used to automatically identify and count key pests in traps, as exemplified by the EyesOnTraps system in grape production (Rosado et al., 2022). This system integrates computer vision, temperature sensors, trap geolocation, and phenological models, such as the degree-day model for the European grapevine moth, into an operational decision support system (DSS), improving the precision of pest management while reducing the labor costs of manual monitoring. In addition, smartphone-based citizen science tools use deep learning algorithms to identify leaf diseases and insect pests, demonstrating the feasibility of real-time diagnosis and data collection at the farm scale (Christakakis et al., 2024). AI and deep learning, combined with unmanned aerial vehicles (UAVs) and ground-based imaging, have become an important foundation of smart agriculture, enabling the classification, segmentation, and prediction of pests and diseases from complex visual information (Zhu et al., 2024).

UAVs and advanced sensing technologies are also playing an increasingly important role in grape health monitoring. UAV systems equipped with RGB, multispectral, and hyperspectral sensors can be used to detect and map grape phylloxera infestation zones, and can be combined with canopy vigor models and vegetation indices to build predictive monitoring tools (Vanegas et al., 2018). Multi-temporal UAV multispectral imaging can also be used to monitor the development of downy mildew, identify early symptoms at both plot and individual vine scales, and track changes in canopy structure as well as near-infrared and red-edge reflectance (Portela et al., 2025). Kouadio et al. (2023) showed that grapevine is one of the crops most intensively studied for UAV-based disease detection, and that the current trend is toward multisensor fusion and machine learning analysis to improve detection accuracy and practical application value. Remote sensing and proximal sensors are also used to monitor vineyard microclimate, soil moisture, and canopy status, thereby supporting precision irrigation, frost protection, and microclimate regulation, which indirectly reduces disease risk and optimizes pest and disease management strategies (Sun et al., 2023).

7.3 Sustainable and climate-resilient strategies

Climate change is reshaping the pattern of grape pests and diseases and is accelerating the development of climate-adaptive management strategies. Rising temperatures, more frequent heat waves, and changing precipitation patterns are altering grape phenology, and in many regions have already advanced harvest time by 2-3 weeks. These changes are also modifying the pressure exerted by pathogens and insect pests, and some traditional wine-growing regions are expected to face severe drought and heat stress by the end of this century (Van Leeuwen et al., 2024). Global-scale analyses indicate that, under climate warming, the synchrony between grapevines and key pests such as Lobesia botrana is changing, which may lead to an increase in pest generations or shifts in the timing of damage.

In response to these changes, adaptation strategies in viticulture include replacing cultivars and rootstocks, promoting drought- and heat-tolerant materials, and optimizing training systems and canopy management to reduce heat load and improve microclimatic conditions that are favorable to disease development (Marín et al., 2020; Van Leeuwen et al., 2024). At the same time, the integration of artificial intelligence-based warning systems and smart agriculture sensors can help growers respond in advance to extreme weather events and climate-driven disease risks (Van Leeuwen et al., 2024).

From a broader perspective, sustainable ecological cultivation provides systemic support for these technologies. Studies in Mediterranean and semi-arid regions have shown that combining deficit irrigation strategies, such as regulated deficit irrigation and partial root-zone drying, with agroecological practices, including cover crops, mulching, compost application, reduced tillage, and the promotion of beneficial microbial interactions, can improve water-use efficiency, enhance soil health, and strengthen plant stress tolerance, while maintaining or even improving fruit quality (Romero et al., 2022). These measures help mitigate drought and heat stress, while also reducing erosion and nutrient loss and supporting natural enemy populations, thereby achieving the dual goals of climate adaptation and pesticide reduction (Marín et al., 2020). The wider adoption of disease-resistant cultivars, especially in the context of the European Green Deal, will further reduce fungicide use, enhance biodiversity, and improve the ecological functioning and long-term sustainability of vineyard systems (Trapp and Töpfer, 2023).