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The threat of Alternaria Late Blight of Pistachio and its integrated management

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Abstract

With the ever-increasing importance of pistachio as a crop nut worldwide, there has developed a parallel ingrowth in fungal diseases pertaining to it. Pistachio trees, being one of the few trees that grow in the Mediterranean climate, have come under several serious pathogens that endanger its very production. Such conditions, therefore, require a review of the major fungal diseases affecting pistachios: namely, Alternaria Late Blight. The biological features and morphology concerning both will be discussed for proper identification and diagnosis. Moreover, the review covers various management practices to control these diseases, which include biological control with the use of beneficial microbes, limited application of chemical fungicides, efficient methods of irrigation to minimize pathogen-conducive conditions, limitation of pathogen reservoirs by management of weeds, and growing resistant varieties of pistachio. Such integrated methods of management will contribute to better plant health and enable pistachio producers to realize full growth potential and continue yields at high levels.

1. INTRODUCTION

Among the 11 species of the genus *Pistacia*, belonging to family *Anacardiaceae*, only the species *Pistacia vera* L. gives edible nuts. Recently, there is an increase in global pistachio production (FAOSTAT, 2017; Gusella et al., 2022). The original home of pistachios is western Asia and Asia Minor; its wild form can still be traced in countries like Turkey, Syria, Iran, Iraq, India, Lebanon, Palestine, the southern parts of Europe, and parts of Africa. These fruits, which botanists classify as drupes, are edible and do best on long, hot summers with temperate winters that have at least 1000 hours below 7.2°C (Gusella et al., 2022). The *Pistacia* does best on fine sandy loams but can put up with salty, alkaline, and even lime-rich soils admirably (Gusella et al., 2022).

Sustainable control methods for fungal diseases are crucial for environmental protection, economic viability, and social responsibility in agriculture (Rovetto et al., 2024). They minimize the use of synthetic chemicals, reducing their impact on the environment and human health (McLaughlin et al., 2023). These methods include cultural practices like crop rotation and sanitation, biological control using beneficial microorganisms, host resistance breeding, biofumigation, solarisation, and integrated pest management, which combines multiple approaches for effective and sustainable disease management (Góngora and Silva, 2024; Rovetto et al., 2024; McLaughlin et al., 2023; Wang, 2023). While they may not always be as effective as chemical fungicides, they offer long-term benefits by preserving soil health, biodiversity, and ecosystem services, ensuring the sustainability of agricultural practices (Góngora and Silva, 2024).

A number of studies have identified new and existing pistachio diseases, some of which caused major yield loss and fruit quality degradation. This emergence is most likely attributed to combined factors, such as advances in our knowledge of the agents causing disease, innovative agricultural utilization of methods, and pistachio agriculture moving into geographically distinct areas with different environmental conditions. These changes have undoubtedly affected the incidence and spread of some diseases of pistachio. In fact, Alternaria Late Blight have been shown to be critical threats with severe yield loss and reduction in fruit quality. For decades, chemical fungicides have been the primary defense against such fungal infections. However, there is now increased interest in the exploration of environmental friendly control tactics, of which biological control measures have emerged (Guldur et al., 2011; Avenot et al., 2016; Ozkiling and Kurt, 2017; López-Moral et al., 2022; Nazarova et al., 2023).

This work focused on the pathogenic processes of the most important fungal disease of pistachio: Alternaria Late Blight. This work, in light of this, was supposed to be directed toward the management of noxious infections by pursuing various approaches. The review will discuss the virulence factors deployed by these fungi once they infect pistachios and cause a disease. It also critically evaluates the current strategies for control, possibly involving chemical fungicides, cultural practices, state-of-the-art methods such as biological control agents. The final objective is to provide an in-depth review regarding the pathogenicity of such fungal infections and different methods that can be applied with success for their management in pistachio production.

2. ALTERNARIA LATE BLIGHT

Alternaria Late Blight, caused by the fungal agent *Alternaria alternata* Fr., was identified in 1985 for the first time as a threat to California pistachio farms (Ozkiling and Kurt, 2017). It habitually advances during the latter half of the active growth season and is defined by the normal angular brown spots on the fruit and lesions on the leaves. These lesions usually originate from the lenticels, which are the small pores on the surface of the plant for gas exchange. Advanced stages of disease often cause lesions that lead to deterioration of the endocarp, the innermost layer of the fruit wall. This may further lead to shell staining and render the nuts unmarketable Unchecked (Khabbaz-Jolfaee et al., 2023). Therefore, the presence of shell staining is, therefore, a good indicator of the infection caused by *Alternaria*; hence, such nuts must be removed to avoid further spread of the disease (Ozkiling and Kurt, 2017).

Moreover, early nut splitting provides a route for fungal invasion of the kernels, which also reduces the quality of the nut. *A. alternata* is not, however, a pistachio-specific pathogen (Ozkiling and Kurt, 2017). Rather, this is a rather cosmopolitan fungal agent of a wide range of crops that are important to commerce throughout much of the world but prefers fruits and berries. Identifying *A. alternata* its implication as an alternating causative agent of black discoloration at the stylar end of developing pistachio nuts in South African orchards in 1998 further underlines its global reach and potential impact (Avenot et al., 2016).

2.1. Symptoms

Symptoms of Alternaria Late Blight on pistachio range from a leaf lesion to blighting symptom on susceptible cultivars, and generally symptoms increase in severity as the growing season progresses (Can et al., 2004). The most common initial symptoms develop during summer expressed as angular or circular spots, 3 to 7 mm diameter on leaves (Ozkiling and Kurt, 2017). This symptom often coalesces into diffuse, fine, dark brown patches with black centers over much of the leaf surface under progressive development. This can result in wilting and defoliation, which is more pronounced on susceptible varieties or under high infection pressure. The petioles and the main veins can be infected also, showing as black spots. Heavy infection results in high reduction of canopy cover due to severe wilting and premature drop of leaves. The immature fruits are equally infected, developing fine brown or black spots. On mature fruits, the lesions become larger in size, typically ranging from 1 to 5 mm in diameter, and are usually encircled by a characteristic red halo (Ash and Lanoiselet, 2001; Chao et al., 2001). The infected fruits can also be covered by mycelial growth and mold, which leads to fruit decay and could make fruits unmarketable. Generally, Alternaria Late Blight significantly reduces crop yield and fruit quality (Fig. 1) (Pryor and Michailides, 2007).

2.2. Morphology

Alternaria Late Blight is an important disease of pistachio, caused by a complex of fungal pathogens representing several species within the genus *Alternaria*. These are Hyphomycetes fungi, which produce asexual spores known as conidia (Chao et al., 2001). The conidia are light green to black, small, with a usual length less than 30 µm, chained together, branched or unbranched (Can et al., 2004). One of the distinctive features of the conidia of *Alternaria* is

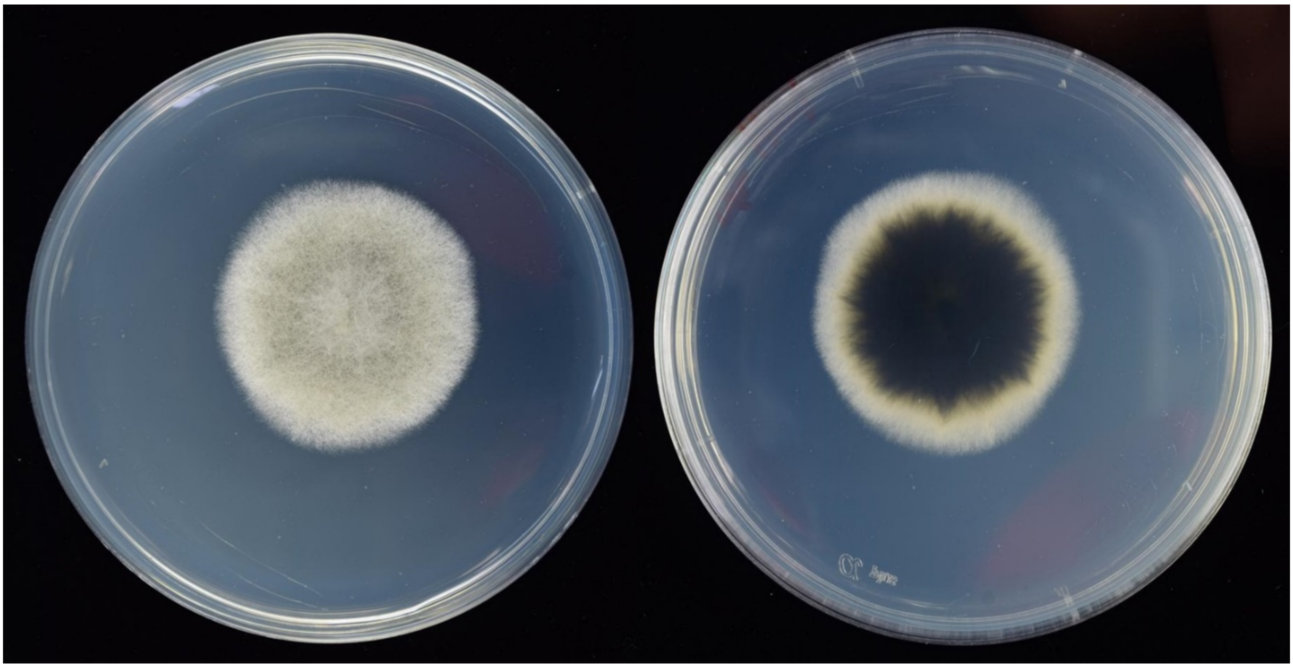
Fig. 1. Principal Alternaria Late Blight symptoms on pistachio: rot lesions on fruit, necrotic lesions on leaves, and close up of large and small black *Alternaria* lesions, leaf lesions and defoliation (Pacific Nut Producer 2024).

the formation of transverse septa - internal walls that divide the spore - in addition to a beak-like formation at the tip. Because the species of *Alternaria* are everywhere, it is easily isolated from soil or plant materials (Fig. 2) (Pryor and Michailides, 2007).

Although *A. alternata* is widely considered the primary causal agent of Alternaria Late Blight in pistachio and even other diseases on this same host, several other species, including *A. arborescens*, *A. tenuissima*, and *A. infectoria*, are attributed to this syndrome. Indeed, this is expected due to the significant morphological variability among these small, spore-forming anamorphic fungi that are chains of spores (Can et al., 2004). The culture medium, temperature, light, and humidity can significantly affect the morphology of fungal cultures; thereby making species differentiation based on morphological characteristics unreliable (Carrascal-Hernández et al., 2022). Besides, the host-specific isolates, that is, those that prefer infecting a particular plant host morphologically differ from the other similar isolates. Further research and possible reclassification are needed to correctly identify these isolates at the species level (Fig. 2) (Ash and Lanoiselet, 2001).

2.3. Disease cycle and conditions for disease

The presence of *Alternaria* spp. has been found to be present throughout the year in orchards, as spore traps have trapped their conidia. These air-borne spores are capable of colonizing a susceptible pistachio host within one day from



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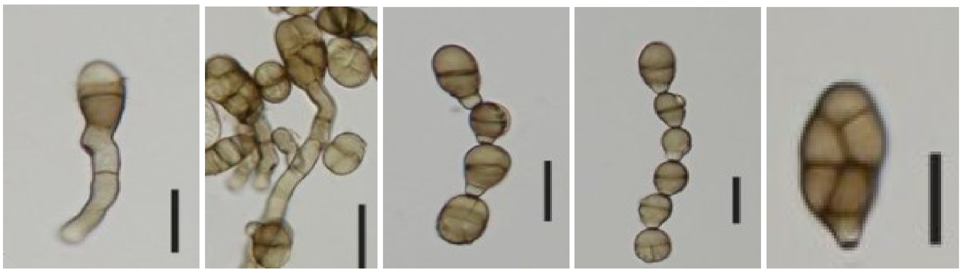

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Fig. 2. *Alternaria alternata* from culture (Potato dextrose agar medium). a Top view of culture. b Reverse view of culture. c-d Conidiophores and conidiogenous cells. e-f Conidial chains. g Conidia (Jayasiri et al., 2019; Saleem and El-Shahir, 2022).

landing on the host. Once colonization takes place, the fungus produces secondary conidia that amplify the inoculums further. These conidia are released readily and their dispersion occurs mainly due to the wind. Interestingly, leaves that are senescing and falling are heavily colonized by *Alternaria* spp. during the latter part of the growing season, thus making them often a source of primary infection for emerging buds the following spring (Can et al., 2004). Due to the nature of pistachio being a deciduous plant, it enhances this cycle of disease infection. The leaves fall and accumulate on the ground beneath the trees, and methods of irrigation, such as sprinklers and flooding, produce a high level of humidity that triggers the conidia to be released from the leaf litter back into the air. Low winter temperatures restrict activities of these opportunistic fungi in the soil, but conidia are remarkably resilient (Carrascal-Hernández et al., 2022). They can have a latent stage of life and remain viable for several months on almost any substrate in the orchard, whether on fallen leaves, pruned branches, groundcover grasses, or organic matter deposited in the soil (Avenot et al., 2016; Ozkiling and Kurt, 2017). Moreover, *Alternaria* spp. can survive asymptomatics on the surface or even inside plant tissues, residing inside as an endophyte, which is a fungus living within a plant that has no visible signs of the disease. However, these endophytic fungi under stress of the host plant turn pathogenic and cause onset of the disease. This is due to the fact that the pathogen *Alternaria* sp. has a high level of ubiquity, can survive well on plant debris, and besides this, high humidity is required hence successful overwintering in soil is achieved upon trees being in a dormant phase. This established spore therefore acts as the major source of inoculums during orchard reinfections the succeeding crop season (Fig. 3) (Pryor and Michailides, 2007).

The fungi responsible for Alternaria Late Blight in pistachios, *Alternaria* spp., have a very complicated infection cycle that includes latent infection and opportunistic infection pathways.

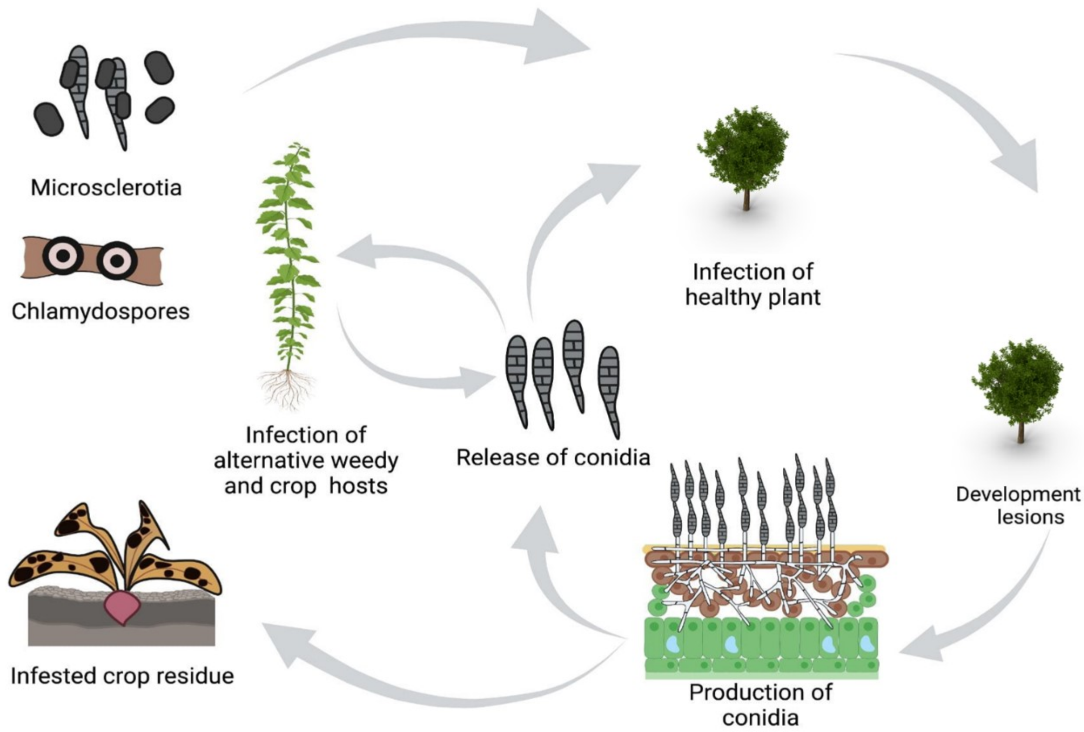

Fig. 3. Life cycle of *Alternaria* spp. on pistachio (Grewling et al., 2020; Carrascal-Hernández et al., 2022).

Initial infections may occur as early as bud break, followed by a latent period that can last as long as six weeks (Can et al., 2004). During this latency period, the fungus will not show symptoms but is instead quiescent within host tissues. This latency period does not represent a lack of infection but symptomless contagiousness. These latent infections can be identified by such techniques as transmission and scanning electron microscopy (Ozkiling and Kurt, 2017). When the conditions become favorable, the fungal growth starts, for example, in fruit when it is in a ripe stage, sugars are on the increase. This release of sugar acts as a signal for a boost in fungal activity and the beginning of the development of symptoms (Carrascal-Hernández et al., 2022). Curiously, it seems that during active plant growth, a high sugar content suppresses fungal spore germination in vitro and may thus be involved in initial plant resistance. At the end of the growing season, when leaf senescence occurs, chlorophyll content naturally degrades. This senescence is correlated with high concentrations of *Alternaria* conidia-asexual spores-on leaves infected by *A. solani*, *A. macrospora*, and *A. alternata* (Ozkiling and Kurt, 2017). This agrees with the apparent development of pistachio leaves, from chlorotic to necrotic, to blackening from profuse *Alternaria* sporulation during the later stage of the season (Fig. 3) (Chao et al., 2001).

Infection by *Alternaria* spp. is opportunistic in various ways. Wind-blown spores readily infect any pre-existing wounds on the tree, which can be caused by mechanical damage or feeding by insects (Can et al., 2004). Further, inappropriate pruning without sealing those wounds afterward with a fungicide can make such opportunistic pathogens find easy entry (Ozkiling and Kurt, 2017). The windblown pattern of spore dispersal by *Alternaria* is consistent with the pistachio floral structure. Pistachio flowers, like all others in the *Anacardiaceae*, possess nectaries specialized to intercept wind-borne pollen grains (Bachelier and Endress, 2009). There is extensive size overlap between the two within *Alternaria* spore dimensions: 25-40 x 15-25 µm for *A. citri*, 30-50 x 8-13 µm in *A. alternata*, up to 60-75 x 12-16 µm in *A. tenuissima* and the diameter of pistachio pollen: 20-31 µm. This size overlap suggests that the same wind currents carrying pollen can deposit *Alternaria* spores on pistachio flowers, thereby infecting flowers with these opportunistic fungal pathogens. In fitting this scenario, *Alternaria* spores may be deposited on pistachio flowers with the same wind currents carrying pollen, thus infecting flowers infected by these opportunistic fungal pathogens (Fig. 3)

(Grewling et al., 2020; Carrascal-Hernández et al., 2022).

Several factors of management and the environment can come together to provide conditions that will predispose pistachio trees to opportunistic fungal colonization by *Alternaria* spp. Following is a breakdown of those contributing factors:

Suboptimal growing conditions: Areas above 800 m above sea level may not get enough summer heat units and hence not allow full development of nuts. This underdeveloped nut may be more prone to fungal infection. Less-than-favorable weather conditions can cause incomplete, irregular, or late bud break, delayed leaf emergence, and distorted leaves. These effects are displayed as a poor yield and, generally, weakened plant condition, which is very easily colonized by opportunistic fungal pathogens (Kaska, 2005).

Soil drainage issues: Poor drainage of pistachio orchards can result in waterlogged conditions that stress a rootstock-the plant onto which the pistachio cultivar is grafted-and the scion, the cultivated pistachio variety. This stressed condition can predispose the rootstock and scion to opportunistic fungal infections. The consecutive number of rainy days during spring was related also to favored conditions for fungi development, making the use of an effective strategy of fungicide management paramount (Pillai, 1995).

Rootstock selection and transplanting practices: Inadequate rootstock may seriously affect new pistachio tree development and prevent the proper growth of the root apparatus. The tree may not survive transplanting, become weakened, and thus more susceptible to opportunistic fungal attacks. Transplanting of seedlings, in the optimum period from December to February, optimizes tree vigor and diminishes their susceptibility to opportunistic fungal infection (Chao et al., 2001).

By understanding and addressing these predisposing factors, pistachio growers are in a better position to develop an orchard environment resilient enough to reduce the frequency of fungal disease outbreaks caused by *Alternaria* spp. (Can et al., 2004). Orchard management practices on a pistachio nut-growing farm greatly affect the susceptibility of the trees to opportunistic fungal pathogens such as *Alternaria* spp. The following are the details that outline these factors:

Nutrient management: Fertilizer applications can enhance plant vigor, which roughly translates into less fungal infection and higher yields. It is also important to note proper use of fungicides. Poor use- especially poor concentrations-will often be ineffective and sometimes support the very target organism by a process called hormesis (Michailides et al., 2002).

Weed control: Uncontrolled weeds compete with pistachio trees for vital resources such as water and nutrients, ensuring the trees are under stress and more opportunistic to infections. Weeds also act as an alternative host for insects, fungi, and viruses. Poor herbicide application methods will injure pistachio trees further, predisposing them to *Alternaria* spp. Even sublethal doses of herbicides may make the problem worse by stimulating weed growth (Norris et al., 2003).

Irrigation practices: The type of irrigation applied may be another factor affecting the incidence of the infections caused by *Alternaria* spp. On one hand, flood irrigation maintains the conditions highly humid, favorable for the fungus *A. alternata*; this type of irrigation, although very cheap, greatly increases the incidence of the disease (Ferguson, 2005). On the other hand, subsurface irrigation reduces the relative humidity inside an orchard, reducing fourfold the Alternaria Late Blight and 45% the fruit infection (Ozkiling and Kurt, 2017). Coupled with this, high potential for airborne inoculums from fallen leaves during overhead irrigation further heightens the importance of seriously considering subsurface irrigation (Carrascal-Hernández et al., 2022). Shallow soil layers and frequent irrigation encourage root activities that may lead to its damage during mechanical weeding or uptake of herbicide from runoff (Can et al., 2004). Besides, pistachio plants are very sensitive to waterlogged root zone conditions; these predispose them well to opportunistic fungal infections such as *Alternaria* spp. (Norris et al., 2003). Conversely, water stress can trigger the switch from fungal dormancy to active growth, creating an environment favorable to the rapid development of a disease. This has been evident in the case of Alternaria Late Blight where it was observed that drought stress in pistachios increased the incidence and severity of the disease (Fragoulis, 2004; Ferguson, 2005).

Good practices in orchard management, which enhance the optimum health of the trees and do not allow the creation of conditions that promote fungal growth, help the pistachio growers to reduce the outbreaks of the *Alternaria* spp. populations and support a healthy, productive orchard (Can et al., 2004).

2.4. Management approaches

The analysis of management strategies is crucial for organizational success, however, current approaches face significant limitations (Jayasiri et al., 2019). Traditional methods often rely on static frameworks, failing to account for the dynamic nature of business environments and the complex interplay of internal and external factors (Carrascal-Hernández et al., 2022). For example, SWOT analysis, while a valuable tool, can be overly simplistic and may not adequately capture the interconnectedness of strengths and weaknesses, or the evolving nature of opportunities and threats (Rhouma et al., 2024). Similarly, Porter's Five Forces model, while insightful for competitive analysis, may not fully account for factors such as technological disruption, globalization, and the rise of new business models (Rhouma et al., 2023b). Moreover, many existing approaches prioritize quantitative data, overlooking the importance of qualitative insights such as organizational culture, leadership styles, and employee engagement in shaping strategic outcomes (Khabbaz-Jolfaee et al., 2023).
To address these limitations, future research should focus on developing more dynamic and holistic frameworks (López-Moral et al., 2002). This could involve incorporating systems thinking approaches, which emphasize the interconnectedness of different organizational elements (Michailides et al., 2002). Additionally, leveraging big data analytics and artificial intelligence can aid in identifying emerging trends and patterns in complex business environments (Gusella et al., 2022). Furthermore, a greater emphasis on qualitative research methods, such as case studies, ethnographic studies, and in-depth interviews, can provide valuable insights into the human element of strategy (McLaughlin et al., 2023). By combining these diverse approaches, researchers can develop a more comprehensive understanding of the factors that drive organizational success and failure (Ozkiling and Kurt, 2017). In conclusion, while current approaches to analyzing management strategies offer valuable insights, they also have significant limitations (Norris et al., 2003). By embracing more dynamic and holistic frameworks, leveraging advanced analytical techniques, and incorporating qualitative research methods, future research can significantly improve our understanding of how organizations can effectively navigate complex and uncertain environments (Chao et al., 2001).
An integrated pest management approach in controlling Alternaria Late Blight in pistachio orchards is important. Components of this strategy involve the following:
Preventive measures: Cultural practices play a major role in disease prevention. These include:
- Resistant cultivars: Planting the resistant variety of pistachio that is naturally resistant to *Alternaria* spp. may reduce disease incidence significantly (Chao et al., 2001).
- Sanitation: Early identification of the disease by frequent orchard surveys is essential. Quick removal and burning of infected plant parts reduce the spread of diseases. Proper pruning during dormancy improves air circulation within the canopy, which further reduces humidity and restricts fungal growth (Chao et al., 2001; Michailides et al., 2002; Norris et al., 2003; Can et al., 2004; Ferguson, 2005; Ozkiling and Kurt, 2017; Carrascal-Hernández et al., 2022).
- Weed control: Undesirable weeds are competing with trees for their needs. Further, these weeds act as an alternative host for a number of pathogens. Therefore, it is of utmost importance that one undertake weed management practices in an effective way (Norris et al., 2003; Can et al., 2004).

Irrigation practices: Overhead irrigation is specifically to be avoided, particularly at fruit ripening because this method favors the fungus through prolonged humidity. Methods of subsurface irrigation are recommended. Sanitation after harvest is equally important. Disposing and destroying post-harvest crop residues eradicate sources of inoculums for the next seasons. Composting plant residues from the field should not be advised because this can encourage a continuous disease cycle (Michailides et al., 2002; Norris et al., 2003; Ferguson, 2005; Carrascal-Hernández et al., 2022).
Application of Fungicides: Ideally, preventive fungicide applications should be done in the early summer and before the ripening of fruits. Several fungicides having different modes of action prove effective against *Alternaria* spp., with active ingredient formulations including methyl thiophanate, mancozeb, and copper. For maximum effect, treatments should follow recommended application rates and be properly timed based on tree age and disease

development (Fragoulis, 2004; Khabbaz-Jolfaee et al., 2023).

Biological control: Although not as widely studied as conventional fungicides, some biological control options are coming into view. These include foliar sprays containing bacteria (*Bacillus* spp. and *Pseudomonas* spp.) and fungi (*Trichoderma* spp.), known antagonist of fungal pathogens. Further studies are required for complete validation of the efficacy and optimization of use of biological control agents for Alternaria Late Blight management in pistachios (Rhouma et al., 2021; Khabbaz-Jolfaee et al., 2023; Rhouma et al., 2023a; Rhouma et al., 2023b; Rhouma et al., 2023c; Rhouma et al., 2024).

To advance sustainable pistachio farming, future research should prioritize climate change adaptation strategies, including developing drought-tolerant cultivars, implementing efficient irrigation techniques, and mitigating the impacts of extreme weather events (Kaska, 2005; Góngora and Silva, 2024). Integrated pest and disease management should focus on biological control methods, precision agriculture technologies, and the development of pest- and disease-resistant cultivars (Rovetto et al., 2024). Soil health can be improved through soil conservation practices, optimized nutrient cycling, and the preservation of soil biodiversity (Saleem and El-Shahir, 2022). Socioeconomic considerations must include economic assessments of sustainable practices, evaluation of social impacts, and understanding consumer preferences (Jayasiri et al., 2019; Nazarova et al., 2023). Finally, knowledge transfer and capacity building are crucial through strengthened extension services, comprehensive education and training programs, and effective farmer-to-farmer networks (López-Moral et al., 2002; Wang, 2023). By addressing these research gaps and implementing the recommended strategies, we can ensure a sustainable and resilient future for pistachio farming, benefiting both the environment and the agricultural community (Chao, 2001; Carrascal-Hernández et al., 2022; McLaughlin et al., 2023).

3. CONCLUSIONS

All diseases and pathogens can be considered severe to the pistachio tree. However, the most damaging one is Alternaria Late Blight. The farmers or the producers can use a combination of a chemical fungicide, reconcile irrigation practices, weed management to reduce the pathogen reservoirs, disease control and host plant resistance to ensure that the pathogens are restricted to optimum for crop development and enhancements. Optimal control of the fungal pathogens would be achieved for instance by chemical fungicides. Nonetheless, the dangers such drugs pose to the environment and the resistance they can breed among fungi populations have also to be taken into consideration. Irrigation practices will be critical in creating unfavorable conditions for the fungus while weed management removes alternative hosts for the pathogen. Practices additional to fungicides may include cultural methods of reducing the pathogen inoculum or restricting the movement of the fungi in the orchard. Selected from these resistant cultivars of pistachios constitute an enduring and effective solution to disease management. Growers would most effectively control fungal diseases, sustain the healthy development of trees, and consequently harvest maximum yields through an integrated approach.

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