large in others as well (Dobrei and Sala, 2025). When variability in these traits is low within a cluster, the overall appearance is visually uniform; otherwise, noticeable size heterogeneity may occur, reducing uniformity.

Beyond size, berry shape provides an important complementary dimension for evaluating uniformity. The shape index, typically defined as the ratio of berry length to width, is used to distinguish morphological types and reflect shape consistency. More advanced descriptors, such as eccentricity, contour curvature, and elliptical Fourier descriptors, allow a more precise characterization of berry outlines, thereby improving the accuracy of shape evaluation (De Sousa Moreira et al., 2024). Previous studies have shown significant differences in shape stability among grape materials, indicating that shape consistency is also an important component of uniformity.

At the structural level, cluster compactness serves as a key link between individual berry traits and overall cluster appearance. This trait integrates berry number, berry size, and rachis structure, and can be interpreted as the degree of space filling within the cluster (Torres-Lomas et al., 2024). Moderately compact clusters contribute to a full and orderly appearance, whereas excessive compactness may lead to berry deformation and uneven development, and overly loose clusters may result in poor arrangement and visual inconsistency. Therefore, berry size, shape, and cluster structure collectively form the core phenotypic basis of berry uniformity, which is essentially the result of the coordinated interaction of multiple traits.

2.3 Quantitative evaluation methods of berry uniformity

To achieve an objective assessment of berry uniformity, phenotypic traits such as berry size, shape, and cluster structure must be transformed into quantifiable indicators. Among these, the coefficient of variation (CV) is the most widely used statistical metric and is employed to describe the dispersion of traits such as berry weight, length, width, and area within a cluster (Dobrei and Sala, 2025; Milišić et al., 2025). A lower CV value indicates smaller differences among berries and thus higher uniformity, whereas a higher CV reflects greater variability. Due to its simplicity and comparability, CV serves as a fundamental quantitative tool for uniformity evaluation.

Building upon this, composite uniformity indices can be constructed to integrate multiple traits into a comprehensive evaluation. Such indices are typically derived by standardizing variables with different units and assigning weights according to research objectives or commercial grading requirements, thereby reflecting both size and shape consistency. Compared with a single CV metric, composite indices provide a more holistic characterization of uniformity, particularly for comparisons among cultivars and for breeding selection. In addition, structural parameters such as compactness indices, berry number per unit cluster length, and spatial distribution descriptors can be incorporated to quantify berry arrangement within clusters.

With the advancement of digital image analysis and high-throughput phenotyping technologies, the evaluation of berry uniformity is transitioning from manual measurement to automated and intelligent approaches. Two-dimensional image analysis can extract parameters such as berry area, length, width, and shape, while three-dimensional reconstruction techniques can provide additional information on berry volume, cluster volume, and spatial distribution. In recent years, instance segmentation methods based on vision models such as the Segment Anything Model (SAM) have enabled automatic identification of individual berries and extraction of multidimensional phenotypic parameters, providing robust support for high-throughput analysis of uniformity-related traits (Torres-Lomas et al., 2024; Sharma et al., 2025). Overall, berry uniformity evaluation is evolving toward a “multi-indicator integration+high-throughput measurement” paradigm, providing an important technical foundation for precision breeding and standardized production.

3 Evaluation Methods of Grape Berry Uniformity

3.1 Traditional evaluation methods

In grape production, postharvest sorting, and market circulation, the evaluation of berry uniformity has long relied on visual grading methods based on cluster appearance. This approach typically assesses the overall coordination of the cluster by observing whether berry size is uniform, whether the arrangement is orderly, whether cluster structure is appropriate, and whether mixed berry sizes occur, thereby classifying clusters into different commercial grades. Clusters with high uniformity usually exhibit consistent berry size, balanced spatial