

Date palm production in Morocco – fungal diseases, with a focus on Bayoud, and the potential of endophytic fungi, arbuscular mycorrhizal fungi and *Trichoderma* for plant growth promotion and disease suppression: A review

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ABSTRACT

In Morocco, the date palm sector constitutes a vital lever for the socio-economic development of oasis regions. Although the literature on abiotic stresses (drought, salinity, degraded soils) and fungal diseases, above all Bayoud caused by *Fusarium oxysporum* f.sp. *albedinis*, is abundant, existing studies addresses these threats without providing solutions and discuss endophytic fungi for managing date palm diseases without succeeding in formulating an inoculant based on these endophytes for industrial production. This narrative review, summarises research conducted mainly in Morocco on these constraints and on the use of two groups of beneficial fungi, Arbuscular mycorrhizal fungi (AMF) and *Trichoderma* spp. applied alone or in combination as valuable biological resources for the formulation of inoculants, to the growth promotion of date palm and the bioprotection against *Fusarium* wilt and other diseases. Studies from other countries are used only to fill gaps in Moroccan data. The literature analysis reveals that research on beneficial endophytes is still limited to a classic sequential approach: isolation, identification, and evaluation of their agronomic effects under inoculation conditions. This observation highlights the need for further investigation beyond this stage and explore techniques for multiplication, formulation, preservation, and application of inoculants in nurseries and in open fields. These studies are fundamental to determining whether locally adapted inoculants could be developed for the agro-ecological conditions of Moroccan oases.

Keywords: Morocco, date palm, *Fusarium oxysporum* f.sp. *albedinis*, inoculant, arbuscular mycorrhizal fungi, *Trichoderma*, growth promotion, bioprotection.

INTRODUCTION

Moroccan palm groves are fragile; they are subject to a series of threats, abiotic and biotic constraints, that compromise their sustainability and resilience (Ait Youssef et al., 2026a). These threats can alter both the abundance and diversity of date palms. Recurrent drought episodes,

whose frequency and severity are being amplified by climate change, place additional pressure on already limited water supplies and contribute to soil salinization, with adverse consequences for palm productivity (Dubost, 1992; Bouaziz et al., 2018; Bouzidi et al., 2026). Inappropriate agricultural practices, fires, and the accumulation of dry biomass under the palm groves also aggravate the

degradation of oasis ecosystems (Mustapha, 2024; Taleb et al., 2025). Likewise, soil-borne fungal pathogens constitute a significant component of the biotic constraints affecting date palm production. Of particular concern is *Fusarium* wilt, or Bayoud disease, which is caused by *Fusarium oxysporum* f. sp. *albedinis* (Foa). (Zeddouk, 2005; Saaidi, 1992; Abohatem, 2011). Indeed, vascular wilt caused by *Fusarium* is regarded as one of the most serious disease constraints affecting date palm cultivation across North Africa. It is a major constraint in the main date palm growing areas of Morocco (Sedra, 2015). Bayoud therefore constitutes a genuine scourge of date-growing regions because of its incurable nature. The causal agent, *F. oxysporum* f. sp. *albedinis* (Foa), was first identified in 1934 by Malençon (Malençon, 1934, 1936), while the symptoms of the disease were first observed in Morocco in 1870, in the Draa valley north of Zagora (Malençon, 1936). The most important means of transmission of Bayoud disease are conidia and chlamydospores (Abdellaoui et al., 2025). In fact, the infection usually starts in the roots and moves through the plant's water channels, causing the date palm to weaken and eventually die (El Modafar, 2010). Date palms serve as the principal host of Foa, the causal agent of *Fusarium* wilt, which is widely distributed throughout Moroccan date palm-growing areas and is also present in the western and central oases of Algeria (Benzaza et al., 1970; Brochard and Dubost, 1970a, 1970b; Fernandez et al., 1995). The disease is destroying over two-thirds of the date palm heritage in the area, particularly because it tends to affect the noble varieties like Majhoul and the high-value commercial types like Boufeggous (Zeddouk, 2005).

The reconstitution of Moroccan palm groves requires providing farmers with a large number of vigorous date palm plants ready to be planted and protected so that they can survive in an environment made hostile (Channaoui et al., 2025; Ait Youssef et al., 2026b) by abiotic and biotic constraints (Chafi et al., 2015; Ait Youssef et al., 2025). The application of new biotechnologies, such as the use of endophyte-based inoculants, mycorrhizal fungi (El Aymani et al., 2019a, 2019b; El Gabardi et al., 2024) and filamentous fungi (Albatnan et al., 2025a, 2025b), could help solve the problems of biotic and abiotic constraints (Hibilik et al., 2018; El Rhoch et al., 2025a, 2025b).

Although several recent reviews have extensively covered the interaction of date palm

cultivation with soil and environmental conditions (Alotaibi et al., 2023), or the industrial valorization of date palm products (Soomro et al., 2023), or even the broad role of arbuscular mycorrhizal fungi (AMF) in enhancing crop resilience against environmental stresses (Nie et al., 2024), a significant gap remains in the current literature. Studies conducted in Moroccan date palm groves and nurseries constitute the core evidence of this review. Studies from other countries are included only where no Moroccan data exist or to provide background on the pathogen and the crop. They are not used to draw conclusions on Moroccan oases.

This narrative review differs from earlier reviews in that it (i) critically analyzes the various research projects conducted in Morocco on abiotic and biotic constraints, that hinder date palm cultivation, (ii) highlights the gaps that have not been addressed in research on fungal pathogens, especially those concerning Bayoud caused by Foa as the central disease, which is the most studied fungus in Morocco, and (iii) compares research work concerning endophyte-based inoculants, AMF, or *Trichoderma* and their combinations as a microbial consortia against Bayoud disease within Moroccan oasis ecosystems, and identifies the gaps still prevent the use of this dual biocontrol strategy to improve date palm cultivation, combat fungal diseases and sustain phoeniculture in Morocco.

ABIOTIC AND BIOTIC CONSTRAINTS AFFECTING DATE PALM PRODUCTION

Abiotic constraints

In Morocco, the date palm (*Phoenix dactylifera* L.) occupies a central place in the agriculture of arid regions, particularly in the palm oases of the south. The national palm population is estimated at 6.9 million (Outghouliast et al., 2020, 2021; Meziani et al., 2016), with an annual production ranging between 100,000 and 120,000 tons. The main growing areas are: Drâa-Tafilalet (77%), Souss-Massa (15%), Oriental (5%), and Guelmim-Oued Noun (4%). It plays a predominant role on the agronomic, ecological, and economic levels, protecting understory crops and constituting an essential source of income for date growers and local traders (Sedra, 2015; Soomro et al., 2023; Ait Youssef et al., 2025). However, date palm cultivation is severely limited by a number

of abiotic and biotic constraints. Among the abiotic constraints are: 1/ drought and water scarcity in arid areas – the scarcity of irrigation water strongly reduces the yield and quality of dates (Alotaibi et al., 2023; Hazzouri et al., 2020; Anli et al., 2020; Toubali et al., 2020; Manikandan et al., 2025); 2/ soil and water salinity – the palm tolerates up to approximately 12 dS/m without visible symptoms, but each unit of salinity above 4 dS/m causes yield to drop by about 3.6% (Hazzouri et al., 2020; Alotaibi et al., 2023); 3/ poor and degraded soils – sandy soils have low levels of organic matter and nutrients, a high pH, and low water retention capacity, thereby influencing productivity (Alotaibi et al., 2023; Anli et al., 2020; Manikandan et al., 2025); and 4/ climate change (high temperatures combined with salinity) increases pressure on the palm (El Hadioui et al., 2023; Manikandan et al., 2025).

Most Moroccan work relating to the various abiotic constraints consists of diagnostic studies that describe the effects observed in the oases on palm grove productivity, date quality, and the resilience of oasis agroecosystems. Mitigation measures have nevertheless been proposed such as protection and rehabilitation program for oases developed in 2022 to address the growing risk of fires (Mustapha, 2024). This program includes technical studies, the development of access tracks, the installation of water points and watchtowers, the rehabilitation of traditional hydraulic infrastructure, the cleaning of palm groves, as well as the strengthening of intervention capacities and local units. The approach adopted is integrated and preventive, combining the mobilization of specialized equipment, training and awareness-raising among local populations, and the valorization of date palm waste, particularly through solar lighting solutions for oasis tracks (Taleb et al., 2025).

Biotic constraints

The modernization of date palm cultivation is also confronted with various phytosanitary problems that hinder its development and expansion (Benzaza et al., 1970; Brochard and Dubost, 1970a, 1970b; Fernandez et al., 1995). Date palm diseases are very numerous; they can be of fungal, bacterial, or viral origin, but are also linked to attacks by insects and mites, which weaken the tree and favor the establishment of secondary infections (Essarioui et al., 2018). These diseases

affect the root system as well as the trunk, fronds, inflorescences, and fruit, causing sometimes considerable quantitative and qualitative losses. High commercial value varieties, such as Mejhoul, Boufeggous, Jihel, and Bouskri, are particularly susceptible to these various types of diseases (Essarioui and Sedra, 2017). In 2017, a highly formidable date palm pest was detected in Moroccan oases, *Potosia opaca* (Meddich and Boumezzough, 2017).

Among the fungal constraints of date palm in Morocco, Bayoud is by far the best documented in the literature. Studies on its causal agent, *F. oxysporum* f. sp. *albedinis* (Foa), cover its biology, host range, genetic diversity, mode of action and diagnosis, and most Moroccan work on biological control with AMF and *Trichoderma* targets this pathogen. Other fungal diseases of date palm have received little attention in Morocco. Bayoud is therefore discussed in greater detail below and the limited coverage of other pathogens is itself identified as a knowledge gap.

Bayoud (*Fusarium* wilt) has led to the disappearance of thousands of natural hybrid Khaltis, as well as significant populations of widely cultivated varieties. Already in 1958, Pereau-Leroy reported the disappearance of two Moroccan varieties, Idrar and Berni, which, alongside Mejhoul, had contributed to the renown of Moroccan dates on European markets in the early 20th century (Sedra, 2015). *Fusarium* wilt, the most studied disease, is considered in the various reported works to be the most destructive disease of palms in almost all Moroccan palm groves and in the oases of western and central Algeria (Benzaza et al., 1970; Tantaoui and Fernandez, 1993; Essarioui et al., 2018; Ziouti et al., 1996; Anli et al., 2020). The causal agent, *F. oxysporum* f. sp. *albedinis* (Foa), is a soil-borne fungus capable of colonizing date palms at various stages of development, with infections occurring in offshoots, young palms, and adult trees. All high-quality date palm varieties (Majhoul, Deglet Nour, Jihel, Boufeggous, etc.) have been reported as susceptible to this disease (Toutain and Louvet, 1974; Saaidi, 1979). Numerous authors have described in detail the macroscopic and microscopic characteristics of the components of the Foa life cycle (Chettab et al., 1978; Sedra and Djerbi, 1986; Djerbi and Sedra, 1985). The mycelium of Foa is septate and branched and presents three types of asexual reproductive spores: microconidia, macroconidia, and chlamydospores (Abdellaoui et al., 2017).

Microconidia are spherical to elongated, slightly curved, often unicellular, and are produced abundantly by the fungus (Sghir et al., 2016). This is the type of conidium frequently observed inside the vessels of infected plants. Macroconidia are composed of 3 cells, with a typical curved shape and a more or less pointed apical cell. Chlamydospores are spherical, isolated or grouped in two to three cells, surrounded by a thick, more or less pigmented wall; they are intercalary, lateral, or terminal in position. These spores can persist in the soil for more than 8 years even in the absence of the host plant (Bounaga, 1975).

Djerbi et al. (1985) reported that the roots of certain plants (henna, alfalfa, barley) grown in association with date palms can harbor *Foa* without showing external symptoms. These plants are considered healthy carriers that can transmit the disease to susceptible palms (Djerbi et al., 1986). In this regard, it is difficult to accept these unsubstantiated reports, which need to be clarified. Indeed, how could a pathogen that penetrates the roots of an unusual host fail to complete its life cycle in that host? Penetration means that the pathogen's component – spore, conidium, or resting spore – was able to germinate, penetrate, and establish itself in the roots, and therefore probably was able to sporulate and produce other spores capable of initiating the disease. In this regard, it would be desirable to study, through cross-inoculation, the pathogenicity of *F. oxysporum* isolates collected from date palm and from plant species growing in the oases, with respect to their usual and unusual hosts, respectively. In this context, the work carried out by Sghir et al. (2016a, 2016b) provided important information. These authors noted for the first time the possible presence of *Foa* isolates capable of attacking both the date palm and companion crop species. An isolate of *Foa*, isolated from the roots of a palm showing *Fusarium* wilt symptoms in the Zagora region (southern Morocco), was able to induce various types of symptoms in tomato and eggplant: yellowing followed by necrosis, wilting, leaf drop, and stunting. Positive re-isolation results were obtained from all examined tissues (roots, hypocotyls, and epicotyls) of the inoculated plants, with the same isolate consistently recovered.

Further studies would be valuable for clarifying the extent of variation in the pathogenicity of this special form affecting the date palm (*Foa*), and of its ecology – necessary to provide information on varietal resistance – by extending to

other species that accompany the date palm, such as tomato, eggplant, alfalfa, and barley, and to other isolates of the pathogen. Cross-inoculations will provide data on the variation in the pathogenic potential of date palm-associated *Foa* isolates, with respect to plant species widely cultivated in the oases. Likewise, isolates collected from unusual host species, referred to as healthy carriers, should be inoculated onto plants of different date palm varieties. Further studies should be initiated to clarify the parasitic specificity of *Foa*. Indeed, variability in parasitic specificity among fungal species has been observed in *Verticillium dahliae* with respect to pepper (Douira et al., 1995) and alfalfa (El Aissami and Lahlou, 1999), as well as in *Curvularia spicifera* with respect to citrus (Kerroum et al., 2024a, 2024b).

The diversity of *Fusarium oxysporum* is also poorly studied. A study of the genetic diversity of different *Foa* isolates from several palm groves showed that these isolates all belong to the same compatibility group and all present the same RFLP (restriction fragment length polymorphism) and RAPD profile of mitochondrial DNA restriction (Tantaoui and Boisson, 1991; Fernandez and Tantaoui, 1993, 1994; Tantaoui et al., 1996), even though they present different phenotypic characteristics. These findings are based solely on the study of mitochondrial DNA and ribosomal DNA, and not on the analysis of chromosomal DNA, which holds the complete information on the pathogen.

The mode of action of *Foa* is also poorly understood and should be elucidated. The involvement of hydrolytic enzymes of the pectinolytic and cellulolytic type (Amraoui, 1993; Amraoui et al., 2005), or of the polygalacturonase, pectin methylesterase, polygalacturonate trans-eliminase, cellulase, and protease type (El Modafar and El Boustani, 2000), has been described. These enzymatic activities should be studied in relation to variation in the aggressiveness of pathogen isolates. Peptide toxins and fusaric and succinic acids (El Fakhouri, 1996a, 1996b) have also been demonstrated in the filtrate of *F. oxysporum*.

Timely pathogen diagnosis is an important step in the fight against date palm *Fusarium* wilt, which continues to spread in Moroccan oases. Current detection protocols rely mainly on morphological examinations, pathogenicity tests, and the study of vegetative compatibility (Tantaoui and Fernandez, 1993). These phenotypic and biochemical approaches are often lengthy

and insufficient to establish a complete diagnosis. Molecular detection of *Foa* reached a milestone in 1998 thanks to the work of Fernandez, who developed two pairs of primers for conventional PCR. These amplify a pathogen-specific sequence similar to the *fof1* transposable element. While this approach proves highly specific, its detection limit remains problematic, sometimes leading to false negatives when the pathogen is present in trace amounts. Consequently, the transition to a more powerful and sensitive amplification system, such as qPCR, is becoming a diagnostic necessity. Currently, advances in *Foa* diagnosis should be achieved thanks to its draft genome, now available (Khayri et al., 2020), which could be exploited through bioinformatics approaches and molecular biology techniques (Nishmitha et al., 2024; Dihazi et al., 2025; Mbaye et al., 2026) to open new avenues of research needed to develop control techniques capable of effectively managing the negative impacts of date palm *Fusarium* wilt.

It emerges from this work that *Foa* has long been the subject of several studies, but information concerning this pathogen remains incomplete and limited. Advances in DNA Next-Generation Sequencing technologies (NGS) will give new impetus to research on this pathogen. The dieback observed in date palms may have other, as yet unstudied, origins. Sometimes this type of symptom may be induced by pests or amplified by the presence of a fungal complex accompanying *Foa*. In this regard, it is important to also give greater importance to isolations made from soil, rachis roots, and other vegetative parts of date palms. In Morocco, the fungi that attack the fronds, inflorescences, heart, trunk, and even the dates themselves are little studied, and the respective contribution of each pathogen to host plant damage is not known.

Knowledge of all the fungal pathogens associated with date palms is far from complete enough to propose an integrated control method capable of reducing the incidence of all pathogens. Thus, the fight against Bayoud combines prevention, soil treatment, and genetic selection, notably through the variety ‘Najda’ (Abdellaoui et al., 2025). However, as in other host–pathogen systems, reliance on a single source of resistance could in principle favour virulent variants. It nonetheless supports diversifying control strategies, including biological approaches. Faced with this threat, the development of new alternatives, such as the use of antagonistic rhizobacteria (Yassine Elmaati et al., 2020; El Kinany et al.,

2022; Ben Zineb et al., 2024) or AMF and filamentous fungal endophytes, is now becoming an agronomic priority. The next two sections of this bibliographic study will be devoted to published data on the contribution of fungal endophytes to improving the nutrition, development, and protection of date palms against pests and pathogens.

BENEFICIAL FUNGI ASSOCIATED WITH DATE PALM

In general, the rhizospheric soil is rich in groups of harmful and beneficial microorganisms, and plant roots recruit species specific to them (Hamonts et al., 2018; Msairi et al., 2019b, 2025). In this regard, according to Mohammed Tellal et al. (2008), Ouazzani Chahdi et al. (2019), and Djaya et al. (2019), Plants harbor diverse microbial populations on their surfaces and within their root systems, many of which can stimulate growth and support plant health (Hamidi et al., 2018; Qostal et al., 2018a, 2019b; Laanaya et al., 2026). Native endophytic bacteria and fungi, those best adapted to climatic and edaphic conditions and to interactions with soil microorganisms, are the most capable of controlling various plant pathogens (Artib et al., 2020; Laanaya et al., 2025a, 2025b). Endophytic fungi colonize internal plant tissues without causing disease symptoms. AMF are obligate root symbionts that form arbuscules in the root cortex; they are usually treated as mycorrhizal symbionts, a category distinct from other endophytes.

Cheffi et al. (2019) noted that the endophytes of diseased date palms represent an interesting niche of endophytes that can be exploited to combat pests and pathogens (Diouf et al., 2026). Beneficial mycorrhizal endophytes (El Khaddari et al., 2020; Sellal et al., 2021; Msairi et al., 2023a; Ballaoui et al., 2024; Boutaj et al., 2025a, 2025b; Sbbar et al., 2025) and filamentous fungi (Elouark et al., 2025a; Ouazzani Chahdi et al., 2025a, 2025b, 2025c) can also facilitate mineral nutrition (Boutaj et al., 2020a; Soufiani et al., 2023, 2026), stimulate growth (Boutaj et al., 2020a, 2020b, 2020c, 2026), promote mineral nutrition (Soufiani et al., 2022a, 2022b), and play an important role in mitigating abiotic stress (Boutasknit et al., 2020, 2026; El Aymani et al., 2023; Sbbar et al., 2026) and biotic stress caused by soil-borne pathogens (Dlamini et al., 2022; Liu et al., 2022; Boutaj et al., 2021, 2025b) (Figure 1).

Arbuscular mycorrhizal fungi (AMF)

Date palms are mycotrophic; the fine roots of the plants show the presence of various structures characteristic of AMF (Sghir et al., 2014a) that can promote growth, reduce damage from *Fusarium*, and improve phosphorus nutrition, photosynthesis and drought tolerance (Sghir et al., 2014b; Anli et al., 2020; Gagou et al., 2025;).

These fungi colonize the roots of date palm plants and provide protection against soil-borne pathogens, such as *Fusarium* (Bayoud, rots, leaf spots) (Abohatem et al., 2011; Jaiti et al., 2008) and other pathogens through competition, antibiosis, and/or induction of resistance (Benatalah et al., 2025; Gómez-Vidal et al., 2006; Gagou et al., 2025; Mefteh et al., 2017; Nishad and Ahmed, 2020). Endomycorrhizae also stimulate growth and improve the availability of water and nutrients for date palm plants, particularly those growing in poor and saline soils, and improve their establishment and survival (Khaliel and Abou-Heilah, 1985; Al-Whaibi and Khaliel, 1994; Jaiti et al., 2007) through better mineral nutrition, osmotic adjustment, and activation of antioxidant enzymes (Anli et al., 2020; Gagou et al., 2025; Damankeshan et al., 2023). They

stimulate the growth of date palm plants under nursery conditions (Sghir et al., 2014b) compared to controls treated with chemical fertilizers (Meddiche et al., 2015).

AMF isolated from date palm roots and rhizosphere number around 87 species reported worldwide (Southern Arabia, Sultanate of Oman, Egypt, Arabian Peninsula, India, London). A marked difference in species richness was observed among the AMF genera. *Glomus* accounted for the largest number of isolates (34 species), with *Scutellospora* (21 species), *Acaulospora* (11 species), *Entrophospora* (5 species), *Gigaspora* (4 species), and *Diversispora* (3 species) occurring at lower richness. All other genera identified (*Ambispora*, *Archaeospora*, *Claroideglomus*, *Funneliformis*, *Paraglomus*, *Rhizophagus*, *Racocetra*, *Sclerocystis* (essentially known currently as *Glomus*), and *Septoglomus*) are each represented by only one species. The distribution of certain species of AMF depends on soil type, host species, and plant–soil relationships (Johnson and Pfleger, 1992; El Gabardi et al., 2020a, 2020b, 2021). AMF community structure and distribution are regulated by multiple environmental drivers, such as physico-chemical characteristics of the soil, phosphorus availability, temperature, moisture regimes, and

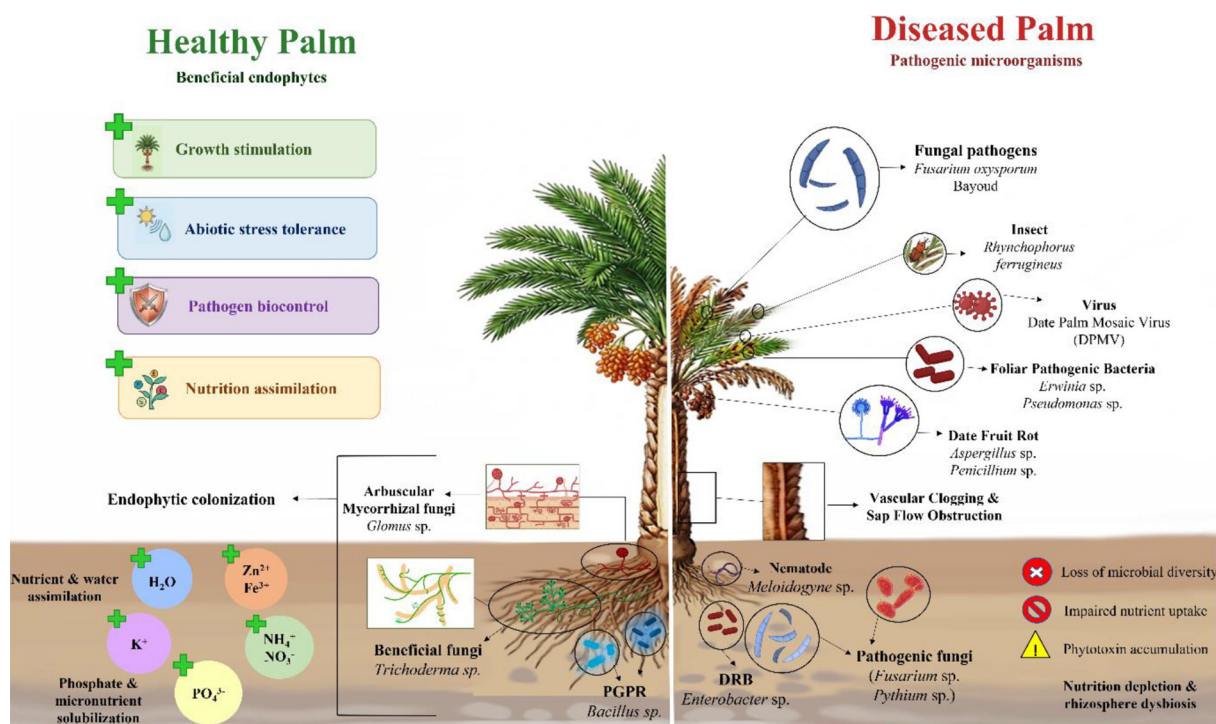


Figure 1. Comparative overview of beneficial endophytes and microbial pathogens in healthy Vs diseased date palm.

Note: PGPR – plant growth-promoting rhizobacteria; DRB – deleterious rhizobacteria; DPMV – date palm mosaic virus

agricultural management practices (Cardoso and Kuyper, 2006; El Hazzat et al., 2018, 2019).

In Morocco, a total of 29 species, belonging to 15 genera, have been recorded, particularly in Tafilalet and Zagora (Sghir et al., 2016c). A study of the diversity of AMF was reported by Bouamri et al. (2006). These authors isolated ten AMF species from ten palm groves distributed across the Ziz valley in southeastern Morocco, within the Tafilalet region: Three undescribed *Acaulospora* species and two *Scutellospora* species were identified, together with five *Glomus* species: *G. aggregatum*, *G. constrictum*, *G. fasciculatum*, *G. macrocarpum*, and *G. mosseae*. An investigation carried out by Sghir focused on AMF communities inhabiting the rhizosphere of date palms in Tafilalet and Zagora (southeastern Morocco). Nine endomycorrhizal fungal species, distributed across *Glomus*, *Acaulospora*, and *Entrophospora* were identified across all study sites. Gagou et al. (2023) studied AMF in association with date palms from the Figuig oasis (southeastern Morocco). These authors noted that representatives of the genus *Glomus* are the most dominant, alongside those belonging to the genera *Acaulospora* and *Sclerocystis*.

In Morocco, various research studies have demonstrated the beneficial effects of indigenous arbuscular mycorrhizal fungi isolated from different palm groves in stimulating growth and resistance of date palms to water stress and *Fusarium* wilt. Thus, different species of AMF isolated from palm groves have been used to inoculate date palm plants. Sghir et al. (2014b) inoculated date palm plants, at the nursery stage, with a composite endomycorrhizal inoculum multiplied in the laboratory. These authors noted, after nine months of cultivation, good development of the root and vegetative mass of the inoculated plants. The endomycorrhizal fungi forming the base of the composite inoculum proved capable of sporulating around the roots of the inoculated plants after nine months of inoculation. The application of a consortium of AMF (*Acaulospora*, *Funnelformis*, *Rhizophagus*, *Scutellospora*, and *Sclerocystis*), originating from the Figuig palm grove in eastern Morocco, resulted in greater plant biomass and improved disease protection in the Boufeggous Gharas cultivar following exposure to *Foa* (Gagou et al., 2025). Likewise, an inoculum based on AMF (*Rhizoglomus irregulare*), alone or combined with PGPR and compost, was able to strongly improve phosphorus nutrition,

photosynthesis, and drought tolerance in date palm plants (Anli et al., 2020 and 2023).

Evidence from earlier studies suggests that the agricultural use of AMF in Morocco remains relatively limited despite their recognized ecological and agronomic benefits. Thus, the multiplication and formulation of inoculants based on these endomycorrhizae remain to be developed. Further investigation into AMF communities adapted to the specific environmental conditions of Moroccan oasis ecosystems is warranted. These endomycorrhizal species should be the best 1/ adapted to the stress conditions prevailing in the oases, 2/ compatible with the characteristics of local oasis soils, which favors the maintenance and multiplication of the inoculum in the date palm rhizosphere, and 3/ effective at inducing physiological and biochemical changes in palms in response to soil-borne pathogens, such as *Foa*, and at strengthening the palm's tolerance to water and salt stress. It is from these native species that one or more inoculants well adapted to the pedoclimatic conditions of the oases will need to be multiplied. Laboratory, greenhouse, and field experiments should assess plant growth responses (morphological, biochemical, and physiological) while characterizing fungus–plant interactions under a range of biotic (soil pathogens) and abiotic (water and salt stress) stresses. The positive effects of these inoculants can be enhanced by the exploration of additional endophytic microorganisms, particularly filamentous fungi belonging to the genus *Trichoderma*. In this context, particular attention should be given to the studies conducted in Morocco on the development of inoculants based on these filamentous fungi.

Filamentous fungi: *Trichoderma* species

Date palms also host a great diversity of useful filamentous endophytic fungi that play key roles in nutrition, stress tolerance, and disease protection (Diouf et al., 2026), such as species of the genus *Trichoderma*, present in various ecosystems (Kribel et al., 2019c; Elouark et al., 2025b; Ourras et al., 2025b) and colonizing several substrates for growth and sporulation (Khirallah et al., 2017, 2025; Kribel et al., 2025). *Trichoderma* spp. are free-living soil fungi, abundant in the rhizosphere, that act as mycoparasites and biostimulants and can colonize root tissues, often superficially and opportunistically. *Trichoderma* species stand out for their triple action in agriculture:

they act as plant growth biostimulants (Qostal et al., 2020a; Kribel et al., 2020; Sellal et al., 2020, 2024; Mouden et al., 2023; El Kaissoumi et al., 2023, 2024; Ouazzani Chahdi et al., 2025), promote the biosolubilization of soil phosphorus (Kribel et al., 2019a, 2019b; Kerroum et al., 2025; Ourras et al., 2025a), and display strong antagonistic activity against numerous soil-borne phytopathogens (Mouria et al., 2007; Adnani et al., 2024a, 2024b; Errifi et al., 2024a, 2024b).

Research has shown the role of *Trichoderma* in protecting date palms against various date palm pathogens and pests. Outside Morocco, El-Sayed et al. (2015) studied *in vitro* and *in vivo* the effect of eight *Trichoderma harzianum* isolates on *Thielaviopsis paradoxa*, a pathogenic fungus responsible for date palm root rot. *In vitro*, the *Trichoderma* isolates tested showed variable effects on the mycelial growth of the pathogen. *In vivo*, soaking germinated date palm seeds in a *T. harzianum* solution before inoculation with *T. paradoxa* stimulated growth and reduced root rot in young date palm plants. Al-Naemi et al. (2016) reported the effectiveness of twenty-five *Trichoderma* spp. isolates, isolated from date palm rhizosphere, in reducing black scorch induced by a soil-borne pathogenic fungus, *Ceratocystis radicola*, which mainly attacks date palm (Linde and Smit, 1999; Al-Raisi et al., 2011). Nishad and Talaa (2020) reported that *Trichoderma harzianum* and *Trichoderma longibrachiatum* are effective antagonistic fungi against *Thielaviopsis punctulata*, *Neodeightonia phoenicum*, *Fusarium brachygibbosum*, and *Fusarium solani*, which qualifies them as potential biocontrol agents against date palm pathogenic fungi. Benzohra et al. (2023) used *Trichoderma harzianum* to protect date palm varieties (Feggous, Toudent, Azraza, Deglet Nour, H'mira, Hartan, Sbaa Soltan, Figuig, and Tanboucht) against *Fusarium* wilt (Bayoud). *In situ* tests revealed that eight of these varieties were 100% protected against Foa. Jassim et al. (2025) reported the role of *T. harzianum* in mitigating the harmful effects of salt stress (NaCl) on date palm (*Phoenix dactylifera* L.) offshoots. These authors noted a significant increase in photosynthetic pigments (chlorophyll and carotenoids), peroxidase and catalase enzyme levels, and total proline and phenolic compound content in date palm offshoots following application of *Trichoderma harzianum*. Also in 2025, Samir et al. highlighted, for the first time, *in vitro*, the potential of *Trichoderma harzianum* as a biological control agent against the

Red Palm Weevil (*Rhynchophorus ferrugineus*) in Iraq. However, further research is needed to evaluate the effectiveness of this filamentous fungus under real field conditions.

In Morocco, the use of filamentous fungi to combat date palm pathogens remains rare. The work of Sghir et al. (2014b) demonstrated the growth-promoting effect of a compost-derived *Trichoderma harzianum* strain in date palm plants. Application of *T. harzianum* induced a significant increase in biometric parameters (plant height and fresh mass of aerial parts) in two date palm varieties, Boufeggous and Majhoul. In 2015, Sghir et al. (2015) reported that inoculation of date palm plants with *T. harzianum* either alone or in combination with endomycorrhizae, following their inoculation with Foa, reduced the impact of *Fusarium* wilt while promoting root development in date palm. Indeed, the composite endomycorrhizal inoculum and *T. harzianum* proved capable of reducing *Fusarium* wilt incidence in plants of the 'Majhoul' and 'Boufeggous' date palm cultivars, following Foa inoculation: improved plant growth and reduced foliar symptoms. A more pronounced reduction occurred when *Trichoderma* and endomycorrhizae were applied concurrently. In this regard, Abellaoui et al. (2025) observed the effect of two inoculants based on *T. asperellum* and AMF on the suppression of *Fusarium* wilt in Najda and Bouzekri palm cultivars. The results obtained showed that the dual application of AMF and *T. asperellum* resulted in a significant reduction in disease severity and markedly improved the plant growth following inoculation with Foa. The double inoculation influenced the progression of the fungus within the vascular tissues of the plants; re-isolation was negative from the trunk, and only 10–20% of roots harbored the pathogen.

The literature reviewed highlights the strong potential of *Trichoderma* species in the development of bioinoculants aimed at protecting date palms from environmental stresses and pests. Used as biofungicides and biostimulants, endophytic fungi of the genus *Trichoderma* offer major agronomic interest. However, their industrial formulation, not addressed in the various works on date palm, requires overcoming several challenges: identifying high-performing strains, reducing the costs of culture media and substrates, and improving preservation and application methods. Validating these solutions also requires *in vivo* tests (greenhouse and open field) to monitor the dynamics of the root symbiosis.

Comparing results across studies is difficult because the experimental conditions differ in ways known to influence outcomes: inoculum type (single species vs. mixed consortia), dose and timing relative to pathogen challenge, plant material (seedlings, offshoots, vitroplants) and age, cultivar susceptibility, substrate sterility, pathogen inoculum and infection method, stress intensity, and duration. Measured variables and disease scoring scales also vary. Most studies were conducted under nursery or greenhouse conditions and none, to our knowledge, under field conditions with natural Bayoud pressure. Furthermore, no date palm study addresses the steps necessary to transform an experimental inoculum into a product: large-scale production, formulation, shelf life, quality control, and cost.

AMF and *Trichoderma* co-inoculation in date palm

This bibliographic synthesis highlights the synergistic and beneficial effects of co-inoculating date palms with AMF and *Trichoderma* on plant growth and reducing symptoms of Foa disease. However, the data are still insufficient to justify the development of inoculants on an industrial scale. Work in this area remains limited, and future research will need to elucidate the behavior of each microorganism forming the basis of the inoculum within the root system under conditions of double inoculation.

Before considering large-scale field trials, it is necessary to determine whether their interaction enhances biological activity or causes mutual interference, and to verify whether double inoculation systematically offers greater efficacy than single treatments, whether in the presence or absence of pathogen pressure. Moreover, the capacity of *Trichoderma* and endomycorrhizae to sporulate and persist durably in the rhizosphere of co-inoculated plants remains to be confirmed. The influence of the mode of application – whether simultaneous or sequential – constitutes also a key technical parameter to clarify in order to optimize this biostimulation approach. Finally, AMF and *Trichoderma* species have been studied for both abiotic and biotic stresses of date palm, but separately. AMF have been tested mainly for drought tolerance (Anli et al., 2020) and Foa suppression (Gagou et al., 2025), whereas *Trichoderma* has been tested mainly against pathogens,

with salt-stress data coming from outside Morocco (Jassim et al., 2025). To our knowledge, no Moroccan study has evaluated the same inoculant under combined abiotic and biotic stress, although these constraints co-occur in the oases.

CONCLUSIONS

This comprehensive review shows that the development of date palm cultivation in Morocco is largely hindered by biotic and abiotic constraints that threaten the date palm and the sustainability of the oases. *Fusarium* wilt (Bayoud) constitutes the major disease that has prompted the most research work. Its economic impact is considerable, as it seriously threatens high commercial value varieties, notably Mejhoul, Boufeggous, Jihel, and Bouskri, known for their high susceptibility to *Fusarium oxysporum* f. sp. *albedinis* (Foa). The diversity and composition of fungal communities associated with date palm decline, including soil-borne species implicated in root rot, remain poorly known in Morocco. Assessing the diversity of pathogens affecting the date palm constitutes a major research priority for oasis agriculture in Morocco. A comprehensive understanding of the phytosanitary constraints is therefore required to design effective management strategies tailored to the different pathogens and to limit their detrimental effects.

Analysis of studies on beneficial fungi, particularly AMF and *Trichoderma* spp, associated with the date palm reveals significant gaps in the identification of endomycorrhizal species, generally based solely on morphological characteristics, thereby limiting the accuracy of inventories. Thus, the integration of molecular tools is required to make species identification more reliable. At the same time, optimizing the processes of multiplication, formulation, preservation, and application of fungal inoculants requires in-depth investigation to ensure their effectiveness and economic viability. Finally, greenhouse and field evaluations are therefore needed to identify the most effective inoculants for application to young date palms and vitroplants during nursery production.

Early inoculation of crops with high-performing inoculants, based on endophytes – native strains selected from the roots or rhizosphere of the date palm – could accelerate the early establishment of the plant/endophyte relationship. In this regard, date palm plants should be inoculated

and developed in nurseries before their transplantation into the oases. Thus, transplanted plants will benefit, from the earliest stages of development, from the recognized properties of these beneficial fungi, notably mineral solubilization, resilience to water and salt stress, and phytosanitary protection. Further investigations will remain necessary to elucidate the mechanisms underlying plant–fungus interactions in the date palm (*Phoenix dactylifera*), with a view to optimizing the use of these beneficial fungi as biofertilizers and biological control agents.

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