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Heterosis Breeding in Cucurbitaceous Vegetable Crops

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Abstract

Cucurbitaceous vegetables constitute an important group of horticultural crops that includes cucumber, bitter gourd, bottle gourd, ridge gourd, sponge gourd, pumpkin, squash, muskmelon and watermelon. Many cucurbits possess biological features that make hybrid breeding particularly attractive, including monoecious or gynoecious sex expression, relatively easy manipulation of pollination, abundant pollen, seed production and substantial exploitable variation for yield, earliness and fruit quality. Heterosis, or hybrid vigour, refers to the superior performance of an F_1 hybrid over its parents. In cucurbitaceous crops, heterosis has been exploited for increasing fruit yield, number of fruits, fruit size, earliness, quality and in some cases, tolerance to biotic and abiotic stresses (Yu et al., 2021). Combining ability analysis, particularly general combining ability (GCA) and specific combining ability (SCA), assists breeders in identifying suitable parents and promising cross combinations (Griffing, 1956). Recent advances in molecular markers, genomics and prediction of hybrid performance are creating opportunities to make heterosis breeding more efficient. This review summarizes the genetic basis, breeding approaches, crop-wise utilization, advantages, constraints and future prospects of heterosis breeding in cucurbitaceous vegetable crops.

Keywords: *Cucurbitaceae; heterosis; hybrid vigour; F_1 hybrids; combining ability; GCA; SCA; hybrid breeding; vegetable crops*

1. Introduction

Cucurbitaceous vegetables are economically important crops cultivated in tropical, subtropical and temperate regions and include cucumber, muskmelon, watermelon, bitter gourd, bottle gourd, ridge gourd, sponge gourd, pumpkin and squash. Their fruits are widely consumed fresh, cooked, processed and pickled, while several species also possess nutritional and medicinal value. Improvement in productivity and quality can be achieved through selection, hybridization, recurrent selection and heterosis breeding. Among these approaches, hybrid breeding is particularly effective because genetically diverse parents can produce F_1 hybrids with superior performance for important traits. In cucumber, heterosis has been reported for earliness, fruit number, fruit length, fruit weight and total fruit yield, demonstrating its potential for commercial hybrid development (Ene et al., 2019; Kumari et al., 2021). The reproductive biology of cucurbits further facilitates hybrid seed production, as monoecious plants possess distinct male and female flowers, while gynoecious lines predominantly produce female flowers. These characteristics make controlled pollination and hybridization comparatively convenient. Moreover, the production of numerous seeds per fruit can support efficient multiplication of hybrid seed. Thus, the combination of favourable reproductive biology and strong heterosis for yield and associated traits has established cucurbits as important crops for the development and utilization of commercial F_1 hybrids.

2. Concept and Genetic Basis of Heterosis

Heterosis, commonly termed hybrid vigour, is the phenomenon in which an F_1 hybrid exhibits greater performance than its parents for one or more traits. The comparison may be made with the mid-parent value, the better parent or a commercial standard. Accordingly, relative heterosis, heterobeltiosis and standard heterosis are commonly estimated in breeding experiments. The genetic basis of heterosis is complex. Dominance, overdominance and epistatic interactions have traditionally been proposed to explain hybrid superiority. The dominance hypothesis attributes hybrid vigour to the masking of deleterious recessive alleles by favourable dominant alleles from the other parent, whereas the overdominance hypothesis proposes that heterozygosity itself can provide an advantage at particular loci. Epistasis emphasizes interactions among genes at different loci (Chen, 2013).

3. Estimation of Heterosis

For a cross between parents P1 and P2 with F_1 performance F, relative heterosis can be expressed as:

Relative heterosis (%) = $[(F - MP) / MP] \times 100$, where MP is the mid-parent value, calculated as $(P1 + P2)/2$.

Heterobeltiosis (%) = $[(F - BP) / BP] \times 100$, where BP is the better parent.

Standard heterosis (%) = $[(F - SC) / SC] \times 100$, where SC represents the standard or commercial check.

For traits in which lower values are desirable, such as days to flowering or days to marketable maturity, negative heterosis can be advantageous.

4. Importance of Combining Ability in Hybrid Breeding

Heterosis studies are often complemented by combining ability analysis. General combining ability reflects the average performance of a parent in hybrid combinations and is commonly associated with additive genetic effects, whereas specific combining ability reflects the performance of particular cross combinations beyond what would be predicted from parental GCA and is commonly associated with non-additive genetic effects, including dominance and epistasis (Griffing, 1956). When SCA variance is greater than GCA variance, non-additive effects may have an important role in determining the trait and hybrid breeding can be particularly useful. Diallel, line × tester and related mating designs are frequently used to evaluate GCA and SCA; the statistical basis for diallel analysis was formalized by Griffing (1956) and Hayman (1954) and these frameworks remain the standard approach in cucurbit breeding studies. Combining ability information helps breeders identify diverse parents, avoid unproductive crosses and select combinations with high yield potential, desirable fruit attributes and suitable adaptation.

5. Heterosis in Major Cucurbitaceous Vegetable Crops

5.1 Cucumber

Cucumber is one of the most important cucurbitaceous crops for heterosis breeding. Commercial hybrid development has benefited from gynoecious lines, which produce predominantly female flowers and can reduce the labour needed for hybrid seed production (Jat et al., 2015). Heterosis has been reported for earliness, number of female flowers, fruit number, fruit length, fruit weight and total fruit yield, with significant GCA and SCA variances typically observed for most yield-related traits (Ene et al., 2019). Hybrid breeding is also important for parthenocarpic cucumber production, particularly under protected cultivation where fruit set and quality must remain stable under specific environmental conditions. The magnitude of heterosis reported for cucumber varies considerably between studies and germplasm sets; while some diallel studies report substantial hybrid vigour for yield. More recent work using introgression of indigenous and exotic sources has demonstrated that residual heterosis for earliness and yield traits can be recovered in advanced generations, broadening the options available for cucumber hybrid development (Kumari et al., 2021). The molecular and genetic resources available in cucumber have expanded substantially, and marker-assisted approaches are increasingly used to track sex-expression traits and to help identify parents with complementary alleles for hybrid combinations.

5.2 Bitter Gourd

Bitter gourd is a highly valued cucurbitaceous vegetable because of its distinctive fruit, nutritional composition and medicinal importance. Heterosis breeding has been widely investigated for fruit yield and its components and hybrids may show superiority for number of fruits per plant, fruit weight, fruit length, earliness and overall yield (Mallikarjunarao et al., 2020). Heterosis has also been examined for quality and biochemical traits; recent diallel work has extended combining-ability and heterosis analysis to biochemical and nutritional attributes, indicating that hybrid breeding in bitter gourd is not limited to yield improvement but can also contribute to nutritional quality improvement (Saini et al., 2026). The crop's sex expression and cross-pollination behaviour provide practical opportunities for controlled hybrid seed production.

5.3 Bottle Gourd

Bottle gourd is another important cucurbit in which heterosis has been exploited for yield and earliness. Important target traits include days to first female flower, number of fruits per plant, fruit weight, fruit length and total yield, with several line × tester and diallel studies reporting substantial standard heterosis for fruit yield (Masud et al., 2021). Recent studies have also demonstrated heterosis for nutritional quality traits such as dry matter content, ascorbic acid, reducing sugars and total soluble solids, highlighting the potential of hybrid breeding to combine productivity gains with improved nutrient content (Bhatt et al., 2023).

5.4 Ridge Gourd and Sponge Gourd

Ridge gourd and sponge gourd have considerable diversity in fruit shape, size, fibre characteristics, earliness and yield. Heterosis breeding can combine desirable attributes from diverse parental lines and may provide gains for fruit number, fruit weight, total yield and mineral content; line × tester studies in ridge gourd have reported significant heterosis together with a predominance of non-additive gene action for most yield-related and quality traits (Singh et al., 2017). Compared with cucumber and bitter gourd, systematic hybrid breeding and genetic studies in some of these crops remain less extensive, creating opportunities for the identification of heterotic groups and the development of locally adapted hybrids.

5.5 Pumpkin and Squash

Pumpkin and squash represent another important segment of cucurbit breeding. Hybridization can generate combinations with improved fruit yield, fruit size, uniformity, maturity and quality; a full-diallel evaluation of pumpkin inbred lines across environments reported significant heterosis and non-additive gene action for yield as well as for sweetness, carotenoid content and antioxidant traits, indicating scope for combining productivity gains with nutritional improvement (Hosen et al., 2022). Interspecific breeding within *Cucurbita* spp. has also been explored for transferring useful traits, although compatibility, fertility and the genetic background of parents must be carefully considered. Heterosis breeding can be particularly valuable where hybrids combine vigorous growth with uniform commercial fruit characteristics.

5.6 Muskmelon and Watermelon

Muskmelon and watermelon have a long history of hybrid breeding. Commercial hybrids are valued for high yield, uniform fruit size, flesh quality, sweetness, earliness and marketability. In muskmelon, half-diallel evaluation of genetically diverse inbred lines, including genic male-sterile lines, has demonstrated substantial standard heterosis for fruit yield together with improvements in sweetness, β-carotene content, ascorbic acid, firmness and Fusarium wilt resistance, illustrating how heterosis breeding can be combined with disease-resistance objectives (Kaur et al., 2022). In watermelon, hybrid breeding has similarly been integrated with disease resistance and seedless fruit production systems. Broader reviews of melon breeding note that, relative to major grain and vegetable crops, empirical heterosis and combining-ability studies in cucurbits remain comparatively limited, leaving considerable scope for further work (Kesh & Kaushik, 2021).

6. Mechanisms and Approaches for Hybrid Seed Production

Successful heterosis breeding requires reliable production of genetically pure parental lines and efficient hybrid seed production. In cucurbits, controlled pollination is facilitated by the distinct male and female flowers. Emasculation, where required, is followed by hand pollination and protection of the female flower from unwanted pollen. Gynoecious lines, sex-expression modifiers and other reproductive traits can reduce the cost and labour involved in hybrid seed production (Jat et al., 2015). The choice of parental lines is critical. Breeders generally seek parents that differ sufficiently to generate useful heterosis while possessing complementary desirable traits. Evaluation of parental per se performance, GCA, genetic diversity and combining ability can improve the probability of obtaining superior F_1 hybrids (Griffing, 1956).

7. Advantages of Heterosis Breeding in Cucurbits

- Higher fruit yield and improved yield components.
- Greater earliness and improved synchronization of marketable harvest.
- Improved fruit uniformity, size, shape and market appeal.
- Potential improvement in nutritional and biochemical quality traits.
- Combination of complementary traits from genetically diverse parents.
- Possibility of combining productivity with tolerance to important stresses.
- Efficient exploitation of non-additive genetic variation.

8. Constraints and Challenges

Despite its advantages, heterosis breeding has several constraints. Maintenance of genetically pure parental lines requires careful isolation and selection. Hybrid seed production can be labour-intensive when hand pollination is required. Environmental effects may alter sex expression, flowering behaviour, fruit set and hybrid performance, making multi-location testing essential — a point underscored by the marked differences in heterosis magnitude reported across independent cucumber studies conducted in different germplasm sets and environments (Ene et al., 2019; Cramer & Wehner, 1999). In addition, the cost of hybrid seed can be higher than that of open-pollinated varieties and farmers cannot normally maintain the same level of performance by saving F_1 seed for the next generation. Another major challenge is the identification of stable heterotic patterns. High heterosis in one environment does not necessarily guarantee superior performance in another. Therefore, genotype × environment interaction, parental adaptation and disease pressure must be considered before commercialization.

9. Future Prospects

The future of heterosis breeding in cucurbitaceous vegetables lies in combining conventional breeding with genomic technologies. Development of well-characterized heterotic groups, efficient gynoecious or other reproductive systems, molecular markers for key traits, genomic prediction and precise phenotyping can accelerate hybrid development. Breeding objectives are also expected to expand from yield alone to include nutritional quality, shelf life, climate resilience, water-use efficiency and resistance to emerging pests and diseases, as already illustrated by combined yield-and-quality heterosis studies in pumpkin, muskmelon and bottle gourd (Hosen et al., 2022; Kaur et al., 2022; Bhatt et al., 2023). Climate change makes these objectives particularly important. Hybrids that maintain flowering, fruit set and quality under heat, drought or irregular rainfall could provide greater stability to vegetable production. Integration of farmer preferences and market requirements with genetic improvement will be essential to ensure that new hybrids are not only biologically superior but also commercially useful.

10. Conclusion

Heterosis breeding is a powerful approach for the genetic improvement of cucurbitaceous vegetable crops. The biological features of cucurbits, including diverse sex-expression systems and manageable pollination, make these crops well suited to hybrid development. Considerable heterosis has been documented for yield, earliness, fruit attributes and quality in cucumber, bitter gourd, bottle gourd, ridge gourd, sponge gourd, pumpkin, squash, muskmelon and watermelon.

Combining ability analysis, grounded in the classical frameworks of Griffing (1956) and Hayman (1954), provides an important tool for identifying superior parents and crosses, while molecular and genomic technologies offer new opportunities for predicting and understanding hybrid performance. Future breeding programmes should integrate heterosis with resistance breeding, nutritional quality, stress resilience and modern genomic tools to develop productive, stable and market-oriented cucurbit hybrids.

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