

Current Status, Challenges and Future Strategies for Watermelon Breeding in China

Xueqiang ZHU

Shangqiu Academy of Agricultural and Forestry Sciences, Shangqiu 476000, China

Abstract Watermelon is a characteristic horticultural cash crop of immense economic value in China. China has consistently ranked first globally in both planting area and total production of watermelon. Domestically developed varieties hold a market share exceeding 98%, achieving self-sufficiency and security in seed sources. However, amidst the rapid industry development, significant challenges persist in watermelon breeding. These include insufficient exploration and utilization of germplasm resources, narrow genetic bases, severe varietal homogeneity, slow progress in pyramiding multiple resistances with high quality, inadequate mechanisms for translating research into practice, shortcomings in intellectual property protection for the seed industry, and a low level of industrialization for cutting-edge biotechnology. This paper systematically reviews the current state of watermelon breeding development in China, provides an in-depth analysis of the bottleneck issues confronting current breeding efforts, and, grounded in the practical production realities of major regions like the Huang – Huai – Hai area, proposes comprehensive strategies and suggestions focusing on germplasm innovation, breeding technology advancement, optimization of breeding objectives, innovation system construction, and intellectual property protection. This aims to provide a theoretical reference for shifting watermelon breeding from "quantity expansion" to "quality enhancement" and supporting the high-quality, sustainable development of the watermelon industry.

Key words Watermelon, Variety breeding, Germplasm resources, Molecular breeding, Varietal homogeneity, Seed industry innovation

0 Introduction

Watermelon (*Citrullus lanatus*) originated in Northeast Africa and has a long history of cultivation in China. Valued both economically and for consumption, it is a dominant fresh fruit during summer. By 2021, global watermelon production reached 101 million t, with a planting area of 3.03 million ha, while melon planting area was approximately 533 000 ha^[1]. With rising consumer demand and the widespread adoption of protected cultivation, the market now demands diversified watermelon varieties: growers seek varieties tolerant to low temperatures, resistant to multiple soil-borne and foliar diseases, with stable fruit setting, and suitable for simplified cultivation; distributors require types with tough rinds that are storage- and transport-tolerant, offering a long shelf life; consumers place greater emphasis on flesh texture, sugar gradient, unique flesh color, and flavor quality.

In recent years, the complete genome map and pan-genome of watermelon have been successively deciphered, SNP liquid-phase breeding chips have been successfully developed, molecular breeding techniques are gradually being implemented, significantly enhancing breeding efficiency. Concurrently, the nationwide implementation of the variety registration system for non-staple crops has led to a sustained and rapid increase in the number of registered watermelon varieties across China. However, a significant portion of these registered varieties exhibit high similarity in appearance and agronomic traits; old continuous cropping regions urgently require breakthrough varieties combining multiple resist-

ances; the efficient introgression of disease resistance from wild germplasm into cultivated varieties remains challenging; persistent issues such as the lengthy cycles and high labor demands of traditional phenotypic selection continue to constrain breeding innovation. Clarifying the current status of watermelon breeding development, identifying the core bottlenecks, and establishing a sustainable innovation mechanism are of significant practical importance for consolidating China's advantage in watermelon "seed sources".

1 Current status of watermelon variety breeding in China

1.1 Diversification of breeding entities and continuous optimization of breeding layout Currently, watermelon breeding in China has established a pattern where research institutes lead fundamental research and seed enterprises dominate commercial breeding. National and provincial research institutions focus primarily on germplasm resource conservation, gene mining, fundamental theory research, and the development of cutting-edge breeding technologies; large seed enterprises concentrate on market demands, conducting hybrid combination screening, variety regional trials, and industrialization promotion; regional breeding teams, based in key production areas like Huang – Huai – Hai, Northwest China, and protected cultivation regions in the South, are dedicated to breeding specialized varieties tailored to local climates and cultivation practices.

1.2 Iterative upgrading of breeding technologies and integrated advancement of traditional and biotechnological methods Traditional cross-breeding remains the predominant method. F₁ hybrid seeds produced through manual emasculation and cross-pollination dominate the market, with breeders developing numerous combinations focusing on maturity periods, fruit shape, flesh color, and sugar content. The breeding technology system for

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Xueqiang ZHU, bachelor's degree, research fields: crop breeding and cultivation.

seedless watermelon is well-established; through tetraploid induction and triploid combination selection, seedless watermelon varieties have achieved large-scale commercialization.

Molecular breeding technologies are rapidly transitioning from the laboratory to field application. Continuous breakthroughs are being made in high-density genetic mapping and pan-genome research for watermelon, molecular markers closely linked to traits like *Fusarium* wilt resistance, powdery mildew resistance, flesh color, and sugar content have been successively developed, SNP liquid-phase chips enable high-throughput genotyping of germplasm; SNP loci associated with fruit shape have been mapped to chromosome 3^[2]. Molecular Marker-Assisted Selection (MAS) is applied for the early-generation screening of disease-resistant materials, shortening the breeding cycle from 7–9 generations to 5–6 generations, significantly reducing the pressure associated with large-scale field phenotypic evaluation. A team led by Xu Yongyang from the Zhengzhou Fruit Research Institute of the Chinese Academy of Agricultural Sciences (CAAS), collaborating with 19 domestic and international research institutions, identified over 200 candidate genes and loci associated with traits such as bitterness, acidity, fruit size, and flesh color in melon^[3]. Gene editing technology has made progress in functional validation of watermelon genes, but due to policy constraints and transformation efficiency limitations, it has not yet yielded commercially available varieties.

1.3 Expanding breeding objectives and increasing variety diversification Early watermelon breeding focused primarily on high yield, early maturity, and transport tolerance as core objectives. Current breeding objectives have shifted towards synergistic enhancement of quality, disease resistance, distinctiveness, and suitability for simplified cultivation. (i) conventional red-fleshed watermelons are continually being optimized, with efforts to breed varieties tolerant to low temperatures for early spring production and heat-tolerant varieties for extended autumn harvests; (ii) there is rapid development of specialty varieties, where yellow-fleshed, orange-fleshed, and red-yellow bicolor-fleshed mini watermelons for the gift market have become breeding hotspots, catering to demand for premium pick-your-own experiences and super-market differentiation; (iii) disease resistance breeding is receiving increased attention, focusing on screening germplasm resistant to *Fusarium* wilt, powdery mildew, and anthracnose; (iv) specialized varieties for simplified cultivation represent a new direction, involving the selection of materials with fewer lateral branches, easy fruit set, and suitability for minimal pruning and mechanical harvesting.

2 Major problems in current watermelon variety breeding

2.1 Narrow genetic base in cultivars and low utilization efficiency of wild germplasm During the long domestication process of watermelon, continuous directional selection for fruit quality traits by humans has led to the progressive loss of a vast

amount of genetic information related to disease resistance and stress tolerance. Currently, the parental lines of the vast majority of hybrid varieties stem from a limited number of elite inbred lines, resulting in a continuous decline in genetic diversity within breeding populations. Although China conserves a significant amount of wild watermelon germplasm, a phenomenon of "prioritizing conservation over deep characterization" exists; many wild accessions have only undergone basic agronomic surveys, and key genes for disease resistance and stress tolerance have not been precisely mapped; wide hybridization faces reproductive barriers, and the process of introgressing disease resistance genes is often accompanied by linkage drag, leading to the problem of "disease resistance but significantly degraded quality".

2.2 Severe varietal homogeneity and prevalent imitative breeding By recent years, the number of registered watermelon varieties nationwide has exceeded 3 800, but a large proportion of these new varieties exhibit extremely high similarity in traits. Many small and medium-sized breeding institutions lack original innovative materials; instead, they make minor modifications to mainstream market varieties, engaging in low-level repetitive breeding. Early-maturing, striped-rind, red-fleshed types and derivatives of the '8424' line are registered in large numbers, with minimal differences in fruit shape, sugar content, and disease resistance. Homogeneity brings two major negative impacts: firstly, the lack of differentiated competitiveness among varieties leads the market into vicious low-price competition; secondly, it results in redundant consumption of human and land resources, disperses efforts for breeding breakthroughs, and hinders the overall technological upgrading of the industry. Concurrently, issues of synonyms (different names for the same variety) and homonyms (same name for different varieties) persist.

2.3 Challenges in pyramiding multiple traits and scarcity of varieties with comprehensive resistance A clear shortcoming in current breeding is the abundance of varieties with single resistance traits and the scarcity of high-quality varieties combining resistance to multiple diseases. Old watermelon production areas commonly suffer from complex infections involving *Fusarium* wilt, gummy stem blight, anthracnose, bacterial fruit blotch, and viral diseases, yet most available materials are only resistant to *Fusarium* wilt, making it difficult to achieve resistance to multiple pathogens simultaneously. A negative genetic correlation exists between quality and resistance; materials with high sugar content and crisp flesh often have thinner rinds, are prone to fruit cracking, and exhibit weak disease resistance; disease-resistant materials commonly suffer from defects such as bland flavor and large sugar gradients within the fruit. It remains challenging for breeders to simultaneously integrate the multiple target traits of "multiple resistances, high sugar content, strong rind toughness, and stable fruit set".

2.4 Insufficient biotechnology translation and disconnect between molecular and conventional breeding Despite abundant achievements in watermelon genome research, the translation of

laboratory findings to the front lines of breeding is slow. (i) the majority of molecular markers remain confined to research papers, with a limited number of practical markers proven stable for large-scale population screening; (ii) many seed companies lack molecular biology laboratories and specialized technical personnel, still relying entirely on visual phenotypic selection in the field; (iii) the costs associated with translating cutting-edge technologies like gene editing and genomic selection are relatively high, placing them beyond the reach of small and medium-sized breeding entities; (iv) there is a lack of platforms for precise phenotypic characterization and standardized, high-throughput field phenotypic data collection systems, constraining genotype-phenotype association analyses. The two paths of traditional breeding and biotechnology have yet to achieve deep integration.

2.5 Misalignment between breeding directions and production needs, insufficient supply of specialized varieties

(i) there is a shortage of varieties adapted to old production areas plagued by continuous cropping obstacles. Grafting seedlings can only combat *Fusarium* wilt, offering limited effectiveness against gummy stem blight, root-knot nematodes, and soil-borne bacterial diseases; the market urgently needs varieties with vigorous root systems tolerant to soil abiotic stresses; (ii) breeding specialized for simplified and mechanized cultivation lags behind. Varieties suitable for pruning-free cultivation, mechanical harvesting, and large-scale intensive farming are scarce, while existing varieties remain highly reliant on manual pruning and pollination; (iii) there is an insufficient number of heat-tolerant and shade-tolerant varieties specifically bred for extended autumn production and rain-sheltered cultivation; (iv) specialized breeding targeting processing uses (*e.g.*, juice, fresh-cut) is virtually non-existent, with breeding efforts predominantly concentrated on the fresh market.

3 Strategies and suggestions for promoting high-quality development of watermelon variety breeding in China

3.1 Systematically conducting precise germplasm characterization to broaden the genetic foundation for breeding

(i) it is essential to enhance the construction of the national watermelon and melon medium-term gene bank platform, continuously collect cultivated germplasm and wild relatives from domestic and international sources, establish standardized resource archives, and persistently domesticate and improve materials into elite varieties, particularly focusing on the domestication of sweetness, bitterness, and flesh color traits^[4]. (ii) it is necessary to initiate large-scale precise germplasm evaluation, prioritizing the screening of excellent resources resistant to gummy stem blight, bacterial fruit blotch, and root-knot nematodes, and tolerant to low temperatures and high humidity/heat, in order to build a core germplasm collection. (iii) efforts should be made to break through the bottlenecks of wide hybridization technology, by utilizing techniques like embryo rescue to overcome reproductive barriers, and emplo-

ying molecular markers to eliminate linkage drag, thereby introducing disease resistance genes from wild germplasm into elite cultivated backgrounds. (iv) encouragement should be given to germplasm sharing among breeding institutions and the establishment of mutually beneficial resource exchange mechanisms, aiming to avoid material isolation and redundant creation. (v) selection should focus on dwarfing varieties, such as short-vined and ultra-short-vined types, which have shortened internodes to increase planting density and enhance yield per unit area^[5].

3.2 Adjusting breeding objectives to promote differentiated and specialized breeding

Breeding efforts must be grounded in the cultivation practices of different ecological zones to implement targeted breeding. For the Huang – Huai – Hai region's early spring mini-arch/multi-span greenhouse production: Varieties should be bred that are tolerant to low temperature and low light, with early female flower differentiation, stable fruit set, low susceptibility to malformed fruit, and tolerance to short-term late spring cold snaps; simultaneously, attention must be paid to improving rind toughness to reduce fruit cracking risk. For extended autumn production and rain-sheltered cultivation in the South: Varieties should be bred that are tolerant to heat, shade, rain, and low light, with resistance to viral diseases. For the specialty gift melon segment: Cultivation efforts should target small-sized watermelons with yellow or bicolor flesh, aiming for balanced improvements in sugar content, flesh flavor, and storage/transportation qualities. For the simplified cultivation direction: New materials should be selected that possess few lateral branches, easy fruit set, and suitability for pruning-free cultivation, thereby aligning with the labor requirements of large-scale farms. A rational layout of early, mid, and late-maturing variety tiers should be established to alleviate price fluctuations caused by concentrated market arrivals.

3.3 Promoting deep integration of conventional and biotechnological breeding to build an efficient breeding system

(i) it is imperative to accelerate the development and dissemination of practical molecular markers, by prioritizing the mapping and screening of markers linked to traits like disease resistance, flesh color, sugar content, rind hardness, and *Fusarium* wilt resistance to reduce early-generation screening costs^[6]; furthermore, it is essential to promote SNP liquid-phase chips to enable high-throughput genotyping. (ii) integrated breeding platforms combining "molecular screening + field phenotypic evaluation" must be established, and the pilot application of genomic selection technology in watermelon breeding should be advanced to shorten breeding cycles. (iii) standardized high-throughput phenotyping bases must be constructed, with unified methods for disease resistance inoculation assays and quality testing standards, in order to enhance data reliability. (iv) foundational research on gene editing technology should be conducted in an orderly manner, including stockpiling valuable mutant materials and monitoring relevant biosafety policies, to prepare reserves for future technology industrialization^[7]. (v) focus should be placed on breeding talent de-

velopment and enterprises should be encouraged to recruit molecular biology specialists, thereby bridging the technological gap between research institutions and seed companies.

3.4 Regulating the breeding innovation order and curbing low-level homogeneous breeding Agricultural and rural authorities must enhance supporting management measures for watermelon variety registration, strengthening DUS (Distinctness, Uniformity, Stability) testing and DNA fingerprint comparison; establish a fingerprint database for registered varieties, subject varieties exhibiting high similarity to rigorous scrutiny, and reduce the registration of homogeneous varieties at the source. Breeding entities should be guided to shift their approach from imitation and modification towards original innovation, and breeding institutions should be encouraged to identify niche segments to develop differentiated advantages. Concurrently, a dynamic variety withdrawal mechanism must be established, whereby varieties with no promotion area over an extended period or possessing significant defects are lawfully phased out of the market, thereby streamlining the varietal supply structure.

3.5 Improving the industry-academia-research collaborative innovation system to unblock technology transfer channels Collaborative breeding platforms integrating research institutes, seed companies, and demonstration bases must be established, and long-term joint research projects should be initiated focusing on the industry's critical challenges. Innovative benefit-sharing mechanisms need to be developed, clearly defining the allocation of variety rights and technology transfer proceeds to foster motivation among both researchers and enterprises. Research teams should be supported to conduct multi-location regional trials for varieties in major production areas, thoroughly accounting for diverse climatic and soil conditions, thus preventing situations where varieties demonstrate "excellent laboratory performance but poor field adaptability". The establishment of new watermelon and melon variety demonstration and evaluation bases should be encouraged in key production regions such as Huang – Huai – Hai and Northwest China to accelerate the demonstration and promotion of superior new varieties.

4 Conclusions

After years of development, watermelon breeding in China has established an independent and comprehensive breeding system, firmly securing seed source autonomy, with breeding technol-

ogies and the number of varieties ranking among the world's leading positions. However, a series of challenges—including a narrow genetic base, variety homogenization, difficulties in pyramiding multiple resistances with high quality, lagging industrialization of biotechnology, and insufficient intellectual property protection—constrain breeding innovation from achieving greater breakthroughs. Future watermelon variety development should adhere to an industry demand-oriented approach, root itself in germplasm resource innovation, and promote the deep integration of conventional breeding with molecular design breeding. On the one hand, efforts should be made to broaden the sources of genetic resources, mine superior genes from wild germplasm, and cultivate breakthrough new varieties that possess multiple resistances, high quality, and broad adaptability; on the other hand, it is essential to improve the institutional environment for breeding innovation, curb low-level repetitive breeding, and unblock the pipeline for transforming industry-academia-research achievements.

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