6.3 Application of intelligent management in precision regulation

Digital and intelligent technologies are not only used for evaluating berry uniformity but are also transforming vineyard resource management. Precision viticulture systems integrate satellite remote sensing, UAVs, ground-based sensors, soil moisture monitoring, and plant physiological data to spatially identify variations in plant growth, water stress, nutrient supply, and canopy status within vineyards, thereby enabling variable-rate irrigation, fertilization, and zone-based management strategies (Mucalo et al., 2024). This management approach helps reduce internal variability in resource supply and minimizes uneven berry development caused by water or nutrient stress.

Internet of Things (IoT)-based fertigation systems represent an important tool for precise regulation of berry uniformity. These systems automatically adjust irrigation volumes and nutrient solution compositions based on soil moisture, irrigation water quality, nutrient status, and plant demand, thereby maintaining stable water and nutrient supply during the berry enlargement stage. Smart fertigation platforms such as NutriBalance can automatically calculate optimal nutrient formulations based on water source quality and reduce fertilizer input by approximately 40% while maintaining nutrient supply accuracy (Imbernón-Mulero et al., 2023). Furthermore, irrigation and fertilization decision models based on mathematical optimization and genetic algorithms can improve economic returns while reducing environmental impacts, demonstrating the dual benefits of intelligent water-fertilizer management.

Intelligent environmental monitoring systems can also support regulation during critical growth stages. Temperature, humidity, and wind speed during flowering affect pollination uniformity; water supply and canopy light conditions during berry enlargement influence developmental synchrony; and microenvironmental variation during veraison and ripening may affect sugar-acid accumulation and maturity consistency. By continuously monitoring these parameters and integrating predictive models for early warning and regulation, it is possible to reduce asynchronous berry development at the source. In the future, improvements in grape berry uniformity will increasingly rely on an intelligent closed-loop system of “perception-diagnosis-prediction-decision-execution.” This involves evaluating berry uniformity through machine vision, predicting risks through multi-source data modeling, implementing regulation via intelligent water-fertilizer and environmental control systems, and continuously optimizing models based on feedback data. Such a framework enables the transition from experience-based management to data-driven precision management, providing sustainable technical support for the production of high-quality table grapes.

7 Challenges and Future Perspectives

7.1 Lack of a unified evaluation system

Currently, research on grape berry uniformity still lacks a unified and standardized evaluation system. Existing grape trait description systems mainly focus on individual traits such as berry size, berry shape, cluster compactness, and cluster color, while the composite trait of “intra-cluster berry uniformity” lacks a dedicated definition and standardized quantitative framework. Different studies and germplasm databases often employ OIV descriptors, self-defined trait systems, or output indicators from high-throughput phenotyping platforms, leading to inconsistencies in indicator definitions, measurement methods, and grading standards. These discrepancies limit cross-study comparisons and hinder industrial application (García-Abadillo et al., 2024; Liu et al., 2024; Zhang et al., 2025).

In recent years, two-dimensional and three-dimensional high-throughput phenotyping technologies have enabled precise extraction of traits such as berry diameter, berry volume, cluster length, cluster width, berry number, and compactness. However, these technologies are primarily applied to cluster architecture or single morphological traits and have not yet formed a dedicated core indicator system specifically for berry uniformity evaluation. Therefore, future efforts should focus on developing a standardized multi-indicator evaluation framework, while retaining the simplicity of traditional methods, with key components including berry size CV, shape consistency, spatial distribution uniformity, and appropriate cluster compactness.