8 Conclusions and Future Perspectives

Current grape pest and disease management is shifting from a model based on sole reliance on chemical pesticides toward an integrated approach that combines multiple control measures. Agronomic management, disease-resistant cultivars, biological control agents, decision support systems (DSS), and more judicious chemical control have become the main tools in grape protection. Combining agronomic regulation, biological control, genetic resistance, and targeted spraying can maintain yield and quality while reducing pesticide inputs and improving the vineyard ecological environment. Some case studies have also shown that combined measures such as reduced-copper programs, resistance inducers, and predictive models are feasible in practical production.

However, in reality, chemical control remains the basic strategy in most vineyards, and total pesticide use has not declined despite the wider adoption of IPM concepts. This is related not only to insufficient policy support and the inadequate application of ecological regulation mechanisms, but also to factors such as growers' awareness, upfront investment, labor requirements, and concerns about production risks. The adoption rates of virus disease management, biological control, and more complex integrated technologies are still relatively low. Difficult access to forecasting tools, insufficient precision in pesticide application, and the high cost of alternative technologies have also limited the effectiveness of implementation. The development of new technologies is also relatively fragmented. Genomics, RNA interference, nanodelivery systems, smart sensors, drone-based monitoring, and advanced DSS are still progressing largely in parallel and have not yet formed a highly coordinated and efficient integrated system.

Future research should focus on improving the stability and substitution potential of non-chemical control technologies so that they can truly serve as major supports for pesticide reduction or even replacement. Plant-derived and microbe-derived biopesticides, nanodelivery systems, and RNA interference technologies show strong promise for controlling major pathogens, but their industrial application still requires large-scale field validation, formulation optimization, and cost reduction. At the same time, breeding cultivars with durable resistance to downy mildew, powdery mildew, gray mold, trunk diseases, and viral diseases through marker-assisted selection, genomic selection, and CRISPR technologies will also reduce the need for chemical intervention at the source. More research in agroecology is also needed, especially through the use of cover crops, vegetation diversification, and semi-natural habitat management, in order to strengthen the natural regulatory capacity of vineyards.

Future grape protection will increasingly depend on interdisciplinary integration. Internet of Things sensors, drone imaging, and artificial intelligence-based decision platforms are expected to improve the coordination of monitoring, forecasting, and precision spraying, but this will require the establishment of a closed-loop system from sensing to action, as well as stable operation under complex environmental conditions. At the same time, socioeconomic and behavioral factors should not be overlooked. Policy support, technical training, and participatory extension are needed to lower the barriers for growers to adopt new technologies. In response to climate change, invasive pests, and the increasing emergence of new pathogens, future grape pest and disease management must move toward a more forward-looking, biosecurity-oriented, and system-integrated direction, ultimately building a modern grape production system that is low-input, highly resilient, and sustainable.

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Conflict of Interest Disclosure

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