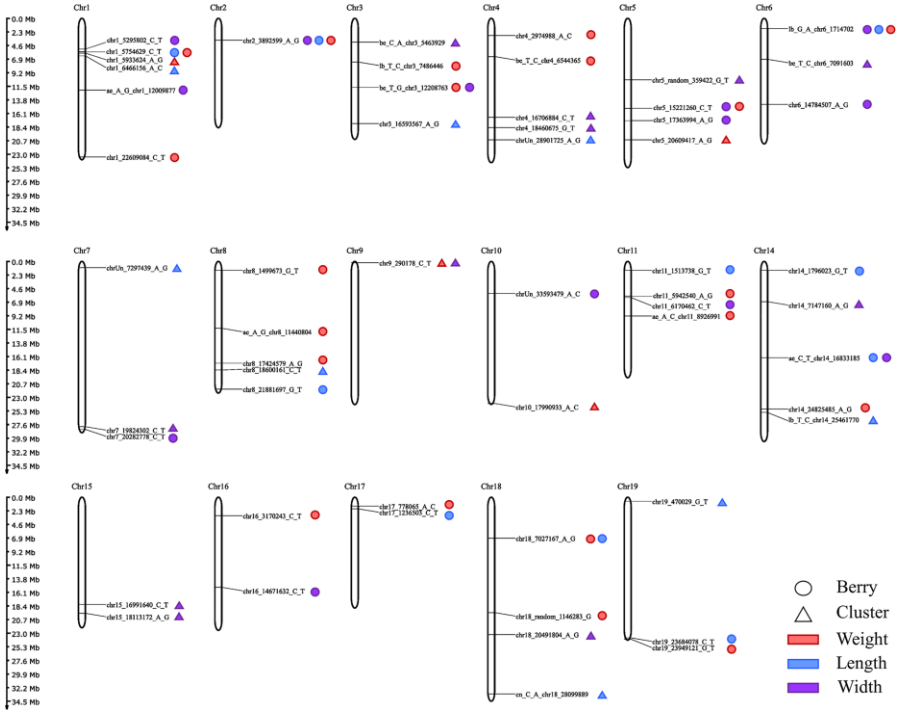


Figure 3 Chromosomal localization of significant SNPs associated with berry- and cluster-related traits (Adopted from De Oliveira et al., 2026)

Image caption: The chromosome number is shown at the top of each chromosome, and chromosome sizes are depicted on a vertical scale (Mb) (Adopted from De Oliveira et al., 2026)

Cluster shaping and quantitative thinning are key techniques for improving cluster structure and berry uniformity. By adjusting inflorescence length, secondary cluster number, and branching density before and after flowering, berry crowding at later stages can be effectively reduced, creating space for uniform berry enlargement. For compact cultivars, shortening inflorescences or removing secondary clusters can reduce berry density, whereas for loose cultivars, excessive thinning should be avoided to maintain cluster fullness. Implementing quantitative berry thinning during the early fruit stage removes underdeveloped or overly dense berries, reduces resource competition, and ensures a more balanced assimilate supply to the remaining berries. Studies have shown that mechanical or chemical thinning can significantly improve berry size and cluster structure in compact cultivars. In 'Shine Muscat', moderate thinning promotes berry enlargement and maintains sugar-acid balance, whereas excessive thinning may reduce fruit quality (Choi et al., 2023), indicating that thinning intensity must be carefully adjusted according to cultivar characteristics and production objectives.

Plant growth regulators, particularly gibberellic acid ($GA_3$), play an important role in regulating berry uniformity. Appropriate timing and concentration of $GA_3$ treatments can promote berry enlargement, increase berry diameter and cluster weight, and act synergistically with thinning practices. However, the effects of $GA_3$ are highly cultivar-dependent and sensitive to dosage, and improper application may result in uneven berry development, altered skin characteristics, or delayed ripening. Therefore, $GA_3$ application should be integrated with cluster shaping, thinning, and water and nutrient management to form a systematic regulation strategy. Overall, the coordinated optimization of multiple cultivation practices can effectively enhance developmental synchrony and represents a key pathway for achieving stable improvement in berry uniformity.

## 6 Digitalization and Intelligent Development Trends

### 6.1 Machine vision-based automatic identification and evaluation systems for berry uniformity

With the rapid development of artificial intelligence, machine vision, and high-throughput phenotyping technologies, image-based automatic evaluation systems for grape berry uniformity have become a key direction for improving efficiency, objectivity, and reproducibility. These systems typically acquire cluster information using high-resolution RGB images, mobile device images, or field close-range images, and integrate image