(Pero et al., 2024). From a broader application perspective, IoT-assisted smart traps and crop health sensors can enable the early detection of pests and diseases, thereby supporting targeted interventions, reducing pesticide use, and better reflecting the core principles of IPM (Mansoor et al., 2025).

Data-driven pest and disease management further builds on these sensing systems and artificial intelligence technologies, driving a transformation in IPM decision-making. AIoT platforms designed for vineyards can integrate field sensors, cloud computing, and machine learning algorithms to predict the infection risks caused by major pathogens such as *Plasmopara viticola*, *Uncinula necator*, and *Botrytis* spp., allowing growers to take action before symptoms appear and thereby avoid the traditional calendar-based practice of broad-area spraying (Fuentes-Peñailillo et al., 2024; Pero et al., 2024). In broader agricultural applications, deep learning models connected to IoT networks have already shown high accuracy in plant disease identification, helping to enable precise, site-specific pesticide application and optimize the timing of control measures (Fuentes-Peñailillo et al., 2024). Research on smart sensors and agricultural IoT has shown that real-time analysis and threshold-based warning functions can be embedded into farm management software, transforming complex data streams into actionable IPM recommendations while also supporting the coordinated optimization of irrigation and fertilization management (Ali et al., 2023; Mansoor et al., 2025). As these technologies become more accessible, “smart IPM” in viticulture is likely to drive pest and disease management toward greater localization, predictive capacity, and resource efficiency.

## 7 Emerging Technologies and Development Trends in Grapevine Protection

### 7.1 Genomic and breeding approaches

Breeding disease-resistant grape cultivars is one of the core directions for future grape protection, offering significant potential to reduce reliance on fungicides. After more than a century of breeding efforts, numerous fungus-resistant varieties (commonly referred to as PIWI types) have been developed, which, depending on the cultivar and environmental conditions, can reduce fungicide use by up to 80% (Trapp and Töpfer, 2023). Multinational trials conducted in France and Germany have shown that some resistant cultivars can even reduce fungicide applications by approximately 90%, while also enhancing arthropod diversity and overall vineyard biodiversity (Trapp et al., 2025). These cultivars are gradually being incorporated into the European Union’s Green Deal and Farm to Fork strategies aimed at pesticide reduction, and are considered important tools for addressing climate change and advancing smart viticulture.

Building on this, rootstock breeding and selection further enhance stress tolerance, including improved resistance to drought, soil-borne pests and diseases, and other belowground stresses, which is particularly critical under future climate change scenarios (Marín et al., 2020). Genomic technologies are now being fully integrated into breeding programs. Marker-assisted selection (MAS) has been widely applied to traits controlled by major genes, such as resistance loci for downy mildew and powdery mildew, while high-resolution melting (HRM)-based marker systems enable rapid screening of quality traits such as fruit color (Magon et al., 2023; Luca et al., 2024). For complex traits, including stress resistance, yield, and quality, genomic selection (GS) and predictive genomics show even greater potential, with prediction accuracies reaching up to 0.9 for certain traits, thereby enabling early selection and shortening breeding cycles (Magon et al., 2023; Brault et al., 2024). Combined with genome-wide association studies (GWAS), germplasm resources, and gene-editing technologies such as CRISPR/Cas9, these approaches are expected to facilitate the development of “climate-smart” grape cultivars with combined resistance to diseases and tolerance to drought, heat, or cold (Magon et al., 2023). At present, gene editing targeting susceptibility genes and stress-response pathways has already shown progress in improving grape cold and drought tolerance, and is expected to complement conventional breeding strategies in the future (Magon et al., 2023).

### 7.2 Digital and precision agriculture technologies

Digital technologies are rapidly transforming pest and disease monitoring and decision support in vineyards. Artificial intelligence-based image analysis, combined with mobile devices and online platforms, has already been