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REDUCING PESTICIDE USE IN VITICULTURE AND NEW PERSPECTIVES FOR THE IMPLEMENTATION OF INTEGRATED PEST MANAGEMENT - AN EXAMPLE OF GB4IPM PROJECT

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Abstract: Viticulture is among the most pesticide-intensive agricultural systems due to the high susceptibility of grapevine to fungal diseases and the strong dependence of disease development on climatic conditions. Increasing regulatory pressure to reduce pesticide use, together with accelerating climate change impacts, requires a fundamental rethinking of plant protection strategies in vineyards. Integrated Pest Management (IPM) offers a systemic framework for reducing chemical inputs while maintaining productivity and quality; however, its effective implementation remains uneven across Europe. This paper provides a comprehensive synthesis of plant protection tools for reducing pesticide use in viticulture, with a particular focus on disease-resistant grapevine varieties, adaptive disease management under climate change, and region-specific implementation of IPM strategies. Special attention is given to Serbia and the Western Balkans as state-of-the-art case vignettes representing high disease pressure, fragmented production structures, and strong dependence on advisory systems. The analysis integrates recent scientific literature with emerging European research perspectives, highlighting pathways toward resilient, knowledge-based viticulture systems.

Keywords: Viticulture, Integrated pest management, Pesticide reduction, Disease-resistant grapevine varieties, Climate change, Plant protection

INTRODUCTION

Viticulture occupies a distinctive position within European agriculture. Despite covering a relatively small proportion of agricultural land, vineyards account for a disproportionately high share of fungicide use, primarily due to their susceptibility to downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), and Botrytis bunch rot (*Botrytis cinerea*). Historically, disease control in grapevine production has relied on frequent preventive fungicide applications, often applied according to calendar-based schedules rather than real-time risk assessment.

While this approach has ensured yield stability, it has also contributed to environmental contamination, non-target effects on biodiversity, and the emergence of fungicide-resistant pathogen populations. At the same time, climate change is profoundly altering disease epidemiology, grapevine phenology, and production risk across Europe. Rising temperatures, modified precipitation regimes, and increasing weather variability challenge

the effectiveness of traditional plant protection strategies and intensify uncertainty in disease management.

In response to these challenges, Integrated Pest Management has emerged as the dominant conceptual framework for sustainable plant protection. IPM emphasizes the combination of genetic resistance, agronomic practices, monitoring, and targeted chemical interventions. However, the practical realization of IPM in viticulture remains constrained by biological, structural, and socio-economic factors. This paper examines the state of the art of plant protection tools for reducing pesticide use in viticulture and discusses new perspectives for IPM implementation under climate change, with particular emphasis on continental and sub-continental production contexts.

Disease Pressure and Climate Change as Structural Drivers of Pesticide Dependence in Viticulture

Viticulture is structurally exposed to high levels of biotic stress due to the intrinsic susceptibility of grapevine (*Vitis vinifera* L.) to a limited number of highly aggressive fungal pathogens, most notably downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), and Botrytis bunch rot (*Botrytis cinerea*). These pathogens possess epidemiological characteristics that enable rapid population growth and epidemic development under favourable environmental conditions, often within short temporal windows. As a result, disease outbreaks can cause severe yield losses and quality degradation if not effectively controlled, placing grapevine production among the most risk-sensitive perennial cropping systems in temperate regions.

The dependency of viticulture on chemical plant protection products is therefore not accidental but structurally embedded in the interaction between pathogen biology and climatic drivers. Downy mildew epidemics are closely linked to rainfall events, leaf wetness duration, and moderate temperatures, conditions that frequently coincide during spring and early summer in large parts of Europe. Powdery mildew, by contrast, develops independently of free water and can proliferate under a broad range of temperature conditions, creating a persistent baseline disease pressure even in relatively dry seasons. Botrytis bunch rot further compounds disease risk by affecting both yield quantity and wine quality during flowering and ripening stages, particularly under humid conditions. The coexistence of these pathogens creates a cumulative and overlapping disease pressure that historically justified preventive and repeated fungicide applications throughout the growing season (Gessler et al., 2011; Pertot et al., 2017).

Climate change has emerged as a critical factor reshaping this already complex phytopathological landscape. Rather than uniformly increasing or decreasing disease pressure, climate change alters the temporal dynamics, intensity, and predictability of epidemics. Rising average temperatures, warmer winters, and extended growing seasons enhance pathogen overwintering survival and increase the availability of primary inoculum early in the season. Earlier budburst and accelerated phenological development expose young, highly susceptible tissues to infection during periods when pathogen pressure is already present. At the same time, changes in precipitation regimes characterized by longer dry periods interrupted by intense rainfall events create conditions for sudden and severe

disease outbreaks that are difficult to anticipate using traditional calendar-based protection strategies (Salinari et al., 2006; Jones et al., 2005).

These climatic shifts increase interannual variability and uncertainty, which in turn reinforces pesticide dependence. Under uncertain disease risk, growers tend to adopt conservative protection strategies to minimize economic losses, often leading to prophylactic treatments even in seasons with moderate disease pressure. This risk-averse behaviour is particularly pronounced in perennial crops such as grapevine, where production losses have long-term economic consequences. As a result, climate change does not automatically lead to reduced pesticide use, but may paradoxically increase spray frequency in some contexts, especially where adaptive decision-support tools and alternative protection strategies are not fully implemented.

The structural nature of pesticide dependence in viticulture has been widely recognized in recent scientific literature and is increasingly framed as a central bottleneck in the transition toward sustainable plant protection. Pertot et al. (2017) emphasized that the persistence of high fungicide inputs in vineyards reflects systemic constraints rather than a lack of available tools, pointing to the need for integrated approaches that address both biological and decision-making drivers of pesticide use. Within this framework, disease-resistant grapevine varieties have gained prominence as a key leverage point for disrupting the pathogen-climate-pesticide nexus.

Recent European research initiatives, including the scientific work coordinated by INRAE within the GrapeBreed4IPM framework, have highlighted the potential of resistant varieties to fundamentally alter disease management paradigms in viticulture. By reducing baseline infection pressure, genetic resistance enables a shift from reactive, input-intensive protection toward adaptive, risk-based management strategies. Monitoring initiatives coordinated within this scientific context have demonstrated that resistant varieties can substantially reduce fungicide applications while maintaining agronomic performance, particularly when resistance is combined with appropriate canopy management and monitoring practices (Miclou et al., 2022; Schneider et al., 2019). GB4IPM have further emphasized the importance of structured deployment and monitoring to assess resistance durability and avoid over-reliance on single resistance mechanisms.

Importantly, the effectiveness of resistance-based strategies is strongly conditioned by climatic context. In regions characterized by sustained humidity and recurrent infection cycles, such as continental and sub-continental viticulture zones, resistance provides not only a reduction in average disease pressure but also a buffer against climate-driven variability. This buffering effect becomes increasingly relevant under climate change scenarios that favour unpredictability over gradual shifts in mean conditions (Fraga et al., 2016). Consequently, genetic resistance should not be viewed as a static trait, but as a dynamic component of adaptive plant protection systems.

Taken together, disease pressure and climate change function as intertwined structural drivers of pesticide dependence in viticulture. Addressing this dependence requires more than incremental optimization of chemical control; it necessitates a systemic redesign of plant protection strategies that integrates genetic resistance, adaptive management, and knowledge-based decision-making. The growing body of scientific evidence supports the

view that such integration is not only technically feasible, but essential for achieving durable pesticide reduction under current and future climatic conditions.

Plant Protection Tools for Reducing Pesticide Use in Viticulture

Among available plant protection tools, disease-resistant grapevine varieties represent the most structurally transformative option for reducing pesticide use. By incorporating genetic resistance to key fungal pathogens, these varieties directly lower infection pressure and reduce the baseline need for chemical interventions. Numerous studies have demonstrated that resistant varieties can achieve substantial reductions in fungicide use, particularly against downy and powdery mildew, without compromising yield stability.

However, resistance is not absolute. Its durability depends on genetic architecture, pathogen adaptation, and management context. Consequently, resistant varieties must be integrated into broader IPM strategies rather than treated as standalone solutions. Agronomic and cultural practices such as canopy management, pruning, and shoot positioning further contribute to disease suppression by modifying vineyard microclimate and reducing leaf wetness duration. Improved canopy aeration has been shown to significantly reduce the severity of downy mildew and Botrytis, thereby enabling additional reductions in fungicide use.

Monitoring and risk-based decision-making represent another critical component of pesticide reduction strategies. Disease forecasting models and decision-support systems integrate weather data, phenological stages, and pathogen biology to optimize intervention timing. When effectively implemented, such tools reduce unnecessary treatments and improve fungicide efficiency. Nevertheless, their adoption remains uneven, particularly in regions characterized by fragmented production structures and limited access to precision agriculture technologies.

Integrated Pest Management in viticulture should be understood not as a single technology, but as a systemic transition from preventive, input-intensive protection toward adaptive, knowledge-based management. Effective IPM requires the alignment of genetic resistance, agronomic practices, monitoring, and targeted chemical interventions within a coherent strategy.

This transition is particularly challenging in viticulture due to high disease pressure and risk aversion among growers. Nevertheless, evidence suggests that IPM systems integrating resistant varieties and risk-based decision-making can achieve substantial reductions in pesticide use while maintaining economic viability. The key challenge lies in translating scientific knowledge into region-specific, practically applicable solutions.

Serbia and the Western Balkans as State-of-the-Art Case Vignettes

Viticulture in Serbia and the Western Balkans represents a scientifically informative case for examining the implementation of Integrated Pest Management (IPM) under conditions of persistently high disease pressure and increasing climatic uncertainty. The region is situated within a continental to sub-continental agro-climatic zone characterized by moderate to high annual precipitation, pronounced intra-seasonal variability, and frequent

rainfall events during spring and early summer. These conditions generate a structurally elevated baseline risk for fungal diseases, making disease management one of the most critical and resource-demanding components of grapevine production.

Unlike Mediterranean viticulture, where disease pressure is often episodic and closely linked to specific rainfall events, the Western Balkan context is characterized by recurrent infection cycles and extended periods of leaf wetness. Consequently, disease outbreaks are not exceptional events but an inherent feature of the production system. This epidemiological setting promotes conservative, preventive fungicide use and reinforces long-term chemical dependency, particularly in years with unstable weather patterns.

The most economically significant diseases affecting vineyards in this region are downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), and Botrytis bunch rot (*Botrytis cinerea*). In addition, black rot (*Guignardia bidwellii*) represents a recurrent threat in specific locations and years, particularly under warm and humid conditions. Downy mildew remains the primary driver of fungicide use in continental and sub-continental viticulture, as its development is strongly dependent on rainfall events, leaf wetness duration, and moderate temperatures conditions that frequently coincide during the early stages of the growing season. Powdery mildew, in contrast, is less dependent on rainfall and can develop across a broad temperature range, maintaining baseline disease pressure even during relatively dry years. Botrytis bunch rot further compounds disease risk by affecting both yield quantity and wine quality during flowering and ripening, especially under humid conditions.

The coexistence of these pathogens creates a multi-disease pressure environment in which control strategies must be continuous and largely preventive. As a result, vineyards traditionally rely on repeated fungicide applications, often exceeding 10-12 treatments per season in years with high disease pressure, placing viticulture among the most pesticide-intensive agricultural sectors. This structural dependence on chemical control reflects not only pathogen biology but also the high economic risks associated with production losses in perennial crops.

Climate change has emerged as a decisive factor altering disease pressure patterns in the Western Balkans. Long-term climatic trends indicate rising average temperatures, increased frequency of heat waves, and shifts in precipitation distribution, characterized by longer dry periods interrupted by intense rainfall events. These changes affect both grapevine physiology and pathogen life cycles. Warmer winters enhance pathogen overwintering survival, increasing the availability of primary inoculum at the beginning of the growing season, while earlier budburst exposes young, highly susceptible tissues to infection during periods of elevated disease risk.

At the same time, extreme rainfall events create highly favorable conditions for rapid pathogen spread, often overwhelming traditional calendar-based protection strategies. Numerous studies have demonstrated that climate change does not necessarily reduce disease pressure but rather increases its variability and unpredictability, thereby complicating disease management and increasing production risk (Gessler et al., 2011; Salinari et al., 2006). Under such conditions, decision-making based solely on historical experience becomes increasingly unreliable.

In Serbia and the Western Balkans, climate-driven disease variability translates directly into heightened vulnerability, particularly for small and medium-scale growers. Structural fragmentation of vineyard holdings predominantly small, family-operated units with limited mechanization and restricted access to capital-intensive technologies limits the capacity to absorb losses or invest in advanced monitoring and decision-support tools. As a consequence, growers rely heavily on generalized advisory recommendations, reinforcing conservative protection strategies and limiting opportunities for input optimization. Advisory services therefore play a decisive role in shaping plant protection practices and represent a critical leverage point for IPM implementation in the region.

Disease-resistant grapevine varieties are currently only marginally adopted in Serbia and most Western Balkan countries. Their limited diffusion reflects a combination of strong attachment to traditional and autochthonous varieties, uncertainty regarding wine typicity and market acceptance, and limited availability of planting material. Nevertheless, the potential benefits of resistant varieties are particularly pronounced under the sustained disease pressure characteristic of this region. Even partial resistance can significantly reduce infection intensity, delay epidemic development, and lower the number of required fungicide applications, resulting in substantial reductions in chemical inputs.

Climate change further amplifies the relevance of resistance-based and adaptive IPM approaches. Heat and drought stress can weaken grapevine defense mechanisms, increasing susceptibility to opportunistic pathogens and secondary infections. The interaction between abiotic and biotic stressors adds an additional layer of complexity to disease management and challenges the stability of conventional protection systems. In this context, genetic resistance provides an important buffer against climate-driven variability, enhancing system resilience and reducing reliance on reactive chemical interventions.

The described disease–climate interactions reinforce the structural dependence of viticulture on chemical plant protection products. Despite advances in fungicide formulation and application technology, chemical control remains the dominant disease management strategy in the region. However, increasing regulatory pressure to reduce pesticide use, coupled with growing societal concerns regarding environmental and human health impacts, limits the long-term sustainability of this approach. Repeated fungicide applications contribute to the accumulation of residues in soil and water bodies, negative effects on non-target organisms and vineyard biodiversity, and increased risk of pathogen resistance to active substances. These concerns are particularly acute in the Western Balkans, where viticulture is often embedded in ecologically sensitive landscapes and rural areas with high socio-economic dependence on agriculture.

From a scientific perspective, initiatives such as GrapeBreed4IPM contribute to addressing these challenges by advancing understanding of durable resistance under sustained disease pressure and by embedding continental viticulture contexts into broader European research frameworks. This integration helps bridge the gap between innovation development and practical applicability in regions where long-term empirical data on resistant variety performance and adaptive IPM strategies remain scarce.

Disease-Resistant Grapevine Varieties Under Changing Climate Conditions

Disease-resistant grapevine varieties represent a strategic response to the combined challenges of climate change and disease pressure. By incorporating genetic resistance to

key fungal pathogens, these varieties reduce the baseline infection risk and allow for significant reductions in fungicide use. Under climate change scenarios characterized by increased variability, resistance offers an additional advantage: it provides a buffer against unexpected disease outbreaks, enhancing system resilience. Nevertheless, resistance is not absolute and must be managed carefully to avoid resistance breakdown due to pathogen adaptation.

In this context, the integration of resistant varieties into region-specific management systems is critical. Resistance must be complemented by appropriate canopy management, monitoring, and reduced-input strategies to ensure long-term effectiveness. The Western Balkans, with their variable climatic conditions, represent a valuable testing ground for assessing resistance durability under stress.

Given the complexity of disease dynamics under climate change, advisory systems play a central role in translating scientific knowledge into practice. In Serbia and the Western Balkans, advisory services are often the primary source of guidance for small and medium-scale growers, particularly in relation to disease management decisions.

Adaptive disease management requires:

- continuous monitoring of climatic conditions and disease risk,
- interpretation of complex information for practical decision-making,
- confidence to reduce chemical inputs without compromising yield and quality.

Strengthening advisory capacity is therefore essential for enabling growers to transition from calendar-based protection toward more adaptive, knowledge-based strategies that leverage genetic resistance and integrated management.

Regional Relevance in the European Context

The disease pressure and climate challenges observed in Serbia and the Western Balkans are not isolated phenomena but reflect broader trends affecting European viticulture. However, the region's combination of high disease pressure, climatic variability, and structural fragmentation amplifies these challenges, making it particularly informative for evaluating sustainable disease management pathways.

Insights gained from this region contribute to a better understanding of how viticulture systems can adapt to climate change while reducing chemical dependence. They underscore the need for context-specific solutions that integrate genetic, agronomic, and institutional dimensions.

The synthesis presented in this paper underscores that future IPM strategies in viticulture must move beyond incremental input reduction toward systemic redesign. Genetic resistance should be prioritized as a foundational element of plant protection systems, complemented by adaptive agronomic practices, monitoring, and targeted chemical use. Strengthening advisory and knowledge-transfer mechanisms is essential, particularly in fragmented production landscapes.

Climate change reinforces the need for flexible, region-specific IPM strategies. As climatic gradients converge and disease dynamics become more unpredictable, resilient, knowledge-based systems outperform rigid, calendar-based protection programs. The successful implementation of IPM therefore depends on the integration of biological, agronomic, and institutional dimensions.

CONCLUSION

Reducing pesticide use in viticulture is both an environmental necessity and a technical challenge shaped by disease biology, climate change, and production structure. Integrated Pest Management provides a robust framework for addressing these challenges, but its success depends on the effective integration of multiple plant protection tools. Disease-resistant grapevine varieties, combined with agronomic practices, monitoring, and adaptive decision-making, represent a viable pathway toward sustainable viticulture. The case of Serbia and the Western Balkans illustrate that even under high disease pressure, pesticide reduction is achievable through systemic approaches grounded in regional realities. Future progress will depend on coordinated efforts across research, advisory services, and policy domains.

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