



Genetic and Biotechnological Strategies for the Development of Seedless Watermelon with Superior Fruit Quality

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Seedless watermelon (*Citrullus lanatus*) is an important specialty crop valued for consumer convenience, attractive eating quality and commercial demand. The development of seedless watermelon is primarily based on triploid breeding, where tetraploid plants are crossed with diploid plants to produce sterile triploid hybrids. Modern breeding has expanded this approach through chromosome doubling, molecular markers, tissue culture, genomic analysis and biotechnology-assisted selection. In addition to seedlessness, current breeding programmes emphasize fruit sweetness, flesh colour, texture, firmness, rind characteristics, nutritional quality, disease resistance and adaptation to changing production environments. Biotechnology can accelerate the identification of desirable parental genotypes and improve the efficiency of tetraploid and triploid development. Molecular markers and genome-wide approaches provide opportunities to associate genetic variation with important fruit-quality traits, while chromosome engineering and advanced tissue-culture techniques can support the production and maintenance of polyploid breeding materials. The integration of conventional genetics with modern biotechnology therefore provides a strong foundation for developing seedless watermelon cultivars with superior fruit quality and stable field performance.

Keywords: Seedless watermelon, Triploid breeding, Tetraploid induction, Fruit quality, Molecular breeding

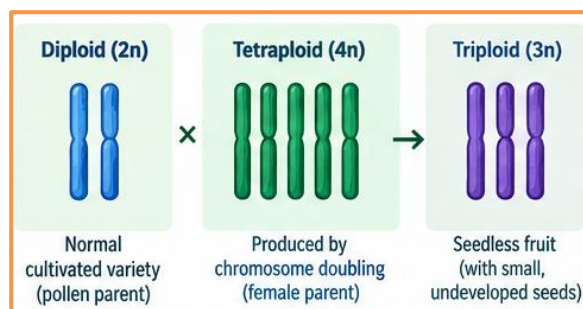
Introduction

Watermelon is an economically important fruit crop cultivated widely in tropical, subtropical and warm temperate regions. Consumer demand has increasingly shifted toward fruits that combine high eating quality with convenience, making seedless watermelon an important segment of the fresh-fruit market. Seedless fruits are particularly attractive because they reduce the inconvenience associated with hard mature seeds during consumption. Commercial seedless watermelon production is mainly based on triploid hybrids. Triploid plants contain three chromosome sets and generally show highly reduced fertility because of irregular chromosome pairing during meiosis. Consequently, they produce fruits with greatly reduced or undeveloped seeds. Although seedlessness remains the primary breeding objective, modern cultivars are expected to provide much more than seedless fruit. High

soluble-solids content, desirable flesh colour, crisp texture, suitable firmness, uniform fruit size, attractive rind pattern and extended shelf life are increasingly important traits. Therefore, current breeding programmes aim to combine seedlessness with superior fruit quality, productivity, disease resistance and environmental adaptation. Genetic improvement, chromosome manipulation and biotechnology can help breeders achieve these multiple objectives more efficiently.

Genetic Basis of Seedlessness in Watermelon

The basic genetic strategy for seedless watermelon production involves manipulating chromosome number. Normal cultivated watermelon is diploid, possessing two sets of chromosomes. Tetraploid plants are produced by chromosome doubling and contain four chromosome sets. When a tetraploid female parent is crossed with a diploid male parent, the resulting progeny generally possess three chromosome sets and are therefore triploid. Triploid plants are highly sterile because their three chromosome sets cannot segregate normally during meiosis. Despite their reproductive sterility, triploid plants retain normal vegetative growth and are capable of producing fruits. The resulting fruits contain only small, soft, undeveloped seed traces rather than mature hard seeds. This genetic mechanism makes triploid breeding the foundation of commercial seedless watermelon production. Successful cultivar development, however, depends on obtaining stable tetraploid parents with good fertility and combining ability.



Development of Tetraploid Watermelon Parents

The production of reliable tetraploid parental lines is one of the most important steps in seedless watermelon breeding. Tetraploids are generally produced by treating actively growing diploid tissues with chromosome-doubling agents. Antimitotic compounds interfere with spindle formation during cell division, resulting in chromosome duplication without normal cell separation. Historically, colchicine has been widely used for chromosome doubling, while other antimitotic compounds have also been investigated. Treated plants must be screened carefully because chromosome doubling may occur in only a proportion of cells. Mixoploidy can also occur, producing plants containing tissues with different chromosome numbers. Flow cytometry, chromosome counting and stomatal characteristics can be used to confirm ploidy. Once stable tetraploid plants are identified, they can be multiplied and evaluated for flowering, pollen fertility, fruit characteristics and combining ability.

Triploid Hybrid Production

Triploid hybrid development begins with crossing selected tetraploid female parents with suitable diploid male parents. The resulting triploid progeny are evaluated for plant vigour, fruit development, seedlessness and fruit quality. The direction of the cross can influence seed development and hybrid-production efficiency. Tetraploid parents should therefore possess adequate female fertility and produce sufficient seed for commercial multiplication. Triploid seedlings are generally more demanding during seed production and early establishment than conventional diploid watermelon. Careful nursery management and optimized seedling production are therefore important. After hybrid development, extensive field testing is necessary to determine whether the triploid genotype combines reliable seedlessness with desirable fruit characteristics.

Biotechnology-Assisted Ploidy Identification

Accurate identification of diploid, tetraploid and triploid plants is essential for successful seedless watermelon breeding. Conventional chromosome counting is effective but can be laborious and requires specialized cytological expertise. Flow cytometry provides a faster

method for estimating nuclear DNA content. It can be particularly useful when large breeding populations need to be screened. Other indirect characteristics, such as stomatal size, stomatal density, pollen morphology and leaf characteristics, can provide preliminary information about ploidy. However, these traits are generally best used together with more reliable cytological or flow-cytometric confirmation. Biotechnology-assisted ploidy screening can therefore reduce the time and labour required to identify useful polyploid plants and improve the efficiency of breeding programmes.

Molecular Breeding for Superior Fruit Quality

Seedlessness alone does not guarantee consumer acceptance. Fruit quality is determined by a combination of genetic, physiological and environmental factors. Important breeding traits include soluble-solids concentration, sugar composition, flesh colour, firmness, texture, aroma, rind thickness and fruit size. Molecular breeding can help identify genomic regions associated with these traits. Quantitative trait loci and genome-wide marker studies have provided opportunities to understand the genetic basis of watermelon fruit characteristics. Markers linked to important traits can potentially be incorporated into marker-assisted selection. This approach is particularly valuable when fruit-quality traits are difficult to measure at early growth stages. Instead of waiting until mature fruits develop, breeders can use molecular information to enrich populations for favourable alleles.

Table 1. Important Fruit-Quality Traits for Seedless Watermelon

Trait	Importance for consumers/production
Soluble solids	Indicator of sweetness
Sugar composition	Determines eating quality
Flesh colour	Consumer appeal and nutritional value
Crispness	Fresh eating quality
Firmness	Handling and shelf life
Fruit size	Market preference
Rind characteristics	Transport and appearance
Lycopene content	Nutritional value
Uniformity	Commercial grading

Improving Sweetness and Nutritional Quality

Sweetness is one of the most important characteristics determining consumer acceptance of watermelon. Soluble-solids concentration is widely used as a practical indicator of sweetness, although individual sugars and their relative proportions also influence taste. Modern breeding increasingly considers sucrose, glucose and fructose accumulation rather than relying only on total soluble solids. Genetic differences in sugar metabolism, transport and storage contribute to variation among watermelon cultivars. Watermelon is also valued for nutritional compounds such as lycopene, citrulline, vitamin C and other bioactive constituents. Red-fleshed cultivars are particularly important sources of lycopene. Combining seedlessness with high nutritional quality can therefore increase the functional-food value of watermelon. Molecular characterization of pigment and metabolic pathways may help breeders select superior genotypes.

Flesh Colour and Texture Improvement

Flesh colour is a major visual quality attribute in watermelon. Red, yellow, orange and other flesh colours are associated with different pigment profiles and consumer preferences. Red-fleshed watermelon is particularly valued for its lycopene content, while yellow and orange types provide opportunities for product diversification. Genetic control of carotenoid accumulation has been studied extensively and can be incorporated into breeding programmes. Texture is another critical characteristic of seedless watermelon. Consumers generally prefer flesh that is crisp, juicy and free from excessive mealiness or hollow areas. Breeding programmes must therefore evaluate flesh firmness, cell structure and texture

together with sweetness. The ideal triploid hybrid should maintain desirable texture without compromising yield or seedless fruit development.

Combining Seedlessness with Disease Resistance

Seedless watermelon hybrids can be vulnerable to many of the same diseases affecting conventional watermelon. Important diseases include Fusarium wilt, powdery mildew, anthracnose and several viral diseases. Disease resistance should therefore be incorporated into tetraploid and diploid breeding parents before hybrid development. Resistant germplasm can be identified through conventional screening, molecular markers and genomic approaches. One challenge is that introducing resistance genes into tetraploid backgrounds can require several generations of selection. Molecular markers can accelerate this process by tracking resistance-associated genomic regions. Combining disease resistance with seedlessness, high fruit quality and productivity will contribute to more resilient commercial cultivars.

Genome-Wide Approaches and Precision Breeding

Advances in watermelon genomics have generated extensive sequence information and molecular markers that can support modern breeding. SNP markers, high-density genetic maps and genome-wide association studies can help identify regions controlling economically important traits. Genomic selection provides another opportunity by using genome-wide marker information to predict the breeding value of plants before complete phenotypic evaluation. This could be especially useful for complex traits such as yield, fruit quality and stress tolerance. Precision breeding can also help investigate genes involved in fruit development, sugar accumulation, pigmentation and disease resistance. However, the biological complexity of many quality traits means that genetic improvement will generally require a combination of molecular and phenotypic selection. Integrating genomic information into triploid breeding could improve the selection of both tetraploid parents and diploid pollen parents.

Tissue Culture and Biotechnology in Tetraploid Development

Tissue culture can support the multiplication and maintenance of valuable polyploid breeding materials. It may also provide opportunities for regeneration after chromosome manipulation or genetic transformation. In vitro techniques can be useful when valuable tetraploid plants are available in limited numbers. Rapid multiplication can help establish sufficient parental material for crossing and evaluation. However, tissue-culture-derived plants must be carefully assessed because somaclonal variation can arise during prolonged culture. Genetic stability is particularly important for parental lines used in hybrid seed production. The combination of tissue culture, ploidy screening and molecular characterization can therefore provide a more reliable biotechnology pipeline for polyploid watermelon improvement.

Challenges in Seedless Watermelon Breeding

Despite major advances, seedless watermelon breeding involves several technical challenges. Tetraploid induction is often inefficient and newly induced tetraploid plants may show reduced vigour or fertility. Triploid seed production can also be more difficult than conventional diploid seed production. Seed germination and seedling establishment may require careful management. Another challenge is maintaining fruit quality while introducing seedlessness. Some triploid combinations may show differences in fruit size, maturity, sweetness or texture compared with their diploid parents. Breeders must therefore evaluate several generations and combinations before identifying commercially useful hybrids. Multi-environment testing is also essential because temperature, water availability and growing conditions can affect fruit quality.

Future Prospects

The future of seedless watermelon breeding will depend on combining traditional polyploid breeding with advanced molecular and biotechnological tools. High-throughput genotyping

can accelerate selection of parents with favourable genetic backgrounds. Genomic selection and genome-wide association studies may improve the identification of alleles controlling fruit sweetness, colour, texture, nutritional quality and disease resistance. Precision chromosome manipulation and improved tissue-culture systems could make tetraploid development more efficient. At the same time, gene-editing research may provide opportunities to study and potentially modify genes involved in fruit quality and plant adaptation.

Conclusion

Seedless watermelon breeding represents a successful application of chromosome manipulation to commercial crop improvement. The development of triploid hybrids through tetraploid $\times$ diploid crosses provides the fundamental genetic mechanism for producing fruits with greatly reduced hard seeds. However, modern consumers and producers demand cultivars that combine seedlessness with sweetness, crisp texture, attractive flesh colour, nutritional value, disease resistance, yield and good shelf life. Achieving these objectives requires coordinated improvement of both tetraploid and diploid parental lines. Molecular markers, genome-wide analysis, flow cytometry, tissue culture and other biotechnology tools can accelerate the identification and development of superior breeding materials. Future integration of genomic selection and precision breeding could further improve the efficiency of cultivar development. Ultimately, the combination of polyploid genetics, molecular breeding, biotechnology and rigorous fruit-quality evaluation offers a promising pathway for developing next-generation seedless watermelon cultivars with superior consumer appeal and production performance.

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