CENTENARY OF THE OIV
45th WORLD CONGRESS OF VINE AND WINE
14-18 OCTOBER 2024 FRANCE-DIJON
OIV
Available on IVES Conference Series vine & wine
DOI : https://doi.org/10.58233/bvgpZmv8

The science of fungi in grapevine: An essential new book covering all aspects of fungi in viticulture

Olivier Viret[1] and Katia Gindro[2]

[1] Department of Finance and Agriculture (DFA), General Directorate of Agriculture, Viticulture, and Veterinary Affairs (DGAV), 29 Marcelin Avenue, 1110 Morges, Switzerland
[2] Agroscope, Plant protection Department, Mycology group, Route de Duillier 60, P.O. Box, 1260 Nyon, Switzerland

Abstract. Grapevine (*Vitis vinifera* subsp. *vinifera*), domesticated over 11,000 years ago from wild lianas has adapted to diverse global environments. Initially, information on fungal vine diseases was limited, until the invention of the microscope in the 17th century. The European phytosanitary crisis of the late 19th century significantly impacted vine cultivation, emphasizing the persistent challenge of managing fungal diseases despite the discover of copper and sulphur as first fungicides. This open access book provides a comprehensive exploration of the relationship between fungi and grapevines, covering contemporary mycological classifications, pathogens, the mycobiome, endophytes, and mycorrhizae. Inspired by the French book "La Vigne, Maladies Fongiques" by the same authors, which won first prize at the 2015 OIV book competition (Organisation Internationale de la Vigne et du Vin, Dijon), this work aims to extend and update that foundational text to worldwide readers.

1. Vines and fungi: An unlikely alliance

1.1. Origins and Plasticity of Grapevine

Grapevine is one of the oldest cultivated plants, with its wild ancestors dating back over 200,000 years. Domesticated in the Near East and South Caucasus around 11,700 years ago, grapevines have adapted to a wide range of climates and conditions. Today, grapevines are grown worldwide, with significant cultivation areas in Europe, the Americas, and Asia. The global warming trend has shifted the geographic boundaries for grapevine cultivation, with the species now thriving in regions as far north as southern England and as high as 3,100 meters in Argentina. Key factors for successful cultivation include temperature, sunlight, and water availability, with specific microclimates enabling grapevines to thrive in otherwise extreme conditions.

1.2. Historical Background of Fungal Diseases in Grapevine

Fungal diseases have probably affected vines since their origin, although no information is available to date, except some indication of moulds. However, the most virulent fungal pathogens emerged in the last two centuries, leading to significant challenges in viticulture. The introduction of powdery and downy mildew in the 19th century devastated European vineyards and necessitated the widespread use of sulphur and copper-based treatments. Despite these advancements, fungal diseases remain a persistent threat, and early viticultural literature only briefly mentions their impact.

The today’s nearly generalised cultivation of *Vitis vinifera*, highly susceptible to fungal diseases, relies heavily on fungicides. Efforts to develop resistant grape varieties have been ongoing since the late 19th century, with varying success. Early hybrids offered resistance but lacked the oenological qualities of traditional varieties. In recent years, molecular biology has enabled more targeted breeding of resistant grape varieties, though agronomic and vinification evaluations are still necessary. Despite these efforts, eliminating the need for fungicides in vineyards remains unlikely, especially under favourable conditions for fungal pathogens.

1.3. Over Two Centuries of Research on Fungi in Grapevine

Fungi, responsible for about 80% of plant diseases, have been a focus of research for over two centuries. Their ability to adapt and survive in extreme conditions makes them particularly challenging to control. The development of fungicides since the late 19th century and later from 1950 of synthetic molecules marked a significant advancement in plant protection, though the emergence of fungicide-resistant fungal strains continues to pose challenges. Depending on the level of resistance of newly breed varieties, the need for plant protection products remains to prevent the adaptation of fungal pathogens able to overcome defence mechanisms.

2. Hidden Secrets of the Vineyard: Anatomy and Defense of the Vine

This chapter explores the vast yet underutilized biodiversity of grapevine. Despite the dominance of a few *Vitis vinifera* cultivars, which are highly susceptible to major fungal diseases, there is significant potential in other *Vitis* species that have evolved varying levels of resistance. The chapter delves into the structure and anatomy of grapevines, the impact of historical phytosanitary crises, and the growing importance of sustainable, fungicide-free viticulture. It also highlights the role of crossbreeding and marker-assisted breeding in developing disease-resistant grape varieties, paving the way for a more resilient future in viticulture.

2.1. Systematics of the Genus *Vitis*

The Vitaceae family comprises around 950 species across 16 genera, including *Vitis*. The Vitaceae, with fossils dating back to the Late Cretaceous, are crucial economically for table grapes, raisins, and wine production. Domestication of the grapevine occurred about 11,000 years ago in Western Asia and the Caucasus, spreading to Europe with early farmers and giving rise to various types, such as Muscat and unique wine grapes. Vitaceae are classified into five tribes: Ampelopsidae, Cissae, Cayratieae, Parthenocissae, and Viteae. The genus *Vitis* is divided into two subgenera: *Vitis* (2n = 38) with 82 described species, and *Muscadinia* (2n = 40) with 3 species, including *Vitis rotundifolia*. *Muscadinia* is found mainly in the southeastern United States, northeastern Mexico, Belize, Guatemala, and the Caribbean, while *Vitis* is widespread globally. *Vitis vinifera* is the primary European species, consisting of two subspecies: subsp. *vinifera* (cultivated) and subsp. *sylvestris* (wild). In North and Central America, there are over 24 species, including *V. riparia*, *V. rupestris*, *V. aestivalis*, *V. labrusca*, and *V. rotundifolia*.

The genetic diversity of grapevines has increased through sexual reproduction, interspecific hybrids, and somatic mutations, with over 21,000 named varieties identified, about 8,000 of which are recognized for *V. vinifera*.

2.2. Development of the Vine and Phenology

The vine has adapted to various environmental conditions and climates over its history. It grows in diverse soils and climates, from extreme drought to high humidity and cold.

Cultivation techniques have evolved from empirical knowledge to scientifically informed practices. Advances in understanding vine physiology, nutrient reserves, and environmental interactions help optimize growth and fruit quality. The vine's annual cycle, from bud burst to berry ripening, follows the BBCH scale (0 to 9), which details developmental stages.

Climate change is affecting vine phenology, causing earlier bud burst, flowering, and harvests, with varying impacts depending on the region. Warmer temperatures are shortening the growing season and altering grape composition, increasing alcohol content, and decreasing acidity. Vineyards are adapting by establishing new growing regions, using irrigation, and selecting climate-resilient varieties. Adjusting vineyard locations and developing suitable rootstocks are essential for coping with climate changes. The adaptation strategies include selecting varieties with different growing cycles and improving rootstocks for drought tolerance, though these solutions face many uncertainties.

2.3. Anatomy

The grapevine (Vitis) is a hardly, perennial, deciduous climber. The wild grapevine, *Vitis sylvestris*, is the ancestor of the cultivated *Vitis vinifera* and typically grows in forests, using its tendrils to climb trees. *Vitis sylvestris* is dioecious, with male and female flowers on separate vines. However, wild grapevines are now rare due to pests, pathogens, and forest management practices. Cultivated grapevines, especially *Vitis vinifera*, are widely grown and regularly pruned, losing their natural creeping habit. Grapevine has an underground root system and an aerial part with the trunk, shoots, leaves, tendrils, and reproductive organs (flowers and berries). The architecture of the vine varies based on training and pruning. Chapter 2 of the book provides a very detailed description at the macroscopic and microscopic level of the structure and anatomy of all the vegetative organs of the grapevine.

The **root system** is vital for anchoring the plant and absorbing water and nutrients from the soil. It also stores carbohydrates, minerals, and phytohormones. Root formation begins from the heel of woody cuttings and develops into a complex network, influenced by soil conditions. Fine rootlets, emerging from main roots in spring, are crucial for water and mineral absorption. They feature apical root caps and absorbent hairs that regenerate continuously, enhancing nutrient uptake. Rootlets have a layered structure, including a cortex, central cylinder, and conducting tissues (xylem and phloem). Over time, they develop secondary structures through lignification, forming protective layers and secondary wood.

The aerial part comprises the **trunk** and **woody shoots**, which vary with age and training method. The trunk can be either short or long and features flexible, twisted bark that sheds in strips. In espaliered systems, the trunk may extend horizontally on a trellis, forming permanent cordons, or be pruned to specific heights, as seen with Guyot training. Shoots are categorized as primary (long) and secondary (shorter, lateral), bearing leaves, buds, and tendrils or inflorescences along nodes. Green shoots, before lignification, have a root-like structure with an outer cortical layer and a central cylinder of conducting tissues. In cross-section, shoots show an epidermal layer, cortical parenchyma with collenchyma, and central pith. The vascular system includes sclerenchyma, primary phloem, cambium, and primary xylem. The cambium produces secondary xylem and phloem, contributing to the shoot's hardening and bark formation. Cambial activity pauses in winter and resumes in spring, creating new layers of secondary xylem and bark. Unlike many woody plants, grapevines have less distinct growth rings due to interrupted cambial activity, and annual pruning wounds leave dead wood, potentially affecting wood diseases.

Buds are essential for shoot development and are categorized based on their structure and function. Each bud acts as an embryo for a shoot, containing a vegetative cone with a growth meristem and remnants of leaves and inflorescences. The bud apex promotes shoot elongation through cell division, forming internodes, nodes, leaves, and tendrils. Buds are located at nodes and include two types: axillary buds, which develop into lateral shoots, and latent buds, which remain dormant in winter but develop into shoots, leaves, tendrils, and inflorescences in the next growing season.

Leaf features a more-or-less dissected, five-lobed blade with a serrated edge, attached to the shoot by a petiole. The leaf blade has five primary veins that split into secondary and tertiary veins, covering the entire surface. The lower surface is lined with numerous stomata for gas exchange. Leaf morphology varies widely among grape varieties, influencing characteristics like hairiness, pigmentation, and blade shape. These traits are used for ampelographic identification.

Tendrils are flexible and can become woody over time. They typically bifurcate into two branches: a larger downward-facing major branch and a smaller upward-facing minor branch. Tendrils can spiral around supports, aiding the vine's growth. Anatomically, tendrils resemble modified flower stalks and may have flowers on them. Their structure includes an outer epidermis, annular layers of collenchyma, a cortical parenchyma, conducting bundles of primary phloem, cambial cells, and primary xylem. Lignified tendrils develop secondary phloem and xylem, along with sclerenchyma clusters.

Vitis vinifera produces compound **inflorescences**, or **bunches**, consisting of clusters of flowers arranged along a central rachis. Each bunch includes a peduncle (stem), the rachis (main axis), and **berries** on pedicels. Inflorescences typically emerge from the first two to three nodes of the shoot and their arrangement varies by grape variety, year, and shoot condition. Initially, they appear as compact cones covered by thin bracts. Each flower has a calyptra (flower hood) and five stamens with filaments and anthers. The superior ovary contains up to four ovules that develop into seeds upon generally self-fertilization. During flowering, the calyptra detaches, allowing the stamens and gynoecium (nectaries, style, stigma) to expand. Pollination occurs when pollen germinates and fertilizes the ovules. Environmental factors can impact ovule development and pollen germination, leading to issues like shot berries or millerandage.

2.4. Grape Varieties Resistant to Fungal Diseases

Grapevine breeding for resistance to fungal diseases and pests began in the mid-19th century in response to the devastating impact of diseases like powdery mildew, downy mildew, and black rot, as well as the phylloxera pest on European vineyards.

In 1845, powdery mildew (*Erysiphe necator*) arrived in Europe, followed by downy mildew (*Plasmopara viticola*) in 1878, causing severe damage to European vineyards. The simultaneous arrival of phylloxera, caused by the aphid-like insect *Daktulosphaira vitifoliae*, necessitated the development of resistant rootstocks.

The recognition of American grapevines resistance potential to mildews led to extensive hybridization (cross of *V. vinifera* with *Vitis* species) efforts starting in the late 19th century. French initiatives, such as the Planchon mission in 1873, highlighted the importance of American species' resistance. From 1880 to 1940, French hybridizers like Seibel, Seyve-Villard, Joannes Seyve, and others developed numerous rootstocks and hybrids. These hybrids, crucial for restoring European viticulture, covered up to 400,000 hectares of French vineyards by 1958. However, early hybrids, especially those from *Vitis labrusca*, were criticized for poor wine quality, leading to their exclusion from French Designation of Origin regions in the 1950s. Despite this, hybridization continued in other countries, including Germany, Austria, Spain, and beyond.

Contemporary research includes Asian species like *Vitis amurensis* and other species to develop polygenic or "pyramidized" varieties with multiple resistance genes, which provide comprehensive protection against pathogens. The ongoing development of such hybrid varieties is crucial for managing fungal diseases in viticulture.

3. The Invisible World of Fungi: Science and Mystery

Chapter three of the book delves into the modern classifications within mycology, focusing on the concepts of the holobiome, microbiome, and mycobiome in grapevines. It highlights the wide range of fungal diversity, from unicellular yeasts to complex filamentous forms, and their evolutionary adaptability. Fungi are essential to ecosystems as decomposers, symbionts, and pathogens. They recycle nutrients, decompose organic matter, and form beneficial relationships with plants, such as mycorrhizae, which improve nutrient uptake. However, some fungi are pathogenic and can cause diseases underscoring the need for effective management strategies. The chapter examines the grapevine mycobiome, including both endophytic fungi within plant tissues and ectophytic fungi on plant surfaces. Understanding this mycobiome is vital for sustainable vineyard management and reveals the complex coevolutionary interactions between fungi and plants.

3.1. Mycology Through the Ages

Fungi have been important throughout human history, with their uses spanning food, medicine, and spiritual practices. Early understanding was limited, and mushrooms were often viewed with suspicion. Systematic classification began with Theophrastus around 300 BCE, and further developments included Dioscorides' medicinal descriptions and Pliny the Elder's truffle cultivation techniques. The 15th and 16th centuries saw more interest, highlighted by Johann Wonnecke von Kaub's mushroom illustrations and Pietro Andrea Matthioli's truffle work. Advances in the 17th and 18th centuries included Robert Hooke's microscopic observations and Pietro Antonio Micheli's introduction of fungal spores. By the 19th century, fungi were recognized as distinct from plants, with Heinrich Anton de Bary exploring their complex life cycles. In 1959, Robert Harding Whittaker proposed a separate kingdom for fungi. Modern mycology continues to advance with ongoing classification revisions and molecular biology research.

3.2. Structure of Fungi

Fungi exhibit diverse structural forms, primarily as filamentous hyphae or unicellular yeasts. Filamentous fungi grow as networks of tubular filaments, while yeasts remain single-celled and reproduce by budding or fission. Some fungi, like *Saccharomyces cerevisiae*, maintain a yeast form throughout their lifecycle. Filamentous fungi have a vegetative body called the thallus, which can be eucarpic, with distinct vegetative and reproductive parts, or holocarpic, where the entire thallus becomes reproductive. Hyphae, which develop from spores, grow apically and form a mycelial network. The "Spitzenkörper", a micro-organelle at the hyphal tip, directs vesicle movement for wall construction. Hyphal growth can be rapid, exceeding 0.8 mm per hour, and hyphae can branch to form complex networks. They are protected by a cell wall made of chitin, cellulose, and sometimes glucans. Hyphae may be septate, with cross-walls, or coenocytic, lacking cross-walls. Septa in Ascomycetes have pores for cytoplasmic flow, while Basidiomycetes have complex dolipores. Fungal cells contain typical eukaryotic organelles but lack chloroplasts. Mitosis in fungi varies. Flagellated fungi use centric mitosis, while non-flagellated fungi use spindle pole bodies (SPBs). Fungal mitosis lacks a metaphase plate. Fungi form a plectenchyma, a mass of interwoven hyphae, which supports the development of macroscopic fruiting bodies that produce spores.

3.3. Reproduction

Fungal reproduction is intricate, involving sexual, asexual, and parasexual methods suited to different life strategies. Spores, the main reproductive units, come in various shapes, sizes, and textures. They can be septate, with compartments that germinate separately, or non-septate. Spores are adapted for different dispersal methods, such as being airborne for dry spores or spread by animals through faeces for others. Unlike seeds, spores do not have a preformed embryo but possess essential organelles within protective walls.

3.3.1. Sexual Reproduction in Fungi

Fungi reproduce sexually through a process that involves three stages. First, plasmogamy occurs, where haploid cells fuse. This is followed by karyogamy, the fusion of haploid nuclei to form a diploid nucleus. Finally, meiosis takes place, producing haploid spores and allowing for genetic recombination. These steps occur in specialized structures such as asci in Ascomycetes and basidia in Basidiomycetes.

3.3.2. Asexual Reproduction in Fungi

Fungi also reproduce asexually, which allows them to spread quickly and produce identical offspring. This process includes the formation of conidia on conidiophores, and in yeasts, reproduction occurs through budding or fission. Asexual fruiting bodies release spores under certain conditions, helping fungi to adapt and thrive in different environments.

3.4. Trophic Modes and Lifestyles

Fungi are highly adaptable, thriving in diverse environments such as Arctic ice, deserts, and oceans. They play a crucial role in nutrient recycling by decomposing organic matter through external digestion. By secreting enzymes, fungi break down complex substances into simpler compounds, which they then absorb, supporting plant photosynthesis and the carbon cycle. For example, white rot fungi are essential for decomposing lignin, aiding in the breakdown of wood and leaf litter.

Saprotrophic fungi decompose dead organic matter, including natural and synthetic polymers, with some targeting simple sugars and others, breaking down complex materials such as lignin.

Necrotrophic fungi, which are common plant pathogens, kill their hosts to feed on dead tissue, while hemibiotrophic fungi initially coexist with their hosts before turning necrotrophic, as for *Botrytis cinerea*.

Symbiotic fungi form mutualistic relationships with plants, animals, and other fungi, ranging from simple partnerships to complex ecosystems. Advances in molecular techniques have enhanced our understanding of these diverse fungal roles in ecosystems.

Microbes significantly influence plant life by affecting nutrition, development, immunity, and behaviour, a result of 500 million years of coevolution. Technological advances have enabled genetic and molecular studies of these interactions, though many mechanisms are still unknown. Plants are holobionts, encompassing the host and its microbiota (including viruses, protists, and archaea). The hologenome combines host and microbial genes, expanding the genetic pool and impacting plant phenotype, adaptation, and resistance.

Microbes inhabit various plant compartments: soil (root microbiota), rhizosphere (shaped by root exudates), phyllosphere (nutrient-poor), and endosphere (housing endophytes). These microbial communities enhance plant fitness by improving nutrient uptake, stress tolerance, and pathogen defence, and transfer resistance traits to offspring.

Fungal communities, though less studied than bacterial ones, are crucial for managing stress and defending against pathogens. They include saprotrophs, pathogens, epiphytes, endophytes, and mycorrhizal fungi. Fungal diversity is highest in the rhizosphere but less explored in other plant compartments.

Grapevines host a varied microbiota shaped by climate, terroir, cultivation practices, plant protection products, grapevine variety, and rootstock. Soil-borne fungi are most common, with their distribution influenced by local conditions and management. Different rootstocks can notably alter the vine's microbiome. Research highlights a core mycobiome in grapevines, including genera such as *Cadophora*, *Cladosporium, Penicillium,* and *Alternaria*, with *Neofusicoccum* being especially persistent. *Aureobasidium pullulans, Cladosporium* spp., and *Alternaria alternata* are regularly found across plant organs, seasons, and locations. These fungal communities are more affected by the plant organ sampled than by regional or climatic factors. Fungi can alternate between latent and active states, impacting plant health. Understanding these dynamics is essential for managing diseases like esca and trunk diseases, which are influenced by climate, soil type, and cultivation practices. Recent studies suggest that while fungal communities are similar in asymptomatic and symptomatic plants, soil water retention and climatic demand are critical factors in their development.

4. Fungal Attack: The Diseases Threatening our Vines

Globally, grapevines are cultivated on 7.3 million hectares (data 2021), producing 73 billion tonnes of grapes used for winemaking (47.8%), fresh consumption (31.7%), and dried fruits (7.5%). Regardless of location and cultivar, the most planted *V. vinifera* is highly vulnerable to major fungal pathogens. This highlights the critical role fungi play in viticulture, with varying intensities of fungal pathogen impact depending on climatic conditions and vine-pathogen co-evolution. All green parts of grapevines are susceptible to diseases that can lead to severe symptoms and economic losses. Although fungal pathogens have been known since the mid-19th century, their life cycles and relationships with grapevines remain partially obscure. As a result, fungicides are still used preventively, despite their application being dependent on unpredictable weather and disease forecasts. Ongoing global research into grapevine fungal pathogens continues to provide new insights into the most common and damaging diseases.

Chapters 4 to 6 provide an in-depth exploration of recent research and publications on fungal diseases affecting grapevines green parts, wood, and roots. These chapters detail common fungal diseases such as downy mildew, powdery mildew, grey mould, anthracnose, ripe rot, rougeot, Septoria leaf spot, sour rot, white rot, and the mycotoxins produced by secondary rots. They also address wood diseases like esca, eutypiosis, and excoriose, as well as root diseases including *Armillaria* root rot, cotton root rot, *Dematophora*, *Phymatotrichopsis* root rot, *Phytophthora* (crown and root rot), *Roesleria* root rot, Verticillium wilt, and woolly root rot. Each section provides comprehensive descriptions of these diseases, outlining their symptoms and the specific pathogens responsible. The chapters further analyse the epidemiological patterns, development cycles and morphological features of these pathogens, offering valuable insights into the complexities of managing grapevine diseases.

5. The Art of Grafting: Protecting Vines from the Nursery

Following the Phylloxera blight of the late 19th century, which devastated European vines by attacking their roots, grafting became a crucial technique. This chapter explains how the grafting process combines *V. Vinifera*, the European vine, vulnerable to the root form of the pest but resistant to its leaf form, with American rootstocks (*Vitis* spp.) that are resistant to the root form but not the leaf form. Learn about the factors influencing rootstock selection, such as soil type and drought resistance, and the meticulous production process by vine nurserymen, including strict hygiene measures to prevent fungal infections. A whole chapter highlights the evolution of grafting practices and their significance in modern viticulture. The grafting process involves various methods such as chip-budding, T-budding, cleft-grafting, or herbaceous grafting, all aiming to align the cambiums of the scion and rootstock to form a uniform callus.

The production of rooted grafts, or 'rootings,' follows a precise procedure. Scions and rootstocks are selected based on lignification and size. Rootstocks undergo preparation steps including the removal of shoots and buds, followed by calibration and rehydration. Both scions and rootstocks are treated with disinfectants like oxyquinoline and stored under controlled conditions to maintain hydration. After grafting, the vines are dipped in paraffin wax to protect the graft union, then subjected to forcing under optimal temperature and humidity conditions to promote callus formation. Following this, the plants are prepared for planting, including a hot-water treatment to eliminate phytoplasmas and bacteria.

The success of grafting largely depends on the quality of the union between the scion and rootstock. Effective callus formation is crucial for the establishment of a strong sap flow and overall plant health. Poor graft unions can lead to issues such as cork formation and necroses, which may predispose the plant to fungal infections. Various grafting systems, including the omega inlay graft and cleft-grafting, each have their strengths and weaknesses, with omega grafts currently being the most used due to their high-quality unions.

Fungal pathogens, particularly *Botrytis cinerea*, have historically posed significant challenges in nurseries, reducing graft success rates. The introduction of oxyquinoline in the 1950s revolutionized graft disinfection, improving plant quality and success rates. This compound, initially used in human medicine, became a staple in nursery practices.

Research has shown that young grapevines harbour a diverse range of fungi, including those associated with wood diseases such as esca and Petri disease. These fungi can affect plant vigour and yield. The interaction between different fungal species and their roles as primary pathogens or endophytes are still not fully understood. Studies indicate that fungal communities vary with grape variety, influencing both pathogenic and saprophytic species.

The scale of grapevine production has evolved from artisanal methods to more industrial approaches since the mid-20th century. Hygiene and certification practices have become crucial in reducing diseases. Hot-water treatment (HWT) at 50 °C for 45 minutes has been effective in eliminating phytoplasmas and bacteria, though it may also alter fungal communities. Other treatments, such as plant-protection products and biocontrol methods, have been explored to manage fungal pathogens. For instance, *Trichoderma* species have shown promise in controlling certain fungi, although their effectiveness in preventing wood diseases in the nursery remains variable.

6. The Future of Viticulture: Towards Sustainable Fungal Protection

Fungal disease management is a key point to produce high-quality grapes. The historical reliance on fungicides is described, from early copper and sulfur-based treatments to the more recent synthetic molecules introduced in the late 1950s. Despite significant advancements, the quest for natural and effective alternatives continues, due to environmental and health concerns. The chapter highlights the complexities of applying fungicide treatments emphasizing the need for precise application, proper dosage, and optimal timing. It also addresses the importance of sprayer performance and calibration in ensuring both efficacy and safety.

6.1. Fungicides in Grapevine

In the late 19th century, sulfur and copper were the primary fungicides to control downy and powdery mildews after their accidental introduction in Europe. The mid-20th century saw the development of organic fungicides, including dithiocarbamates and systemic fungicides. While these innovations offered better control, they quickly led to resistant fungal strains. Modern fungicides such as strobilurins also faced similar issues with resistance. Since the 1970s, the negative environmental and health impacts of synthetic fungicides have prompted stricter regulations in Europe, leading to the more recent removal of many substances.

Fungicides disrupt critical fungal functions like respiration or cell division. Modern fungicides are designed to target specific fungal processes with minimal side effects for the environment and human health. Multisite active ingredients, such as copper and sulfur, are toxic to aquatic life and copper contribute to heavy metal accumulation in soil.

Fungicides are categorized based on their modes of action, affecting their application and effectiveness. Contact fungicides operate exclusively on the plant surface where they are applied. Examples include copper and sulfur, which provide a protective layer against fungal pathogens. Penetrating or locally systemic fungicides are absorbed by plant tissues and move within them, but they do not travel throughout the entire plant. This category includes products like DMIs (demethylation inhibitors) or strobilurins, which offer targeted protection. Systemic fungicides, on the other hand, penetrate the plant tissues and spread throughout the entire plant, though their effectiveness can be reduced as the plant grows and dilutes the active substance. Aluminum fosetyl and phenylamides are examples of systemic fungicides. Fungicides can be preventive, curative, or eradicative. Most fungicides act preventively, protecting plants before infection occurs. Curative fungicides target infections already present but only during the incubation phase, from penetration into the vine tissues to the sporulation. Eradicative fungicides aim to eliminate all fungal particles but are currently limited to sulfur vapor for powdery mildew. Combining fungicides with different modes of action helps manage resistance and ensure effective control. This approach is crucial given the high risk of resistance, especially in perennial crops like grapevines, which are sprayed at regular intervals during the growing season of the vine. Resistance risks vary depending on the fungicide type and pathogen biology, with some combinations posing higher risks than others.

6.2. Control stategies

Effective management of fungal diseases in grapevines necessitates regular fungicide applications, raising to environmental and health concerns. This led to the development of integrated, organic, and biodynamic management methods focusing on sustainability and reduced use of chemicals.

Integrated pest management (IPM), developed from the 1950s, emphasizes observing crops and their environment to apply treatments only when necessary, prioritizing ecological and biological methods. In Switzerland, successful biological controls using predatory mites and synthetic pheromones to control spider mites and vine moths. IPM strategies involve creating a supportive environment for beneficial organisms and using plant protection products as a last resort. Although natural alternatives may require more frequent applications and higher costs, planting resistant grape varieties can reduce economic losses and enhance flexibility in disease management. IPM aims to minimize residues, protect winegrowers' health, maintain biodiversity, and preserve soil fertility. The International Organisation of Vine and Wine (OIV) supports IPM principles in its various resolutions on integrated and organic production, on biodiversity preservation, and on sustainable grape production.

Organic viticulture emphasizes environmental respect and relies on natural preparations, including copper and sulfur. It involves preventative measures such as selecting resistant grape varieties, maintaining soil health, and encouraging beneficial organisms through diverse planting and habitat creation. Approved organic treatments include copper products, sulfur, potassium bicarbonate, plant extracts, and biological agents. Regulations vary by country regarding permissible substances.

Biodynamic farming, rooted in Rudolf Steiner's 1924 philosophy, integrates organic principles with cosmic and rhythmic influences. It minimizes synthetic inputs, using natural preparations and compost based on Steiner's methods. Biodynamic practices consider lunar and zodiacal rhythms for farming activities, aiming to enhance plant health and resilience through cosmic forces. Common biodynamic treatments involve plant extracts, silica, and mineral-based preparations based on copper and sulphur.

Overall, modern viticulture combines these approaches to balance effective fungal disease control with sustainability and environmental stewardship.

6.3. Disease management

Managing fungal diseases in *Vitis vinifera* requires a consistent application of plant-protection products, and the effectiveness of these measures is influenced by a range of factors. Key variables include geographic location, climatic conditions, grape variety, the physiological state of the vine, and the characteristics of the plant-protection products used, including their application methods.

Effective application techniques involve producing fine droplets from fungicides dissolved in water to ensure even coverage of plant surfaces, while minimizing environmental dispersal. However, powdered treatments such as sulphur for controlling powdery mildew often face challenges with precise application, leading to potential uncontrolled dispersal. Disease management decisions must consider several elements. Site selection and grape variety are crucial, with a focus on choosing resistant varieties and optimal vineyard locations. Weather conditions play a significant role in predicting disease outbreaks, and environmental considerations are important for protecting public health, water, air, and beneficial organisms. Additionally, economic factors must be balanced with the anticipated grape quality and yield. Successful disease management involves creating environments that are unfavourable to pathogens and ensuring thorough coverage with plant protection products. Risk forecasting using weather data and plant receptivity helps predict disease outbreaks. The choice of active ingredients should be based on their mode of action, environmental impact, and potential for resistance. Adjusting the dosage according to leaf area, planting density, and vine configuration is essential, along with using appropriate application techniques and calibrating sprayers for optimal coverage. Safety measures must also be observed in the handling, storage, and disposal of plant protection products and residues.

Overall, effective disease management seeks to balance efficacy, environmental impact, and user safety to ensure high-quality grape production.

7. References

1. O. Viret, K. Gindro, Science of Fungi in Grapevine, Ed. Springer open access book, ISBN 978-3-031-68662-7 (2025)