

## Citrus farming in Morocco – fungal constraints and interactions with endophytes for growth and protection: A review

Jihane Laanaya<sup>1\*</sup> , Mariam Artib<sup>1</sup>, Dalal Boudoudou<sup>1</sup>, Najoua Mouden<sup>1,2</sup>, Soukaina Msairi<sup>1,3</sup>, Amina Ouazzani Touhami<sup>1</sup>, Allal Douira<sup>1</sup>

<sup>1</sup> Laboratory of Botany, Biotechnologies and Plant Protection, Department of Biology, Faculty of Sciences, Ibn Tofail University, P.O. Box 133, Kénitra, Morocco

<sup>2</sup> Laboratory of Molecular Chemistry and Environmental Molecules, Multidisciplinary Faculty of Nador Mohammed 1er University Oujda, Morocco

<sup>3</sup> Laboratory of Botany and Valorization of Plant and Fungal Resources, Department of Biology, Faculty of Sciences, Research Center of Plant and Microbial Biotechnologies, Biodiversity and Environment, Mohammed V University of Rabat, Morocco

\* Corresponding author's: e-mail: [jihane.laanaya@uit.ac.ma](mailto:jihane.laanaya@uit.ac.ma)

### ABSTRACT

In Morocco, the citrus industry represents a lever for socio-economic growth at both regional and national levels. Despite numerous publications, existing reviews often treat biotic and abiotic stress types separately and address the use of endophytes as biostimulants for citrus plant growth and as bio-protectors for roots. The present work aims to highlight the interest in using fungal endophytes as a basis for developing inoculants to mitigate the effects of abiotic and biotic stresses. To achieve this objective, this review compiles and analyzes over a hundred published articles dealing with the problems of citrus farming in Morocco and the practices likely to optimize the processes of valorizing fungal endophytes, such as arbuscular mycorrhizal fungi (AMF) and filamentous fungi, or both in synergy. In this sense, this synthesis shows researchers that work on beneficial endophytes is still at the stage of isolation, identification, plant inoculation, and observation of the effect on various agronomic parameters. No endophyte-based inoculant has been formulated as a product that can be commercialized. Furthermore, to reach this stage, it is wise to clarify many points, such as the techniques for multiplying inoculants, formulation, preservation, and application. This information is necessary and offers perspectives to begin cycles of testing in the laboratory, greenhouse, and fields. These tests can form the basis for commercial formulations, based on endophytes, well-suited to Moroccan conditions, thereby offering better performance and greater resilience in the face of environmental challenges, notably drought and soil-borne diseases. They will present a significant opportunity to reduce dependence on imports and pave the way for greater aspirations for the citrus sector.

**Keywords:** Citrus, inoculants, endophytes, arbuscular mycorrhizal fungi, *Trichoderma*, biostimulants, bioprotection, sustainable citrus farming.

### INTRODUCTION

Citrus farming occupies an important position in the global agri-food economy among perennial fruit crops, due to its wide geographic distribution, high commercial value, and nutritional significance (Torres et al., 2016; Chinnici et al., 2019; Becerra and Villa, 2020). Citrus production started in East Asia and has since expanded to tropical, subtropical, and Mediterranean areas.

Mediterranean countries are currently making up the majority of the international fresh fruit market (Ciancio and Mukerji, 2008). This growing demand has stimulated continuous intensification of citrus production systems, often under increasingly constrained environmental conditions.

In Morocco, the citrus sector represents a strategic pillar of agricultural development, providing more than 120,000 permanent jobs and generating an annual production of approximately 2.3

million tons, of which nearly 650,000 tons are exported, corresponding to an estimated turnover of 3 billion dirhams (Oubelkacem et al., 2020). Despite this socio-economic importance, average national yields remain relatively low (around 18 t/ha) compared with those of major producing countries such as the United States, China, and Spain. This yield gap reflects the combined influence of genetic factors (rootstock and cultivar choice), agronomic practices, and environmental constraints specific to Moroccan citrus-growing regions (Benyahia et al., 2017; Luro et al., 2020; Willer and Lernoud, 2019; Urbaneja et al., 2020).

Soil-related constraints are a significant part of these limitations. Under Moroccan pedoclimatic conditions, widely used citrus rootstocks are susceptible to root rot and gummosis diseases due to their marked sensitivity to calcareous soils and varying tolerance to salinity (Benyahia et al., 2004, 2011; El Oumlouki et al., 2018; Khankahdani et al., 2019; Shafqat et al., 2019; El Bouzaidi et al., 2020; Jaouad et al., 2020; Yao et al., 2020). These stresses, which frequently occur at the same time, emphasize the need for complementary or alternative approaches to traditional chemical inputs, especially those based on biological regulation and interactions between soil, plants, and microorganisms.

In this regard, the functions of endophytic fungi, such as filamentous fungi like *Trichoderma* and arbuscular mycorrhizal fungi, in plant physiology, nutrition, and resistance to biotic and abiotic stresses have drawn increasing attention (Nicoletti, 2019; Tang et al., 2023). Their possible effects on citrus growth, nutrient uptake, disease suppression, and general plant health have been shown by a number of experimental studies carried out in Morocco (El Khaddari et al., 2020; Msairi et al., 2020, 2023a,b; El Aymani et al., 2019a,b; Artib et al., 2020; Boutasknit et al., 2020; Bourazza et al., 2023; Adnani et al., 2024a,b; El Rhoch et al., 2025; Boutaj et al., 2025a,b; Sbbar et al., 2025). However, a critical examination of the literature reveals that most studies remain fragmented, focusing either on specific fungal groups, isolated stress factors, or short-term agronomic responses.

Endophytic fungi have been discussed as biostimulants or biocontrol agents in citrus and horticultural systems in a number of review articles published internationally. However, these reviews rarely take into consideration the unique agronomic, environmental, and socioeconomic

context of Moroccan citrus production, or even combine biotic and abiotic stress mitigation within an integrated framework. Furthermore, there is still insufficient synthesis of elements associated with the shift from experimental research to operational inoculant development, including mass production, formulation, preservation, and field-scale application.

Against this background, the purpose of the present review is to critically analyze and integrate existing research on fungal endophytes associated with citrus in Morocco in order to identify consistent patterns, unresolved limitations, and technological bottlenecks. The main hypothesis is that fungal endophytes are an underutilized biological resource whose full functional potential can only be achieved by an integrated strategy that combines inoculant development, stress ecology, and microbial synergy. This review aims to close a clear knowledge gap and offer a conceptual and technical basis for the future development of endophyte-based bio-inoculants adapted to local conditions through placing Moroccan studies within the larger international literature.

## BIOTIC AND ABIOTIC CONSTRAINTS IN CITRUS

Among the biotic constraints affecting citrus production in Morocco, soil-borne diseases represent the most significant threat (Talha et al., 2021). Among these, *Phytophthora* diseases are considered the most destructive (Benhayia, 2007; Boudoudou et al., 2023, 2025a, 2025b, 2025c; Dalal et al., 2025). These pathogens attack citrus trees at all developmental stages, causing root rot and gummosis, and are capable of infecting all plant organs, including roots, trunks, branches, leaves, and fruits (Tuset, 2006; Talha et al., 2021). Multiple *Phytophthora* species may coexist within the same orchard (Donald et al., 1996).

*Phytophthora* spp. are regarded as the most harmful pathogens in Moroccan citrus orchards. According to Benyahia et al. (2004), citrus-associated *Phytophthora* species are responsible for root rot, gummosis affecting the trunk and branches, as well as brown rot of fruits. In Morocco, the species most frequently isolated from citrus orchards include *Phytophthora citrophthora*, *P. parasitica*, and *P. syringae* (Vanderweyn, 1974). However, only *P. citrophthora* and *P. parasitica* are widely distributed and capable of

causing severe damage. *Phytophthora citrophthora* is the most commonly isolated and geographically widespread species in Mediterranean citrus-growing regions (Serrhini, 1986; Donald et al., 1996; Boudoudou et al., 2015, 2016). In the same context, Benyahia (2007) reported that *P. parasitica* is the predominant species in soil, whereas *P. citrophthora* is more frequently associated with trunk gummosis.

The main method of controlling *Phytophthora* diseases in citrus fruits is to prevent infections while using resistant rootstocks. Thus, research studies have confirmed that the rootstock, in addition to its resistance to *Phytophthora* diseases, has a highly significant effect on citrus production and fruit quality (Nadori et al., 1988; Jacquemond et al., 1998; Gallash, 1992; Fallahi et al., 1989; Aubert and Vullin, 1997; Gonzalez-Altozano and Castel 1999; Wright and Peña, 2002; Zekri and Al-Jaleel, 2004; Bouazzama and Bahri, 2009; Cautuarias-Aviles et al., 2010; Benyahia et al., 2017). The rootstock also plays an important role in tolerance to different types of abiotic stress (salinity, drought, limestone, cold, etc.) while preserving the desired characteristics of the variety (Pompeu junior, 1991). Calcareous soils are among the limiting factors for the development of citrus rootstocks. Their tolerances to this abiotic stress vary from one rootstock to another, with trifoliolate oranges being the most sensitive citrus species to alkalinity (Benyahia et al., 2011). The monitoring of the seasonal evolution of *Phytophthora* spp. inoculum at the rhizosphere level of two rootstocks, *Citrus aurantium* L. and *Citrus macrophylla*, growing in the heavy soils of Morocco, showed that *Phytophthora parasitica* was the predominant isolated species, followed by *Phytophthora citrophthora*.

*Citrus aurantium* is the most widely adopted rootstock in Morocco (Benyahia et al., 2004). The current citrus plantations have been established at over 95% with this rootstock, which is highly appreciated by producers due to its better affinity with most commercial varieties, its adaptation to a wide range of soils, and especially its resistance to *Phytophthora* spp. diseases. However, the resistance of this rootstock to *Phytophthora* spp. attacks is also affected under conditions of soil or irrigation water salinity (Benyahia, 2014). Furthermore, the widespread use of this rootstock poses a potential danger to national citrus farming due to its sensitivity to *Tristeza*, a viral disease already existing endemically in Spain and Portugal (Cassin,

1963). Similarly, this rootstock has shown sensitivity to other fungal pathogens, such as *Curvularia spicifera* (Kerroum et al., 2024a, 2024b). Anthracnose, caused by *Colletotrichum* sp., is another disease that is gradually establishing itself in citrus orchards. It causes the death of young branches, leaves, buds, and flowers (Benyahia et al., 2003). The symptoms of anthracnose also resemble wilting, which is observed on the twigs, and tear spots on the fruits. In this sense, in Morocco, research programs for alternative rootstocks to the sour orange have been initiated in Morocco since 1964 at INRA. These research programs have led to the selection of certain rootstocks tolerant to *Tristeza* and resistant to *Phytophthora*, notably the citrange group (Vanderweyen, 1974), in addition to their notable effect on citrus yield (Nadori et al., 1988, Benyahia et al., 2017). Unfortunately, it turns out that these rootstocks are sensitive to calcareous soil (Benyahia, et al., 2011), and their resistance to *Phytophthora* diseases is affected under saline conditions (Benyahia et al., 2007, Benyahia, 2007).

Moreover, among the major constraints of the national orchard, mineral nutrition is a significant issue. In fact, mineral nutrition plays a very important role in the growth and development of the rootstock at the nursery stage and also in the orchard, significantly affecting productivity and fruit quality. Major elements such as nitrogen, phosphorus, potassium, and magnesium directly affect fruit quality (Zekri et al., 2003; Omari et al., 2020a and b).

In citrus fruits, the rootstock has a very significant effect on the composition of nutrients in the leaves of several citrus varieties (Toplu and Uygur, 2010; Toplu et al., 2008). The rootstock has an influence on the absorption and translocation of mineral elements in citrus (Waqar et al., 2007). This shows a high selectivity of rootstocks regarding the absorption of nutrients (Omari et al., 2012). Like any other crop, citrus fruits need major elements, or macroelements, and trace elements, also known as microelements, in their mineral nutrition. Although the need for trace elements is significantly lower than that for macronutrients, their role is just as important as that of macronutrients (Obérez et al., 2008). Furthermore, trace elements serve as catalysts in several metabolic activities and play a role in vital functions such as respiration, photosynthesis, and the assimilation of major nutrients (Abadia et al., 2004). Therefore, any deficiency or excess in trace elements can, on the one hand, cause a

nutritional disorder that results in a significant decrease in fruit production and quality (Khankahdani et al., 2019). On the other hand, an excessive supply of these elements can alter the biochemical balance of the soil and reach toxic levels that harm the crop itself and its environment (Shafqat et al., 2019; El Bouzaidi et al., 2020).

As a result, and to achieve optimal and rational productivity, the reasoned fertilization of *citrus* fruits must consider both the needs for macronutrients and micronutrients. Unfortunately, little attention has been given to trace mineral nutrition, although deficiency symptoms have often been reported (Ghanem and El Alami, 1979). These deficiencies can be true or induced. True deficiency comes from the lack of the element in the soil; while induced deficiency occurs when the element is abundant in the soil, but it is made unassimilable. Low levels of Zn and Mn have been observed in the soils of some Moroccan orchards (Penkov et al., 1979), nevertheless, induced deficiency is probably the most widespread since citrus-growing areas are mostly located on basic (pH between 7.5 to 8.5) and calcareous soils. In general, the availability of micronutrients, particularly Zn, Fe, Mn, and Cu, decreases with increasing pH and calcareous soil content (Obreza et al., 2008). A significant decrease in clementine yields was observed in the Souss region when the total and active calcareous soil contents were respectively above 20% and 10%, causing a deficiency in Fe, Mn, Cu, and Zn (El-Otmani et al., 2020). Moreover, similar to other countries in the Mediterranean basin, where 20% to 50% of fruit trees are affected by iron deficiency (Jaegger et al., 2000), iron chlorosis in citrus trees is a well-established observation in Morocco.

Moroccan *citrus* growers often resort to curative measures to address trace element deficiency problems, which consist of applying mineral fertilizers to the soil (chelated forms being the most efficient) or through foliar application (Omari et al., 2020; Barakat et al., 2017; Khfif et al., 2020). However, these applications are expensive and are done in the absence of standards adapted to the conditions of Moroccan orchards, which can result in insufficient or sometimes excessive inputs. However, beneficial effects have been demonstrated regarding mycorrhizal symbiosis on the mineral nutrition of *citrus* fruits, which are considered highly dependent on mycorrhizae (Ortas et al., 2012). This root symbiosis between the plant and the fungal symbiont allows for the

expansion of the soil volume explored by the plant and the mobilization of nutrients retained in the soil. This is particularly important in basic soils where phosphorus and certain trace elements, such as Zn, Fe, Mn, and Cu, become immobile and consequently unavailable to the plant. In this sense, Wang et al. (2008) highlighted the potential that endophytic microorganisms could have in the nutrition and protection of *citrus* against abiotic and biotic stresses.

This analysis of the literature reveals that biotic and abiotic limitations have significant effects on citrus fruits and provide a wide range of opportunities to identify solutions that can lessen their effects. The analyzed articles show that Moroccan farmers face the problems of nutritional deficiencies by applying mineral fertilizers at the soil level or through foliar application. They also face phytosanitary problems and fungal diseases, not yet sufficiently elucidated, through the use of rootstocks. This latter path could open up broad perspectives for the selection and improvement of rootstocks in order to obtain genotypes resistant to biotic and abiotic stresses and compatible with the different productive varieties. Depending on the constraints encountered, the behavior of the rootstocks may vary from one region to another, and their adaptation to different soil types, as well as their resistance to pathogens, can be enhanced by utilizing the beneficial effects of endophyte-based inoculants, arbuscular mycorrhizal fungi, and filamentous fungi. In this sense, we will present in the other three sections of this work the published research results on the use of endophyte-based inoculants to improve fertilization, growth, and root protection of citrus rootstock plants against diseases.

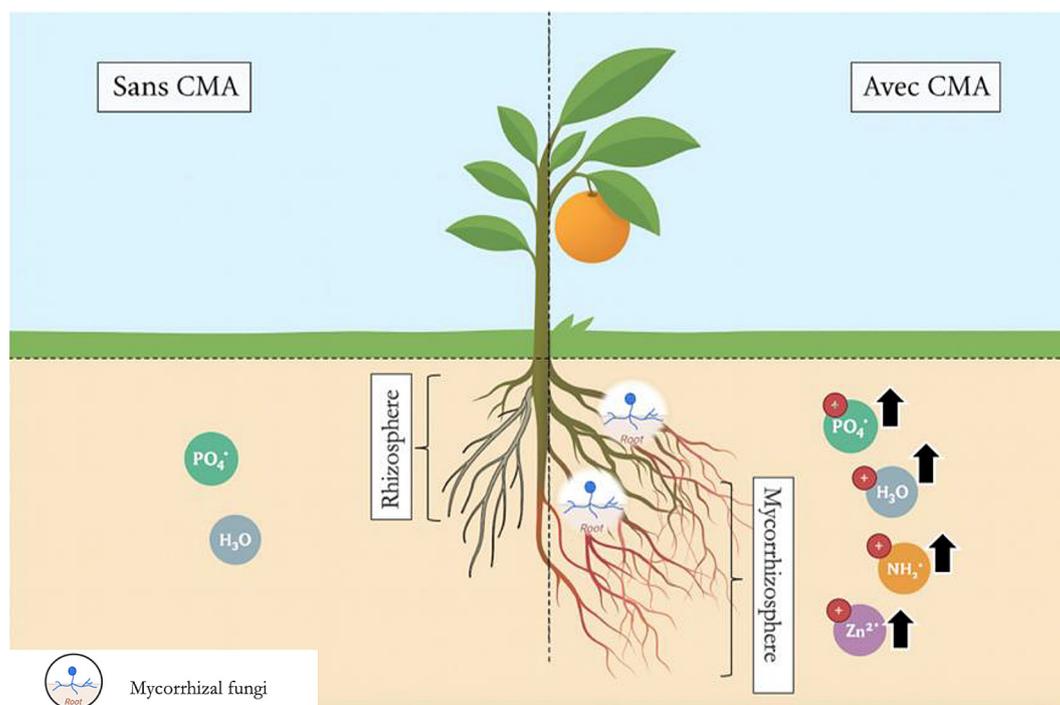
## ARBUSCULAR MYCORRHIZAL FUNGI-BASED INOCULANTS

In Europe, the use of mycorrhizal inoculation in agriculture and arboriculture is not widespread (Jochems-Tanguay, 2014), and in Morocco, it is not yet known. However, developing countries such as Cuba and India are the true pioneers in the development of this biotechnology. These countries have made significant progress in the field of inoculation and have demonstrated the enormous potential that mycorrhizal inoculants offer in their agriculture to increase yields and reduce the consumption of fertilizers and pesticides

(Jochems-Tanguay, 2014). Today, agriculture in these countries greatly benefits from mycorrhizal inoculation. In the USA, for example, the inoculation of citrus plants in nurseries with arbuscular mycorrhizal fungi has become a common practice (Menge et al., 1977; Giri, 2017; Artib et al., 2017; Zou et al., 2020). Furthermore, mycorrhizal plants produced in nurseries have a more vigorous and highly branched root system and are, consequently, able to withstand the various types of stress they will face after transplantation ( El Hazzat et al., 2018, 2019; El Aymani et al., 2023; Sellal et al., 2020, 2024). It is therefore important to develop this biotechnology in Morocco and to highlight mycorrhizal symbiosis for the benefit of citrus farming (Figure 1). That is why the development of new techniques for producing high-quality, vigorous plants in nurseries becomes necessary. These plants will be able to adapt to different pedoclimatic conditions once replanted, which will help reduce the use of chemical inputs while ensuring crop profitability and environmental quality. It is in this sense that mycorrhizal symbiosis for the benefit of citrus farming has proven to be important.

In general, arbuscular mycorrhizal fungi form specialized symbiotic structures in the cortical cells of the roots, such as arbuscules,

which serve as sites for intensive nutrient exchange between the fungus and the plant (Lü et al., 2024; Bruyant et al., 2024). This symbiotic association is particularly advantageous in soils poor in phosphorus (P), a common problem for *citrus* and plants grown in acidic soils (El Gabardi et al., 2019, 2020, 2021, 2024; Lü et al., 2024; Ballaoui et al., 2024; Achajri et al., 2025). The extraradical mycelial network of the endomycorrhizal fungus extends into the soil beyond the root zone, inspecting a much larger volume than the roots themselves, which allows it to efficiently capture immobile inorganic phosphorus and transfer it to the host plant. In exchange, the plant provides the fungus with photosynthesized sugars (Hamidi et al., 2017, Hibilik et al., 2018; Bahouq et al., 2017, 2018, 2019). The positive impact of this symbiosis on mineral nutrition has been clearly demonstrated: a study on bitter orange (*Citrus aurantium*) seedlings showed that inoculation with AMF significantly increased the phosphorus concentration in the leaves, from about 16–17 mmol kg<sup>-1</sup> dry weight without inoculation to 30-38 mmol kg<sup>-1</sup> with inoculation (Navarro et al., 2024). This nutritional improvement directly translates into increased growth, better fruit quality, and increased tolerance to various stresses (Tang et al., 2023).



**Figure 1.** Diagram showing the role of the symbiotic association, *Citrus* plant roots/arbuscular mycorrhizal fungi, in the creation at the rhizosphere level of an active ‘mycorrhizosphere’ zone facilitating plant nutrition Without AMF: without arbuscular mycorrhizal fungi; with AMF: with arbuscular mycorrhizal fungi

Studies have shown that the inoculation of *citrus* plants with endomycorrhizal species has improved the absorption of Zn, Fe, Mn, and Cu, whose concentrations were higher in the leaves and roots of mycorrhizal plants than in non-mycorrhizal ones (Chen, 2014; Ortas et al., 2018). Wang et al. (2008) even highlighted the potential that inoculation with arbuscular mycorrhizal fungi could have in the bioremediation of iron chlorosis in *citrus*. Artib et al. (2020) reported that the treatment of *Citrus aurantium* L. seeds with a consortium of arbuscular mycorrhizal fungi, originating from the rhizosphere of different *citrus* species (Artib et al., 2016, 2017), allowed for the mycorrhization of the roots and the improvement of all agronomic parameters of the plants grown from these coated seeds, compared to plants grown from control seeds. According to these authors, some species of arbuscular mycorrhizal fungi from the inoculum sporulated in the rhizospheric soil of *Citrus aurantium* plants originating from the coated seeds. Furthermore, a study was conducted to compare the effectiveness of mycorrhization on the seedlings of five citrus rootstocks (*Poncirus trifoliata*, *Rangpur lime*, *Citrus macrophylla*, *Carrizo citrange*, and *Cleopatra mandarin*) that underwent saline stress during their greenhouse development (Bourazza et al., 2021). The analyzes conducted after two months of cultivation showed that mycorrhization was able to improve the growth of non-stressed plants (with the highest values observed in *Citrus macrophylla*). This growth significantly decreases in the case of saline stress, but remains comparatively higher than that of non-mycorrhizal plants. The comparison of the different measured parameters (morphological and biochemical) led to the conclusion that the rootstocks exhibited significant differences (threshold of 5%) according to the different NaCl treatments and the presence or absence of mycorrhization.

It emerges from previous studies that the use of arbuscular mycorrhizal fungi is beneficial for the growth and development of rootstock plants. On the other hand, the development and formulation of inoculants based on these endophytes is still far from being achieved. Further research on the diversity of arbuscular mycorrhizal fungi species in the rhizosphere of citrus rootstocks used in Morocco is necessary. It is from these species that we will need to multiply one or more inoculants containing species well-adapted to the pedoclimatic conditions of Morocco. The tests in the

laboratory, greenhouse, or open field must cover various growth parameters (morphological, biochemical, and physiological) and the analysis of fungus/plant interactions under different types of abiotic (saline and water stress) and biotic (soil pathogens) constraints. Research must be programmed regarding the use of other filamentous endophytes, such as fungi of the genus *Trichoderma*, which are currently exploited as biofertilizers (ability to deliver ammonium and solubilize phosphorus) and as biofungicides against a large number of soilborne pathogens. In this sense, it is important, first, to know the research work carried out on *Trichoderma*-based inoculants in Morocco.

## THE INOCULANTS BASED ON FILAMENTOUS FUNGI

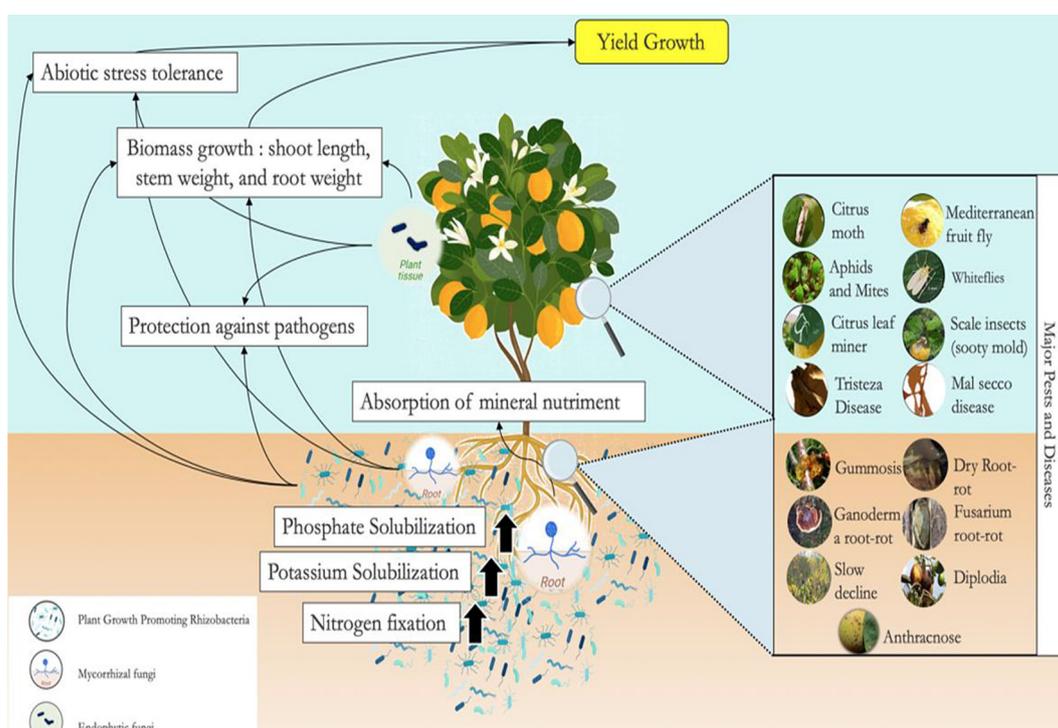
Filamentous endophytic fungi colonize the interior of plant tissues, roots, stems, leaves, without inducing disease symptoms (Msairi et al., 2025; Laanaya et al., 2025a, 2025b), establishing a stable mutualistic relationship (Kumar et al., 2019; de Carvalho et al., 2020). Studies have allowed for the isolation of various genera of filamentous endophytes from different *citrus* species, such as the lime tree (*Citrus aurantifolia*), the mandarin tree (*Citrus reticulata*), and the sour orange tree (*Citrus aurantium*), demonstrating a great specific diversity depending on the host and the environment (Oktarina et al., 2022; Riza Umami et al., 2023; Kerroum et al., 2025). These fungi produce a range of bioactive secondary metabolites, such as lytic enzymes, antibiotics, and antioxidant compounds, which directly or indirectly enhance the plant's resistance to pathogens and abiotic stresses (Alurappa et al., 2018; Bhosale et al., 2024; Khirallah et al., 2025; Kribel et al., 2025). For example, they can inhibit the growth of phytopathogenic fungi through antibiosis, competition for resources, or parasitism (Nasehi et al., 2023). A recent study highlighted their potential as post-harvest biocontrol agents on *citrus* fruits, where endophytic yeast strains, such as *Meyerozyma* and *Pseudozyma* (Edward-Rajanayagam et al., 2023), and *Trichoderma*, such as *Trichoderma asperellum* (Adnani et al., 2024a, 2024b; Errifi et al., 2024a, 2024b; Elouark et al., 2025a, 2025b, Ourras et al., 2025; El Rhoch et al., 2025), respectively showed significant effectiveness in reducing diseases caused by *Penicillium* spp. on fruits and by *Fusarium* spp. and

*Rhizoctonia* spp., responsible for root rot and dieback of the aerial parts of trees. Moreover, some endophytes can induce systemic resistance in the host, activating signaling pathways involving hormones such as salicylic acid, jasmonic acid, and ethylene, which prepares the plant to respond more quickly and effectively to a subsequent pathogenic attack (Nawfetría et al., 2024).

Bousslim et al. (2025) reported that several groups of microorganisms, such as Proteobacteria and Ascomycota, play a key role in soil fertility and health, as well as in stimulating the growth of citrus trees and the production of high-quality fruits. The study of the mycoflora associated with the roots of *Citrus aurantium* revealed remarkable fungal diversity, reflecting the coexistence of pathogenic species, such as *Fusarium oxysporum*, *F. solani*, *F. brachygibbosum*, or even *Curvularia spicifera*, as well as beneficial fungi including several *Trichoderma* isolates (Kerroum, 2026). These *Trichoderma* have shown the ability to solubilize insoluble phosphate, making this essential nutrient more available to the roots (Kribel et al., 2019a, 2019b; Kerroum et al., 2025). This activity is ensured by the secretion of organic acids that acidify the rhizosphere, which promotes the release of phosphate ions assimilable by the plant, and specific enzymes, contributing not only to improving the plant’s mineral nutrition but also

to enhancing its ability to withstand biological (Kribel et al., 2019c, 2020; Qostal et al., 2020a, 2020b) and environmental (temperature, salinity, drought) (Altomare et al., 1999; Ma et al., 2025; Pang et al., 2024) aggressions. Moreover, Rukuna et al. (2025) reported that fungi of the genus *Trichoderma* are effective against pathogens responsible for fungal diseases of citrus fruits, which are widely distributed and affect the main citrus-growing areas worldwide. According to these authors, the dual action: bioprotection against pathogens and nutritional stimulation, makes *Trichoderma* spp. a strategic tool for the integrated management of citrus root diseases.

Based on the reviewed literature, it shows that representatives of the genus *Trichoderma* can be good candidates to initiate the formulation of inoculants that will be used to mitigate the abiotic and biotic stresses of citrus fruits. Moreover, *Trichoderma* are endophytes used as biocontrol agents for pathogens (natural fungicides), plant growth biostimulants (improving nutrient absorption), and as agents capable of enhancing resistance to abiotic stress (Figure 2). However, for the formulation of *Trichoderma*-based inoculants, not mentioned in this literature review, it is important to have more efficient strains, low-cost culture substrates, and more adequate methods of conservation and application of these inoculants.



**Figure 2.** Citrus endophytes and their multiple roles, biofertilizers, biostimulants, and bioprotectors

Inoculation tests and monitoring the development of the association between plant roots and fungi in greenhouses and in the field are also mandatory. In the last section of this study, we will analyze the positive effects, reported in the literature, of the double inoculation of plants with arbuscular mycorrhizal fungi and *Trichoderma*.

## SYNERGY BETWEEN ARBUSCULAR MYCORRHIZAL FUNGI AND FILAMENTOUS FUNGI

The interaction between endophytic fungi, arbuscular mycorrhizal fungi (AMF), and filamentous fungi, such as *Trichoderma spp.*, can be synergistic. The combined use of filamentous endophytes and AMF, in the form of co-inoculants, represents a promising strategy for sustainable agriculture, as it can simultaneously improve plant nutrition, growth, and defense (Díaz-Urbano et al., 2023). For example, while AMF optimize phosphorus absorption, filamentous endophytes can protect roots against nematodes or soil-borne pathogenic fungi, thereby creating a more robust and efficient root system (Poveda et al., 2020). This holistic approach leverages the functional complementarity of plant-associated microorganisms to reduce dependence on chemical fertilizers and pesticides, aligning agricultural production with the principles of environmental sustainability. A study was conducted by Abdellaoui et al. (2025) to evaluate the effectiveness of this holistic approach combining arbuscular mycorrhizal fungi and *Trichoderma asperellum* against *Fusarium oxysporum* f.sp. *albedinis*, the causal agent of vascular wilt in *Phoenix dactylifera*. The results demonstrated that the combined treatment of AMF and *T. asperellum* reduces the severity of the disease and significantly stimulates the growth of date palm plants. In the same vein, the co-inoculation of tomato and eggplant with arbuscular mycorrhizal fungi and *Trichoderma harzianum* induced a stimulation of plant growth and protection of roots against *Fusarium* wilt caused by *Fusarium oxysporum* (Sghir et al., 2016). The double inoculation with endomycorrhizal fungi and *Trichoderma harzianum* also stimulated all agronomic parameters of carob plants, but to a lesser extent than the inoculation of these plants with mycorrhizae alone (Talbi et al., 2016). The positive effect of this double inoculation (Mycorrhizae + *Trichoderma*) was more pronounced than that with mycorrhizae

alone on *Tagetes erecta* and *Citrus Tanaka* (Calvet et al., 1993; Camprubí et al., 1995). In the same vein, a co-inoculation with a mixture of four species of *Glomus spp.* and *T. harzianum* promoted the growth of three plant species: *Verbena*, *Torenia*, and *Diascia* (Sramek et al., 2000).

This literature review reveals that the double inoculation of citrus plants with mycorrhizal fungi and *Trichoderma* has beneficial effects on the plants. However, studies in this direction are still rare, and future research must provide information regarding the behavior of each inoculant in the roots of plants that have undergone double inoculation. It is also important to know, for example: (1) whether the presence of one inoculant reduces or stimulates the effect of the other inoculant; (2) whether the positive impact of double inoculation is always higher than that of inoculation with a single inoculant; (3) whether the positive effect of double inoculation is always significant in the presence and absence of pathogens; (4) do the fungal species, *Trichoderma* and endomycorrhizae, manage to sporulate over time at the root level of co-inoculated plants; (5) the two inoculants must be applied simultaneously or in an alternating manner. All these questions and others must be clarified before proceeding with the co-inoculation tests of plants in the field.

## CONCLUSIONS

This comprehensive review demonstrates the diverse challenges faced in the advancement of Moroccan citrus agriculture. Diseases, particularly those caused by *Phytophthora*, associated with saline stress, significantly impact the development of this crop. In Morocco, diseases caused by *Phytophthora parasitica* and *P. citrophthora* are the most studied, and no information has been reported in the literature on those caused by *P. palmivora* and *P. citrophthora*. In fact, these two pathogens are known elsewhere in citrus orchards. Similarly, the fungal complex responsible for citrus twig dieback as well as the species responsible for root rot, such as species belonging to the genera *Fusarium* and *Rhizoctonia*, are not yet well studied in Morocco. In this sense, it is essential to elucidate all phytosanitary issues in order to develop an effective control method capable of mitigating the harmful effects of each pathogen. Similarly, the various studies conducted on citrus fruits in Morocco mention *Citrus aurantium*, an

elite rootstock, used for many years in all national citrus plantations. However, this species, with several advantages, has become highly sensitive to *tristeza*, a viral disease that poses a significant problem for Morocco. Thus, the use of other resistant and/or tolerant rootstocks adapted to each citrus-growing region has currently become a necessity. The behavior of these rootstocks in different pedoclimatic zones of Morocco and in relation to diseases could represent a relevant research path in the coming years.

The analysis of reviews that focus on endophytes, filamentous fungi, and arbuscular mycorrhizal fungi in citrus production reveals significant gaps in the identification of endomycorrhizal species, which is typically based only on spore morphology, while molecular biology tools are necessary to confirm species determination. The best and most economical ways to multiply, formulate, conserve, and apply fungal endophyte-based inoculants will also require more investigation. More research in this area should be conducted through greenhouse and field trials in order to select the most appropriate inoculants suitable for use in nurseries for the treatment of seeds, cuttings, rootstock seedlings, and citrus vitroplants.

The transmission of endophytes from the beginning will facilitate the rapid establishment of symbiosis at the root level of the plants, which will benefit early from all the advantages of the roles already highlighted for endophytes, such as solubilization of mineral nutrients, tolerance to different types of stress, hydric and saline, and protection against bioaggressors. This biological approach will also reduce the duration of the plants' stay in the nursery. Similarly, research needs to be conducted to better understand the precise role of fungal endophytes in citrus, as well as their interactions that could be beneficial for growth and biological control against bioaggressors of representatives of this genus.

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