high-precision forecasting and guiding regional spray decisions (Bregaglio et al., 2022). In pest management, phenology and population dynamics models for grape moths, leafhoppers, mealybugs, and vector insects are also being progressively incorporated into DSS platforms to predict key developmental stages and outbreak risks (Lessio and Alma, 2021). These systems translate complex epidemiological and entomological knowledge into practical decision rules, enabling growers to identify risk windows in advance, optimize spray timing, and, when conditions permit, reduce or even omit control measures (Pertot et al., 2017; Román et al., 2021).

5.3 Integration of control technologies

In practical production, grape IPM relies on the coordinated application of multiple technologies rather than the isolated use of a single measure. Studies have shown that chemical pesticides (fungicides, herbicides, and insecticides) remain important components, but their use can be reduced by integrating biological control, mating disruption, resistant cultivars, as well as agronomic and physical measures (Zhou et al., 2024; Pavan et al., 2026). Cultivation practices—such as the selection of cultivars and rootstocks, training systems, pruning, fertilization, and irrigation—have a decisive influence on pest populations and disease pressure, and can simultaneously affect multiple pests and pathogens (Wilson and Daane, 2017; Pavan et al., 2026). Biological control agents and organically compatible products are increasingly combined with reduced chemical inputs to form hybrid strategies that balance efficacy and environmental safety (Pertot et al., 2017; Alimzhanova et al., 2025). For example, combining reduced fungicide use with resistance-inducing biostimulants or biocontrol agents can maintain control efficacy close to conventional programs while improving sustainability indicators (Pertot et al., 2017; Valleggi et al., 2023).

Within these integrated strategies, optimizing the timing and method of application is particularly important. For instance, the DOSA3D system adjusts pesticide dosage according to canopy structure and target pests or diseases, achieving up to approximately 60% reduction in pesticide use by matching leaf area index and spray efficiency without compromising crop health (Román et al., 2021). The application of robotics and sensor technologies further enhances precision: modular robots equipped with multispectral imaging can identify powdery mildew lesions and spray only infected areas, reducing pesticide use by 65%-85% compared with conventional uniform spraying (Oberti et al., 2016). In addition, predictive DSS systems allow growers to concentrate control measures during high-risk periods and reduce or avoid spraying during low-risk periods, aligning interventions more closely with pathogen biology and host susceptibility (Pertot et al., 2017; Román et al., 2021).

With the development of AIoT and computer vision technologies, real-time monitoring systems for diseases and vectors are gradually being applied in practice. These technologies are expected to further optimize the timing of interventions and enable data-driven, site-specific management, promoting grape IPM toward greater precision and intelligence while maintaining stable and efficient protection with reduced chemical inputs (Checola et al., 2024).

6 Case Studies of Grapevine IPM Applications

6.1 IPM implementation in European vineyards

In European viticulture, large-scale projects and regional practices have demonstrated that integrated pest management strategies can reduce pesticide use without compromising yield. The European PURE project showed that, in grape production, some application programs based on synthetic fungicides and insecticides can be partly replaced by biological control agents, mating disruption techniques, and decision support systems (DSS) that optimize spray timing, thereby reducing the overall number of applications (Pertot et al., 2017). At the same time, IPM frameworks in European vineyards emphasize that intervention decisions should be based on monitoring data and economic thresholds, with agronomic management and biological control prioritized, while synthetic pesticides are retained as a last resort, thus effectively limiting chemical inputs (Figure 3) (Pertot et al., 2017; Galli et al., 2024). In addition, landscape-scale management strategies, such as the conservation or restoration of semi-natural habitats, can enhance the role of natural enemies in pest suppression and reduce