

Chapter

Grapevine Powdery Mildew: Epidemiology, Impact on Grape Production and Advances in Management Strategies

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Abstract

Grapevine (*Vitis vinifera* subsp. *vinifera*) is one of the most economically significant and widely cultivated plants in the world. Its economical and beneficial effects on human health make grapevine an important agricultural product worldwide. However, grapevine cultivation faces several critical challenges associated with growth, production, and disease management. On the other hand, climate change and disease resistance represent significant challenges for the development of healthy plant life globally. Moreover, the grapevine quality and quantity have been severely threatened by different pests, pathogens, viruses, and fungi. They can lead to decreasing quantity of grapes, delayed grape ripening, affected grape composition, and reduced grape quality. Grapevine powdery mildew, caused by the fungus *Erysiphe necator*, is one of the most consequentiality diseases affecting cultivated and wild grapevine in the world. To effectively combat this disease, grapevines are predominantly sprayed with fungicides, and this leads to environmental hazards, adverse health effects for humans, and increased resistance to fungicides. Taking all of these into account, understanding the life cycle of fungi, biocontrol agents, some early disease detection methods like scouting, and molecular techniques might help to mitigate the disease.

Keywords: grapevine, grapevine diseases, grapevine powdery mildew, *Erysiphe necator*, disease management strategies

1. Introduction

Grapevine is one of the most economically cultivated fruit crops around the world. The grapevine, a resilient perennial woody vine classified under the genus *Vitis* ssp., traces its origins to the Mediterranean region and Central Asia. It has long held a significant place in history, with its cultivation closely tied to the growth and advancement of civilizations worldwide. From the ancient Greeks and Romans to the expanding wine industries of the New World, the grapevine has captivated the imagination of people throughout the ages [1, 2]. When comparing the world production, China dominates with approximately 19% of total. Italy ranks second in the

world in grape production with 9%, following China. France is, also, a significant grape producer, accounting for around 8.5% of global grape production, while Spain and France contribute to 7.4% and 6.6% of the world's grape production, respectively in 2023. Given that grape production fluctuates from an estimated 70–75 million tons/year, production volumes of these countries alone make up a substantial proportion of total grape production worldwide [3]. Grapes were the 305th most traded commodity (out of 1217) in the world in 2023. The leading exporters were Peru (\$1.99B), Chile (\$1.36B), China (\$985M), South Africa (\$938M), and Mexico (\$911M). For importation, the biggest customer was the United States, spending \$2.49 billion on titles, followed by Germany (\$966M), the Netherlands (\$925M), the United Kingdom (\$782M), and China (\$631M) [4]. Broadly, these numbers show the significance of grapes, in their quantitative, monetary value during trades, and segment of the countries that are in the grape trade leagues table.

The grapevines (*Vitis* spp.) of the Vitaceae family includes approximately 60 species, and it is, for strict taxonomic purposes, grouped into two subgenera—the *Eu vitis* and *Muscadinia* [5]. Among all these species, the most important one that has been cultivated is *Vitis vinifera* L., which is particularly interesting as it can exploit a wide range of climate habitats from temperate to subtropical and tropical areas and adapted to diverse environments. *V. vinifera*, the common grapevine (*Vitis vinifera*), and its hybrids have together become the most widely planted varieties of all the grapevines, and they hold the largest share of the grape market [6, 7].

Grapevines (*Vitis* spp.) suffer from several threats from pests, pathogens, and viruses. All of these can lead to increased losses of fruit, reduced productive life of the vineyard, delayed maturation of fruit, changes in juice chemistry, and negative sensory impacts on wines [8, 9]. Understanding the etiology and epidemiology of grapevine diseases is critical to the development of effective control measures and to the sustainability of production [10]. The viral diseases are also taking a heavy toll on grapevine decline. Recently, it is reported that latent viruses, including grapevine rupestris stem pitting-associated virus (GRSPaV), can enhance the symptoms of other co-inhabited pathogens that cause grapevine decline. Grapevine leafroll disease, caused by several grapevine leafroll-associated viruses (GLRaVs), and red blotch disease, caused by grapevine red blotch virus (GRBV), represent two of the most economically destructive viral pathogens. They lead to a reduction in photosynthesis, later maturation of fruit, and reduced sugar accumulation, all of which influence wine quality [11]. Many viruses are insect-transmitted (list of mealybugs, soft-scale insects), which makes controlling them difficult.

Fungal pathogens, such as *Erysiphe necator* (causing powdery mildew), *Botrytis cinerea* (causing gray mold) and *Guignardia bidwellii* (black rot), can devastate grape clusters, particularly in humid climates [12]. For example, black rot mostly affects leaves, berries, and shoots, resulting in shriveled, unmarketable fruits. Moreover, vascular diseases such as Eutypa dieback and Esca disease represent major challenges for vine longevity due to vascular damage and vine decline due to these vascular diseases.

While grape production is affected by various economically important pathogens, powdery mildew (*Erysiphe necator*) and downy mildew (*Plasmopara viticola*) are particularly well-known for their capacity of rapid spread in favorable environmental conditions and high levels of defoliation and fruit quality [13].

Integrated pest management (IPM) approaches are the basis of sustainable management of grapevine diseases. These include cultural practices like canopy management, resistant rootstocks, biological control agents, and appropriate fungicides and bactericides. Advances in molecular biology have also enabled the development

of diagnostic tools for early pathogen detection that is crucial for effective disease management [14]. This enables targeted intervention by allowing rapid and accurate identification of pathogens through rapid DNA-based techniques like PCR, next-generation sequencing, etc.

Part of the problem lies with changing weather patterns, since climate change is predicted to increase the frequency and intensity of grapevine diseases as higher temperatures and altered precipitation patterns create ideal conditions for pathogens to proliferate [15]. Warming climates might expand the geographical range of some pathogens, and extreme weather events can put stress on vines, making them more susceptible to infections. Consequently, the need for further exploration of breeding grapevines with increased disease resistance and modifying management strategies to suit shifting environmental conditions is pressing.

In summary, grapevine diseases threaten viticulture worldwide. To face these threats and secure grape production for the future, a multidisciplinary approach between traditional practices and new scientific developments is needed.

2. Grapevine powdery mildew (*Erysiphe necator*)

Grapevine powdery mildew, caused by *Erysiphe necator* Schwein [(formerly *Uncinula necator* (Schweinitz) Burrill; anamorph *Oidium tuckeri* Berkeley.)], is one of the most significant fungal diseases affecting both cultivated and wild grapevines worldwide [16]. This fungus is originated in the northern United States and developed in the genus of *Vitis* as well as *Parthenocissus*, *Cissus*, and *Ampelopsis* generas. Moreover, *Erysiphe necator*, the pathogen responsible for grapevine powdery mildew, first spread from Eastern America to England in 1845 where first case observed, and then to France in 1847. Powdery mildew was the first economically important fungal disease of the vine to appear in Europe. Currently, powdery mildew has been seen all vineyards across the world and Wild American vines are typically resistant or less susceptible to this pathogen. It primarily infects green tissues, including leaves, shoots, flowers, and bunches [17].

2.1 Morphology of *Erysiphe necator*

Erysiphe necator belongs to Fungi kingdom, the phylum of Ascomycta and the family of Erysiphaceae [18]. Berkeley, in Europe, reclassified the species' asexual form, naming it *Oidium tuckeri*. Also, various names were assigned to the fungus' sexual and/or asexual forms. The designation *Uncinula necator* remained prevalent until Braun and Takamatsu reassigned the species to the genus *Erysiphe*, following the earlier proposal by Saccardo [19, 20]. They also attributed the species to Schweinitz, adhering to the principle of priority. *Erysiphe necator* is an obligate ectoparasite (a parasite that lives on the outer surface of a host) found on members of the Vitaceae family, including the genera *Ampelopsis*, *Cissus*, *Parthenocissus*, and *Vitis*. The fungus' hyphae are superficial, septate, and hyaline, with a diameter of 4–5 µm. These hyphae develop appressoria, which are thickened structures that penetrate host tissues. Within the host tissue, haustoria (specialized structures) extract nutrients necessary for fungal growth (Figure 1). Asexual reproduction occurs through multiseptate conidiophores (to produce and hold asexual spores-conidia), measuring 40–400 µm in length, which grow on the mycelium. These conidiophores produce hyaline conidia measuring 23–48 × 12–22 µm, which are cylindrical-ovoid to barrel-shaped

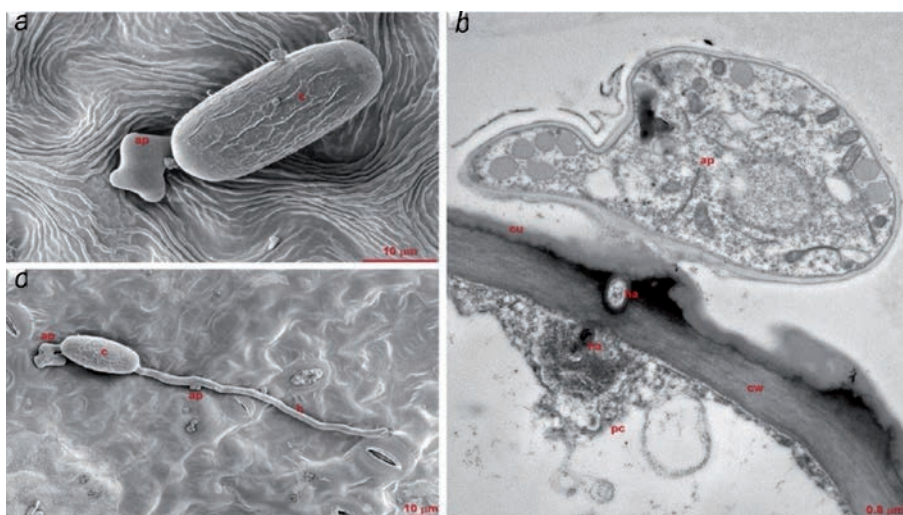


Figure 1.

Infection process of Erysiphe necator: (a) the conidia of the fungus forming an appressorium, (b) germ tubes improves appressoria, (c) appressorium (ap), conidium (c), cuticle (cu), cell wall (cw), hypha (h), haustorium (ha), and plant cell (pc) [21].

(doliiform). Unlike earlier descriptions of *E. necator*, the conidiophores do not form chains of multiple conidia simultaneously but instead produce single conidia of the Pseudoidium type. However, the conidia may adhere to each other through mucilage, giving the appearance of a chain [21].

Cleistothecia (80–130 μm in diameter) form from the fusion of compatible mating hyphae. Initially yellowish white, they turn blackish-brown at maturity. Each cleistothecium has 10–30 bristle-like appendages called fulcra. Inside, they contain four to eight asci (40–70 × 25–45 μm) with four to six hyaline ascospores (15–25 × 9–15 μm) (**Figure 2**). The ascospores germinate into short hyphae that develop into appressoria [21].

2.2 Epidemiology and life cycle of *Erysiphe necator*

The obligate biotrophic fungus, *E. necator*, can attack all green parts of the grapevine, including flowers, buds, berries, and shoots. This fungus decays various parts of the grape by forming haustoria through its mycelium in the epidermal cells. The disease appears as white to grayish powdery spots with a mealy texture, which can eventually cover entire plant organs. *E. necator* survives the winter as dark, spherical cleistothecia, typically located at the base of the vine's bark or on fallen leaves [22]. In spring, the infection begins on young vine organs when these cleistothecia absorb moisture and crack open, releasing mature ascospores (**Figure 3**). These spores, then, develop mycelium that thrives on leaf surfaces under optimal conditions—specifically, temperatures between 15°C to 25°C, a minimum of 2 mm of rainfall, 40% relative humidity, and at least 12 hours of darkness [23].

The basal leaves are generally the first to be infected due to their proximity to the overwintered cleistothecia. Once established, the mycelium can spread rapidly across the green tissues, creating a pale white network of hyphae. Upon reaching maturity, the mycelium begins asexual reproduction, typically starting sporulation within



Figure 2.
 Formation of the conidia of *Erysiphe necator*. A single conidium forms at the tip of each conidiophore (red arrows); however, they may be attached to one another by a mucilage to give the appearance of a chain (called a pseudochain) (black arrow) [21].

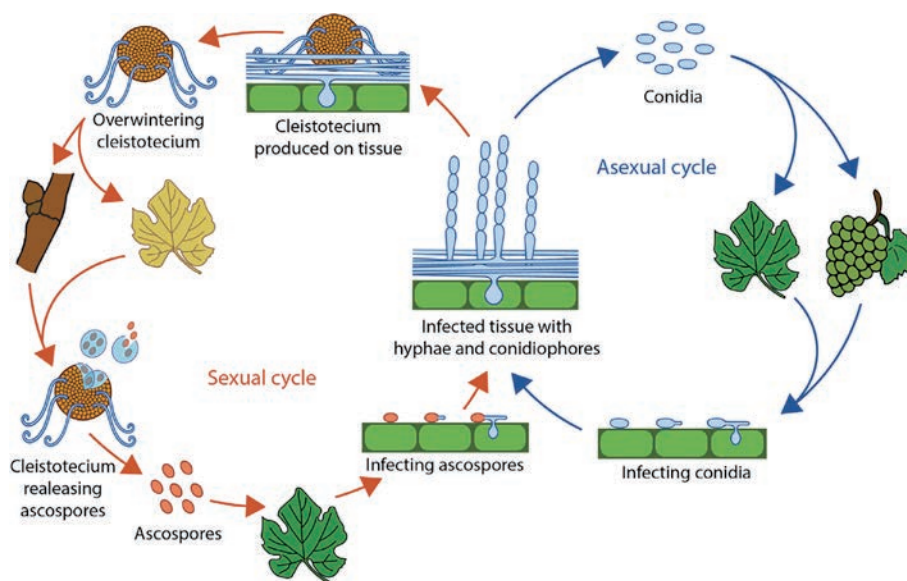


Figure 3.
 The life cycle of powdery mildew caused by *Uncinula necator*. Red arrows indicate to the sexual cycle. Blue arrows indicate to the asexual cycle [23].

5 days under optimal conditions [23]. This process involves the formation of egg-shaped conidia that develop in chains on short, upright conidiophores. These conidia are dispersed by wind and do not require wet leaves, provided that atmospheric moisture levels are sufficiently high [24, 25]. As temperatures drop, cleistothecia are formed primarily on wood, resulting from the fusion of antheridia and oogonia from different mating types. These cleistothecia can become partially embedded in the mycelial network on plant tissues and, when they detach, retain myceloid appendages. Some cleistothecia may release ascospores during autumn [26]. Additionally, the

fungus can survive winter as mycelium within infected dormant buds, which can lead to the emergence of “flag shoots” in the following growing season, serving as a source for secondary infections [23].

Dormant infected lateral buds successfully generate flag shoots in the spring in the mild winter areas [27]. In contrast, the effect of flag shoots should not appear in colder viticulture regions, as the infected buds have low winter hardiness [28]. What's more, it is possible that when the pathogen first enters the plant and is not yet established, its survival on dormant bud tissues may be limited by low temperatures. Although previous studies suggest that extremities in temperature can cause debilitation, hyphal mortality of developing colonies causes leaf nascent colonies to form [17]. This insight illustrates the intricate relationship between climate factors and pathogen viability in a viticultural context, emphasizing the importance of further research and adaptive management practices.

Cleistothecia is particularly important to the infection cycle of the grape powdery mildew pathogen *Uncinula necator* and its successful dispersion. They are an important source of primary inoculum within these structures, especially in areas where needle cast flag shoots are common (present in multiple tons), but also in areas with rare flag shoots.

Sexual structures, called cleistothecia, are produced mainly on diseased foliage [28], but also on berries and shoots when disease intensity is such that compatible mating types pair [29]. When mature, cleistothecia disperse in rain events, scattering on the bark of vines or soil. They can also be borne on powerful winds. For regions such as the Mediterranean that have the development of cleistothecia during mid-summer, ascospores are released later in the same growing season [30, 31]. Cleistothecia accumulate as overwintering structures for the pathogen. In regions with low precipitation and mild winters, cleistothecia are able to survive in leaf litter on vineyard floors [32]. In cold areas, they mostly live on the bark of vines [33].

There is some evidence showing that although many cleistothecia do not survive winter or do not liberate ascospores, most of those found in crevices of infected tree bark remain viable. Excel sheet of current powdery mildew and blackleg ascospores and ascospore release occurs from bud burst to bloom, making this the time to manage skirt powdery outbreaks. Weather conditions (e.g., rainfall, temperature) affect the timing and conditions at which ascospores are released and can therefore affect subsequent infection rates. Cleistothecia are crucial for the life cycle of *Uncinula necator*; it acts as both the overwintering structure and a critical means of inoculum for grape powdery mildew. Knowledge of their formation, dispersal, and survival mechanisms is important for successful vineyard management and disease control [34].

In addition, in areas where ascospores are the sole source of primary inoculum, increasingly younger leaves can become infected as they expand. However, high rates of foliar diseases are generally recorded after the flowering stage [35]. In contrast, when flag shoots act as primary inoculum sources, they add another layer of complexity to the epidemic's progression. Each flag shoot becomes a focal point for disease spread, as the production of conidia intensifies and infects nearby shoots and vines [36]. The lateral buds that give rise to flag shoots are generally infected during the early stages of an outbreak. Consequently, early flag shoots contribute to the infection of new lateral buds, often leading to the repeated appearance of flag shoots on the same vine or in the same vicinity over consecutive years [37].

2.3 Disease symptoms

The fungus of grapevine powdery mildew, caused by *Erysiphe necator*, can affect all the green plant tissues of grapevine. *E. necator* is an ectoparasitic fungus that can form specialized structures called haustoria, which invade the epidermal cells. This fungus reduces photosynthesis with causing leaf drop, to decrease yield and quality. Also, it can lead to early vine death [16], and infected grapevine with powdery mildew creates skin cracks as well. Having 5% of grape berries infected with powdery mildew at harvest can negatively impact wine quality [38].

Disease symptoms can be seen both earlier in the season and in the late summer. Suitable weather (rain shower, clouds that restrict the canopy's exposure to the sun's UV rays) conditions, combined with comfortably mild temperatures and humidity levels consistently above 75%, foster an environment that is exceptionally favorable to the infection and proliferation of fungus. The humidity in the air and the coolness of the surroundings create an ideal breeding ground for fungus, allowing it to thrive and spread rapidly. The covering of dusty appearance helps to recognize the disease on leaves, berries, shoots, and cane. Infected cells turn brownish gray beneath the gray fungal mycelium as an initial symptom of disease (**Figure 4A–B**) [21]. It can be

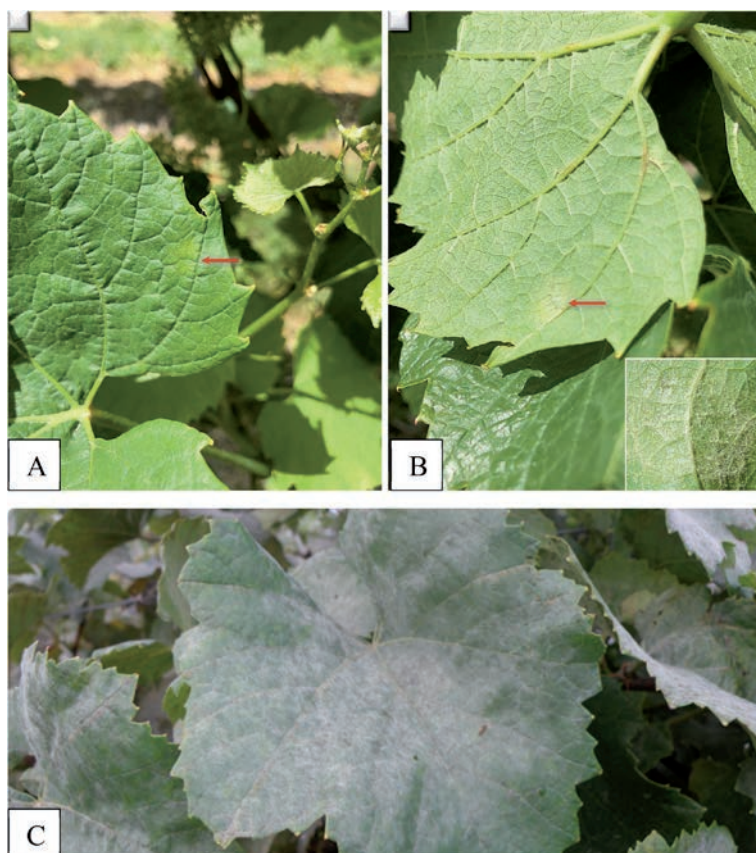


Figure 4.
Early stage of *Erysiphe necator* on grapevine leaves (upper and underneath leaves—from yellowing spot to grayish brown mycelium network of powdery mildew) [21, 39].

observed with white-gray or greenish-white coating on leaves and other green parts of grape (**Figure 4C**) [39].

Additionally, flag shoots are immature growths that may be covered partially or entirely with a powdery coating that varies in color from ash-gray to white. The leaves on these shoots often appear warped and tend to curl upwards. Typically, these shoots become noticeable within 2 to 8 weeks after the buds have burst (**Figure 5**) [40].

In shoots, a powdery ash-gray to white coating appears in patches and gradually spreads until the entire shoot is affected, and in severe cases, infected shoots become weakened, stunted, and may eventually die (**Figure 6A**) [39]. Reddish-brown spots



Figure 5.
Infected flag shoot indicates warped and curl leaves [40].

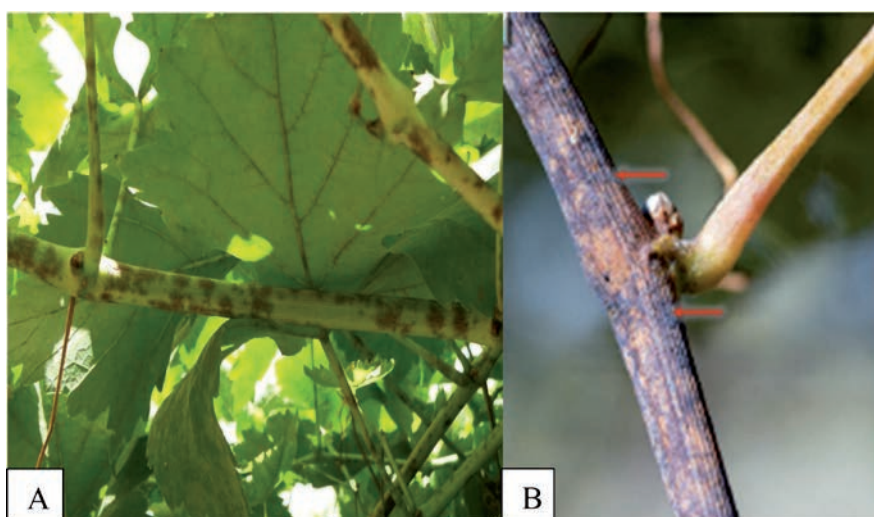


Figure 6.
Infected shoots of grapevine [21, 39].

seem on woody shoots (**Figure 6B**) [21] in winter, indicating the severity of the disease in the previous year.

Most cultivars are susceptible to bunch rots during flowering and 5 weeks afterward. Resilience increases with age, though; the bunch stalk and stems stay prone.

A grayish-white powdery growth appears on the young berries and bunch stalks. Consequently, with an increase in pulp volume, the infected epidermis becomes inelastic, leading to berry splitting and finally desiccation. Grapes that are severely infected have a musty smell, which persists, making them unsuitable for winemaking [21] (**Figure 7A–B**).

Severely infected berries can become misshapen, split, and rotten. Red varieties may not color evenly. After veraison, the berries develop a brown web pattern on their surface, making them particularly visible on white varieties. As time goes on, berries become resistant to powdery mildew infection, and so, when this happens, the fungus dies within the berry, leaving scar tissue on the berry.

2.4 Disease management strategies

Grapevine powdery mildew is one of the most devastating diseases affecting grapevine in the world and the fungus of *Erysiphe necator*, is one of the main challenges to combat in grapevine production. The disease can severely affect the grape and wine quality [41].

Control and management strategies are receiving more attention to fight with grape diseases. Currently, efficiency in management strategies focus on prevention and timely intervention to reduce the effect of this on grapevine yield, quality, and wine quality. Prevention is often considered more critical than the eradication of existing diseases. When the grapevine gets infected, damage has been started and irreversible during the growing season. The timing of leaf outbreaks plays a crucial role in determining how often and how severely grape bunches become infected. There, thus, is a significant relationship between the occurrence of affected leaves

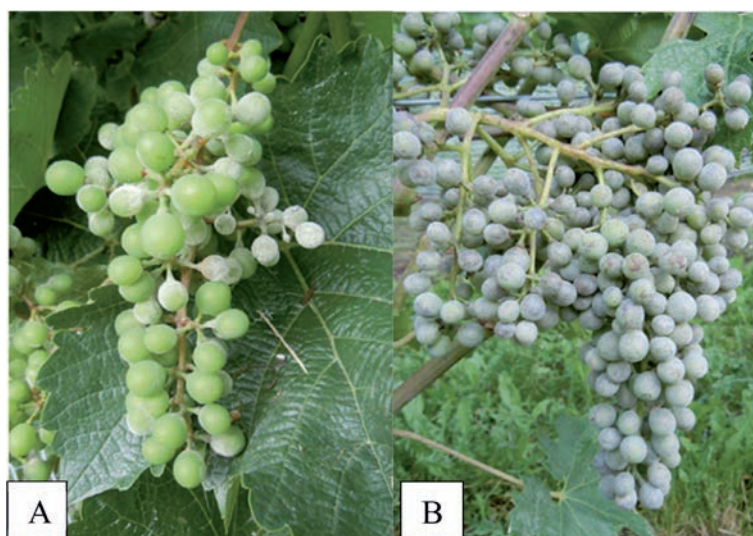


Figure 7.
(A) A light, powdery coating of mildew appears on the surface of small, undeveloped berries. (B) The whole bunch is covered with a dense layer of mildew [21].

during flowering and the intensity of berry symptoms observed at the time of bunch closure. The date of primary contamination affects disease development on leaves and damage on grape [42].

There are numerous strategies to decrease the rate of disease's effect such as cultural practices, fungicides applications, resistance cultivars and rootstock, post-harvest managements and genetic engineering. Scouting might be the primary detection of the disease [43]. Examining the leaves from different angles with a hand lens can help to easily detect infections (**Figure 8A-B**).

Most grape cultivars, especially *Vitis vinifera* L., European grapes, are not fully resistant to this pathogen, and therefore, the selection of powdery mildew resistant cultivars or rootstocks might be helpful to reduce the infection [44]. Conversely, among the species in the *Vitis* genus, North American varieties such as *V. riparia*, *V. aestivalis*, and *V. rupestris* are recognized for their lower susceptibility to powdery mildew compared to *V. vinifera* [45, 46]. In a study examining 24 grape species, it was found that *V. cordifolia*, *V. lanata*, *V. rupestris*, and *V. vulpina* exhibited high susceptibility to powdery mildew, whereas *V. candicans*, *V. munsoniana*, *V. piasezkii*, and *V. rotundifolia* were identified as resistant to the disease [47]. Another resistant species is *Muscadinia rotundifolia* [48], which is vine species native to the United States. Numerous studies have indicated that the resistance to powdery mildew is associated with the Run1 locus (designated for resistance to *Uncinula necator* 1), which is connected to the interleukin-1 receptor (TIR) family, nucleotide binding site (NBS), and C-terminal leucine-rich repeat (LRR) resistance gene candidates [49].

One of the other strategies for the combatting to disease is to avoid planting grapevines in low-lying or shaded areas, as these environments can trap moisture and create conditions conducive to fungus development. To enhance air circulation and reduce humidity, it is important to maintain proper spacing between plants and thin out the canopy. This practice not only promotes healthier growth but also minimizes the risk of fungal infections. Additionally, at the end of the growing season, it is crucial to remove and destroy any diseased plant material. This helps to prevent the spread of pathogens and ensures a healthier vineyard for the following year. By implementing these practices, grape growers can significantly improve the resilience of their vines against disease. This study discusses the genetic factors contributing to resistance against powdery mildew and highlights the importance of management practices in vineyards [50].

Furthermore, cultural practices make a significantly impact to mitigate the diseases. To effectively spray and air flow/movement, canopy management can be

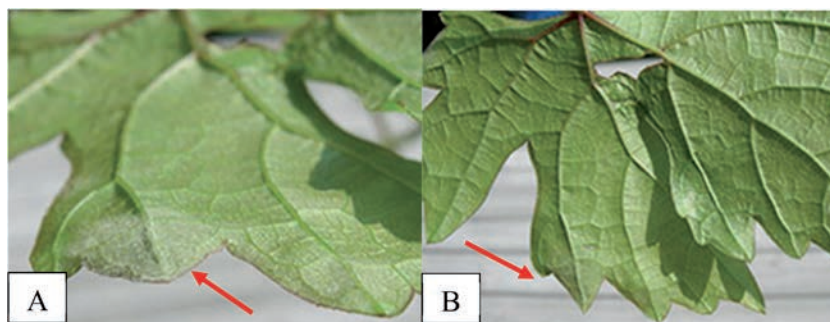


Figure 8.
Scouting from different angle for detection of powdery mildew [43].

effective for spraying, air flow/movement, and penetration of sunlight. Reducing canopy density contributes to improved air circulation within the vineyard.

Leaf canopy management practices showed important impact, and this impact helped to achieve efficiency of chemical treatments. A 2-year experiment conducted by Chellemi and Marois [51] revealed that removing basal leaves reduced the frequency of powdery mildew, and this result doubled in the following year. They combined basal leaf removal with three fungicide applications and achieved better results compared to using approximately 12 fungicide applications alone. Furthermore, the application of leaf removal combined with biopesticides can enhance the grape's resistance to powdery mildew. Leaf removal has shown promising results in improving the efficiency of fungicide, offering a sustainable and effective management strategy.

In vineyard, the training system or the canopy manipulation has a played role to control the air circulation and light exposure which are crucial to manage powdery mildew. A study used two different grape cultivars which are "Chardonnay and Cabernet Sauvignon," and two different training systems that are vertical shoot positioned vines (VSP) and free positioned vines (FC) with no foliage support wires on the development of powdery mildew. This experiment took 5 years (1994–1998) and no fungicides were employed, and the disease levels were recorded 4 to 7 days after the first appearance of symptoms. According to this study, high light intensity is crucial to limit powdery mildew development, and the employment of FC

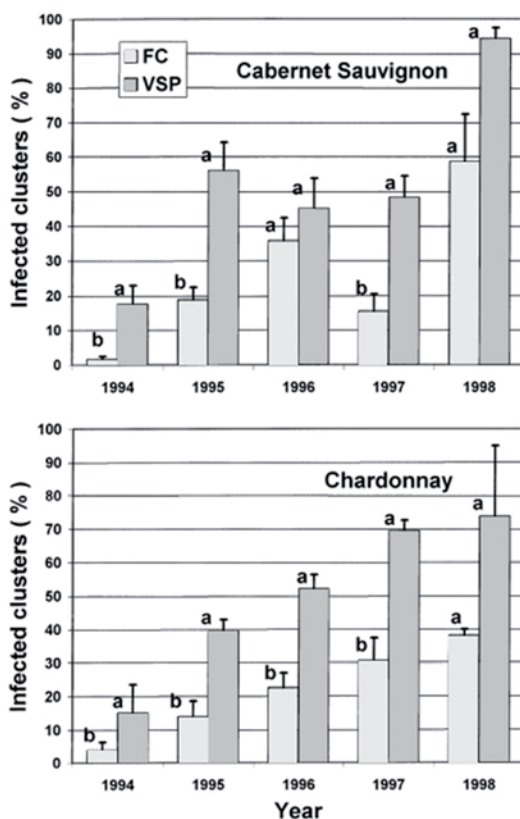


Figure 9.
 Two canopy management systems (vertical shoot positioning (VSP) and free canopy (FC)) on occurrence of powdery mildew in cultivars of "Cabernet Sauvignon" and "Chardonnay" between 1994 and 1998 [52].

training system may be beneficial in decreasing the reliance on fungicides (**Figure 9**) [52]. Adapting strategies and continuously monitoring vineyard conditions are critical for achieving successful grape production while managing the persistent threat of powdery mildew and other fungal diseases.

Grape powdery mildew can significantly reduce grape quality and yield and vine quality in which these factors lead to economic loss [53]. The use of fungicides can reduce the grape powdery mildew, and almost all grape vineyards are subject to fungicides [54].

The intensive use of fungicides makes the fungus more resistant to chemical treatments, poses risks to human health and the environment, and increases in the reliance of fungicides, prompting the consideration of new approaches like biological methods [55]. Additionally, pesticides and fungicides are prohibited in some countries or regions, such as Catalonia, where nearly half of the wine production is organic, and the use of protective chemicals is banned. Biocontrol or biological control is being more important to lessening the level of powdery mildew in grapevine. In biological control, or biocontrol, natural organisms are believed to be effective in managing diseases that affect grape production. Biological fungicides (natural predation or parasitism) which are beneficial microorganisms are products that, when sprayed on the plant, can inhibit or destroy the pathogen [56].

Several species of parasitic or antagonistic fungi like *Verticillium lecanii*, *Ampelomyces quisqualis*, *Sporothrix flocculosa*, *Ampelomyces quisqualis*, and *Tilletiopsis pallescens* have been examined for their ability to suppress powdery mildews of grapevine [57, 58]. Among all studies about bioagents, there are promising results while some barriers are rising. The first is that the agents should be applied repeatedly and second is about suitable environment to accomplish their tasks [59]. Also, the biocontrol agent which are fungi are sensitive to many of the fungicides that are used for controlling powdery mildew [60]. A study employed a mycophagous tydeid mite, *Orthotydeus lambi*, which is able to consume the spores and mycelium of the fungus *U. necator*, to control grape powdery mildew with nine different grape cultivars and one unnamed hybrid over a 3-year period. The use of *O. lambi* significantly reduced powdery mildew infection on fruit and foliage. For the experiment, *O. lambi* was used alone as fungicide and showed promising effective results. Moreover, employing *O. lambi* with mites and fungicides treatments showed important disease control. Vines treated with *O. lambi*, fungicide, or a combination of both showed significantly higher masses of pruning material and leaf photosynthetic rates compared to the untreated vines. In all together, *O. lambi* as a biocontrol agent have a high potential to combat with grape powdery mildew, while emphasizing the limitations related to variations among grape genotypes in their inherent susceptibility to mildew and their compatibility with mites. These differences might complicate efforts to develop effective strategies for disease management, as susceptibility levels and mite suitability vary widely across genotypes, requiring tailored approaches for each scenario [61, 62].

A recent comprehensive and promising research showed the significance of biocontrol agents for the reducing effect of powdery mildew on grapevine. *Bacillus subtilis* bacterium and Red Globe cv. were employed for the research. *B. subtilis* is known to be an effective bioagent in disease management. The experimental design consisted of three distinct treatments: (i) a combination of two fungicides (Myclobutanil and Pyraclostrobin), (ii) a biocontrol treatment using *B. subtilis*, and (iii) a control group that treated with sterilized water. Myclobutanil is a triazole fungicide which inhibits the growth of fungi and widely used to combat for fungal diseases [63]. Pyraclostrobin also is a methoxyacrylate fungicide which inhibits

cellular respiration of fungi [63]. The results indicated that after 2 days, treatment F significantly reduced the grape powdery mildew disease index, while treatment B showed no significant difference (**Figure 10A**). By day 7, both treatments F and B significantly lowered the disease index (**Figure 10B**). At the end of the 14-day trial, both treatments reduced the powdery mildew index to below 60%, significantly lower than the control treatment (CK), with treatment B decreasing further to 35% (**Figure 10C**). These findings suggest that treatments F and B effectively suppressed powdery mildew on grapes. According to these results, bacterium *Bacillus subtilis* significantly decreased the disease index and demonstrated a lower disease index in comparison to fungicides [64].

Erysiphe necator rarely causes the direct death of the plant. However, severe infections can lead to significant yield losses, and even mild infections might negatively impact the quality of wine produced. Intensive fungicide spraying is important and commonly applied to control the disease [16]. The primary goal of disease management is to prevent or delay the appearance of the disease on the leaves, thereby reducing the amount of inoculum present during the critical period from flowering to fruit set, when grape clusters are particularly vulnerable. To achieve this, effective spraying is crucial, especially during times when the bunches are at their highest risk. On the other hand, intensive spraying programs lead to the emergence and spread of powdery mildew strains that are resistant to various fungicides. To combat with grape powdery mildew, the spraying program mostly consist of 5 to 15 applications, rely on the purpose (vine making or table grape production). The sensitive of *V. vinifera* cultivars and management of the disease are lead to apply regular fungicide applications and this can quantity roughly 37% grass value of production [65]. Giannesi and Reigner [66] claimed that the amount of fungicides on grapes was 45 million pounds on grapes at a cost of around \$123 million for the US. Improving the management of powdery mildew and decreasing the frequency of fungicide applications can be achieved by minimizing early-season inoculum and subsequent infections. This proactive approach aims to halt the epidemic before it enters the exponential growth phase [67]. The disease management programs begin after bud break (March to April) and until late August to delay the exponential phase of the epidemic for as long as possible [68]. The spraying continues a 7 to 21 days depending to production instructions.

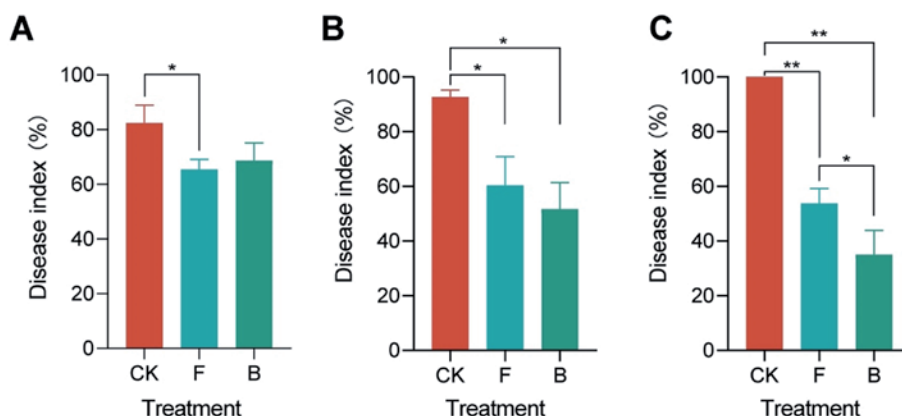


Figure 10. Grapevine powdery mildew disease index under different treatments (CK: control, F: combination of two fungicides, B: *B. subtilis*) [64].

For spraying programs, strobilurins, demethylation inhibitors (triazols, DMIs), phenyl-acetamides, dinitroanilines, azanaphtalenes (AZNs), succinate dehydrogenase inhibitors (SDHIs), quinoxyfen, meptyldinocap, sulfur, spiroxmine and metafrenone are the most used active ingredients as fungicides with different percentage [69]. To date, sulfur is one of the oldest active ingredients used to repel fungi. It was first utilized in Europe when the disease arrived there, initially in powder form. Its ability to change directly from a solid to a gaseous state made it a remarkable phenomenon. Its efficacy is closely tied to its vapor phase, which is influenced by temperature. The optimum temperature range for sulfur's effectiveness is between 25°C and 30°C. Below 18°C, sulfur does not vaporize, and high humidity can also limit its effectiveness. Conversely, temperatures above 30°C can lead to phytotoxicity, causing leaf burn [70]. Additionally, copper-based products can help slow the progression of powdery mildew after flowering. The introduction of triazoles in 1978 provided alternatives to sulfur for managing powdery mildew. Currently, various penetrant fungicides, including strobilurins and demethylation inhibitors, are widely used globally to combat this fungal disease.

3. Current trends in grapevine powdery mildew

3.1 Crosstalk between climate change and grapevine

Integrated, suitable and high-tech solutions might help to mitigate the effect of grapevine powdery mildew and the excessive use of chemical fungicides. Genetics, genomics and precision agricultural practices holds promise for the long-term strategies to combat with the disease. Also, rising global temperature is affecting grapevine ripening progress and this might affect cluster composition, altering wine quality [71]. Phenology is the stages of growth and development. The major phenological stages of *V. vinifera* (bud break, flowering, fruit-set, pea-size berries, veraison and harvest) are highly affected by climate such as temperature, solar radiation, altitude [72, 73]. Furthermore, rising temperature will create water efficacy for grapevine and this causes in decrease for yield. Disease pressure is one of the most devastating outputs because of climate change. Changes in temperature can alter pest and disease cycle due to increased humidity and more warmer temperatures. New pathogens can emerge, and this needs to new management strategies to protect grapevines [74].

Powdery mildew can be more dangerous and prevalent disease because of favorable conditions by climate change. Changes in the climate, farmers are changing how and where they grow crops. For vineyards, especially grapes are cultivating for wine, are particularly sensitive to climate changes. Grape's terroir (unique environment where grapes are grown in case of soil, climate and topography) influences the taste and quality of wine. Vineyards are currently moving higher altitude to cope with climate change. Cooler temperature is better for grape growing and higher altitudes is receiving more sunlight, especially in the ultraviolet (UV) range, which can help grapes develop better. On the other hand, high altitudes for grapes have some disadvantages like delayed growth cycle and smaller berries but it causes better antioxidants and more anthocyanins which mean richer colors in the grapes and the wine. Higher acidity is another benefit of high altitude, and it helps to balance the flavors and make the wine taste fresher [75].

In conclusion for climate change, this obstacle is pressing vineyards to adapt by moving to higher places in aspects of rising temperature. This adaptation is vital for the continued success of winemaking in the face of shifting environmental conditions.

3.2 Latest advances in grapevine molecular genetics and genomics

Grapevine powdery mildew remains an important threat to viticulture industry because of disease's detrimental effect. Currently, some innovative advancements such as resistance gene discovery, CRISPR/Cas9 gene editing, transcriptomics and proteomics, genomic and marker assisted selections are under the progress.

Discovery of genes such as RUN1, REN1, REN3 and REN6 have been introduced into *Vitis vinifera* cultivars. These genes are related to disease resistance, especially for grapevine powdery mildew. RUN1 genes was derived from *Muscadinia rotundifolia*, and it plays an important role in the plant's immune response. This gene showed significantly restrict fungal development and enhancing resistance to *E. necator* Phd. REN1 gene has similar resistance locus like RUN1. It also has contribution to defense against powdery mildew. Also, low fungal penetration and reduced hyphal development are provided with these two genes [76].

Agurto et al. [77] showed in their work how RUN1 and REN1 genes which are powerful genes to enhance resistance against powdery mildew. They crossed *Muscadinia rotundifolia* which carries RUN1 and REN1 genes with *V. vinifera*, susceptible commercial table grape cv. "Crimson Seedles." After the crossing, RUN1REN1 resistant genotypes were obtained and identified by marker-assisted selection. Their results revealed that RUN1REN1 plants exhibit enhanced defense response upon *E. necator* infection, resulting in ineffective fungal establishment along with a low penetration rate and inadequate hyphal growth. This resistance mechanism encompasses: (a) The production of reactive oxygen species (ROS); (b) the accumulation of callose; (c) the induction of programmed cell death (PCD); and (d) above all, the activation of the VvSTS36 and VvPEN1 genes. RUN1REN1 plants hold great promise as new table grape cultivars with durable complete resistance to *E. necator* and constitute valuable germplasm to be integrated into grape breeding programs aimed to further pyramid with other resistance sources to viticultural pests and diseases.

Susceptibility genes (S genes) like Mildew Locus O (MLO) are responsible for pathogen infection and have a role in plant-pathogen interaction by facilitating pathogen infection. S genes can enable pathogen establishment within the host plant. The pathogen effectors that are molecules produced by pathogens to defeat plant immune responses and encourage susceptibility. In grapevine, MLO genes are crucial for the initial stages of pathogen invasion. Mutations in the MLO gene have been demonstrated to provide resistance to powdery mildew in several plant species, including barley and grapevines [78]. Important research about using CRISPR/Cas9 gene editing tool on grapevine showed that this genome editing tool successfully edited VvMLO3 and VvMLO4 genes in grapevines, which are linked to susceptibility to powdery mildew. They generated 20 edited lines and different types of mutations (chimeric, biallelic, and heterozygous). In these edited lines, four lines with mutations in VvMLO3 (responsible gene for pathogen's entry and colonization within the plant tissue) exhibited enhanced resistance to powdery mildew which was linked to increased cell death, cell wall apposition, and hydrogen peroxide (H_2O_2) accumulation in the plant tissues. According to these results, mutagenesis of VvMLO3 can successfully enhance disease resistance in grapevines, demonstrating the potential of CRISPR/Cas9 technology in agricultural biotechnology [79].

4. Concluding remarks

Grapevine powdery mildew remains a significant challenge for viticulture world-wide, posing threats to both grape quality and yield. This chapter has explored the biology and lifecycle of the pathogen *Erysiphe necator*, highlighting its adaptability and the conditions that favor its proliferation. We have examined the various symptoms of infection, the economic impact on grape production, and the complexities involved in managing this pervasive disease.

Effective management strategies are crucial for mitigating the effects of powdery mildew. Integrated approaches that combine cultural practices, chemical controls, and biological alternatives offer the best potential for sustainable management. Emphasizing preventive measures, such as proper canopy management and the use of resistant grapevine varieties, can significantly reduce disease incidence and severity.

Moreover, ongoing research into the pathogen's resistance mechanisms and the development of innovative treatments will play a vital role in future management practices. As climate change continues to influence agricultural practices, understanding the dynamics of powdery mildew in changing environmental conditions will be essential for grape growers.

In closing, the fight against grapevine powdery mildew underscores the importance of a collaborative approach among researchers, growers, and industry stakeholders. By sharing knowledge and resources, the viticulture community can develop resilient strategies to safeguard grape production and ensure the sustainability of vineyards for generations to come.

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