al., 2017). In addition, the manual removal of infested clusters, diseased leaves, or severely infected young shoots is still practiced in high-value or small-scale vineyards to reduce local pest and disease sources and to improve spray penetration and canopy ventilation (Pertot et al., 2017; Testempasis et al., 2023).

Environmental modifications for pest suppression, beyond standard canopy and irrigation management, include targeted manipulation of microclimate and habitat at the vineyard scale. Practices such as strategic defoliation and bunch thinning at specific phenological stages have been shown to reduce the incidence of bunch rots and mycotoxin-producing fungi by decreasing humidity around clusters and altering the composition of the berry-associated microbiota (Gutiérrez-Gamboa et al., 2021; Testempasis et al., 2023). Landscape-level decisions—choice of vineyard site, row orientation, training system, and surrounding vegetation—also influence pest and vector populations, their movement into vineyards, and the effectiveness of natural enemies (Pertot et al., 2017; Pavan et al., 2026).

4 Biological Control and Eco-friendly Approaches in Grapevine Management

4.1 Microbial control agents

Microbial biocontrol agents have become an important component of green disease management in grape production and have shown strong potential against downy mildew, powdery mildew, gray mold, and bunch rot. Commonly effective microorganisms include *Trichoderma*, *Bacillus*, *Aureobasidium pullulans*, and *Pseudomonas*, all of which can reduce disease incidence under field conditions. Some studies have reported control efficacies of 60%-90% (Thiéry et al., 2018; Alimzhanova et al., 2025). Yeasts and microbial consortia also show advantages in suppressing gray mold and improving fruit quality, and they have demonstrated good control effects against trunk diseases such as Botryosphaeria dieback during the nursery stage (Leal et al., 2022; Mesguida et al., 2023).

These microorganisms act through multiple mechanisms, including competition for nutrients and space, secretion of antimicrobial compounds and degradative enzymes, parasitism of pathogen structures, and competition for key elements through siderophore production, thereby directly inhibiting pathogen growth (Compant et al., 2013). Some strains can also induce systemic resistance (ISR) in plants, activate defense-related signaling pathways, and enhance the overall resistance of grapevines to multiple diseases. As reported by Lakkis et al. (2019), using the grapevine cultivars Pinot Noir and Solaris as study materials, the differential mechanisms of resistance induced by the beneficial rhizobacterium *Pseudomonas fluorescens* PTA-CT2 were investigated. The results showed that this bacterium could enhance the plant's own defense capacity through a "priming" effect. Against downy mildew, it mainly activated the SA-related signaling pathway and induced a more pronounced hypersensitive response (HR) in Solaris. Against gray mold, however, resistance relied more on JA/ET signaling and was associated with suppression of excessive cell death (Figure 1). Although microbial biocontrol agents have clear advantages such as environmental friendliness, their efficacy still varies across regions and years, and there is still room for improvement in formulation stability and environmental adaptability.

4.2 Natural enemies and biological regulation

Natural enemy regulation is a key component of ecological pest management in vineyards and plays an important role in suppressing pests such as grape moths, leafhoppers, and mealybugs. Vineyards host diverse communities of predators and parasitoids, including hymenopteran parasitoids attacking grape moths, lacewings such as Chrysoperla externa, spiders, predatory mites, and vertebrates such as insectivorous birds and bats. Under appropriate management conditions, these natural enemies can reduce pest populations and crop damage (Thiéry et al., 2018; Korányi et al., 2025). Studies on grape moth control have shown that parasitoids and predators can exert strong suppression at the local scale, although their effectiveness depends on specific ecological conditions and remains underutilized compared with chemical control and pheromone disruption techniques (Thiéry et al., 2018).

Recent field exclusion experiments have demonstrated that birds and bats can reduce leaf-feeding damage and injury caused by *Lobesia botrana*. In landscapes connected to forests, bat activity is more frequent and is closely associated with reduced moth populations and increased yields (Korányi et al., 2025). For grape mealybugs,