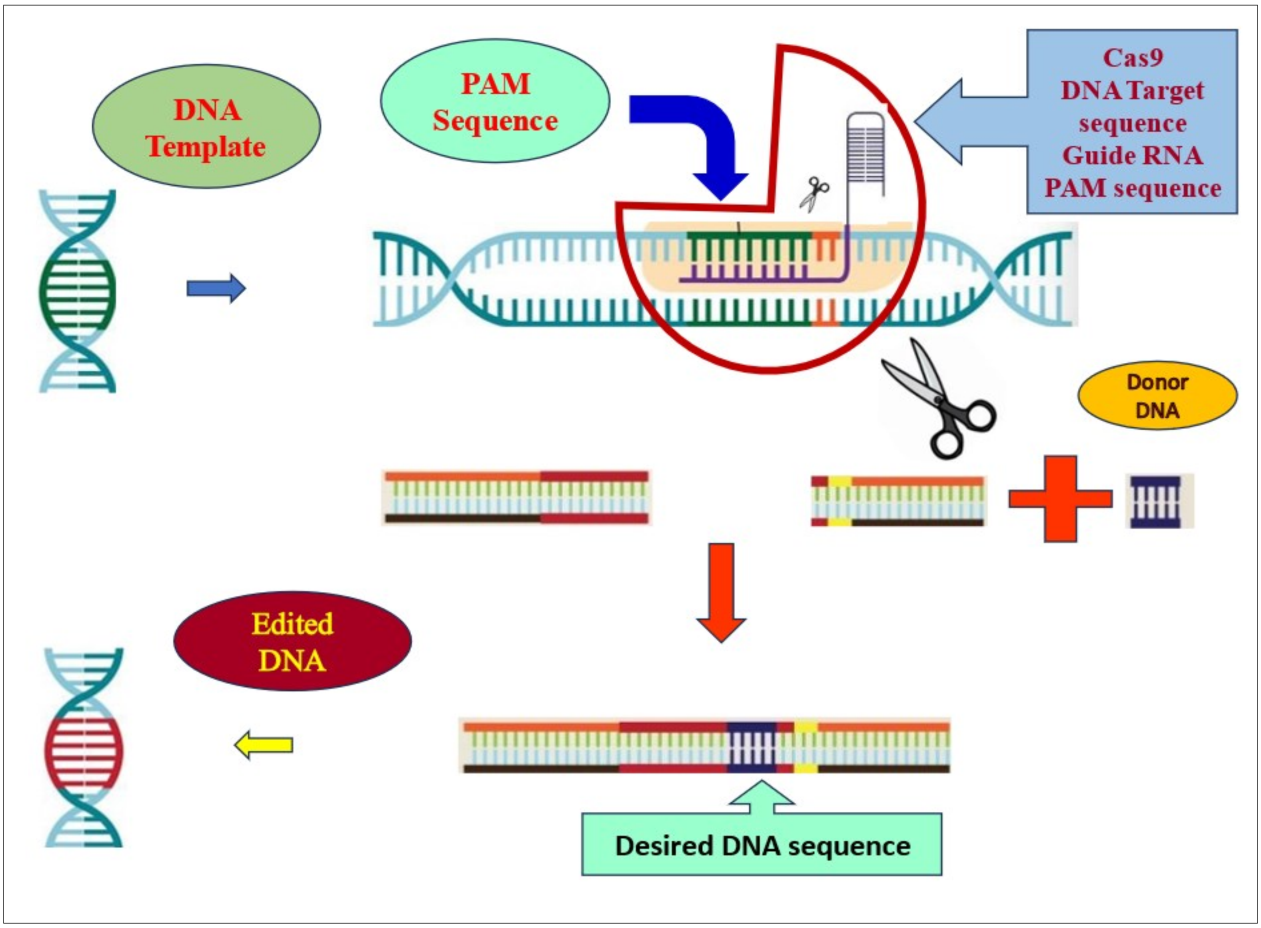

Fig. 3. A diagrammatic representation of CRISPR/Cas9 gene editing mechanism.

mechanism of CRISPR utilizes RNA-DNA binding for its sequence target specificity, in contrast to ZFNs (zinc finger nucleases) and TALENS (transcription-activator-like effector nucleases), which depend on protein-DNA interaction. A protospacer adjacent pattern (PAM) domain and two RNA-binding domains make up the recognizing domain of the Cas9 nuclease, assisting in its binding to the target DNA (65). With the aid of the HNH and RuvC -like nuclease modules found inside the Cas9 protein, the nuclease domain 20 of 42 of Cas9 breaks down the DNA at the target position, resulting in double-strand breaks (DSBs) at the target DNA sequence (66).

CRISPR-Cas9 (clustered regularly interspaced short palindromic repeats) and genome editing have revolutionized genetic modification, allowing for precise and targeted changes in plant DNA. Continuous developments in CRISPR technology, such as base and prime editing, have increased the efficiency and accuracy of these genomic modifications. This allows for the introduction of desirable features while avoiding the use of foreign genes.

Heat tolerance

Phenological alterations caused by heat stress have been extensively documented in various grape varieties. High temperatures have been found to stimulate plant developmental processes like organogenesis and leaf area expansion, although they slightly reduced the carbon balance. Notably, heat stress led to increased biomass allocation to vegetative parts and had a significant negative impact on grape berry development. Brief periods of elevated temperatures during berry development also delayed the onset of veraison.

Several genes, including *VvGolS1*, *VvHsfA2* and *VvMBF1c*, have been identified as being expressed in grape berries under heat stress. However, further research is needed to clarify their exact roles in responding to high-temperature stress. Various transcription factors from the *VvbHLH* and *VvAP2/ERF* families have also been recognized as heat-responsive genes (67, 68). Grapevines initiate various physiological processes when the average temperature reaches approximately 10 °C; however, plant adaptation mechanisms are triggered at temperatures exceeding 35 °C (69).

Cold tolerance

Due to its superior resistance to low-temperature stress, *Vitis amurensis* was chosen as the experimental material for studying the expression of *VaIAA* genes in grapes (70). To gain deeper insights into the expression patterns of *VaIAA* genes under cold stress, the expression levels of 18 *VaIAA* genes in grapevine phloem subjected to low-temperature treatment were examined using *qRT-PCR*. *qRT-PCR* results showed that the expression patterns of the 18 *VaIAA* genes in the phloem of the branches of *V. amurensis* were different during different temperature periods. With the prolongation of low-temperature treatment, the expression levels of *VaIAA3*, *VaIAA7* and *VaIAA9* reached the highest in the period and were up-regulated by 26.7, 41.7 and 47.05-fold, respectively, compared with that in the A period. VaIAA3 exhibited varying levels of induction across the different stages of low-temperature exposure. Conversely, the expression levels of *VaIAA12*, *VaIAA14*, *VaIAA15*, *VaIAA16*, *VaIAA17* and *VaIAA18* decreased as the temperature dropped. Meanwhile, *VaIAA2*, *VaIAA3*, *VaIAA4*, *VaIAA5*, *VaIAA6*, *VaIAA7*, *VaIAA8*, *VaIAA9*, *VaIAA10* and *VaIAA11* were significantly upregulated, although their expression was downregulated during other periods. These findings indicate that cold stress triggers the expression of certain *VaIAA* genes.

Conclusion

The impacts of climate change on horticultural crops require a multifaceted approach. This includes developing heat-tolerant, through advanced genomic research and stress physiology studies. Molecular markers and high-throughput genotyping, gene-based selection can be enhanced, broadening the genetic pool for improved stress tolerance. Adaptation of current horticultural practices and responsible resource management and maintaining future productivity. Integrating horticultural technologies will be essential for overcoming these challenges.

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Authors' contributions

RVS wrote the original draft and conceptualized the research. RJ conducted the revision of the draft, the inclusion of tables and figures, proofreading. SS contributed to the revision, formatting and supervision. All the authors read and approved the final version of the manuscript

Compliance with ethical standards

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