horticulturae

Review

Research Progress of Arbuscular Mycorrhizal Fungi Promoting Citrus Growth

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Abstract: Citrus, the world's most common fruit, boasts an abundance of resources and varieties and possesses a high commodity value. Arbuscular mycorrhizal fungi (AMF) and citrus roots can form a symbiotic relationship, promoting citrus growth, improving its disease resistance, and increasing the quality of the fruits. However, the literature lacks a detailed understanding of the symbiotic citrus–AMF relationship in cultivation. In this study, we reviewed the diversity (different citrus species and habitats), stress resistance (disease, drought, saline-alkali, temperature stresses), expression of defense genes, and underlying mechanisms of symbiotic AMF in citrus. Our aim was to provide a robust reference point and offer valuable insights to guide future studies on citrus symbiotic AMF and their applications in citrus planting. This review could help to facilitate AMF applications in citrus biological control (particularly in the citrus Huanglongbing) and sustainable development.

Keywords: diversity; stress resistance; expression of defense gene; growth benefit

Citation: Tang, C.; Zhang, Z.; Yu, L.; Li, Y. Research Progress of Arbuscular Mycorrhizal Fungi Promoting Citrus Growth. *Horticulturae* **2023**, *9*, 1162. https://doi.org/10.3390/horticulturae9111162

Academic Editor: Qiang-Sheng Wu

Received: 7 September 2023
Revised: 19 October 2023
Accepted: 19 October 2023
Published: 24 October 2023

1. Introduction

Arbuscular mycorrhizal fungi (AMF) are a group of beneficial microorganisms that form symbiotic systems with the root systems of superior plants [1]. AMF not only promote the uptake of nutrients (N, P, K, Ca, Zn, and Cu) and water [2–4] but also improve the tolerance of plants to abiotic factors and their resistance to biotic factors [5–8]; thus, they promote plant growth and development. The mycelial network formed by AMF promotes the dissolution of soil mineral nutrients, improves soil structure [9], regulates root osmotic balance [10], and induces root growth and dry matter accumulation, which in turn better supports the growth and development of the plant [11].

AMF are frequently utilized in orchard production, particularly in citrus, grapes, apples, bayberries, and other fruit trees. Citrus has sparse, short, and shallow root hairs, resulting in poor absorption and use of nutrients. However, it forms a mycorrhizal structure with AMF, relying on them to absorb nutrients and minerals from the soil [12,13]. Thus, AMF inoculation has multiple effects on citrus growth and development; it promotes root hair growth, improves root morphology [14], promotes nutrient uptake and water utilization [15,16], and enhances plant stress resistance [17]. Consequently, it improves yield and fruit quality [18].

Citrus symbiotic AMF in cultivation is not well described in the literature. In this study, we comprehensively reviewed the diverse array of symbiotic AMF present in citrus. We also explored how AMF contribute to stress resistance, their influence on the expression of defense genes, and their mechanisms for promoting citrus growth. Our goal is to provide valuable references and insights, paving the way for future research on citrus–AMF symbiosis and its potential applications in citrus cultivation. Unlike other reviews, this review discusses the favorable conditions for AMF applications in citrus biological control (particularly in Huanglongbing management) and sustainable development.

2. Diversity of Symbiotic AMF Present in Citrus

The type and diversity of symbiotic AMF differ among distinct citrus species. In an arid area of northeastern Mexico, Senes-Guerrero et al. [19] reported the presence of five endemic AMF species preferentially living in the rhizosphere soil of *Citrus sinensis* (L.) Osbeck: *Dominikia distichi*, *D. iranica*, *D. achra*, *Kamienskia bistrata*, and *Dentiscutata savannicola*. Li et al. [20] identified 15 different AMF species in the root system of *Citrus junossieb* Sieb. ex Tanaka, with *Claroideoglomus etunicatum* and *Funneliformis mosseae* being identified as high-quality symbiotic AMF strains for citrus. Zhang Jinlian et al. [21] found that under potted conditions, the root system of *Fructus aurantii* could form a symbiotic relationship with 14 AMF species; among them, *Redeckera fulvum*, *F. mosseae*, and *Glomus coronatum* were the dominant symbiotic strains of *Fructus aurantii*, promoting its growth. Song et al. [22] conducted a comprehensive examination of citrus root systems in an orange orchard in Ganzhou, identifying 80 AMF species, including 44 previously known AMF species and 36 new species, with *Glomus* being the dominant genus. In summary, these studies collectively emphasize the dynamic interplay between AMF species and various host plants [23].

Different habitats affect AMF diversity in symbiotic citrus. del Mar Alguacil et al. [24] studied a semiarid orange tree orchard and found that long-term irrigation with untreated urban sewage led to lower AMF diversity in the soil compared to freshwater irrigation. This discrepancy was attributed to the inhibitory effects of pollutants present in untreated urban sewage on AMF colonization. Wang et al. [25] found more mycelia and arbuscular colonization, as well as higher spore and mycelial length densities, in citrus orchards at elevations <600 m compared to those at higher elevations ($\geq$700 m), where species richness decreased significantly. Xi et al. [26] studied the diversity of citrus symbiotic AMF in two distinct agroecosystems in California and found that AMF abundance and diversity were higher under organic than under conventional management practices. Mullath et al. [27] reported that organic farming promotes AMF diversity in desert ecosystems in the Arabian Peninsula. Wang et al. [28] showed that the species richness of AMF in sod culture orchards was significantly higher than that in orchards under other treatments (straw mulching, herbicide treatment, and no-tillage citrus orchards). Overall, the diversity of citrus symbiotic AMF is affected by irrigation methods, elevation, desert, and agricultural management practices. Favorable environmental conditions tend to support higher AMF diversity in these habitats.

3. AMF Promotes the Mineral Nutrient Absorption of Citrus

The symbiosis of AMF with plants enhances the uptake of essential nutrients [29–31], including microelements. The low availability of soluble inorganic phosphorus in the soil, coupled with its poor mobility, often leads to symptoms of phosphorus deficiency in plants [32]. Inoculating *Poncirus trifoliata* (L.) Raf. with *G. versiforme* promoted phosphorus uptake and increased the phosphorus content, which, in turn, affected the transpiration rate and the opening and closing of the leaf stomata [33]. Navarro and Morte [34] showed that mixed inoculation with *Rhizophagus irregularis* and *F. mosseae* favorably affected growth and significantly improved phosphorus nutrition in *Citrus macrophylla* Wester. Under low-phosphorus conditions, the inoculation of *Poncirus trifoliata* (L.) Raf. with *R. intraradices* improved rhizosphere soil microbial activity, which effectively enhanced the utilization of organic phosphorus [35]. Furthermore, the inoculation of *Poncirus trifoliata* (L.) Raf. with *R. intraradices*, *Diversispora epigaea*, and *Paraglomus occultum* increased total plant biomass, total root length, surface area, and volume, as well as leaf and root nitrogen content [36].

In high-pH soils, inoculation with *G. mosseae* significantly promoted iron uptake in the root system of *Carrizo citrange* [37], improving the iron deficiency-induced yellowing [38]. Under bicarbonate stress at pH 7.0 and pH 8.0, inoculating *Poncirus trifoliata* (L.) Raf. with *G. versiforme* promotes the accumulation of chlorophyll and active iron, ameliorating the iron deficiency induced by high calcium and bicarbonate concentrations. This indicates that AMF inoculation can improve iron absorption [39]. Inoculation with *G. versiforme* had no significant impact on iron levels in the root system of *Citrus tangerine* Hort. Ex Tanaka seedlings, whether they were under normal moisture conditions or water stress. However, it did significantly increase the root content of P, Ca, Mg, Cu, and Mn [40]. Under low-efficiency P conditions, AMF inoculation may help citrus utilize organic P sources effectively by increasing microbial biomass and enzyme activity [35]. Under Mg deficiency, the concentration of chlorophyll a and chlorophyll a + b can be significantly increased by AMF inoculation of trifoliate orange, which may alleviate leaf chlorosis [41]. In low-Mg soils, citrus seedlings inoculated with *G. versiforme* exhibited higher levels of soil enzymes, osmoregulation, and antioxidant substances, resulting in improved seedling growth and nutrition [42]. Multiple studies indicated that the inoculation of citrus with AMF improved the N, P, K, Ca, Mg, Zn, and Mn contents in the leaves (Table 1). These nutrient levels were significantly higher than those found in the leaves of citrus not inoculated with AMF [43]. The proliferation of AMF mycelia in the soil greatly improved the ability of citrus to obtain nutrients from the soil, which improved the growth.

Table 1. Effect of arbuscular mycorrhizal fungi (AMF) on the absorption of mineral nutrients in citrus.

AMF Species	Host Plant	Effect of AMF on the Uptake of Mineral Nutrients	Reference
Glomus intraradices, *Glomus versiforme*	*Poncirus trifoliata* (L.) Raf.	Concentrations of Zn, P, K, and Mg increase in branches and roots.	[44]
Rhizophagus intraradices	*Citrus limon* L.	P content and root acid phosphatase activity increase.	[45]
Rhizophagus irregularis	*Poncirus trifoliata* (L.) Raf.	P absorption by citrus increases.	[46]
Glomus mosseae, *Glomus etunicatum*	*Tarocco Xinxi*	The content of inorganic calcium, water-soluble calcium, and pectin calcium in the root system of citrus seedlings increases.	[47]
Glomus versiforme	*Poncirus trifoliata* (L.) Raf., *Citrus reticulate Blanco*	Phenolic secretion by citrus roots is enhanced. It chelates Fe, facilitating its binding and retention in the root cell walls for later reuse.	[48]
Glomus versiforme, *Glomus intraradices*	*Poncirus trifoliata* (L.) Raf. *"Ponkan", "Newhall" trifoliate orange*	Levels of Zn, P, K, Mg, Ca, and Cu significantly increased in various parts of citrus.	[49]

4. Effects of AMF on the Growth of Citrus Roots

The mycorrhizal structure formed by AMF and the roots of the fruit trees offers several advantages. It extends the range of nutrient uptake by the roots, improves their ability to adsorb nutrients, and facilitates nutrient transfer, promoting the growth, yield, and quality of the fruit trees [50,51]. Inoculating *Poncirus trifoliata* (L.) Raf. with *R. irregularis* significantly increased lateral root quantity and biomass, elevated the content of glucose and fructose in taproots and that of sucrose in lateral roots, and promoted the growth of seedlings, but reduced the root–shoot ratio [52]. Additionally, AMF can induce citrus roots to secrete more organic small-molecule phenolic acids, modify the microbial environment around citrus roots [53], reduce the root damage-induced secretion of endogenous hormones, and promote root injury repair [54].

Inoculation with *Paraglomus occultum* significantly improved the root traits in polyamine-treated *Citrus tangerine* Hort. ex Tanaka but had no significant effect on the root configuration of non-mycorrhizal orange seedlings [55]. The inoculation of *Poncirus trifoliata* (L.) Raf. with *F. mosseae* significantly increased the total root length and elevated the concentrations of indoleacetic and indolebutyric acids in the root system [56]. The simultaneous inoculation of *Poncirus trifoliata* (L.) Raf. with AMF and plant growth-promoting rhizobacteria significantly increased the root biomass [57]. Nitric oxide, an important regulator of root growth and development, when applied exogenously (as sodium nitropropyl treatment), significantly enhanced the mycorrhizal effects [58]. In summary, AMF increased root growth and repaired root damage in citrus seedlings to varying degrees, which ultimately promoted plant growth. The interactions between AMF, rhizosphere growth-promoting bacteria, polyamines, and nitric oxide significantly enhance the mycorrhizal effects on plants, leading to improved citrus yield and quality.

5. Effect and Mechanism of AMF on Citrus Disease Resistance

AMF inoculation improves citrus resistance to biotic stress by promoting the expression of various proteins associated with disease resistance [59]. Citrus Huanglongbing (HLB) is a devastating disease affecting citrus production [26] and causing significant economic loss worldwide. *Candidatus Liberibacter asiaticus* (CLas) infestation affects the AMF community structure by altering species composition, relative abundance [22], citrus rhizosphere secretions, and rhizosphere environmental conditions [60]. During HLB stress, citrus inoculation with AMF reduced the content of CLas and malondialdehyde (MDA) in the leaves, significantly enhanced peroxide (POD) activity in the leaves, and increased the proline (Pro) content, superoxide dismutase (SOD) activity, and catalase (CAT) content in both the leaves and roots [61] (Figure 1).

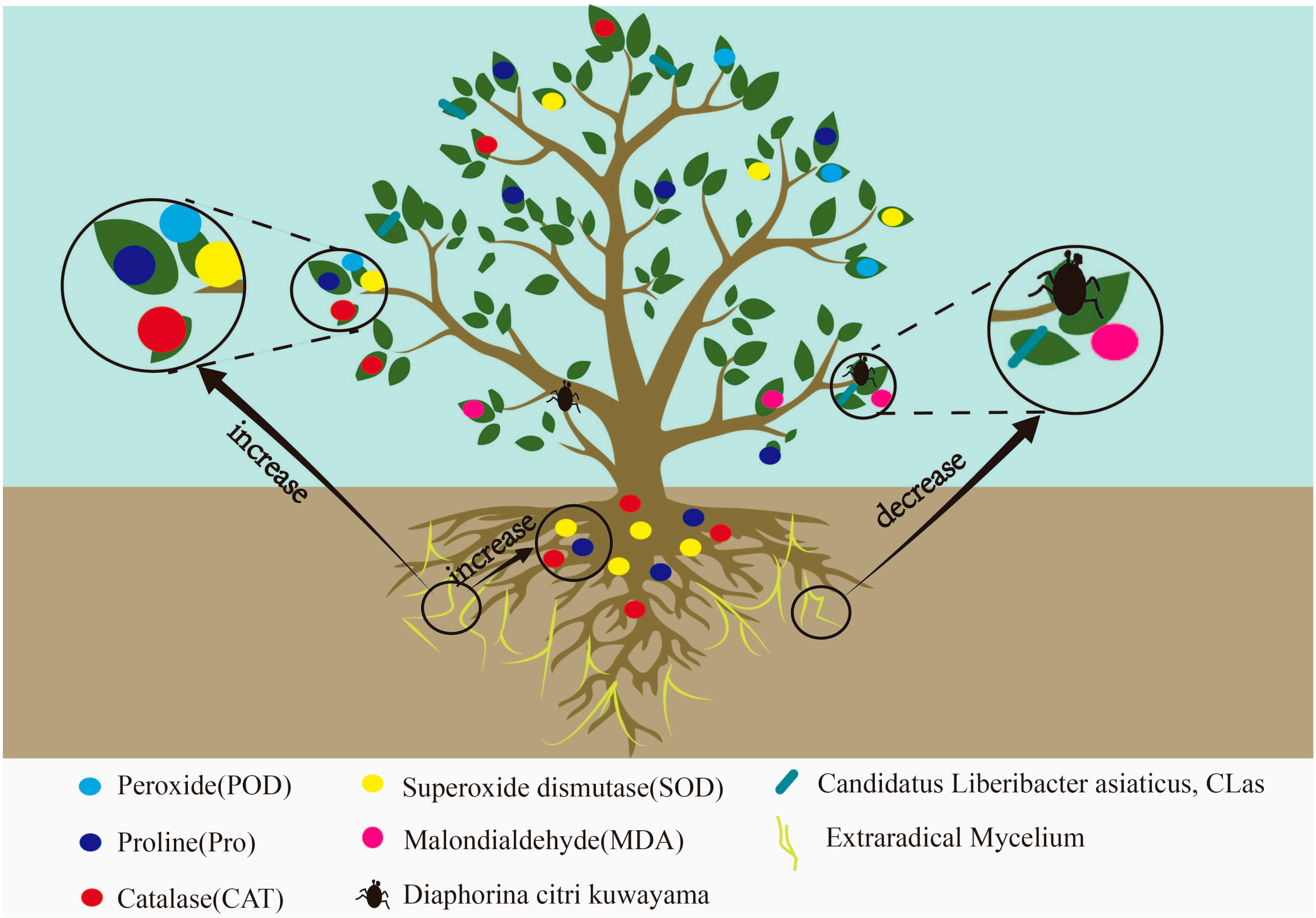

Figure 1. Effect of inoculation with AMF on citrus Huanglongbing (HLB). Note: Under citrus HLB stress, inoculation with AMF reduces the content of CLas, the number of psyllids, and the content of malondialdehyde in citrus leaves. Furthermore, it increases peroxidase activity, superoxide dismutase activity, proline content, and catalase content in the leaves, as well as superoxide dismutase activity, proline content, and catalase content in citrus roots.

In the context of disease resistance screening, Quan Dawan et al. [62] found that periwinkles inoculated with *Acaulospora scrobiculata*, *Glomeromycota sp2*, and *Glomeromycota* *sp7* displayed a significant increase resistance to citrus HLB. Citrus roots often face various phytophthora infestations, which can lead to root rot, stem dieback, and fruit brown rot [13]. When trifoliate orange becomes infected with bipolaris leaf spot, the inoculation of *F. mosseae* helps to regulate the expression of the plant defense genes, offering protection against pathogenic bacteria [63]. Moreover, the inoculation of *Poncirus trifoliata* with *Paraglomus occultum* significantly reduced the symptoms triggered by canker pathogens and enhanced the resistance to these pathogens by increasing the accumulation of signaling substrates [64]. *F. mosseae* induces calmodulin-mediated signaling pathways to activate disease-resistant genes, proteins, and compounds that provide an early warning of *Phytophthora parasitica* infection and improve the tolerance of trifoliate orange to root rot [65]. Common mycorrhizal networks transfer salicylic acid signals from the infected seedling to neighboring healthy seedlings to activate defense responses and provide protection to neighboring plants against citrus canker infection [66]. In conclusion, after citrus is affected by HLB, bipolaris leaf spot, root rot, or canker, AMF inoculation can alleviate the stress of disease on citrus growth and enhance citrus resistance to these diseases.

6. AMF Induces the Expression of Citrus Defense Genes

AMF can promote the synthesis of secondary metabolites by regulating the expression of defense genes; therefore, they affect plant growth and fruit quality. Thus, 12 mycorrhizal signal receptor protein *Lysin Motif Receptor-like Kinases* (*LYK*) genes were identified in the genome of *Poncirus trifoliata* (L.) Raf. [67]. The expression of *PtrLYK2* in the roots of *Poncirus trifoliata* (L.) Raf. was induced by mycorrhizal infection, with the expression level being the highest at the early stage of mycorrhizal infection. These results suggest that *PtrLYK2* plays a critical role in early signal recognition within the context of citrus mycorrhizal symbiosis [67]. *Exonuclease70I* (*EXO70I*) might be involved in the extension and branching of mycelia or the transport and transfer of nutrients in mycorrhizal symbiosis [68]. In *Citrus sinensis* (L.) Osbeck cv. Valencia inoculated with AMF, the levels of expression of *calcineurin B-like protein 1—interacting protein kinase 1* (*CsCBL1-CsCIPK1*), *CsCBL1-CsCIPK3*, *CsCBL1-CsCIPK6*, and *CsCBL1-CsCIPK9* were significantly and positively correlated with drought and AMF response [69]. Additionally, the inoculation of citrus with AMF can alleviate water deficiency and improve nutrient transport efficiency by upregulating or downregulating the expression of relevant genes. It is also critical for signal recognition and nitrate transport (Table 2).

Table 2. AMF induces the expression of defense genes in citrus.

AMF Species	Host Plant	AMF Effect on the Expression of Defense Genes	Reference
Glomus versiforme	*Poncirus trifoliata* L., *Citrus reticulate Blanco*	Significant upregulation of phenylalanine deaminase *PAL1* gene expression in the roots.	[48]
Funneliformis mosseae	*Poncirus trifoliata*	The significant expression of *PtAHA2* was induced to resist soil drought.	[70]
Rhizophagus irregularis	*Poncirus trifoliata* (L.) Raf.	Nitrate transporter protein gene *PtrNPF5.2* significantly upregulated expression.	[71]
Glomus versiforme	*Poncirus trifoliata* (L.) Raf.	Increased *CHS* activity and PtCHS expression.	[72]
five Glomus species	*Poncirus trifoliata* L. Raf.	The genes *PtaPT4* and *PtaPT5* were expressed upstream after AMF infection, while the genes *PtaPT1*, *PtaPT2*, *PtaPT3*, and *PtaPT7* were expressed downstream.	[73]
Glomus versiforme	*"Newhall"* (*Citrus sinensis*), *Poncirus trifoliata*	Upregulation of chlorophyll and transport-related gene expression at protein level and downregulation of protease inhibitor gene expression.	[74]

Note: Phenylalnine ammonia-lyase (PAL), Arabidopsis plasma membrane H^+-ATPase isoform (AHA), Nitrate transporter 1/peptide transporter (NRT1/PTR) family (NPF), Chalcone synthase (CHS), Phosphate transporter (PT).

7. Effect of AMF Inoculation on the Response of Citrus to Abiotic Stress

7.1. AMF Improves Drought Tolerance in Citrus

Under drought stress, AMF inoculation can promote water uptake by plants [15,75], alleviate physiological drought, and modulate the ionic balance within plants, reducing the damage to the plasma membrane and enzymes [76]. Moreover, it can directly or indirectly boost photosynthetic efficiency, mitigate the inhibitory effects of drought, minimize damage to plant growth, and ultimately fortify plant resilience to drought [77,78].

Under water stress conditions, the inoculation of *Poncirus trifoliata* (L.) Raf. with *F. mosseae* promotes growth, improves the leaf water status [79], and reduces the salicylic acid content in the leaves [80]. Furthermore, the dependence of *Citrus junos* Sieb. ex Tanaka seedlings on mycorrhizae increased as the drought stress intensified, peaking under severe drought conditions [77]. Under water stress, the inoculation of *Poncirus trifoliata* (L.) Raf. with *F. mosseae* lowers leaf temperature [81] and thereby reduces leaf water evaporation. AMF colonization affects soil moisture retention via glomalin's effect on water-stable aggregates, indirectly promoting *Poncirus trifoliata* growth under drought stress [82]. Mycorrhizas can regulate polyamine metabolism and enhance the drought tolerance of trifoliate orange [83]. Additionally, it regulates osmotic capacity and improves antioxidant enzyme activity [84] and thereby improves the drought tolerance in citrus. Inoculation with AMF improved water use efficiency in citrus by increasing soil porosity and water retention capacity. Thus, it affects water metabolism, increases soluble carbohydrate levels in root cells, reduces cellular osmotic potential, and improves citrus drought tolerance and recovery following drought stress by promoting photosynthesis (Table 3).

Table 3. Effect of AMF inoculation on citrus growth under drought stress.

AMF Species	Host Plant	Effect of AMF Inoculation on Citrus Growth under Drought Stress	Reference
Glomus mosseae	*Poncirus trifoliata/Citrus sinensis*	The plant height, spike thickness, leaf area, and shoot growth of citrus were significantly increased.	[40]
Funneliformis mosseae	*Poncirus trifoliata*	Root growth and leaf gas exchange are enhanced.	[70]
Rhizoglomus intraradices	*Trifoliate orange*	Aboveground and root biomass with greater metabolic activity increase.	[85]
Funneliformis mosseae	*Trifoliate orange*	It regulates root phytohormones and root morphology.	[86]
Funneliformis mosseae and *Paraglomus occultum*	*Trifoliate orange*	Leaf sucrose, fructose, and glucose concentrations increased, while proline levels decreased.	[87,88]
Funneliformis mosseae	*Poncirus trifoliata*	The unsaturation index of root FAs increased, and the composition of root FAs significantly changed.	[89]
Funneliformis mosseae	*Trifoliate orange*	The root volume increased while proline concentration and content in leaves, roots, and total plants decreased.	[90]
Funneliformis mosseae	*Trifoliate orange*	Plant height and chlorophyll and water content increased.	[91]

7.2. AMF Improves the Tolerance of Citrus to Salt and Alkali

Citrus is highly susceptible to yellowing, wilting, and shedding in alkaline soils with iron and zinc deficiencies, which are important factors hindering citrus development. Under salt stress, the inoculation of *Poncirus trifoliata* (L.) Raf. with *R. intraradices* increased the plant height, stem diameter, and dry matter mass. Moreover, the root content of abscisic acid, indole-3-acetic acid, and methyl jasmonate also increased [92]. Furthermore, under salt stress, mycorrhizal symbiosis increased root H^+ outflow and improved the root structure of trifoliate orange seedings [93], and the salicylic acid concentration in the root was significantly higher than that of nonmycorrhizal seedlings [94]. Zhang et al. [95] showed that the better soil structure resulting from the mycorrhization of trifoliate orange seedlings provided higher leaf water potential under salt stress. Trifoliate orange inoculation with AMF under salt stress induced the production of 14 aquaporins, which increased membrane permeability and facilitated water transport [75]. Under alkaline stress, the inoculation of *Citrus junos* Sieb. ex Tanaka with *F. mosseae* improved the osmotic regulation and antioxidant capacity of the seedlings, altered the endogenous hormone levels [96], and affected the soil physicochemical properties and enzyme activities around the root [97]. The inoculation of *Poncirus trifoliata* (L.) Raf. with *G. versiforme* mitigated bicarbonate stress-induced growth inhibition [39]. In summary, the citrus root system and AMF form a symbiotic relationship that can improve the resistance of citrus to soil salinization. This not only mitigates the adverse effects of soil salinity but also ensures the preservation of fruit yield and quality.

7.3. AMF Impacts the Response of Citrus Plants to Temperature Stress

Citrus root systems inoculated with AMF can exhibit different effects in response to both high and low temperatures. *Poncirus trifoliata* (L.) Raf. seedlings inoculated with AMF and cultured in pots at 25 °C for 4 months showed significant improvements in plant height, stem thickness, root vigor, and the activity of protective enzymes in the leaf blades after 30 days of high-temperature stress at 40 °C [98]. Wu and Zhou [99] indicated that mycorrhizal formation had beneficial effects on the growth, photosynthesis, root morphology, and nutrient uptake of citrus seedlings grown at a moderate temperature (25 °C). Under different temperature stresses, inoculation with AMF increased the soluble sugar and soluble protein content, POD and CAT activities, and cold tolerance of *Poncirus aurantii* seedlings [100,101]. Zeng's [102] research showed that AMF inoculation could significantly reduce the MDA content and plasma membrane permeability in *Fructus aurantii* leaves under temperature stress and increase the root activity of cumulative seedlings. In summary, mycorrhizal citrus plants exhibit higher root activity and possess a stronger antioxidant capacity than citrus plants that have not formed a symbiotic relationship with AMF. These factors collectively contribute to improved temperature stress resilience in citrus plants.

8. Application of AMF in Citrus Cultivation

AMF establish a symbiotic relationship with citrus roots, offering numerous benefits, particularly under potting conditions. However, research on AMF inoculation in the field settings remains limited. Inoculation of AMF in the field can promote mycorrhiza growth and improve the root vitality of *Citrus reticulata* Blanco var. Ponkan mandarin cv, which improves the fruit quality [103]. Moreover, the mixed inoculation with AMF (*Diversispora versiformis*, *F. mosseae*, and *R. intraradices*) produced more significant effects than the single inoculation with *F. mosseae*.

Interplanting *Trifolium repens* Linn. inoculated with AMF effectively increased the biomass of *Citrus sinensis* (L.) Osbeck [104]. This approach also increased citrus photosynthetic rates, improved the efficiency of carbon assimilation in photosynthesis, and enhanced citrus root growth. The content of soluble sugars and proteins in these citrus seedlings was higher than that associated with only AMF [104]. *Trifolium repens* Linn inoculated with rhizobacteria and AMF increased biomass production and N accumulation in *Citrus sinensis* (L.) Osbeck [105]; this indicates that the N in *Trifolium repens* Linn was transferred to citrus through common mycorrhizal networks.

In summary, in the context of citrus cultivation, it may be advantageous to simultaneously introduce AMF and *Trifolium repens* Linn. inoculation into citrus orchards to some extent. This practice may improve citrus yields and quality by increasing soil fertility. Importantly, it contributes to reducing the need for fertilizers and pesticides, especially herbicides, while also increasing the income of fruit farmers and promoting regional development. However, current AMF pure culture technology is still limited to the mass production of AMF spores; therefore, further research is needed before purified AMF can be effectively introduced into field applications.

9. Prospects

Currently, the inoculation of citrus with AMF is widely emphasized in sustainable agricultural production. The diversity of AMF forming symbiotic relations with citrus is closely associated with the habitat and citrus species. AMF can improve citrus water and nutrient uptake, promoting the growth and development of the citrus root system and enhancing citrus resistance to biotic (citrus HLB, bipolaris leaf spot, root rot, and canker) and abiotic stressors (saline-alkali, drought, and temperature stresses). Our review provides theoretical knowledge to elucidate the roles of mycorrhizae and their usefulness in citrus cultivation. As we look to the future, several critical areas warrant urgent attention.

Screening for dominant strains of citrus symbiotic AMF in different habitats:

AMF have no host specificity; some AMF species can promote citrus growth in different habitats, while others do not interfere with or even inhibit citrus growth. While many AMF perform well in controlled pot experiments, their effectiveness can diminish in actual farmland cultivation. This discrepancy may be due to the non-native dominant strains being less effective than local dominant strains. Future research should focus on screening and cultivating the dominant strains of citrus symbiotic AMF specific to local habitats, emphasizing their application in citrus tree planting.

Addressing citrus HLB:

Citrus HLB poses a significant threat to citrus production; thus far, CLas cannot be cultured in isolation, and its pathogenic mechanism remains unclear. As important symbionts of citrus, AMF alleviate the stress induced by citrus HLB on citrus growth. However, studies on this subject are scarce. In the future, screening should be expanded to AMF that are resistant to citrus HLB. Furthermore, field planting trials should be enhanced to promote the use of disease-resistant AMF. Additionally, the specific mechanisms of how AMF contribute to citrus resistance to HLB should be further explored to advance the management of citrus HLB and foster the sustainable development of the citrus industry.

Widespread adoption of citrus mycorrhizalization technologies:

Citrus mycorrhizalization technologies should be popularized and applied vigorously. AMF are widely used microorganisms; however, large-scale purification technologies are limited. Recently, Japanese scientists have shown that AMF can use myristate as a carbon source to complete its life cycle under host-free conditions [106].

However, only a few related studies exist. In the future, we will search for more plant-derived fatty acids that are symbiotic with AMF. Critical questions, such as whether myristate is the primary carbon source for citrus symbiotic AMF, whether it is preferentially utilized by AMF, and whether its utilization is influenced by AMF species, must be addressed to further our understanding of these complex interactions.

Author Contributions: Conceptualization, Z.Z. and C.T.; methodology, C.T.; software, C.T.; validation, C.T., L.Y. and Y.L.; formal analysis, C.T.; investigation, C.T.; resources, C.T.; data curation, C.T.; writing—original draft preparation, C.T., L.Y. and Y.L.; writing—review and editing, Z.Z. and C.T.; visualization, C.T.; supervision, Z.Z.; project administration, Z.Z.; funding acquisition, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by National Natural Science Foundation of China (31960272), Scientific Research and Technology Development Plan of Guilin (20210217-13) and the Basic Research Foundation of Guangxi Academy of Sciences (CQz-E-1909).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. He, X.M.; Xiang, Q.; Tang, T.T.; Tian, Z.K.; Chen, C. Research on Soil Lead and Cadmium Pollution Control by Arbuscular Mycorrhizal Fung. *Biol. Chem. Eng.* **2017**, *3*, 91–93+97.
2. Gong, Y.L.; Bi, Y.L.; Hu, J.J.; Guo, C. Effect of Inoculation with AM Fungi on Maize Growth and Hyperspectral Estimation of Total Nitrogen Content in Maize Leaves. *Environ. Manag.* **2020**, *38*, 210–214. [CrossRef]

3. Lei, M.; Ding, C.; Gan, Z.Y.; Qiu, Q.Y. Effects of Arbuscular Mycorrhizal Fungi and Application of Different Nitrogen Fertilizers on Nutrient Absorption of Chinese Fir Seedlings. *J. Trop. Subtrop. Bot.* **2022**, *30*, 518–527. [CrossRef]
4. Ma, X.N.; Luo, W.Q.; Xu, F.F.; Wu, F.Y. Effects of two AM fungi on zinc uptake of winter wheat roots. *Mycosystema* **2017**, *36*, 933–941. [CrossRef]
5. Wang, Y.; Xing, D.; Song, L.L.; Han, S.Y.; Chen, T.S. Effects of Arbuscular Mycorrhizal Fungi on Nutrient Exchange in Mulberry Plant in Rocky Desertification Areas. *Chin. J. Trop. Crops* **2020**, *41*, 7–14. [CrossRef]
6. Jiang, L.; Li, H.Y.; Zhang, Q.; Zhang, H.L.; Qiao, Y.H.; Zhang, H.X.; Yang, X.Y. Effects of arbuscular mycorrhiza fungi on the growth and physiological metabolism of Pyrus betulaefolia Bunge seedlings under saline-alkaline stress. *J. Nanjing For. Univ. (Nat. Sci. Ed.)* **2020**, *44*, 152–160. [CrossRef]
7. Hou, S.J.; Li, T.; Lin, G.; Chen, B.D. Effects of biogas slurry and AM fungi on growth and heavy metal accumulation of licorice plants. *J. Agro-Environ. Sci.* **2016**, *35*, 1465–1472. [CrossRef]
8. Li, Y.D.; Duan, T.Y. AM Effects of AM fungi on alfalfa leaf spot caused by *Phoma medicaginis* and pea aphids *Acyrthosiphon pisum*. *Chin. J. Ecol.* **2020**, *39*, 1214–1221. [CrossRef]
9. Qu, M.H.; Yu, Y.C.; Li, S.; Zhang, J.C. Advances in research on activation of mineral nutrients by arbuscular mycorrhizal fungi. *J. Zhejiang Agric. For. Univ.* **2019**, *36*, 394–405. [CrossRef]
10. Arif, Y.; Singh, P.; Siddiqui, H.; Bajguz, A.; Hayat, S. Salinity induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. *Plant Physiol. Biochem.* **2020**, *156*, 64–77. [CrossRef]
11. Liu, N.; Zhao, Z.Y.; Jiang, X.L.; Xing, X.K. Review and prospect of researches on the mechanisms of mycorrhizal fungi in improving plant drought resistance. *Mycosystema* **2021**, *40*, 851–872. [CrossRef]
12. Wu, Q.S.; Srivastava, A.K.; Zou, Y.N.; Malhotra, S.K. Mycorrhizas in citrus: Beyond soil fertility and plant nutrition. *Indian J. Agric. Sci.* **2017**, *87*, 427–443. [CrossRef]
13. Wu, Q.S.; Zou, Y.N. New Advances in the Research of Arbuscular Mycorrhizas in Citrus. *Acta. Agric. Univ. Jiangxi* **2014**, *36*, 279–284.
14. Liu, C.Y.; Zhang, F.; Zhang, D.J.; Srivastava, A.; Wu, Q.S.; Zou, Y.N. Mycorrhiza Stimulates Root-Hair Growth and IAA Synthesis and Transport in Trifoliate Orange under Drought Stress. *Sci. Rep.* **2018**, *8*, 1978. [CrossRef]
15. Zhang, F.; Zou, Y.N.; Wu, Q.S. Quantitative estimation of water uptake by mycorrhizal extraradical hyphae in citrus under drought stress. *Sci. Hortic.* **2018**, *229*, 132–136. [CrossRef]
16. Telajin, N.S.E.; Li, Y.B.; Huang, J.G. Effects of arbuscular mycorrhizal fungi on growth, nutrition and water use of jujube seedlings in Xinjiang. *Agric. Technol. Serv.* **2014**, *31*, 63–64.
17. Liu, C.Y.; Zou, Y.N.; Zhang, D.J.; Shu, B.; Wu, Q.S. Mycorrhizae and Tolerance of Abiotic Stress in Citrus Plants. *Soil Biol.* **2019**. [CrossRef]
18. Ortas, I. Role of mycorrhizae on mineral nutrition of fruit trees. *Acta Hortic.* **2018**, 271–284. [CrossRef]
19. Senes-Guerrero, C.; Gimenez, S.; Pacheco, A.; Gradilla-Hernandez, M.S.; Schuessler, A. New MiSeq based strategy exposed plant-preferential arbuscular mycorrhizal fungal communities in arid soils of Mexico. *Symbiosis* **2020**, *81*, 235–246. [CrossRef]
20. Li, G.G.; Liu, J.H.; Song, J.; Li, M.Y.; Li, D.P.; Liu, S.Q.; Zhang, J.L.; Chen, Y.S. Research on Arbuscular Mycorrhizal Fungi on the Growth of Ziyang Xiangcheng Seedling. *J. Yunnan Agric. Univ. (Nat. Sci.)* **2021**, *36*, 1022–1027.
21. Zhang, J.L.; Li, M.Y.; Kang, Y.H.; Liu, J.H.; Chen, Y.S.; Li, X.L.; Song, J.; Liu, S.Q. Effect of Fourteen Arbuscular Mycorrhizal Fungi on Growth of Fructus aurantii. *Chin. J. Trop. Crops* **2021**, *42*, 3278–3283.
22. Song, F.; Wu, L.M.; Li, H.F.; He, L.G.; Wang, Z.J.; Huang, Y.M.; Jiang, Y.C. Identification of root endophytic arbuscular mycorrhizal fungi community diversity and its variations under the infection of *Candidatus* Liberibacter asiaticus in the citrus orchard of Ganzhou city. *J. Fruit Sci.* **2019**, *36*, 892–902. [CrossRef]
23. Liu, R.J.; Jiao, H.; Li, Y.; Li, M.; Zhu, X.C. Research advances in species diversity of arbuscular mycorrhizal fungi. *Chin. J. Appl. Ecol.* **2009**, *20*, 2301–2307.
24. del Mar Alguacil, M.; Torrecillas, E.; Torres, P.; Garcia-Orenes, F.; Roldan, A. Long-Term Effects of Irrigation with Waste Water on Soil AM Fungi Diversity and Microbial Activities: The Implications for Agro-Ecosystem Resilience. *PLoS ONE* **2012**, *7*, e47680. [CrossRef]
25. Wang, P.; Shu, B.; Wang, Y.; Zhang, D.J.; Liu, J.F.; Xia, R.X. Diversity of arbuscular mycorrhizal fungi in red tangerine (*Citrus reticulata* Blanco) rootstock rhizospheric soils from hillside citrus orchards. *Pedobiologia* **2013**, *56*, 161–167. [CrossRef]
26. Xi, M.Y.; Deyett, E.; Ginnan, N.; Ashworth, V.E.T.M.; Dang, T.; Bodaghi, S.; Vidalakis, G.; Roper, M.C.; Glassman, S.I.; Rolshausen, P.E. Geographic Location, Management Strategy, and Huanglongbing Disease Affect Arbuscular Mycorrhizal Fungal Communities Across U.S. Citrus Orchards. *Phytobiomes J.* **2022**, *6*, 342–353. [CrossRef]
27. Mullath, S.K.; Blaszkowski, J.; Govindan, B.N.; Al Dhaheri, L.; Symanczik, S.; Al-Yahya'ei, M.N. Organic farming practices in a desert habitat increased the abundance, richness, and diversity of arbuscular mycorrhizal fungi. *Emir. J. Food Agric.* **2019**, *31*, 969–979. [CrossRef]
28. Wang, P.; Zhang, J.J.; Shu, B.; Xia, R.X. Arbuscular mycorrhizal fungi associated with citrus orchards under different types of soil management, southern China. *Plant Soil Environ.* **2012**, *58*, 302–308. [CrossRef]
29. Yang, L.; Zou, Y.N.; Tian, Z.H.; Wu, Q.S.; Kuca, K. Effects of beneficial endophytic fungal inoculants on plant growth and nutrient absorption of trifoliate orange seedlings. *Sci. Hortic.* **2021**, *277*, 109815. [CrossRef]

30. Rahimi, S.; Baninasab, B.; Talebi, M.; Gholami, M.; Zarei, M. Arbuscular mycorrhizal fungi inoculation improves iron deficiency in quince via alterations in host root phenolic compounds and expression of genes. *Sci. Hortic.* **2021**, *285*, 110165. [CrossRef]
31. Wu, Q.S.; Gao, W.Q.; Srivastava, A.K.; Zhang, F.; Zou, Y.N. Nutrient acquisition and fruit quality of Ponkan mandarin in response to AMF inoculation. *Indian J. Agric. Sci.* **2020**, *90*, 1563–1567. [CrossRef]
32. Ortas, I. Comparison of indigenous and selected mycorrhiza in terms of growth increases and mycorrhizal dependency of sour orange under phosphorus and zinc deficient soils. *Eur. J. Hortic. Sci.* **2019**, *84*, 218–225. [CrossRef]
33. Shu, B. Effects and Mechanism of Arbuscular Mycorrhizal Fungi on Phosphrous Uptake in Trifoliate Orange (*Poncirus trifoliata* L. Raf). Ph.D. Dissertation, Huazhong Agricultural University, Wuhan, China, 2013.
34. Navarro, J.M.; Morte, A. Mycorrhizal effectiveness in *Citrus macrophylla* at low phosphorus fertilization. *J. Plant Physiol.* **2018**, *232*, 301–310. [CrossRef]
35. Wang, P.; Wang, T.Y.; Wu, S.H.; Wen, M.X.; Lu, L.M.; Ke, F.Z.; Wu, Q.S. Effect of arbuscular mycorrhizal fungi on rhizosphere organic acid content and microbial activity of trifoliate orange under different low P conditions. *Arch. Agron. Soil Sci.* **2019**, *65*, 2029–2042. [CrossRef]
36. Meng, L.L.; He, J.D.; Zou, Y.N.; Wu, Q.S.; Kuca, K. Mycorrhiza-Released Glomalin-Related Soil Protein Fractions Contribute to Soil Total Nitrogen in Trifoliate Orange. *Plant Soil Environ.* **2020**, *66*, 183–189. [CrossRef]
37. Liu, P. The Effect of Inoculation of AM Fungi on The Fe Absorption of Citrus. Master's Dissertation, Southwest University, Chongqing, China, 2010.
38. Wang, M.Y.; Xia, R.X. Effects of arbuscular mycorrhizal fungi on growth and iron uptake of *Poncirus trifoliata* under different pH. *Acta Microbiol. Sin.* **2009**, *49*, 1374–1379. [CrossRef]
39. Wang, M.Y.; Xia, R.X.; Wang, Y.S.; Zhou, K.B.; Ni, H.Z. Effects of Arbuscular Mycorrhizal Fungi on Growth of *Poncirus trifoliata* Seedlings under Iron Deficiency and Heavy Bicarbonate Stresses. *Acta Hortic. Sin.* **2008**, 469–474. [CrossRef]
40. Wu, Q.S.; Zou, Y.N. Influence of Arbuscular Mycorrhizal Fungi on Mineral Nutrition in Roots of Red Tangerine Seedlings Exposed to Water Stress. *J. Xinyang Norm. Univ. (Nat. Sci. Ed.)* **2009**, *22*, 526–529+543.
41. Zhang, F.; Du, P.; Song, C.X.; Wu, Q.S. Alleviation of magnesium deficiency by mycorrhiza in trifoliate orange: Changes in physiological activity. *Emir. J. Food Agri.* **2015**, *27*, 763–769. [CrossRef]
42. Xiao, J.X.; Hu, C.Y.; Chen, Y.Y.; Hua, J.; Yang, B. Growth and Nutrient Content of Trifoliate Orange Seedlings Influenced by Arbuscular Mycorrhizal Fungi Inoculation in Low Magnesium Soil. *J. Plant Nutr.* **2014**, *38*, 1516–1529. [CrossRef]
43. Shao, Y.D.; Zhang, D.J.; Hu, X.C.; Wu, Q.S.; Jiang, C.J.; Xia, T.J.; Gao, X.B.; Kuca, K. Mycorrhiza-induced changes in root growth and nutrient absorption of tea plants. *Plant Soil Environ.* **2018**, *64*, 283–289. [CrossRef]
44. Chen, Y.Y.; Hu, C.Y.; Xiao, J.X. Effects of arbuscular mycorrhizal fungi on the growth and zinc uptake of trifoliate orange (*Poncirus trifoliata*) seedlings grown in low-zinc soil. *J. Plant Nutr.* **2016**, *40*, 324–331. [CrossRef]
45. Liu, C.Y.; Guo, X.N.; Wu, X.L.; Dai, F.J.; Wu, Q.S. The Comprehensive Effects of *Rhizophagus intraradices* and P on Root System Architecture and P Transportation in *Citrus limon* L. *Agriculture* **2022**, *12*, 317. [CrossRef]
46. Xu, P.Y. Regulation of Arbuscular Mycorrhizal Fungi and Phosphorus on Plant Lateral Root Formation and Involved Auxin Signaling Pathways. Master's Dissertation, South China Agricultural University, Guangzhou, China, 2017.
47. Deng, L. Effects of Arbuscular Mycorrhizal Fungi on Plant Growth and Calcium Uptake in Citrus Seedlings. Master's Dissertation, Southwest University, Chongqing, China, 2016.
48. Li, J.F. Study on Phenolis and Key Gene in Citrus Mycorrhizal Symbiont under Iron deficiency. Master's Dissertation, Huaqiao University, Quanzhou, China, 2015.
49. Song, Y.L. Effects and Mechanisms of Arbuscular Mycorrhizal Fungi on Zinc Uptake by Citrus. Master's Dissertation, Hunan Agricultural University, Changsha, China, 2015.
50. Seguel, A.; Cumming, J.R.; Klugh-Stewart, K.; Cornejo, P.; Borie, F. The role of arbuscular mycorrhizas in decreasing aluminium phytotoxicity in acidic soils: A review. *Mycorrhiza* **2013**, *23*, 167–183. [CrossRef] [PubMed]
51. Meier, S.; Borie, F.; Bolan, N.; Cornejo, P. Phytoremediation of metal-polluted soils by arbuscular mycorrhizal fungi. *Crit. Rev. Environ. Sci. Technol.* **2011**, *42*, 741–775. [CrossRef]
52. Chen, W.L.; Li, J.; Zhu, H.H.; Xu, P.Y.; Chen, J.Z.; Yao, Q. Arbuscular Mycorrhizal Fungus Enhances Lateral Root Formation in *Poncirus trifoliata* (L.) as Revealed by RNA-Seq Analysis. *Front. Plant Sci.* **2017**, *8*, 2039. [CrossRef] [PubMed]
53. Zhang, M.Y.; Wang, M.Y.; Hou, S.Z.; Liu, J.F.; Lin, P.; Li, Y.Q. Effects of Arbuscular Mycorrhizal Fungi on Plant Growth and Secondary Metabolism in Citrus reticulata. *J. Trop. Subtrop. Bot.* **2020**, *28*, 78–83.
54. Bi, Y.L.; Sun, J.H.; Zhang, J.; Song, Z.H.; Cai, Y.; Sun, H. Remediation effects of plant root growth inoculated with AM fungi on simulation subsidence injured. *J. China Coal Soc.* **2017**, *42*, 1013–1020. [CrossRef]
55. Wu, Q.S.; Zou, Y.N.; Liu, C.Y.; Lu, T. Interacted Effect of Arbuscular Mycorrhizal Fungi and Polyamines on Root System Architecture of Citrus Seedlings. *J. Integr. Agric.* **2012**, *11*, 1675–1681. [CrossRef]
56. Liu, R.C.; Yang, L.; Zou, Y.N.; Wu, Q.S. Root-associated endophytic fungi modulate endogenous auxin and cytokinin levels to improve plant biomass and root morphology of trifoliate orange. *Hortic. Plant J.* **2023**, *9*, 463–472. [CrossRef]
57. Chai, Y.J. Effect of Plant Growth-Promoting Rhizobacteria and Arbuscular Mycorrhizal Fungi on Growth and Development of Trifoliate Orange. Master's Dissertation, Southwest University, Chongqing, China, 2022. [CrossRef]
58. Tian, L.; Nasrullah, N.; Huang, X.Y.; Wu, Q.S. Nitric Oxide Accelerates Mycorrhizal Effects on Plant Growth and Root Development of Trifoliate Orange. *Sains Malays.* **2017**, *46*, 1687–1691. [CrossRef]

59. Wu, X.Y.; Cui, X.Y. Effects of Arbuscular Mycorrhizal Fungi on Plant Growth and Fruit Quality. *Tianjin Agric. Sci.* **2016**, *22*, 116–119. [CrossRef]
60. Song, F. Characterization of Roof Microbiome and Identification of miRNAs Involved in Arbuscular Mycorrhizal Symbiosis in Citrus. Ph.D. Dissertation, Huazhong Agricultural University, Wuhan, China, 2018.
61. Kang, Y.H. Study on the Defense Effect of Inoculation with Mycorrhizal Fungi on Citrus Huanglongbing and Its Vector Diaphorina Citri. Master's Dissertation, Fujian Agriculture and Forestry University, Fuzhou, China, 2022.
62. Quan, D.W.; Li, D.; Zhang, J.L.; Song, J.; Hu, L.; Cheng, T.; Huang, J.H.; Chen, T.S. Effects of Inhibition Citrus Huanglongbing on Catharanthus roseus with Different Arbuscular Mycorrhizal Fungi Species. *Chin. J. Trop. Crops* **2020**, *41*, 2259–2266. [CrossRef]
63. Cheng, S.; Tian, L.; Zou, Y.N.; Wu, Q.S.; Kuca, K.; Bora, P. Molecular responses of arbuscular mycorrhizal fungi in tolerating root rot of trifoliate orange. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2020**, *48*, 558–571. [CrossRef]
64. Xie, M.M.; Zhang, Y.C.; Liu, L.P.; Zou, Y.N.; Wu, Q.S.; Kuca, K. Mycorrhiza regulates signal substance levels and pathogen defense gene expression to resist citrus canker. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2019**, *47*, 1161–1167. [CrossRef]
65. Tian, L.; Zou, Y.N.; Wu, Q.S.; Kuča, K. Mycorrhiza-induced plant defence responses in trifoliate orange infected by Phytophthora parasitica. *Acta Physiol. Plant.* **2021**, *43*, 45. [CrossRef]
66. Zhang, Y.C.; Zou, Y.N.; Liu, L.P.; Wu, Q.S. Common mycorrhizal networks activate salicylic acid defense responses of trifoliate orange (*Poncirus trifoliata*). *J. Integr. Plant Biol.* **2018**, *61*, 1099–1111. [CrossRef] [PubMed]
67. Song, F.; Li, Z.X.; Wang, C.; Wang, Z.J.; He, L.G.; Jiang, Y.C.; Wu, L.M.; Bai, F.X. Cloning and Function Analysis of Mycorrhizal Signaling Receptor Protein Lysin Motif Receptor-like Kinases 2 Gene (LYK2) in Citrus. *Acta Hortic. Sin.* **2022**, *49*, 281–292. [CrossRef]
68. Sun, M.Q. Functional Analysis of Mycorrhizal-Induced Gene EXO70I and Lipase3 from Citrus and Their Homolog Genes in Medicago. Master's Dissertation, Huazhong Agricultural University, Wuhan, China, 2016.
69. Shu, B.; Cai, D.; Zhang, F.; Zhang, D.J.; Liu, C.Y.; Wu, Q.S.; Luo, C. Identifying citrus CBL and CIPK gene families and their expressions in response to drought and arbuscular mycorrhizal fungi colonization. *Biol. Plant* **2020**, *64*, 773–783. [CrossRef]
70. Cheng, H.Q.; Zou, Y.N.; Wu, Q.S.; Kuca, K. Arbuscular Mycorrhizal Fungi Alleviate Drought Stress in Trifoliate Orange by Regulating H^+-ATPase Activity and Gene Expression. *Front. Plant Sci.* **2021**, *12*, 659694. [CrossRef]
71. Huang, S.Y. Expression and Function Analysis of A Nitrate Transpoter Gene PtrNPF5.2 Associated with Arbuscular Mycorrhizal Symbiosis in Poncirus Trifolata. Master's Dissertation, Huazhong Agricultural University, Wuhan, China, 2021.
72. Liu, Z.; Cheng, S.; Liu, X.Q.; Kuca, K.; Hashem, A.; Al-Arjani, A.F.; Almutairi, K.F.; Abd Allah, E.F.; Wu, Q.S.; Zou, Y.N. Cloning of a CHS gene of *Poncirus trifoliata* and its expression in response to soil water deficit and arbuscular mycorrhizal fungi. *Front. Plant Sci.* **2022**, *13*, 1101212. [CrossRef]
73. Shu, B.; Xia, R.X.; Wang, P. Differential regulation of Pht1 phosphate transporters from trifoliate orange (*Poncirus trifoliata* L. Raf) seedlings. *Sci. Hortic.* **2012**, *146*, 115–123. [CrossRef]
74. Gao, X.; Zhao, S.; Xu, Q.L.; Xiao, J.X. Transcriptome responses of grafted *Citrus sinensis* plants to inoculation with the arbuscular mycorrhizal fungus *Glomus versiforme*. *Trees-Struct. Funct.* **2016**, *30*, 1073–1082. [CrossRef]
75. Cheng, X.F.; Wu, H.H.; Zou, Y.N.; Wu, Q.S.; Kuca, K. Mycorrhizal response strategies of trifoliate orange under well-watered, salt stress, and waterlogging stress by regulating leaf aquaporin expression. *Plant Physiol. Biochem.* **2021**, *162*, 27–35. [CrossRef]
76. Huang, Y.F.; Wu, Q.L.; Wan, Q.; Shu, B. Research progress of arbuscular mycorrhizal fungi. *Mod. Agric.* **2019**, *12*, 9–12. [CrossRef]
77. Li, X. Effects of Arbuscular Mycorrhizal Fungi on Growth and Drought Resistance of Citrus Seedlings under Water Stress. Master's Dissertation, Southwest University, Chongqing, China, 2022.
78. Peng, F. Effects of Arbuscular Mycorrhizal Fungi and Nutrient Interaction on the Drought Resistance of *Leymus chinensis*. Master's Dissertation, Northeast Normal University, Changchun, China, 2019.
79. Zou, Y.N.; Wu, H.H.; Giri, B.; Wu, Q.S.; Kuca, K. Mycorrhizal symbiosis down-regulates or does not change root aquaporin expression in trifoliate orange under drought stress. *Plant Physiol. Biochem.* **2019**, *144*, 292–299. [CrossRef]
80. Luo, Y. The Effects of AMF on Cell Membrane Endogenous Polyamines and Salicylic Acid in Cirtus Under Drought Stress. Master's Dissertation, Huazhong Agricultural University, Wuhan, China, 2009.
81. Wang, W.X.; Zhang, F.; Chen, Z.L.; Liu, J.; Guo, C.; He, J.D.; Zou, Y.N.; Wu, Q.S. Responses of phytohormones and gas exchange to mycorrhizal colonization in trifoliate orange subjected to drought stress. *Arch. Agron. Soil Sci.* **2016**, *63*, 14–23. [CrossRef]
82. Wu, Q.S.; Xia, R.X.; Zou, Y.N. Improved soil structure and citrus growth after inoculation with three arbuscular mycorrhizal fungi under drought stress. *Eur. J. Soil Biol.* **2008**, *44*, 122–128. [CrossRef]
83. Zhang, F.; Zou, Y.N.; Wu, Q.S.; Kuča, K. Arbuscular mycorrhizas modulate root polyamine metabolism to enhance drought tolerance of trifoliate orange. *Environ. Exp. Bot.* **2019**, *171*, 103926. [CrossRef]
84. He, J.D.; Zou, Y.N.; Wu, Q.S.; Kuca, K. Mycorrhizas enhance drought tolerance of trifoliate orange by enhancing activities and gene expression of antioxidant enzymes. *Sci. Hortic.* **2019**, *262*, 108745. [CrossRef]
85. Liang, S.M.; Zhang, F.; Zou, Y.N.; Kuca, K.; Wu, Q.S. Metabolomics Analysis Reveals Drought Responses of Trifoliate Orange by Arbuscular Mycorrhizal Fungi with a Focus on Terpenoid Profile. *Front. Plant Sci.* **2021**, *12*, 740524. [CrossRef]
86. Liu, J.; Guo, C.; Chen, Z.L.; He, J.D.; Zou, Y.N. Mycorrhizal Inoculation Modulates Root Morphology and Root Phytohormone Responses in Trifoliate Orange under Drought Stress. *Emir. J. Food Agric. (EJFA)* **2016**, *28*, 251–256. [CrossRef]
87. Wu, H.H.; Zou, Y.N.; Rahman, M.M.; Ni, Q.D.; Wu, Q.S. Mycorrhizas alter sucrose and proline metabolism in trifoliate orange exposed to drought stress. *Sci. Rep.* **2017**, *7*, 42389. [CrossRef]

88. Zhang, F.; He, J.D.; Ni, Q.D.; Wu, Q.S.; Zou, Y.N. Enhancement of Drought Tolerance in Trifoliate Orange by Mycorrhiza: Changes in Root Sucrose and Proline Metabolisms. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2017**, *46*, 270–276. [CrossRef]
89. Wu, Q.S.; He, J.D.; Srivastava, A.K.; Zou, Y.N.; Kuca, K. Mycorrhizas enhance drought tolerance of citrus by altering root fatty acid compositions and their saturation levels. *Tree Physiol.* **2019**, *39*, 1149–1158. [CrossRef] [PubMed]
90. Zou, Y.N.; Wu, Q.S.; Huang, Y.M.; Ni, Q.D.; He, X.H. Mycorrhizal-Mediated Lower Proline Accumulation in *Poncirus trifoliata* under Water Deficit Derives from the Integration of Inhibition of Proline Synthesis with Increase of Proline Degradation. *PLoS ONE* **2013**, *8*, e80568. [CrossRef] [PubMed]
91. Zou, Y.N.; Zhang, F.; Srivastava, A.K.; Wu, Q.S.; Kuca, K. Arbuscular Mycorrhizal Fungi Regulate Polyamine Homeostasis in Roots of Trifoliate Orange for Improved Adaptation to Soil Moisture Deficit Stress. *Front. Plant Sci.* **2021**, *11*, 600792. [CrossRef]
92. He, J.D.; Li, J.L.; Wu, Q.S. Effects of *Rhizoglomus intraradices* on plant growth and root endogenous hormones of trifoliate orange under salt stress. *J. Anim. Plant Sci.* **2019**, *29*, 245–250.
93. Wu, Q.S.; Zou, Y.N. Mycorrhizal Symbiosis Alters Root H^+ Effluxes and Root System Architechure of Trifollate Orange Seedlings Under Salt Stress. *J. Anim. Plant Sci.* **2013**, *23*, 143–148.
94. Ding, Y.E.; Fan, Q.F.; He, J.D.; Wu, H.H.; Zou, Y.N.; Wu, Q.S.; Kuča, K. Effects of mycorrhizas on physiological performance and root TIPs expression in trifoliate orange under salt stress. *Arch. Agron. Soil Sci.* **2019**, *66*, 182–192. [CrossRef]
95. Zhang, Y.C.; Wang, P.; Wu, Q.H.; Zou, Y.N.; Bao, Q.; Wu, Q.S. Arbuscular mycorrhizas improve plant growth and soil structure in trifoliate orange under salt stress. *Arch. Agron. Soil Sci.* **2017**, *63*, 491–500. [CrossRef]
96. Xie, X.J. Effects of Arbuscular Mycorrhizal Fungi on Alkaline Tolerance of Citrus and Its Alleviative Mechanism. Master's Dissertation, Southwest University, Chongqing, China, 2022.
97. Cheng, H.Q.; Giri, B.; Wu, Q.S.; Zou, Y.N.; Kuca, K. Arbuscular mycorrhizal fungi mitigate drought stress in citrus by modulating root microenvironment. *Arch. Agron. Soil Sci.* **2021**, *68*, 1217–1228. [CrossRef]
98. Yang, X.H.; Zeng, B.; Li, X.G.; Sun, Z.H. The effects of inter-species different of arbuscular mycorrhizal fungi on growth and heat-resistant of trifoliate (*Poncirus trifoliata* Raf.) seedlings. *Mycosystema* **2005**, *24*, 582–589.
99. Wu, Q.S.; Zou, Y.N. Beneficial roles of arbuscular mycorrhizas in citrus seedlings at temperature stress. *Sci. Hortic.* **2010**, *125*, 289–293. [CrossRef]
100. Cao, M.A.; Zhang, F.; Abd, A.E.F.; Wu, Q.S. Mycorrhiza improves cold tolerance of Satsuma orange by inducing antioxidant enzyme gene expression. *Biocell* **2022**, *46*, 1959–1966. [CrossRef]
101. Pan, C.W.; Liu, X.F.; Qu, P.F.; Wu, Q.S. Enhancement of Arbuscular Mycorrhizal Fungi on Antioxidant Capacity of Roots of Trifoliate Orange under Temperature Conditions. *J. Yangtze Univ. (Nat. Sci. Ed.)* **2011**, *8*, 245–247+18.
102. Zeng, B. Effects of Arbuscular Mycorrhizal Fungi on Growths and High Temperature Tolerance of Trifoliate Orange Seedling. Master's Dissertation, Huazhong Agricultural University, Wuhan, China, 2005.
103. Cao, M.A.; Wang, P.; Hashem, A.; Wirth, S.; Abd Allah, E.F.; Wu, Q.S. Field Inoculation of Arbuscular Mycorrhizal Fungi Improves Fruit Quality and Root Physiological Activity of Citrus. *Agriculture* **2021**, *11*, 1297. [CrossRef]
104. Cao, S.C. Effect of interaction between Rhizobia and Arbuscular Mycorrhizal Fungi on Nutrient Absorption and Physiological Effect of Hongjiang Orange. Master's Dissertation, Southwest University, Chongqing, China, 2020.
105. Fang, L.F.; He, X.H.; Zhang, X.L.; Yang, Y.H.; Liu, R.; Shi, S.M.; Shi, X.J.; Zhang, Y.T. A Small Amount of Nitrogen Transfer from White Clover to Citrus Seedling via Common Arbuscular Mycorrhizal Networks. *Agronomy* **2020**, *11*, 32. [CrossRef]
106. Sugiura, Y.; Akiyama, R.; Tanaka, S.; Yano, K.; Kameoka, H.; Marui, S.; Saito, M.; Kawaguchi, M.; Akiyama, K.; Saito, K. Myristate can be used as a carbon and energy source for the asymbiotic growth of arbuscular mycorrhizal fungi. *BioRxiv* **2020**, *117*, 25779–25788. [CrossRef]