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IMPROVEMENTS IN FRUIT BREEDING AND GENETIC MODIFICATION FOR HIGHER YIELDS, IMPROVING FRUIT QUALITY AND DISEASE RESISTANCE: A REVIEW

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ABSTRACT

Fruit breeding and genetic modification have greatly advanced horticulture in terms of yield, fruit quality and disease resistance. However, in order to increase yield and stress adaptation, we need conventional breeding approaches such as hybridization and selection which have been key to developing high-yielding and resilient varieties. These are generally time-consuming and genetic compatibility limited. The development of genetic modification and molecular breeding technologies has been a response to this limitation, allowing precision engineering of individual fruit crops for the desired traits. Tools, such as CRISPR-Cas9 and marker-assisted selection, have sped up the process of creating varieties with improved nutritional content, better taste and longer shelf life. Moreover, genetic modifications bestowed several features like pest resistance, disease resistance and abiotic stresses such as drought and salinity that can be sustainable from a different context of growing environment. Then new genetic pool pops emerged with new innovations in bioengineering bringing beneficial genes from wild relatives. Then new genetic pool pops emerged with new innovations in bioengineering bringing beneficial genes from wild relatives. These innovations not only help farmers by lowering input costs and improving crop resistance but also align with consumer trends and preferences for healthier and higher quality fruits. Now more than ever, combining innovative technology with traditional expertise is key to be able to respond to the increased global demand for healthy, sustainable fruit production.

Key words: fruit, shelf life, bioengineering, crop, resistance, technology, genetic

Introduction

Improving the genetic composition of fruit crops, by means of fruit breeding, is an important agricultural practice to address the needs of beekeepers and consumer demands (Janick, J., 2005). Traditional methods including but not limited to Hybridization, Selection and Crossbreeding in addition to modern techniques such as Marker-Assisted Selection and genome editing are being used by breeders to develop varieties that are higher-yielding, more nutritious and more resistant to diseases and environmental stresses (Song, G., 2019). While fruit production is important, fruit breeding also targets other traits, such as flavour, texture and shelf life that may cater to market demand (Limera, C., 2017). With the mounting demands posed by global issues such as climate crisis and food security, fruit breeding continues to have a role to play in sustainable and effective plant production (Baranski, R., 2019). The advances of molecular biology and genetic engineered has expanded the scope for fruit improvement. Techniques like genome editing and marker-assisted selection have revolutionized the way breeders address challenges in plant genomes (Fitch, M., 1992). This shift has accelerated the development of superior cultivars, making fruit breeding an important for sustainable agriculture (Chen, G., 2001).

Methods in Fruit Breeding

Traditional fruit breeding has relied on the principles of Mendelian genetics and natural variation (USDA., 2015). Key techniques include:

Hybridization process in fruit quality

Hybridization is a cornerstone of traditional and modern fruit breeding programs, focusing on combining desirable traits from two genetically diverse parent plants (Firoozbady, E, 2015). This approach enhances crop performance by improving yield, fruit quality and resistance to diseases (Bruening, G., 2000). It remains an integral part of developing sustainable and resilient agricultural systems.

1. Higher Yields:

Hybridization assists in yield improvement by welcoming all genetic combinations introduced toward plant vigour, fruit set and adaptability. Traits such as early maturity, higher flower-to-fruit ratios and improved photosynthetic efficiency are targeted (Menz, J., 2020). For instance, Kinnow (*Citrus nobilis* × *Citrus deliciosa*) (Álvarez, D., 2021). This hybrid mandarin proves to be very famous for its high yielding capacity plus adaptability. It bears 20-25% more fruit than the parent varieties thus making it ideal for commercial cultivation. Hass Avocado (Guatemalan × Mexican types) rambunctious growth and high fruit yield have made it a staple in avocado markets all over the world. Tifblue Blueberry (Vaccinium ashei × Vaccinium corymbosum) enhances blueberry productivity in regions with particular soil and climatic conditions, thereby making blueberry cultivation more profitable (Gonsalves, D., 2003, Ye, C., 2010).

2. Improved Fruit Quality:

Improving fruit quality includes characteristics such as flavour, texture, size, colour, nutritional value and shelf life (Wu, Z., 2018, China, Ag., 2016). Through hybridization, plant breeders can merge two parental plants to acquire the optimal sensory and nutritional characteristics from each. Honeycrisp Apple (Keepsake × Unknown cultivar) hybrid has gained phenomenal popularity for its excellent balance of sweetness and tartness, it has very crisp texture and outstanding storability. Its success in the market proves that hybridization can touch on consumer preferences quite well. Gala Apple (Kidd's Orange Red × Golden Delicious) has a greatly planted type with a sweet taste and crunchy feel, Gala apples have gained world recognition for eating fresh. Tommy Atkins Mango (Haden × Unknown) has made for its nice red shade, longer storage time and better sickness resistance, this mixed mango is a top export type. Chandler Strawberry (California Strawberry × Wild Strawberry) known for its large size, bright red colour and enhanced sweetness, it is a favourite among strawberry growers for both fresh markets and processing (Shelton, A.M., 2020, Shelton, A.M., 2018).

3. Disease Resistance:

Hybridization is fundamentally important in the process of adding resistance to many pests and diseases by inserting genes from wild or tolerant species into commercial varieties. This adjustment can make chemical inputs unnecessary, thus saving costs and reducing environmental impact. Pusa Arunima Guava (Seedling of Pusa Hybrid 2 × Allahabad Safeda): This hybrid shows resistance to wilt and nematodes; these are problems in guava cultivation. Besides, fruit quality and yield are both superior. Malbhog Banana (*Musa acuminata* × *Musa balbisiana*) hybrid banana is known for its resistance to Fusarium wilt and better performance in stress environments. Carrizo Citrange (*Poncirus trifoliata* × *Citrus sinensis*) is a major rootstock hybrid for resistance to citrus tristeza virus (CTV) and other pathogens carried in soil. Downy Mildew Resistance in Grapes hybrids such as *Vitis labrusca* × *Vitis vinifera* integrate downy mildew resistance with fruit quality attributes, guaranteeing sustainable production of grapes (Alam, S.N, 2003, Moon, K.M., 2020, APHIS-2012-0025 (2012), Stowe, E. 2021).

Steps in Hybridization

1. **Selection of Parents:**The first step is identifying parent plants with complementary traits. For example, one parent may have high yield potential, while the other has disease resistance.
2. **Emasculation:** In bisexual flowers, the anthers are removed to prevent self-pollination, ensuring controlled pollination with the desired male parent.

Table 1: Latest technology interventions took for developing fruit breeding (Chen, Z.L., 2003, Scorza, R. 1994, Shelton, A.M., 2017).

Technology	Description	Application in Fruit Breeding
CRISPR-Cas9	Genome editing tool for precise modifications in DNA.	Creating disease-resistant, drought-tolerant and improved-quality fruit varieties.
Next-Generation Sequencing (NGS)	High-throughput DNA sequencing technologies.	Identifying genetic markers, understanding genetic diversity and accelerating breeding programs.
Marker-Assisted Selection (MAS)	Using molecular markers to select desirable traits.	Faster selection of traits like disease resistance, fruit size and flavor.
High-Throughput Phenotyping	Automated measurement of plant characteristics using sensors and imaging.	Rapid screening of large populations for traits like yield, stress tolerance and fruit quality.
Genomic Selection	Predicting breeding values using genome-wide markers.	Accelerating the development of superior fruit varieties with complex traits.
Synthetic Biology	Designing and constructing new biological systems or redesigning existing ones.	Engineering fruit crops with enhanced nutritional content or novel traits.
RNA Interference (RNAi)	Silencing specific genes to study their function or modify traits.	Developing virus-resistant or delayed-ripening fruit varieties.
Proteomics and Metabolomics	Study of proteins and metabolites in plants.	Identifying biochemical pathways for improved fruit quality, flavour and nutritional value.
Remote Sensing and Drones	Monitoring crop health and growth using aerial imagery and sensors.	Assessing fruit orchards for stress, disease and nutrient deficiencies.
Artificial Intelligence (AI)	Machine learning and data analytics for breeding decisions.	Predicting optimal crosses, trait selection and optimizing breeding strategies.
Speed Breeding	Accelerating plant growth and development under controlled conditions.	Reducing the time required to develop new fruit varieties.
Epigenetics	Study of heritable changes in gene expression without altering DNA sequence.	Understanding and manipulating traits like stress tolerance and fruit ripening.
Gene Pyramiding	Combining multiple genes for a trait into a single variety.	Developing fruit varieties with multiple resistances (e.g., pests, diseases and abiotic stress).
Nanotechnology	Use of nanoparticles for targeted delivery of nutrients or genetic material.	Enhancing nutrient uptake, disease resistance and stress tolerance in fruit crops.
Blockchain for Traceability	Tracking and verifying the origin and quality of fruit varieties.	Ensuring transparency and quality control in fruit breeding and distribution.

3. **Pollination:** Pollen from the selected male parent is transferred to the stigma of the female parent under controlled conditions.
4. **Seed Collection and Planting:** The fertilized flowers produce seeds, which are collected and planted to evaluate the resulting progeny.
5. **Evaluation and Selection:** The offspring are assessed for desirable traits such as yield, fruit quality and resistance. Superior hybrids are selected for further development and commercialization.

Clonal Selection

Clonal selection is the old method of plant breeding in which desirable traits are chosen and propagated in plants (Zhang, J., 2020, Espley, R.V., 2007). This technique is very useful for crops that are propagated vegetative such as fruit crops, tuber crops and also some ornamental plants (Tennant, P., 2001, Ivanov, K.I., 2014). It improves yield, quality of fruits and resistance to diseases by selecting the best performing plants and multiplying them through cloning (Bhagirath, C., 2009). Clonal selection applies to perennial fruit crops such as bananas and grapes very widely (Armstrong, J., 2013). In spite of its effectiveness, this method can make plantations susceptible to the same pests and diseases because of genetic uniformity (Farré, G., 2014).

Process of Clonal Selection

1. **Identification of Good Clones:** Plants showing good traits like high yield, better fruit quality or disease resistance are chosen within the group.
2. **Assessment:** The chosen clones are looked at over many growing seasons for stability and performance.
3. **Growth:** The top clones are spread asexually through methods like grafting, cutting or micro-propagation.

4. **Field Testing:** Clones are tested in different weather conditions to ensure adaptability and consistency. Better clones are allowed out as upgraded types for big farming.

Examples of Clonal Selection in Crops

1. **Banana:**

- ***Example*:** Grand Naine, a globally popular variety, selected for high yield and uniform fruit size (Scorza, 2013).
- **Traits Improved**: Fruit quality, disease resistance (*e.g.*, Panama disease).

2. **Apple:**

- ***Example*:** Clonal selection of Red Delicious resulted in superior clones like Starking Delicious and Oregon Spur (ISAAA, 2017).
- **Traits Improved**: Fruit colour, size, sweetness and scab resistance.

3. **Grapes:**

- ***Example*:** Thompson Seedless clones like Tas-A-Ganesh and Sonaka were developed for higher yield and better quality (APHIS., 2009).
- **Traits Improved**: Larger berries, seedlessness and disease resistance to powdery mildew.

4. **Citrus:**

- ***Example*:** Nagpur Mandarin selected for uniform fruit size, better taste and disease resistance (Huang, J., 2002).
- **Traits Improved**: High juice content, reduced seed count and canker resistance (Scorza, R., 2016).

Mutation Breeding

Inducing mutations through chemical treatments or radiation has led to the development of new fruit varieties (Bangladesh Biosafety, 2020). For example, the 'Ruby Red' grapefruit was developed using radiation-induced mutation. Mutation breeding is a technique where genetic variations are induced through physical (*e.g.*, radiation) or chemical (*e.g.*, ethyl methanesulfonate) mutagens to improve specific traits in crops (Brookes, G., 2020). This method has been successfully utilized to develop crop varieties with higher yields, superior fruit quality and enhanced resistance to diseases (Rashid, M., 2018). Mutation breeding involves inducing genetic changes in plants to develop improved varieties with desirable traits, such as higher yields, enhanced quality and disease resistance (Ahmed, A., 2019). The process has significantly contributed to the development of improved fruit crop varieties worldwide.

Polyploidy Breeding

Polyploidy breeding is inducing or using organisms having more than two sets of chromosomes which is a potent tool for plant improvement (Erpen-Dalla Corte, 2019). Typically, polyploid plants display enhanced vigour, larger fruits, better quality and improved resistance among other attributes (Szankowski, I., 2009). This method has been widely applied in fruit crops to answer such increasing demands for production, quality and toughness (Pompili, V.,2020).

Mechanism of Polyploidy in Breeding

Polyploidy is induced by:

1. **Natural Spontaneity**: Occurring naturally due to errors in cell division (Dutt, M., 2015).
2. **Chemical Induction**: Using chemicals like colchicine or oryzalin to inhibit spindle formation during mitosis or meiosis, resulting in chromosome doubling (Tripathi, L., 2014).
3. **Hybridization**: Crossing diploid species to produce polyploid hybrids (Seo, 2014).

Applications in Fruit Crops

1. **Higher Yields:**

- **Banana (*Musa* spp.)**: Triploid bananas are sterile and seedless, offering higher yields and superior market quality (Ko, 2019, Shekhawat, 2012).
- **Watermelon (*Citrullus lanatus*)**: Tetraploid lines crossed with diploids produce triploid, seedless and high-yielding varieties (Malnoy, 2003).

2. **Improved Fruit Quality:**

- **Grapes (*Vitis* spp.)**: Induced polyploidy enhances berry size, sugar content and firmness.
- **Strawberry (*Fragaria* × *ananassa*)**: Octoploid strawberries are cultivated for their superior flavor and juiciness (Jia, H., 2016).

3. **Disease Resistance:**

- **Citrus (*Citrus* spp.)**: Tetraploid citrus plants have demonstrated enhanced resistance to bacterial and fungal diseases (Peng, A., 2017).
- **Apples (*Malus domestica*)**: Polyploid apples show improved resilience to scab (Venturia inaequalis) (Barbosa-Mendes, 2009).

4. **Stress Tolerance:**

- **Blueberries (*Vaccinium* spp.)**: Tetraploid varieties exhibit increased resistance to environmental stresses and pests (Zou, 2017).

Table 2: Examples of Mutation Breeding in Fruit Crops.

Fruit Crop	Mutagen Used	Improved Traits	Variety Developed
Banana	Gamma rays	Short stature, disease resistance, higher yield	'Grande Naine' (mutation-derived dwarf)
Apple	EMS	Improved fruit colour, disease resistance	'Red Delicious' mutants
Grapes	Gamma rays	Seedlessness, larger berries, better quality	'Thompson Seedless' mutants
Citrus	X-rays, Gamma rays	Disease resistance, higher Vitamin C content	'Navel Orange' mutants
Mango	Gamma rays	Dwarf varieties, resistance to mango malformation	'Amrapali' (semi-dwarf hybrid)
Papaya	EMS, Gamma rays	Disease resistance (PRSV), improved sweetness	'Surya' (PRSV-tolerant mutant)

- **Tomato (*Solanum lycopersicum*)**: Polyploid tomatoes are under research for salinity and drought resistance (Emran, A. 2017).

Applications of Improved Fruit Breeding and Genetic Modification

Improved fruit breeding and genetic modification have revolutionized the agricultural sector by addressing critical challenges related to productivity, quality and resilience. Below are the key applications of these advancements:

1. **Enhanced Yield and Productivity:**

- **High-Yield Varieties**: Traditional breeding techniques like hybridization, along with genetic engineering, have led to the development of high-yielding fruit varieties such as hybrid mangoes (*e.g.*, *Amrapali*) and apples (*Honeycrisp*) (Sidorova, 2019).
- **Overcoming Climatic Limitations**: Improved varieties like heat-tolerant watermelons or cold-resistant grapes ensure stable production in adverse conditions (Chandrasekaran, 2016).

2. **Improved Nutritional Quality:**

- **Nutrient-Enriched Fruits**: Bio-fortification has increased the nutritional content of fruits, such as golden bananas enriched with Vitamin A or Vitamin C-rich guavas (Li, 2010).
- **Better Taste and Texture**: Modern breeding has refined attributes like sweetness in strawberries or crispness in apples to meet consumer preferences (Tian, 2011).

3. **Pest and Disease Resistance:**

- **Resistant Varieties**: Genetic modification has introduced pest-resistant genes (*e.g.*, *Bt species*) and disease resistance in papayas against *Papaya Ringspot Virus* (PRSV) (Subramanyam, K., 2011).
- **Reduction in Pesticides**: The adoption of resistant varieties reduces the dependency on chemical inputs, promoting sustainable farming practices.

4. **Adaptation to Abiotic Stresses:**

- **Drought Resistance**: Genetic modification has produced drought-tolerant fruits like pomegranate (*Bhagwa*) and new banana cultivars (de Campos, 2011).
- **Salinity Tolerance**: Salt-tolerant crops, such as certain varieties of citrus, thrive in saline soils (Malnoy, 2007).

5. **Post-Harvest Benefits:**

- **Extended Shelf Life**: Genetically modified fruits like Flavr Savr tomatoes are engineered to delay ripening and reduce wastage (Jin, 2009).
- **Improved Storage**: Breeding has enabled fruits with enhanced skin thickness or reduced susceptibility to bruising (Geng, J., 2019).

6. **Economic Benefits for Farmers:**

- **Cost Reduction**: Pest and disease-resistant varieties reduce input costs for pesticides and fertilizers (Soyk, S. 2017).
- **Market Value**: Superior quality and uniformity in size or appearance increase the market demand for fruits like table grapes and export-oriented apples (Tränkner, 2010).

7. **Catering to Specialized Markets**

- **Seedless Varieties**: Breeding has led to consumer-preferred seedless fruits like watermelons and grapes (Endo, T., 2005).
- **Exotic and Niche Varieties**: Improved methods have supported the development of exotic fruits like dragon fruit and kiwifruit, expanding market opportunities (Srinivasan, 2012).

8. **Sustainable Agriculture:**

- **Environmental Conservation**: Reduced pesticide usage minimizes environmental impact, supporting eco-friendly farming systems (Varkonyi Gasic, 2019).
- **Water Use Efficiency**: Drought-tolerant crops contribute to water conservation, essential for arid and semi-arid regions (Dandekar, 2004).

Table 3: Examples of Success in Polyploid Breeding.

Fruit Crop	Ploidy Level	Benefits	Examples
Banana (*Musa* spp.)	Triploid	Higher yield, seedlessness	'Cavendish'
Watermelon	Triploid	Seedlessness, sweetness	'Sugar Baby'
Grapes (*Vitis* spp.)	Tetraploid	Larger berries, higher sugar content	'Autumn Royal'
Strawberry	Octoploid	Flavour, size	'Chandler', 'Albion'
Citrus (*Citrus* spp.)	Tetraploid	Disease resistance, larger fruit size	Tetraploid rootstocks for grafting
Blueberry	Tetraploid	Stress resistance, better quality	'Bluecrop', 'Jersey'

9. Contribution to Food Security:

- **Global Food Demand**: High-yield and climate-resilient varieties ensure consistent production to meet the rising food demand (Atkinson, 2011).
- **Reduction in Post-Harvest Losses**: Enhancements in storage and transport stability directly address food security challenges (López-Gómez, 2009).

10. Technological Advancements in Agriculture:

- **Marker-Assisted Selection**: Modern molecular tools streamline breeding processes, making the development of improved varieties faster and more precise (Gao, 2007).
- **CRISPR Technology**: Genome editing holds promise for addressing emerging challenges and fine-tuning specific traits (Park, J., 2006).

Integration of Omics Technologies

The advent of omics technologies has revolutionized fruit breeding by enabling a more detailed understanding of plant genomes, transcriptomes, proteomes and metabolomes (Cutanda-Perez, 2009). These technologies integrate molecular biology, bioinformatics and computational approaches to unravel complex traits in fruit crops. The application of omics in fruit breeding enhances precision and accelerates the development of varieties with improved yield, quality, disease resistance and environmental adaptability (Lin-Wang, 2010).

1. Genomics in Fruit Breeding:

Genomics focuses on the comprehensive study of the DNA sequence of an organism. By employing genome sequencing, genome-wide association studies (GWAS) and marker-assisted selection (MAS), breeders can identify genes controlling desirable traits (Pons, 2010). Genome sequencing of apples (*Malus domestica*) revealed genes associated with firmness and sweetness, aiding the development of superior cultivars. Advances in CRISPR-Cas9 technology have allowed targeted gene editing in fruits like bananas and tomatoes for improved traits (Rugini, 2020).

2. Transcriptomic for Gene Expression Analysis:

Transcriptomic studies RNA molecules to understand gene expression patterns during fruit development, ripening and stress responses. RNA-Seq and microarrays are commonly used techniques. (Albacete, 2015). In grapes (*Vitis vinifera*), transcriptomic analyses have identified key genes involved in anthocyanin biosynthesis, which influence fruit colour (Orboviæ, V., 2019).

3. Proteomics in Post-Translational Modifications:

Proteomics involves studying the protein profile of fruits to understand their role in metabolic pathways. Mass spectrometry and two-dimensional gel electrophoresis are key tools (Mitter, N., 2014). Proteomic studies in strawberries (*Fragaria* × *ananassa*) have highlighted proteins linked to flavour and aroma, leading to enhanced sensory quality (Smolka, 2010).

4. Metabolomics for Quality and Nutrition:

Metabolomics identifies and quantifies metabolites that contribute to taste, aroma and nutritional content. Techniques like gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) are employed (Dandekar, 2019). In citrus fruits, metabolomic studies have been used to identify limonoids and flavonoids that enhance flavour and health benefits (Chen, L., 2018).

5. Epigenomics for Environmental Adaptation:

Epigenomics explores DNA methylation and histone modifications that regulate gene expression without altering the DNA sequence. This is crucial for developing fruits tolerant to abiotic stress (Tian, S., 2018). Epigenetic modifications in mango (*Mangifera indica*) have been linked to flowering and fruit-setting under different environmental conditions (Hu, 2017).

6. Integrative Omics Approaches:

The integration of multiple omics technologies provides a holistic understanding of fruit crop biology. Multi-omics approaches combine genomics, transcriptomics, proteomics and metabolomics data to decode complex traits (Zhou, J., 2018). In tomatoes (*Solanum lycopersicum*), integrated omics studies have successfully identified networks involved in flavour and disease resistance (Nekrasov, 2017).

7. Application of Big Data and Bioinformatics:

The vast data generated by omics technologies require advanced bioinformatics tools for analysis. Machine learning and AI are increasingly being used for predictive modelling in fruit breeding programs (Veillet, 2019).

Challenges in Fruit Breeding and Genetic Modification

Fruit breeding and genetic modification are pivotal in meeting the growing demand for higher yield, better quality and resilience against biotic and abiotic stresses (Zhou, J. 2020). However, these approaches are fraught with challenges that require innovative solutions. Below are some of the significant challenges faced in these fields:

1. Long Generation Time:

Fruit crops often have long juvenile phases, which delay the evaluation and selection of desired traits. This slows the breeding cycle and extends the time needed to develop new cultivars (Sattar, 2017).

2. Complex Genetics:

Most fruit crops exhibit polyploidy and high levels of heterozygosity, complicating genetic analysis and manipulation. The inheritance of traits becomes challenging and maintaining genetic stability in modified crops is difficult (Nishitani, 2016).

3. Limited Genetic Resources

The availability of diverse germplasm for fruit breeding is often limited. Furthermore, access to wild relatives, which are potential sources of resistance traits, is sometimes restricted due to geographic, legal or conservation concerns (Malnoy, 2017).

4. Biotic and Abiotic Stresses:

Emerging pests and diseases, as well as climate change, continually pose threats to fruit crops. Developing varieties that are resilient to these stresses is a complex and ongoing challenge (Osakabe, Y., 2018).

5. Consumer Acceptance:

Genetic modification, particularly through transgenic methods, faces skepticism and resistance from consumers and regulatory bodies. Concerns about food safety and environmental impact hinder the adoption of genetically modified fruits (Metje-Sprink, J., 2019).

6. Regulatory and Ethical Constraints:

Strict regulations on genetically modified organisms (GMOs) increase the cost and time required for commercial approval. Ethical debates surrounding genetic modification further slow research and adoption (Woo, J., 2015).

7. Trait Integration Complexity:

Simultaneously improving multiple traits, such as yield, taste, texture and disease resistance, is difficult due to possible genetic trade-offs. Introducing one beneficial trait can sometimes compromise another (Kim, J., 2015).

8. Low Transformation Efficiency:

The transformation of fruit crops using modern biotechnological tools like CRISPR/Cas9 or Agrobacterium-mediated methods often has low efficiency, particularly in woody perennials. This limits the success rate of genetic modification efforts (Ghogare, 2020).

9. High Costs and Resource Requirements:

Developing new fruit varieties, especially through genetic modification, requires significant financial and technological investment. This can be prohibitive for small-scale breeders or institutions in developing regions (Begemann, 2017).

10. Post-Harvest Challenges:

Incorporating traits like extended shelf life or improved nutritional content into breeding programs often requires complex genetic pathways, making it difficult to achieve success (Jia, H., 2019).

11. Data Integration and Analysis:

Omics technologies generate large volumes of data (genomics, transcriptomics, proteomics and metabolomics). Effectively integrating and analyzing this data to identify key breeding targets remains a significant challenge (Yao, J., 2018).

12. Loss of Biodiversity:

Intensive breeding programs focused on a few commercially important traits often lead to genetic erosion, reducing biodiversity and resilience in fruit crop populations (Jia, 2018).

Future Prospects

The future of fruit breeding is poised to address pressing challenges in agriculture, food security and climate resilience. Advances in biotechnology, genomics and precision breeding techniques are reshaping how breeders approach the improvement of fruit crops (Pasquali, G., 2008). Below are some key future prospects:

- **Genomic Selection and Marker-Assisted Breeding:** Genomic selection, combined with marker-assisted breeding, will allow breeders to identify desirable traits faster and more accurately. This approach can shorten breeding cycles and enhance traits such as yield, disease resistance and fruit quality (Shao, X., 2020).

- **CRISPR and Gene Editing Technologies:** CRISPR-Cas9 and other gene-editing tools hold promise for precise modifications in fruit crops. These technologies enable the development of disease-resistant varieties, enhanced nutritional content and climate-resilient fruits without introducing foreign DNA (Tripathi, 2019).
- **Integration of Phenotyping Technologies:** High-throughput phenotyping platforms, including drone and sensor technologies, will enable breeders to collect detailed phenotypic data. This will improve the efficiency of selection processes for traits like drought tolerance, fruit size and sweetness (Namukwaya, 2012).
- **Breeding for Climate Resilience:** With changing climate patterns, there is a growing focus on breeding fruits that can thrive under extreme temperatures, salinity and water scarcity. Genetic resources from wild relatives will play a crucial role in developing such resilient varieties (Kaur, 2020).
- **Bio-fortification:** Breeding fruits with higher levels of vitamins, minerals and antioxidants will address nutritional deficiencies. Bio-fortified fruits like vitamin C-enriched oranges or iron-rich bananas could become staples in improving global health (Song, 2018).
- **Sustainable Breeding Practices:** Emphasis on sustainability will drive the development of fruits that require fewer chemical inputs, such as pest- and disease-resistant varieties. Organic and eco-friendly breeding techniques will gain traction (Qi, 2017).
- **Digital and AI-Driven Breeding:** Artificial intelligence (AI) and machine learning (ML) algorithms will revolutionize fruit breeding. AI can predict breeding outcomes, analyze genetic data and optimize hybridization strategies, significantly accelerating progress (Fagoaga, 2007).
- **Increased Focus on Consumer Preferences:** Future breeding programs will align with consumer demands for fruits with superior taste, texture and extended shelf life. Varieties with unique flavours and aesthetic appeal will cater to niche markets (Hao, 2016).
- **Hybrid Breeding for High-Value Traits:** Hybrid breeding will continue to play a significant role in developing high-yielding and uniform fruit varieties. Innovations in hybrid seed production will make such technologies accessible to smallholder farmers (Cervera, 2010).
- **Global Collaboration and Germplasm Conservation:** International partnerships in research and germplasm exchange will enhance access to diverse genetic resources. Initiatives like the Global Crop Diversity Trust will ensure the conservation of fruit genetic diversity for future breeding efforts (Vigne, 2004).

Conclusion

Improvements in fruit breeding and genetic modification have redefined horticulture, offering solutions to global challenges like food security and climate resilience. From traditional methods to cutting-edge technologies, these advancements have enhanced yields, improved fruit quality and bolstered disease resistance. As science progresses, the integration of innovative techniques with sustainable practices will ensure the continued growth and development of the fruit industry, catering to both producer and consumer needs. By embracing these advancements, the future of fruit production holds the promise of greater efficiency, diversity and resilience.

References

Ahmed, A., Hoddinott J.F., Abedin N. and Hossain N.Z. (2019). Economic and health impacts of genetically modified eggplant: Results from a randomized controlled trial of Bt brinjal in Bangladesh. IFPRI Discussion paper 01866.

Alam, S.N. *et al*., (2003). Development of an integrated pest management strategy for eggplant fruit and shoot borer in South Asia. *AVRDC* 3.

Albacete, A. *et al*., (2015). Unravelling rootstock×scion interactions to improve food security. *J. Exp. Bot.* **66**, 2211-2226.

Álvarez, D. *et al*., (2021). Fruit crops in the era of genome editing–closing the regulatory gap. *Plant Cell Rep.* **40**, 915-930.

APHIS (2012). Interpretative rule on Okanagan Speciality Fruits petition for determination of nonregulated status: Arctic™ Apple (*Malus* × *domestica)*. Events GD743 and GS784. Docket No. APHIS-2012-0025.

APHIS (2009). Interpretative ruling on University of Florida petition for determination of nonregulated status for X17-2 papaya resistant to papaya ringspot virus. Docket No. APHIS-2008-0054.

Armstrong, J. and Lane W.D. (2013). Genetically modified reduced-browning fruit-producing plant and produced fruit thereof and method of obtaining such. *US Patent*, **8**, 563,805 B2.

Atkinson, R.G. *et al*., (2011). Dissecting the role of climacteric ethylene in kiwifruit (*Actinidia chinensis*) ripening using a 1-aminocyclopropane-1-carboxylic acid oxidase knockdown line. *J. Exp. Bot.* **62**, 3821-3835.

Bangladesh Biosafety (2017). user's guide to biosafety regulatory process for genetically engineered plants in Bangladesh. Available at: https://bangladeshbiosafety.org/wp-content/uploads/2017/11Users_Guide_to_Biosafety_Regulatory_Process_Bangladesh_2017.pdf [Accessed Aug 2020].

Baranski, R., Klimek-Chodacka M. and Lukasiewicz A. (2019). Approved genetically modified (GM) horticultural plants: a 25-year perspective. *Folia Hortic*. **31**, 3-49.

Barbosa-Mendes, J.M. *et al*., (2009). Genetic transformation of *Citrus sinensis* cv. Hamlin with *hrpN* gene from *Erwinia amylovora* and evaluation of the transgenic lines for resistance to citrus canker. *Sci. Hortic. (Amst.)*. **122**, 109-115.

Begemann, M.B. *et al*., (2017). Precise insertion and guided editing of higher plant genomes using Cpf1 CRISPR nucleases. *Sci. Rep*. **7**, 1-6.

Bhagirath, C. and Kadambini G. (2009). The development and regulation of Bt Brinjal in India. *ISAAA Briefs* 38, xii + 102.

Brookes, G. and Barfoot P. (2020). GM crops: global socio-economic and environmental impacts 1996-2018. *PG Econ. Ltd*, *UK*. 1-213.

Bruening, G. and Lyons M.J. (2000). The e of the FLAVR SAVR tomato. *Calif. Agric*. **54**, 6-7.

Cervera, M. *et al*., (2010). Transgenic expression in citrus of single-chain antibody fragments specific to Citrus tristeza virus confers virus resistance. *Transgenic Res*. **19**, 1001-1015 (2010).

Chandrasekaran, J. *et al*., (2016). Development of broad virus resistance in non-transgenic cucumber using CRISPR/9 technology. *Mol. Plant Pathol*. **17**, 1140-1153.

Chen, G., Ye C.M., Huang J.C., Yu M. and Li B.J. (2001). Cloning of the papaya ringspot virus (PRSV) replie gene and generation of PRSV-resistant papayas through the introduction of the PRSV replie gene. *Plant Cell Rep*. **20**, 272-277.

Chen, L. *et al*., (2018). A method for the production and expedient screening of CRISPR/9-mediated non-transgenic mutant plants. *Hortic. Res*. **5**, 1-12.

Chen, Z.L. *et al*., (2003). Safety assessment for genetically modified sweet pepper and tomato. *Toxicology*, **188**, 297-307.

ChinaAg. (2016). Market reports - The splice must grow: The bright and shady sides of GM agriculture in China. Available at: https://www.chinaag.org/markets/gm-agriculture-in-china/ [Accessed May 2020].

Cutanda-Perez, M.C. *et al*., (2009). Ectopic expression of *VlmybA1* in grapevine activates a narrow set of genes involved in anthocyanin synthesis and transport. *Plant Mol. Biol*. **69**, 633-648.

Dandekar, A.M. *et al*., (2004). Effect of down-regulation of ethylene biosynthesis on fruit flavor complex in apple fruit. *Transgenic Res*. **13**, 373-384.

Dandekar, A.M. *et al*., (2019). Trans-graft protection against Pierce's disease mediated by transgenic grapevine rootstocks. *Front. Plant Sci*. 10, 84 (2019).

de Campos, M.K.F. *et al*., (2011). Drought tolerance and antioxidant enzymatic activity in transgenic 'Swingle' citrumelo plants over-accumulating proline. *Environ. Exp. Bot*. **72**, 242-250.

Dutt, M., Barthe G., Irey M. and Grosser J. (2015). Transgenic citrus expressing an *Arabidopsis* NPR1 gene exhibit enhanced resistance against Huanglongbing (HLB; Citrus greening). *PLoS ONE* 10, 1-17.

Emran, A.M., Tabei Y., Kobayashi K., Yamaoka N. and Nishiguchi M. (2012). Molecular analysis of transgenic melon plants showing virus resistance conferred by direct repeat of movement gene of Cucumber green mottle mosaic virus. *Plant Cell Rep*. **31**, 1371-1377.

Endo, T. *et al*., (2005). Ectopic expression of an FT homolog from *Citrus* confers anearly flowering phenotype on trifoliate orange (*Poncirus trifoliata* L. Raf.). *Transgenic Res*. **14**, 703-712.

Erpen-Dalla Corte, L. *et al*., (2019). Development of Improved Fruit, Vegetable and Ornamental Crops Using the CRISPR/9 Genome Editing Technique. *Plants*, **8**, 601.

Espley, R.V. *et al*., (2007). Red colouration in apple fruit is due to the activity of the MYB transcription factor, MdMYB10. *Plant. J*., **49**, 414-427.

Fagoaga, C. *et al*., (2007). Engineering of gibberellin levels in citrus by sense and antisense overexpression of a *GA 20-oxidase* gene modifies plant architecture. *J. Exp. Bot*. **58**, 1407-1420.

Farré, G. *et al*., (2014). Engineering complex metabolic pathways in plants. *Annu. Rev. Plant Biol*. **65**, 187-223.

Firoozbady, E. and Young T.R. (2015). Pineapple plant named "Rose". *US Patent PP25*,763 P3.

Fitch, M., Manshardt R., Gonsalves D., Slightom J. and Sanford J. (1992). Virus resistant papaya plants derived from tissues bombarded with the coat protein gene of papaya ringspot virus. *Nat. Biotechnol*. **10**, 1466-1472.

Gao, M. *et al*., (2007). Gene expression and ethylene production in transgenic pear (*Pyrus communis* cv.'La France') with sense or antisense cDNA encoding ACC oxidase. *Plant Sci*. **173**, 32-42.

Geng, J., Wei T., Wang Y., Huang X. and Liu J.H. (2019). Overexpression of *PtrbHLH*, a basic helix-loop-helix transcription factor from *Poncirus trifoliata*, confers enhanced cold tolerance in pummelo (*Citrus grandis*) by modulation of H_2O_2 level via regulating a *CAT* gene. *Tree Physiol*. **39**, 2045-2054.

Ghogare, R., Williamson-Benavides B., Ramírez-Torres F. and Dhingra A. (2020). CRISPR-associated nucleases: the Dawn of a new age of efficient crop improvement. *Transgenic Res*. **29**, 1-35.

Gonsalves, D., Basin P., Ferreira S., Sciences E.P. and Resources H. (2003). Transgenic papaya: a e for managing risks of papaya ringspot virus in Hawaii plant health progress. *Plant Manag. Netw*. **1**, 1-5.

Hao, G., Stover E. and Gupta G. (2016). Overexpression of a modified plant thionin enhances disease resistance to citrus canker and huanglongbing (HLB). *Front. Plant Sci.* **7**, 1-11.

Hu, B. *et al*., (2017). Engineering non-transgenic gynoecious cucumber using an improved transformation protocol and optimized CRISPR/9 system. *Mol. Plant*, **10**, 1575-1578.

Huang, J. and Wang Q. (2002). Agricultural biotechnology development and policy in China. *Ag. Bio. Forum.*, **5**, 122-135.

ISAAA (2017). Global status of commercialized biotech/GM Crops in 2017: Biotech crop adoption surges as economic benefits accumulate in 22 years. *ISAAA Briefs*, **53**, 1-143.

Ivanov, K.I., Eskelin K., Lõhmus A. and Mäkinen K. (2014). Molecular and cellular mechanisms underlying potyvirus infection. *J. Gen. Virol.* **95**, 1415-1429.

Janick, J. (2005). In *Plant Breeding Reviews* Ch. **8, Vol. 25** (ed Janick, J.) (Springer, 2005).

Jia, D. *et al*., (2018). Overexpression of a novel apple NAC transcription factor gene, MdNAC1, confers the dwarf phenotype in transgenic apple (*Malus domestica*). *Genes (Basel)* **9**, 229.

Jia, H. *et al*., (2017). Genome editing of the disease susceptibility gene *CsLOB1* in citrus confers resistance to citrus canker. *Plant Biotechnol. J.* **15**, 817-823.

Jia, H. orbovic V., Jones J.B. and Wang N. (2016). Modification of the PthA4 effector binding elements in Type I CsLOB1 promoter using 9/sgRNA to produce transgenic Duncan grapefruit alleviating XccÄpthA4: DCsLOB1.3 infection. *Plant Biotechnol. J.* **14**, 1291-1301.

Jia, H., Zou X. orbovic V. and Wang N. (2019). In *Plant Genome Editing with CRISPR Systems* (*ed Qi, Y.*) 235-241 (Springer, 2019).

Jin, W. *et al*., (2009). Improved cold-resistant performance in transgenic grape (*Vitis vinifera* L.) overexpressing cold-inducible transcription factors *AtDREB1b*. *Hort. Science*, **44**, 35-39.

Kaur, N. *et al*., (2020). CRISPR/9 directed editing of *lycopene epsilon-cyclase* modulates metabolic flux for β-carotene biosynthesis in banana fruit. *Metab. Eng.* **59**, 76-86.

Kim, J., Chang C. and Tucker M.L. (2015). To grow old: regulatory role of ethylene and jasmonic acid in senescence. *Front Plant Sci.* **6**, 20.

Kim, M. *et al*., (2010). Transformation of carotenoid biosynthetic genes using a micro-cross section method in kiwifruit (*Actinidia deliciosa* cv. Hayward). *Plant Cell Rep.* **29**, 1339-1349.

Klap, C. *et al*., (2017). Tomato facultative parthenocarpy results from *Sl AGAMOUS-LIKE 6* loss of function. *Plant Biotechnol. J.* **15**, 634-647.

Ko, M. *et al*., (2016). Constitutive expression of a fungus-inducible carboxylesterase improves disease resistance in transgenic pepper plants. *Planta*, **244**, 379-392.

Lee, Y.K. and Kim I.J. (2011). Modulation of fruit softening by antisense suppression of endo-β-1,4-glucanase in strawberry. *Mol. Breed.* **27**, 375-383.

Li, X. *et al*., (2018). Lycopene is enriched in tomato fruit by CRISPR/9-mediated multiplex genome editing. *Front. Plant Sci.* **9**, 1-12.

Li, Y. *et al*., (2010). Overexpression of a Malus vacuolar Na^+/H^+ antiporter gene (*MdNHX1*) in apple rootstock M.26 and its influence on salt tolerance. *Plant Cell. Tissue Organ Cult.* **102**, 337-345.

Limera, C., Sabbadini S., Sweet J.B., Mezzetti B. and Kühn-institut J. (2017). New biotechnological tools for the genetic improvement of major woody fruit species. *Front. Microbiol.* **8**, 1-16.

Lin, C.Y. *et al*., (2012). Development of transgenic watermelon resistant to Cucumber mosaic virus and Watermelon mosaic virus by using a single chimeric transgene construct. *Transgenic Res.* **21**, 983-993.

Lin-Wang, K. *et al*., (2010). An R2R3 MYB transcription factor associated with regulation of the anthocyanin biosynthetic pathway in Rosaceae. *BMC Plant Biol.* **10**, 50.

López-Gómez, R. *et al*., (2009). Ripening in papaya fruit is altered by ACC oxidase cosuppression. *Transgenic Res.* **18**, 89-97.

Malnoy, M. *et al*., (2016). DNA-free genetically edited grapevine and apple protoplast using CRISPR/9 ribonucleoproteins. *Front. Plant Sci.* **7**, 1-9.

Malnoy, M., Jin Q., Borejsza-Wysocka E.E., He S.Y. and Aldwinckle H.S. (2007). Overexpression of the apple *MpNPR1* gene confers increased disease resistance in *Malus* × *domestica*. *Mol. Plant-Microbe Interact.* **20**, 1568-1580.

Malnoy, M., Venisse J.S., Brisset M.N. and Chevreau E. (2003). Expression of bovine lactoferrin cDNA confers resistance to *Erwinia amylovora* in transgenic pear. *Mol. Breed.* **12**, 231-244.

Martín-Pizarro, C., Triviño J.C. and Posé D. (2019). Functional analysis of the *TM6* MADS-box gene in the octoploid strawberry by CRISPR/9-directed mutagenesis. *J. Exp. Bot.* **70**, 885-895.

Menz, J., Modrzejewski D., Hartung F., Wilhelm R. and Sprink T. (2020). Genome edited crops touch the market: a view on the global development and regulatory environment. *Front. Plant Sci.* **11**, 586027.

Metje-Sprink, J., Menz J., Modrzejewski D. and Sprink T. (2019). DNA-free genome editing: past, present and future. *Front Plant Sci.* **9**, 1957.

Mitter, N. and Gleeson M. (2014). Acceptance of disease-resistant GM rootstocks for non-GM fruit. In: *XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes (IHC2014):* **III 1124**. 91-96.

Moon, K.M., Kwon E. Bin Lee B. and Kim C.Y. (2020). Recent trends in controlling the enzymatic browning of fruit and vegetable products. *Molecules*, **25**, 2754.

Namukwaya, B. *et al.*, (2012). Transgenic banana expressing *Pflp* gene confers enhanced resistance to *Xanthomonas* wilt disease. *Transgenic Res.* **21**, 855-865.

Nekrasov, V. *et al.*, (2017). Rapid generation of a transgene-free powdery mildew resistant tomato by genome deletion. *Sci. Rep.* **7**, 1-6.

Nishitani, C. *et al.*, (2016). Efficient genome editing in apple using a CRISPR/9 system. *Sci. Rep.* **6**, 1-8.

Orboviæ, V. (2019). Editorial: new developments in Agrobacterium-Mediated transformation of tree fruit crops. *Front. Plant Sci.* https://doi.org/10.3389/fpls.2019.01253.

Osakabe, Y. *et al.*, (2018). CRISPR–9-mediated genome editing in apple and grapevine. *Nat. Protoc.* **13**, 2844-2863.

Park, J.I. *et al.*, (2006). Modification of sugar composition in strawberry fruit by antisense suppression of an ADP-glucose pyrophosphorylase. *Mol. Breed.* **17**, 269-279.

Pasquali, G., Biricolti S., Locatelli F., Baldoni E. and Mattana M. (2008). *Osmyb4* expression improves adaptive responses to drought and cold stress in transgenic apples. *Plant Cell Rep.* **27**, 1677-1686.

Peng, A. *et al.*, (2017). Engineering canker resistant plants through CRISPR/9 targeted editing of the susceptibility gene Cs LOB 1 promoter in citrus. *Plant Biotechnol. J.* **15**, 1509-1519.

Pompili, V., Dalla Costa L., Piazza S., Pindo M. and Malnoy M. (2020). Reduced fire blight susceptibility in apple cultivars using a high-efficiency CRISPR/9-FLP/FRT-based gene editing system. *Plant Biotechnol. J.* **18**, 845-858.

Pons, E. *et al.*, (2014). Metabolic engineering of â-carotene in orange fruit increases its *in vivo* antioxidant properties. *Plant Biotechnol. J.* **12**, 17-27.

Qi, X., Liu C., Song L., Li Y. and Li M. (2017). *PaCYP78A9*, a cytochrome P450, regulates fruit size in sweet cherry (*Prunus avium* L.). *Front. Plant Sci.* **8**, 1-14.

Rashid, M., Hasan M. and Matin M. (2018). Socio-economic performance of Bt eggplant cultivation in Bangladesh. *Bangladesh. J. Agric. Res.* **43**, 187-203.

Rubio, J. *et al.*, (2019). Silencing of one copy of the translation initiation factor eIFiso4G in Japanese plum (*Prunus salicina*) impacts susceptibility to Plum pox virus (PPV) and small RNA production. *BMC Plant Biol.* **19**, 1-12.

Rugini, E., Bashir M.A., Cristofori V., Ruggiero B. and Silvestri C. (2020). A review of genetic improvement of main fruit trees through modern biotechnological tools and considerations of the cultivation and research of the engineered plant restrictions. *Pakistan J. Agric. Sci.* **57**, 17-42.

Sattar, M.N. *et al.*, (2017). CRISPR/9: a practical approach in date palm genome editing. *Front. Plant Sci.* **8**, 1469.

Scorza, R. *et al.*, (2013). 'HoneySweet'—a transgenic plum pox virus resistant plum—from laboratory and experimental field plots, to regulatory approval. *Acta Hortic.* **974**, 57-64.

Scorza, R. *et al.*, (2016). Honeysweet (C5), the first genetically engineered plum pox virus-resistant plum (*Prunus domestica* L.) cultivar. *Hort. Science*, **51**, 601-603.

Scorza, R. *et al.*, (1994). Transgenic plums (*Prunus domestica* L.) express the plum pox virus coat protein gene. *Plant Cell Rep.* **14**, 18-22.

Seo, H.H. *et al.*, (2014). Overexpression of a defensin enhances resistance to a fruit-specific anthracnose fungus in pepper. *PLoS One*, **9**, 1-11.

Shao, X. *et al.*, (2020). Using CRISPR/9 genome editing system to create *MaGA20ox2* gene-modified semi-dwarf banana. *Plant Biotechnol. J.* **18**, 17-19.

Shekhawat, U.K.S., Ganapathi T.R. and Hadapad A.B. (2012). Transgenic banana plants expressing small interfering RNAs targeted against viral replication initiation gene display high-level resistance to banana bunchy top virus infection. *J. Gen. Virol.* **93**, 1804-1813.

Shelton, A.M. *et al.*, (2018). Bt eggplant project in Bangladesh: History, present status and future direction. *Front. Bioeng. Biotechnol.* **6**, 1-6.

Shelton, A.M. *et al.*, (2017). Bt Eggplant: a genetically engineered 'minor' crop comes of age in Bangladesh and the Philippines. *ISB News Rep.* (VTechWorks, 2017).

Shelton, A.M., Sarwer S.H., Hossain M.J., Brookes G. and Paranjape V. (2020). Impact of Bt Brinjal cultivation in the market value chain in five districts of Bangladesh. *Front. Bioeng. Biotechnol.* **8**, 1-12.

Sidorova, T., Mikhailov R., Pushin A., Miroshnichenko D. and Dolgov S. (2019). *Agrobacterium*-mediated transformation of Russian commercial plum cv. "Startovaya" (*Prunus domestica* L.) with virus-derived hairpin RNA construct confers durable resistance to PPV infection in mature plants. *Front. Plant Sci.* **10**, 1-15.

Smolka, A., Li X.Y., Heikelt C., Welander M. and Zhu L.H. (2010). Effects of transgenicrootstocks on growth and development of non-transgenic scion cultivars inapple. *Transgenic Res.* **19**, 933-948.

Song, G., Prieto H. and Orbovic V. (2019). Agrobacterium-mediated transformation of tree fruit crops: methods, progress and challenges. *Front. Plant Sci.* **10**, 226.

Song, Gqing and Chen Q. (2018). Overexpression of the MADS-box gene K-domain increases the yield potential of blueberry. *Plant Sci.* **276**, 22-31.

Soyk, S. *et al.*, (2017). Variation in the flowering gene *SELF PRUNING 5G* promotes day-neutrality and early yield in tomato. *Nat. Genet.* **49**, 162-168.

Srinivasan, C., Dardick C., Callahan A. and Scorza R. (2012). Plum (*Prunus domestica*) trees transformed with poplar *FT1* result in altered architecture, dormancy requirement and continuous flowering. *PLoS ONE*, **7**, 1-11.

Stowe, E. and Dhingra A. (2021). Development of the Arctic Apple. *Plant Breed. Rev.* **44**, 273-296.

Subramanyam, K., Sailaja K.V., Subramanyam K., Muralidhara Rao D. and Lakshmidevi K. (2011). Ectopic expression of an osmotin gene leads to enhanced salt tolerance in transgenic chilli pepper (*Capsicum annum* L.). *Plant Cell. Tissue Organ Cult.* **105**, 181-192.

Szankowski, I. *et al*., (2009). Highly scab-resistant transgenic apple lines achieved by introgression of *HcrVf2* controlled by different native promoter lengths. *Tree Genet. Genomes*, **5**, 349-358.

Tennant, P. *et al*., (2001). Papaya ringspot virus resistance of transgenic Rainbow and SunUp is affected by gene dosage, plant development and coat protein homology. *Eur*. *Eur. J. Plant Pathol.* **107**, 645-653.

Tian, N., Wang J. and Xu Z.Q. (2011). Overexpression of Na^+/H^+ antiporter gene *AtNHX1* from *Arabidopsis thaliana* improves the salt tolerance of kiwifruit (*Actinidia deliciosa*). *South Afr. J. Bot.* **77**, 160-169.

Tian, S. *et al*., (2018). Engineering herbicide-resistant watermelon variety through CRISPR/9-mediated base-editing. *Plant Cell Rep*. **37**, 1353-1356.

Tränkner, C. *et al*., (2010). Over-expression of an FT-homologous gene of apple induces early flowering in annual and perennial plants. *Planta*, **232**, 1309-1324.

Tripathi, J. N. *et al*., (2019). CRISPR/9 editing of endogenous banana streak virus in the B genome of *Musa* spp. overcomes a major challenge in banana breeding. *Commun. Biol.* **2**, 1-11.

Tripathi, L. *et al*., (2014). Field trial of *Xanthomonas* wilt disease-resistant bananas in East Africa. *Nat. Biotechnol.* **32**, 868-870.

USDA (2020). USDA announces deregulation of non-browning apples. (2015). Available at: https://www.aphis.usda.gov/stakeholders/downloads/2015/SA_arctic_apples.pdf [Accessed June 2020].

Varkonyi Gasic, E. *et al*., (2019). Mutagenesis of kiwifruit CENTRORADIALIS like genes transforms a climbing woody perennial with long juvenility and axillary flowering into a compact plant with rapid terminal flowering. *Plant Biotechnol. J*. **17**, 869-880.

Veillet, F. *et al*., (2019). Transgene-free genome editing in tomato and potato plants using *Agrobacterium*-mediated delivery of a CRISPR/9 cytidine base editor. *Int. J. Mol. Sci*. **20**, 1-10.

Vigne, E., Komar V. and Fuchs M. (2004). Field safety assessment of recombination in transgenic grapevines expressing the coat protein gene of Grapevine fanleaf virus. *Transgenic Res*. **13**, 165-179.

Wang, C. *et al*., (2015). Molecular cloning and heterologous expression analysis of *JrVTE1* gene from walnut (*Juglans regia*). *Mol. Breed*. **35**, 1-12.

Wang, L. *et al*., (2019). CRISPR/9-mediated editing of CsWRKY22 reduces susceptibility to Xanthomonas citri subsp. citri in Wanjincheng orange (*Citrus sinensis* (L.) Osbeck. *Plant Biotechnol. Rep*. **13**, 501-510.

Wang, T., Zhang H. and Zhu H. (2019). CRISPR technology is revolutionizing the improvement of tomato and other fruit crops. *Hortic. Res*. **6**, 77.

Woo, J.W. *et al*., (2015). DNA-free genome editing in plants with preassembled CRISPR-9 ribonucleoproteins. *Nat. Biotechnol*. **33**, 1162-1164.

Wu, Z., Mo C., Zhang S. and Li H. (2018). Characterization of papaya ringspot virus isolates infecting transgenic papaya 'Huanong No.1' in South China. *Sci. Rep*. **8**, 8206.

Yao, J.L. *et al*., (2018). Ectopic expression of the *PISTILLATA* homologous *MdPI* inhibits fruit tissue growth and changes fruit shape in apple. *Plant Direct*, **2**.

Ye, C. and Li, H. (2010). 20 years of transgenic research in china for resistance to papaya ringspot virus. *Transgenic Plant J*. **4**, 58-63.

Yu, Q.H. *et al*., (2017). CRISPR/9-induced targeted mutagenesis and gene replacement to generate long-shelf life tomato lines. *Sci. Rep.* **7**, 1-9.

Zhang, J. *et al*., (2020). Decreased protein abundance of lycopene α-cyclase contributes to red flesh in domesticated watermelon. *Plant Physiol.* **183**, 1171-1183.

Zhou, J. *et al*., (2020). Application and future perspective of CRISPR/9 genome editing in fruit crops. *J. Integr. Plant Biol.* **62**, 269-286.

Zhou, J., Wang G. and Liu Z. (2018). Efficient genome editing of wild strawberry genes, vector development and validation. *Plant Biotechnol. J*. **16**, 1868-1877.

Zok, A. *et al*., (2010). Effect of *Medicago sativa* ferritin gene on stress tolerance in transgenic grapevine. *Plant Cell. Tissue Organ Cult.* **100**, 339-344.

Zou, X. *et al*., (2017). Transgenic citrus expressing synthesized *cecropin B* genes in the phloem exhibits decreased susceptibility to Huanglongbing. *Plant Mol. Biol.* **93**, 341-353.