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Advancing Fruit Breeding for Climate-Resilient and Sustainable Production

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Climate change is expected to have a significant impact on water resources and the natural water cycle. The melting of polar ice caps, rising sea levels and changes in rainfall patterns are some of the major consequences already being observed. Climate change is also closely connected with food security because changes in temperature and rainfall can affect agricultural productivity, which in turn influences the availability, stability and sustainability of food production (Nguyen et al., 2024).

The effects of climate change become more serious when communities have limited capacity to adapt. Poverty, weak governance, lack of financial resources, limited access to markets, infrastructure and modern technologies, environmental degradation, natural disasters and conflicts can make adaptation more difficult (Shivanna, 2024). Human activities, particularly the excessive use of fossil fuels and deforestation, further increase climate-related problems and contribute to the loss of biodiversity. Rising carbon dioxide (CO_2) emissions are therefore a major global concern, highlighting the need for effective measures to reduce emissions and strengthen climate resilience (Abbass et al., 2022).

Global warming and climate change are among the major challenges facing humanity in the 21st century. Rising temperatures, changing rainfall patterns and the increasing frequency of extreme weather events such as heatwaves, cold spells, droughts and floods are already affecting agricultural production. These changes are particularly important for fruit crops because their growth, flowering, fruit development and maturity are highly sensitive to environmental conditions.

High temperatures during flowering and fruit set can reduce pollen viability, affect fertilization and ultimately lower fruit production. Similarly, irregular and unpredictable rainfall can interfere with pollination and create favourable conditions for pests and diseases. Increasing levels of carbon dioxide may also influence important fruit quality characteristics. As climate-related stresses continue to increase, maintaining stable and sustainable fruit production will require the development of more resilient crops. Therefore, future breeding efforts should focus on producing fruit varieties with good yield potential and improved tolerance to major stresses such as heat, drought, flooding and salinity (Sundarrajan et al., 2024).

Advances in molecular biology and digital agriculture are transforming the breeding process. Genome-wide markers, genomic prediction, high-throughput phenotyping, multi-omics and genome editing can shorten selection cycles and improve the identification of desirable genotypes. In fruit crops, genomic selection is particularly promising because long juvenile phases and expensive phenotyping make conventional selection inefficient. Studies in apple and citrus have demonstrated the potential of genomic prediction for complex fruit-quality traits.

Climate Change as a New Breeding Challenge in Fruit Crops

A. Temperature rise and heat stress

Temperature is one of the most important environmental factors controlling fruit-tree growth, flowering, fruit development and maturation. Increasing temperatures can accelerate phenological development, shorten developmental periods and disrupt the synchronization between flowering and pollinator activity. Heat stress may also reduce pollen viability, impair fertilization and decrease fruit set. In temperate fruit crops, warming can reduce winter chilling and cause irregular bud break and flowering. Such changes are particularly important in apple, peach, plum and related crops because successful flowering depends on the interaction between chilling and heat accumulation. A mismatch between chilling requirements and future temperature patterns can consequently reduce yield stability. Tropical and subtropical fruits experience different problems. Mango, banana, citrus and papaya may tolerate relatively high temperatures, but excessive heat can reduce fruit quality, accelerate ripening and increase physiological stress. Heat may also interact with drought, creating combined stress conditions that are more difficult to manage than individual stresses. Therefore, future breeding programs should evaluate genotypes under realistic combinations of heat and water stress rather than considering temperature tolerance in isolation.

B. Drought and water scarcity

Water scarcity is becoming a major limitation in fruit production, particularly in arid and semi-arid environments. Drought reduces vegetative growth, photosynthesis, fruit size and yield and can alter soluble solids and fruit maturation. Long-lived fruit trees require reliable water availability over many seasons, making drought resilience a particularly important breeding objective. Breeding for drought adaptation should consider both above-ground and below-ground characteristics. Important traits include efficient stomatal regulation, deep and extensive root systems, osmotic adjustment, water-use efficiency, maintenance of photosynthesis under stress and rapid recovery after rehydration. Rootstocks are especially important because they influence water uptake, nutrient acquisition, tree vigour and stress tolerance. Selection of drought-adapted rootstocks can therefore provide an important component of climate-resilient orchard systems.

C. Salinity, flooding and other abiotic stresses

Climate change can increase salinity risks through irrigation dependence, groundwater depletion and increased evaporation. Excess salts interfere with water uptake and ion balance and may cause toxicity. Similarly, intense rainfall and poor drainage can create temporary waterlogging and oxygen deficiency around roots. Future fruit breeding should therefore move toward **multiple-stress resilience**, combining drought, salinity, heat and waterlogging tolerance where appropriate. This is important because farmers rarely experience one environmental stress at a time.

D. Changing pest and disease pressure

Climate change also changes the geographical distribution, reproduction and seasonal activity of pests and pathogens. Warmer and more humid environments may favour several insect pests and fungal diseases. Consequently, disease resistance and pest tolerance must be integrated with abiotic-stress resistance. Breeding resistant cultivars can reduce dependence on pesticides and therefore contribute directly to sustainable production. Genome-wide studies and molecular breeding can assist in identifying resistance loci and incorporating them into elite cultivars.

Breeding Objectives for Climate-Resilient and Sustainable Fruit Production

A. Yield stability

Yield stability should become a primary selection criterion. A cultivar that produces exceptionally high yields in favourable years but suffers severe losses during drought or heat may be less useful than a moderately high-yielding genotype with consistent performance across environments. Multi-environment trials are therefore essential. Genotypes should be evaluated across contrasting temperature, rainfall, soil and management conditions to identify stable performers and genotype × environment interactions.

B. Fruit quality and nutritional value

Climate resilience should not be achieved at the expense of fruit quality. Heat and water stress can alter sugar-acid balance, firmness, colour, aroma and antioxidant composition. Therefore, breeding programs should simultaneously evaluate stress tolerance and quality attributes. Nutritional improvement is also increasingly important. Genomic and metabolomic approaches can support selection for antioxidants, vitamins, minerals, polyphenols and other beneficial compounds. The integration of nutritional traits into climate-resilient breeding can provide both agricultural and public-health benefits.

C. Water-use and nutrient-use efficiency

Future cultivars should produce acceptable yields with lower water and fertilizer requirements. This objective is particularly relevant to sustainable intensification because improved resource-use efficiency reduces production costs and environmental pressure. Root architecture, stomatal behaviour, nutrient uptake and plant–microbe interactions should therefore receive greater attention in breeding programs.

D. Resistance to pests and diseases

Climate-resilient cultivars should possess durable resistance against major and emerging pests and diseases. Genetic resistance can reduce pesticide requirements and contribute to biodiversity conservation by reducing chemical pressure on beneficial organisms.

The integration of resistance breeding with biological control and integrated pest management is particularly important because genetic resistance alone may not provide permanent protection.

Genetic Resources and Conventional Breeding as the Foundation of Climate Resilience

A. Landraces, traditional cultivars and wild relatives

Traditional cultivars and wild relatives often contain adaptive traits that have been lost during intensive selection for commercial characteristics. These materials may possess drought tolerance, disease resistance, salinity tolerance, heat adaptation or unusual root characteristics. The conservation and characterization of germplasm should therefore be treated as a central component of climate-resilient breeding. Genetic resources should be evaluated not only for conventional fruit traits but also under stress environments.

Recent climate-change research emphasizes that breeding programs need access to genetic diversity originating from marginal and stress-prone environments.

B. Conventional hybridization and pre-breeding

Crossing remains fundamental to fruit improvement. Conventional hybridization can combine desirable traits from different parents and generate populations for subsequent selection. However, introgression from wild relatives may introduce undesirable characteristics, creating linkage drag. Pre-breeding is therefore important for transferring useful alleles from exotic and wild materials into agronomically acceptable backgrounds before these materials are used in commercial breeding. In perennial fruit crops, however, long juvenile phases make conventional selection expensive and time-consuming. This is one reason molecular breeding has become increasingly important.

C. Rootstock breeding

Rootstocks deserve greater attention in climate-resilient fruit production. Rootstocks influence water acquisition, mineral nutrition, vigour, canopy development and tolerance to environmental stresses. Climate-adapted rootstocks can therefore be combined with high-quality scion cultivars to create resilient scion–rootstock combinations. Such combinations may provide greater flexibility than attempting to place every desirable trait into a single cultivar.

High-Throughput Phenotyping, AI and Genome Editing in Fruit Breeding

A. High-throughput phenotyping

One of the major limitations in fruit breeding is not necessarily the availability of genomic information but the difficulty of measuring phenotypes accurately and repeatedly.

High-throughput phenotyping can use RGB cameras, multispectral and hyperspectral imaging, LiDAR, thermal sensors, drones and automated platforms to characterize canopy structure, plant vigour, water stress, disease symptoms, fruit size, colour and other traits.

The development of the "digital orchard" is particularly relevant to perennial fruit breeding because sensors can collect large numbers of observations while reducing manual measurement. Recent reviews identify high-throughput phenotyping as one of the central pillars of emerging digital breeding systems in apple.

B. Artificial intelligence and machine learning

Artificial intelligence can integrate genomic, phenotypic, environmental and climatic information to improve breeding decisions. Machine-learning algorithms can identify complex relationships between genotype, phenotype and environment that may not be captured by conventional statistical models.

AI-assisted prediction can help breeders prioritize parents, identify promising seedlings and predict performance under future environmental conditions. Recent work in genomic prediction demonstrates continued progress toward more robust machine-learning approaches for genotype-to-phenotype prediction.

C. CRISPR and genome editing

Genome editing provides an opportunity to modify specific genes or regulatory regions associated with important traits. CRISPR/Cas systems have been investigated for improving resistance to biotic and abiotic stresses and for modifying quality-related characteristics in horticultural crops. For climate-resilient fruit breeding, potential targets include genes associated with drought response, disease resistance, plant architecture, fruit ripening, shelf life and stress signalling. However, genome editing should be regarded as a complementary tool rather than a universal replacement for conventional breeding. Many climate-resilience traits are polygenic and strongly influenced by the environment. Consequently, genome editing is likely to be most effective when integrated with genomic information, functional genomics and precise phenotyping.

D. Integrating genomic selection and genome editing

A particularly promising future strategy is the combination of genomic selection with genome editing. Genomic selection can identify high-value genetic backgrounds and predict complex traits, while genome editing can modify specific genes or alleles.

Such integration could reduce the time required to develop climate-adapted cultivars while maintaining desirable fruit quality. However, validation under field conditions remains essential because laboratory performance does not necessarily translate into stable performance under diverse orchard environments.

Integrating Climate-Resilient Breeding with Sustainable Orchard Systems

Genetically improved cultivars cannot achieve sustainability independently of orchard management. The strongest approach is to combine genetic improvement with ecological and technological management.

A. Soil health and plant–microbe interaction

Climate-resilient cultivars should be evaluated within soil systems that support biological activity and nutrient cycling. Compost, vermicompost, biochar, cover crops and beneficial microorganisms can improve soil structure, nutrient availability and water retention. Plant-growth-promoting rhizobacteria and mycorrhizal fungi may also increase nutrient acquisition and stress tolerance. Therefore, future breeding programs should consider genotype × microbiome interactions rather than treating the plant genotype as an isolated unit.

B. Water-efficient orchard systems

Breeding for drought tolerance should be combined with drip irrigation, soil-moisture monitoring, mulching, rainwater harvesting and precision irrigation. The supplied material reports that micro-irrigation can substantially improve water-use efficiency, while sensor-based irrigation enables more precise scheduling. This suggests a shift toward genotype × management × environment breeding, where cultivars are selected according to their performance under realistic sustainable management systems.

C. Biodiversity and ecosystem services

Climate-resilient orchards should conserve pollinators and natural enemies. Intercropping, agroforestry, cover crops, flowering strips and habitat corridors can improve biodiversity and ecosystem services. Breeding programs should therefore consider compatibility with diversified orchard systems. For example, cultivars with improved disease resistance can reduce pesticide pressure and support greater biological diversity.

D. Carbon sequestration and low-carbon production

Perennial orchards can contribute to carbon storage through biomass and soil organic carbon. Regenerative management practices such as cover cropping; organic amendments and reduced soil disturbance can further improve carbon storage. The combination of climate-resilient cultivars with renewable-energy irrigation, efficient fertilization and regenerative soil management can simultaneously support climate adaptation and mitigation.

Future prospects

The future prospects of fruit crop breeding under climate change are highly promising, particularly through the integration of genetic improvement, advanced biotechnology and sustainable orchard management. Future breeding programmes are expected to focus on developing cultivars with stable yields under heat, drought, salinity, flooding and changing pest and disease pressures. Greater emphasis will be placed on multiple-stress tolerance rather than resistance to individual stresses, because fruit crops are increasingly exposed to combinations of environmental stresses.

The conservation and utilization of landraces, traditional cultivars and wild relatives will remain important sources of genetic diversity for climate adaptation. Rootstock breeding will also gain greater importance because climate-adapted rootstocks can improve water and nutrient uptake, tree vigour and tolerance to environmental stresses. Along with yield stability, future breeding will increasingly target fruit quality, nutritional value, water-use efficiency and nutrient-use efficiency.

Rapid advances in molecular biology and digital agriculture will further accelerate fruit breeding. Genomic selection, genome-wide markers, multi-omics and high-throughput phenotyping can improve the identification of desirable genotypes and shorten selection cycles, which is especially valuable in perennial fruit crops with long juvenile phases. Artificial intelligence and machine learning are expected to enhance prediction of genotype × environment interactions and help breeders identify cultivars suited to future climatic conditions. CRISPR and other genome-editing technologies may provide precise modification of genes related to stress tolerance, disease resistance, fruit quality, ripening and shelf life.

Future progress will also depend on integrating improved cultivars with sustainable orchard systems. Genotype × management × environment approaches can combine climate-resilient varieties with precision irrigation, soil-moisture monitoring, mulching, beneficial microorganisms and improved soil health. Greater consideration of biodiversity, pollination, ecosystem services and carbon sequestration will support both adaptation and mitigation. Overall, the future of fruit breeding will depend on combining conventional genetic resources with genomic technologies, AI, precise phenotyping and sustainable management to develop productive, nutritious and resilient fruit production systems under changing climatic conditions.

References

1. Abbass K, Qasim MZ, Song H, Murshed M, Mahmood H, Younis I. A review of the global climate change impacts, adaptation and sustainable mitigation measures. Environmental Science and Pollution Research. 2022;29(28):42539-59.
2. Ali, İ. (2025). Effects of climate change on fruit growing: Risks and solutions for the future. *International Journal of Environment and Climate Change*, *15*(3), 268–284.
3. Baruah, S. P. (2024). Climate resilient horticulture: Sustainable fruit crop production in North Bengal Region of India. *Journal of Agriculture and Technology*, *11*(1–2), 105–111.
4. Boko M, Niang I, Nyong A, Vogel C, Githeko A, Medany M, et al. Africa: In ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, & CE Hanson (Eds.), Climate change (2007): Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change (pp. 433-467). Cambridge: Cambridge University Press; 2007.
5. Borah, R., & Saikia, L. (2024). Climate impact on fruit crops and mitigation through climate-smart production practices. *Journal of Scientific Research and Reports*, *30*(6), 106–118.
6. Deori, M., Manasa, S., PB, K., Saikanth, D. R. K., Ranganna, G., & Prasad, L. (2024). A comprehensive review on the impact of climate change on fruit yield and quality in modern horticultural practices. *International Journal of Plant & Soil Science*, *36*(1), 177–187.
7. FAO. (2024). *Renewable energy for agriculture*. Food and Agriculture Organization of the United Nations.
8. Jain, S., Lamo, K., Walling, S., Imchen, A., Tirkey, J. F., & Singh, A. (2024). Climate-resilient horticulture: Adapting to climate change through innovative practices and technologies. *International Journal of Environment and Climate Change*, *14*(11), 219–233.
9. Karagatiya, F. P., Patel, S., Parasana, J. S., Vasava, H. V., Chaudhari, T. M., Kanzaria, D. R., & Paramar, V. (2023). Adapting fruit crops to climate change: Strengthening resilience and implementing adaptation measures in fruit crops. *The Pharma Innovation Journal*, *12*(7), 3159–3164.
10. Karkee, M., & Padhiary, A. (2024). Digital innovation in sustainable fruit production. *Frontiers in Agronomy*, *6*, 1482893.
11. Kumar, S., Karwoski, J., & Thapar, K. (2022). Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability in crop production. *Agronomy*, *11*(4), 676.
12. Marappan, K., Sadasivam, S., Natarajan, N., Arumugam, V. A., Lakshmaiah, K., Thangaraj, M., Gopal, M. G., & Asokan, A. (2025). Underutilized fruit crops as a sustainable approach to enhancing nutritional security and promoting economic growth. *Frontiers in Sustainable Food Systems*, *9*, 1618112.
13. Nguyen H, Randall M, Lewis A. Factors affecting crop prices in the context of climate change - A Review. Agriculture. 2024;14(1):135.
14. Rajan, R., Feza, M., Pandey, K., Aman, A., & Kumar, V. (2020). Climate change and resilience in fruit crops. In *Climate Change and Its Effects on Agriculture* (pp. 337–354).
15. Roth, M., et al. (2020). Genomic prediction of fruit texture and training population optimization towards the application of genomic selection in apple. *Horticulture Research*.
16. Sardar, A. S. (2023). Genetic amelioration of fruit and vegetable crops to increase biotic and abiotic stress resistance through CRISPR genome editing. *Frontiers in Plant Science*.
17. Shivanna KR. Climate change and its impact on biodiversity and human welfare. Proceedings of the Indian National Science Academy. 2022;88(2):160-71.
18. Srivastav, A. L., Dhyani, R., Ranjan, M., Madhav, S., & Sillanpää, M. (2021). Climate-resilient strategies for sustainable management of water resources and agriculture. *Environmental Science and Pollution Research*, *28*(31), 41576–41595.

19. Sundarrajan, R.V., Rajangam, J., Saraswathy, S., Gnanasekaran, M., Rajesh, S., Anitha, T., Muthuramalingam, S. & Sankar, C. (2025). A comprehensive review on impact of climatic change on adaptability and mitigation in fruit crop. Plant Science Today, 12(1), 1–10.
20. Wang, Y., Hafeez, A., Shahbaz, P., ul Haq, S., & Nadeem, M. (2025). Sustainable fruit production: Enhancing technical efficiency and climate resilience in apple orchards. *Applied Fruit Science*, *67*(5), 339.
21. Yang, L., Wang, M., Yu, J., Liu, J., Ye, S., & Hong, L. (2025). Materials and duration of mulching mediate soil and fruit quality in citrus orchard. *Plant and Soil*.
22. Zhang, F., Lin, X., Liu, Q., Zhou, J., & Zhu, L. (2020). China's Eco-Orchard Program: Advances in precision ecological orchard management. *Frontiers in Plant Science*, *11*, 553212.