Two-dimensional image analysis typically uses RGB images to identify berry contours and extract parameters such as berry number, projected area, length, width, aspect ratio, and cluster dimensions. The tools such as the Berry Analysis Tool (BAT) and Cluster Analysis Tool (CAT) can achieve automatic berry counting and size estimation, with results highly consistent with manual measurements, providing an efficient and objective basis for uniformity evaluation.

Building upon 2D image analysis, deep learning-based segmentation models have significantly improved the accuracy of berry detection under complex conditions. Instance segmentation methods such as Mask R-CNN, as well as foundation vision models like the Segment Anything Model (SAM), can automatically identify individual berries under varying lighting, occlusion, and background interference, and extract key parameters such as size distribution and compactness (Figure 1) (Kim et al., 2023; Torres-Lomas et al., 2024; Sharma et al., 2025). These approaches enable the transition from manual sampling to high-throughput measurement at the whole-cluster or population scale, providing more reliable phenotypic data for breeding selection and genetic analysis.

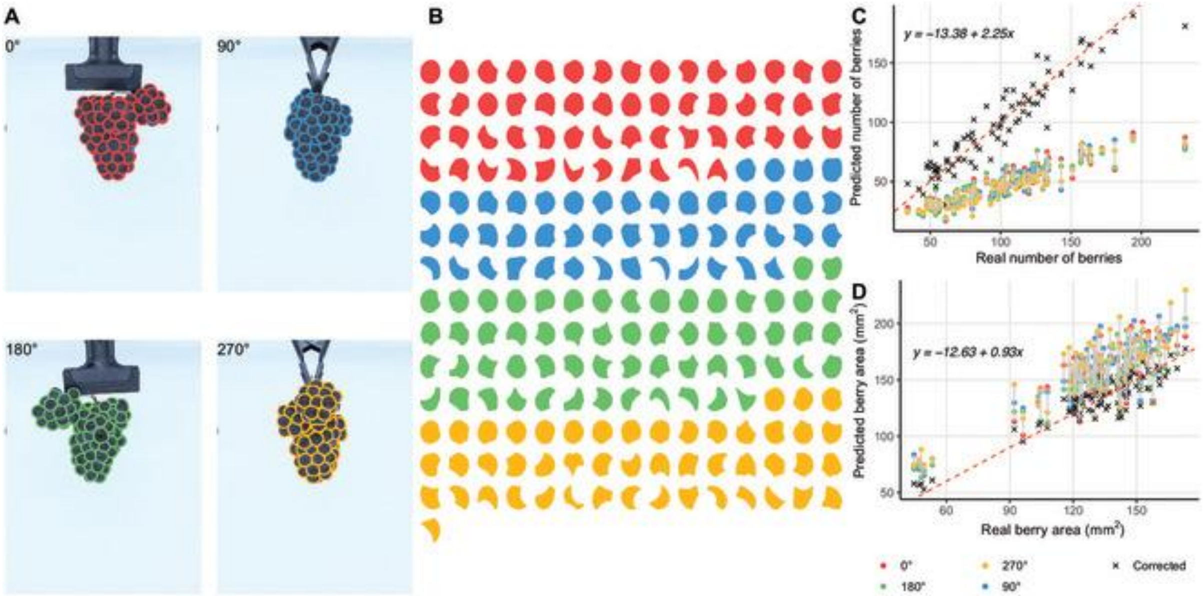

Figure 1 Prediction of berry number using SAM from cluster images (Adopted from Torres-Lomas et al., 2024)

Image caption: (A) Identification of individual berries from 4 angles on the same cluster. (B) Berry masks from cluster images in panel A, color-coded by angle view. (C) Correlation between real and predicted berry counts from SAM; predicted counts for each angle view in panel A are displayed. Points marked with an X represent corrected counts using the angle view with the maximum berries, adjusted with a linear model. (D) Correlation between real and predicted berry area; color and shape patterns are similar to panel C; corrected points were generated with a linear model of the form $y \sim \beta_0 + \beta_1 x$. The vertical red line indicates a one-to-one relationship between variables (Adopted from Torres-Lomas et al., 2024)

Furthermore, three-dimensional modeling techniques overcome the limitations of 2D image analysis in representing spatial structure. Through 3D scanning, stereo vision, or point cloud reconstruction, parameters such as berry number, average diameter, individual berry volume, cluster envelope volume, and spatial compactness can be obtained. Compared with 2D methods, 3D analysis provides a more accurate description of inter-berry distances, internal voids, and cluster closure, and is suitable for dynamic monitoring of cluster development (Trivedi et al., 2023). Combined with mobile devices and field platforms, these technologies are driving berry uniformity evaluation toward automation, scalability, and intelligent applications.

4 Factors Affecting Grape Berry Uniformity

4.1 Genetic factors

Grape berry uniformity is primarily influenced by genetic background. Different cultivars exhibit inherent differences in berry size, shape, and cluster structure, which arise from genetic traits such as berry developmental potential, fruit set stability, seed formation capacity, and cluster architectural formation. Studies have shown that berry size and cluster structure display extensive variation within grape germplasm, with berry weight ranging