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Arbuscular mycorrhiza as an essential ecotechnological tool: a critical review of literature on the role of Arbuscular Mycorrhizal Fungi in the sustainability of cultivation and conservation of palms

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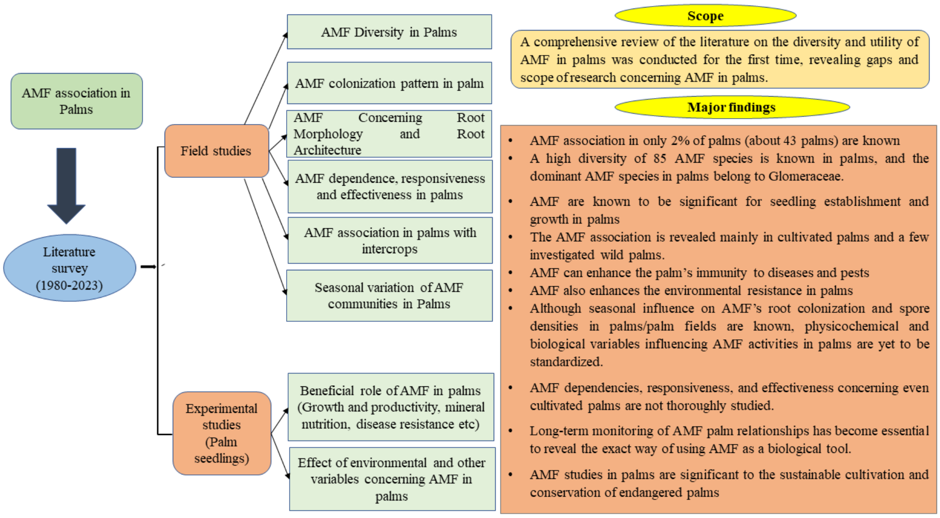
Abstract

Palms are an ecologically and economically significant family of plants, including many crops. Sound knowledge of the ecology of arbuscular mycorrhizal fungal (AMF) association in plants is essential to the sustainable cultivation of crops and the conservation of sensitive species. The current Review is the first-ever comprehensive critical analysis of literature on AMF in the sustainable cultivation and conservation of palms, which reveals the gaps in existing studies and explains the specific needs of future investigations on AMF in Palms. AMF in only 2% of the known palms are explored so far; a majority of wild palms and cultivated palms in many different regions remain unexplored. However, per the current literature, a high diversity of about 85 species of AMF from about 43 palms are known. The beneficial roles of AMF in palms include boosting productivity, assisting in the in-vitro raising of seedlings, and providing immunity to diseases and environmental stress. However, the identification of external and internal variables crucial to AMF association in palms in the field, long-term monitoring of AMF's beneficial influence in palms, and experimental application of AMF from wild palms in cultivated palms are further required. Overall, AMF dependence, responsiveness, and effectiveness in palms also need thorough investigation in the future.

Keywords: Mycorrhiza, Sustainable Agriculture, Palm Diversity, Optimization of Variables, Agricultural Sustainability.

Graphical abstract



Scope

A comprehensive review of the literature on the diversity and utility of AMF in palms was conducted for the first time, revealing gaps and scope of research concerning AMF in palms.

Major findings

- AMF association in only 2% of palms (about 43 palms) are known
- A high diversity of 85 AMF species is known in palms, and the dominant AMF species in palms belong to Glomeraceae.
- AMF are known to be significant for seedling establishment and growth in palms
- The AMF association is revealed mainly in cultivated palms and a few investigated wild palms.
- AMF can enhance the palm's immunity to diseases and pests
- AMF also enhances the environmental resistance in palms
- Although seasonal influence on AMF's root colonization and spore densities in palms/palm fields are known, physicochemical and biological variables influencing AMF activities in palms are yet to be standardized.
- AMF dependencies, responsiveness, and effectiveness concerning even cultivated palms are not thoroughly studied.
- Long-term monitoring of AMF palm relationships has become essential to reveal the exact way of using AMF as a biological tool.
- AMF studies in palms are significant to the sustainable cultivation and conservation of endangered palms

Recommended Citation

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1. Introduction

Palms, one of the most ecologically and economically versatile plants [1], mainly tropical and subtropical and rarely temperate [2, 3], belong to the family Arecaceae. There are about 2600 species of palms in the world, belonging to 181 genera [3, 4], growing in diverse geographic areas [5], including swamps, deserts, coasts, and highlands up to 3000 meters high [6]. Palms are significant economic crops in many countries, widely cultivated for various industrial products, mainly oil and fruits, fiber, wood, starch, sugar, juice, and wine [7, 8]. Accordingly, Arecaceae stands out as a unique plant family that is highly useful to humans [9]. In addition to the commercially cultivated palms such as coconut palm (*Cocos nucifera* L.), date palm (*Phoenix dactylifera* L.), and African oil palm (*Elaeis guineensis* Jacq.) [10, 11], there are many palms cultivated for ornamental and medicinal purposes [9, 12, 13, 14, 15, 16]. Palms and palm products will continue contributing significantly to human life and will remain inevitable to human sustainability and progress.

Palm cultivation is currently facing diverse challenges worldwide. Heavy usage of chemical fertilizers in palm groves [17] causes harmful effects on soil fertility and ecosystems. The success of acquiring sustainability in palm cultivation and palm-based industries depends on finding alternative measures to avoid excessive use of chemicalized inputs, such as regular applications of organic or biofertilizers [18, 19, 20, 21, 22]. An expert recommendation of 560 g N, 320 g P2O5, and 1200 g K2O for an adult coconut tree in two equal splits per year [23] shows the burden of chemical addition into soils [24] in palm fields. Often, farmers add fertilizers excessively, exceeding the recommended doses [25]. Reducing chemicalized inputs into agricultural fields is also significant to 'environment safety' and 'safe food for all' as envisaged in the UN goals for the future world [26]. Since sustainability in agriculture is one of the crucial goals of the UN Sustainable Development Goals 2030 (SDG 30), it cannot be fulfilled without taking measures for the sustainability of palm cultivation as well.

The plant-microbial interaction plays a crucial role [27] in improving all kinds of crops' sustainability and performance, especially in a less or non-chemicalized or organic agricultural environment. Among the diverse types of microbial associations in plants [28], the symbiotic mycorrhizal association is one of the earliest adaptations subjected to about 400 million years of evolution [29]. Among the natural mycorrhizal associations in plants, the arbuscular mycorrhizal fungi (AMF) are well-known natural microbial associates of plants with varying dependence, responsiveness, and effectiveness [30] concerning plants, soils, and AMF.

The AMF is essential to enhance plant nutrition and to minimize chemical fertilizer inputs to crops [31]. The introduction of specific AMF into crop fields is crucial in improving soil health by enhancing soil aggregation [32, 33] and helping plants resist stress and grow healthy, even in heavy metal-contaminated soils [34]. Recently, AMF has been identified as inevitable in organic agriculture [35].

Khudairi [36] first demonstrated AMF association in date palms. However, [37], for the first time, explained its beneficial roles in the peach palm (*Bactris gasipaes*). Since then, the beneficial roles of AMF as a significant microbial symbiont actively involved in the palm′s nutrient supply have been demonstrated by many authors in diverse palms [38, 39, 40, 41, 42]. However, despite the great diversity of palms, the AMF associations in only a few cultivated palm species have been intensively investigated. It is now well known that palms with a coarse root system characterized by limited root branching and root hairs require mycorrhizae to meet their high demand for nutrients to support the large biomass and fruit production [43, 44]. However, the investigation on AMF concerning root morphology and architecture of palms is quite limited [45, 46, 47].

St. John [48] perhaps presents the first historical review of AMF and their role in cultivating palms. Since then, many new studies on AMF in diverse palms have appeared in the literature. However, reviews are available on the status of mycorrhizal research and the beneficial role of AMF association only on two cultivated palms, the oil palms [49, 50] and date palms [43, 51]. It may be noted that although the information on AMF association in about 43 palms, including oil palm, date palm, and coconut palm, is available in the literature, a comprehensive review of the entire literature on AMF association in all the studied palms together has not yet been done. Since AMF association is an established reality in most of the cultivated palm species [52, 53, 54, 55, 56] such a complete review of the literature on AMF in Arecaceae has become highly essential, especially in advancing further research on sustainable palm cultivation and conservation of endangered and threatened palm species. The current review enabled the fulfillment of this task.

The primary goals of the current review included: (1) Identification of AMF diversity known in palms per the existing literature; (2) Understanding the root colonization pattern known in palms and checking whether the pattern of root colonization concerning root morphology and architecture is sufficiently investigated; (3)

Understand whether a seasonal variation of AMF in palms is known per existing literature; (4) Know the exact beneficial effect of mycorrhizae on palm growth, production, and soil health; (5) Check whether the role of AMF in alleviating various environmental stresses and diseases in palms is known; (6) Know the extent of available information on variables (plant, fungal and environmental) concerning AMF in palms; (7) Identify further research requirements on judicious application of AMF as a biological tool in palms. The current review represents the first critical analysis of all the existing research information on AMF in diverse palms. It explains the significant gaps in research information on mycorrhizal application in palms for sustainable farming and the scope of further research on the conservation of rare palms.

2. Materials and Methods

The methodology employed was similar to recent reviews on AMF in other plants [57, 58, 59]. The literature period was set from the first available study on AMF in date palms in 1969 to the most recent AMF studies in diverse palms up to 2023. The bibliometric studies on AMF in palms are systematically carried out using primary databases such as Google Scholar, JSTOR, PubMed, Science Direct, SciELO, and Web of Science. The main keywords chosen to find out the literature for the current review included "arbuscular mycorrhizal fungi," "AMF," "Mycorrhiza," "occurrence," "diversity," "seasonal changes," "Palms," "coconut palm," "date palm," "oil palm," "palm cultivation," "ecosystem sustainability," "crop productivity," "environmental factors," "stress alleviation," "soil health" " variables," "root morphology" and "root architecture." Among them, keywords such as "Palms," "coconut palm," "date palm," "oil palm," and "palm cultivation" were searched along with each of the other keywords individually and in diverse combinations per Boolean logic for obtaining the maximum research reports on AMF concerning palms in the literature. Mendeley Desktop was used to arrange literature systematically and retrieve the required information using the keywords mentioned above. Out of the 246 research papers collected using the keywords mentioned above, only 118 were found relevant as research pertaining to AMF in palms. The collected literature was analyzed using Microsoft Excel, and the number of literature country-wise (**Fig. 1**) and year-wise (**Fig. 2**) are graphically shown (as per the data on Web of Science) below to provide an overview of AMF concerning palms in the world.

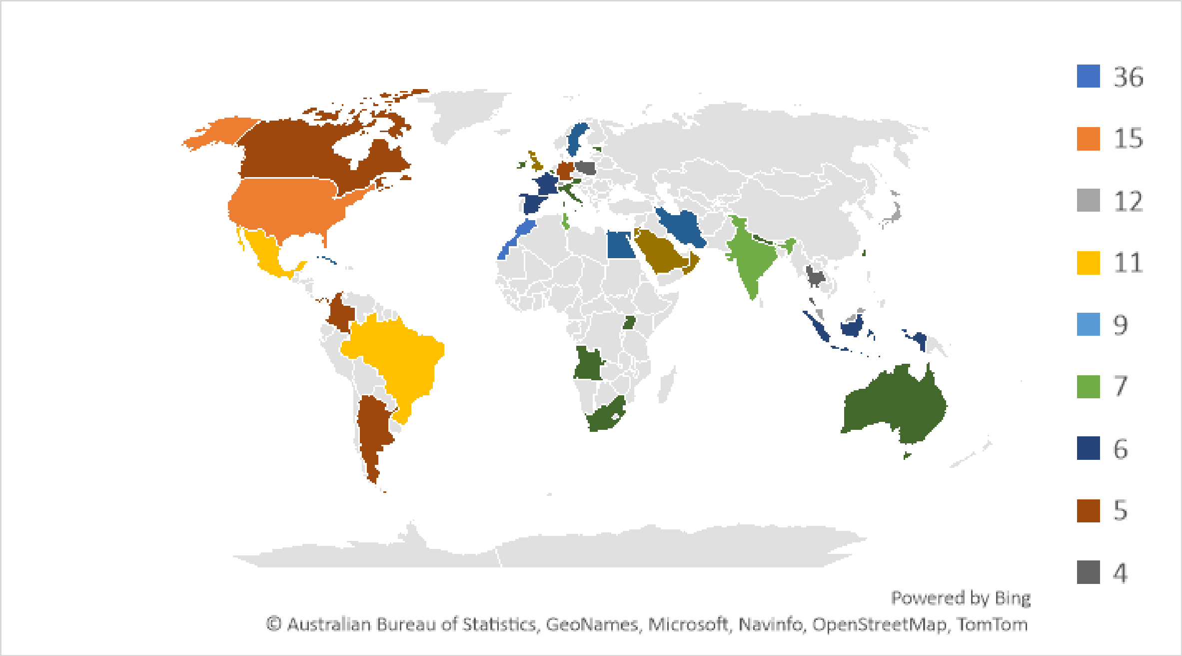

Figure 1 Graphical representation of the country-wise distribution of literature related to AMF in palms.

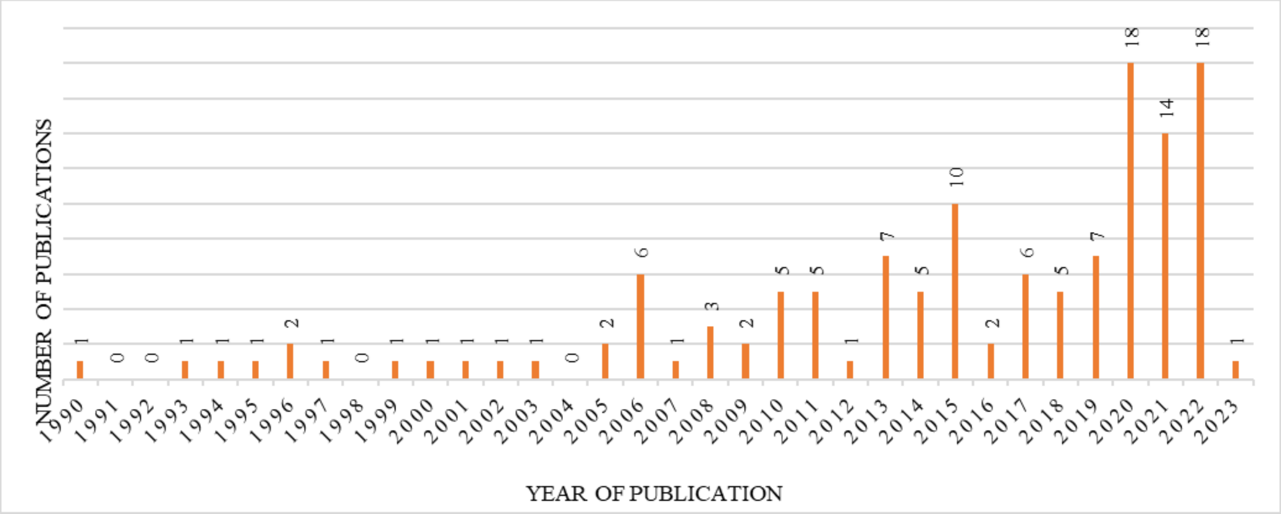

Figure 2 Year-wise studies published on AMF symbiosis in Palms as per Web of Science between 1990-2023

3. Results and Discussion

AMF diversity in palms:

Numerous studies have shown the natural occurrence of AMF in the soils of palm fields, as well as the presence of mycorrhizal structures inside the palm roots [36, 53, 54, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69]. Among the field and experimental studies on AMF diversity and root colonization in palms, most of the studies were on AMF in the date palm (17 studies), followed by oil palms (14 studies) and coconut (9 studies). A review of the literature on date palms by Al-Karaki [43] shows that it is very responsive to the mycorrhizal association, and AMF application is essential to sustainable palm cultivation. Similarly, in a review of the mycorrhizal status and applications of AMF in oil palms [49], the significance of AMF for its successful cultivation is emphasized. A critical summary of the AMF diversity and AMF root colonization characteristics in palms per the existing literature is given in **Table 1** and **Table 2**.

Table 1: Literature on diversity of arbuscular mycorrhizal fungi in palms.

Palms and their common names	**AMF species/ Genera / Families**	**Morphological or Molecular**	**Country**	**References**
Acoelorrhaphe wrightii (Griseb. & H. Wendl.) H. Wendl. Ex Becc (Palmetto palm or Tasiste)	*Acaulospora* (4 spp.), ^{5}*Claroideoglomus* (2 spp.), *Diversispora* (1 sp.), *Entrophospora* (1 sp.), *Funneliformis* (2 spp.), *Gigaspora* (1 sp.), ^{8}*Glomus* (3 spp.), *Paraglomus* (1 sp.), *Rhizophagus* (3 spp.), *Sclerocystis* (2 spp.), *Septoglomus* (1 sp.) and ^{3}*Scutellospora* (1 sp.)	Morphological	Mexico	[70]
Areca catechu L. (Arecanut or Betel nut palm)	*Acaulospora* (1 sp.), ^{5}*Claroideoglomus* (1 sp.), *Funneliformis* (3 spp.), ^{9}*Glomus* (4 spp.), and *Rhizophagus* (1 sp.)	Morphological	India	[54, 71]
Attalea speciosa Mart. ex-Spreng. (Babassu palms)	*Acaulospora* (6 spp.), *Cetraspora* (1 sp.), *Entrophospora* (1 sp.), *Funneliformis* (1 sp.) *Fuscutata* (1 sp.), *Glomus* (3 spp.), *Orbispora* (1 sp.), *Sclerocystis* (1 sp.),	Morphological	Brazil	[72]

	Scutellospora (1 sp.)			
Bactris gasipaes Kunth (Peach palm)	*Glomus* (14 spp.) and *Acaulospora* (8 spp.)	Morphological	Colombia	[13]
Bactris major Jacq.	*Acaulospora* (1 sp.), *Gigaspora* (1 sp.), *Glomus* (3 spp.) and *Scutellispora* (1 sp.)	Morphological	Mexico	[46]
Bactris mexicana Mart.	*Acaulospora* (1 sp.), *Glomus* (2 spp.)	Morphological	Mexico	[46]
Butia yatay (Mart.) Becc.	*Acaulospora* (16 spp.), *Archaeospora* (1 sp.), *Claroideoglomus* (2 spp.), *Entrophospora* (1 sp.), *Funneliformis* (2 spp.), *Gigaspora* (4 spp.), *Glomus* (9 spp.), *Racocetra* (2 spp.), *Rhizophagus* (2 spp.) and [2]*Scutellospora* (7 spp.)	Morphological	Argentina	[73, 74, 75, 76]
Coccothrinax crinite (Griseb., & H.Wendl. ex C.H.Wright) Becc.(Old man palm" or "Palma petate)	*Acaulospora* (3 spp.), *Funneliformis* (2 spp.), *Gigaspora* (1 sp.), [10, 13]*Glomus* (7 spp.), [1]*Kuklospora* (1 sp.), *Scutellospora* (1 sp.) and [12]*Viscospora* (1 sp.)	Morphological	Western Cuba	[77]
Cocos nucifera L. (Coconut palm)	*Acaulospora* (5 spp.), [5]*Claroideoglomus* (3 spp.), *Dentiscutata* (1 sp.), *Diverssipora* (2 spp.), *Funneliformis* (3 spp.), [7, 11]*Gigaspora* (8 spp.), [9, 10]*Glomus* (21 spp.), *Redeckera* (1 sp.), *Rhizophagus* (2 spp.), [3]*Scutellospora* (1 sp.), *Septoglomus* (1 sp.)	Morphological	India	[54, 55, 62]
	Acaulospora, *Claroideoglomus*, *Diversispora*, *Dominikia*, *Gigaspora*, *Glomus*, *Racocetra*, *Redeckera*, *Rhizophagus*, *Sclerocystis* and *Septoglomus*	Morphological and molecular	Mexico	[78]
	Acaulospora, *Gigaspora*, *Glomus*, and *Scutellospora*	Morphological	Lakshadweep	[79]
Desmoncus orthacanthos Mart.	*Acaulospora* (1 sp.) *Glomus* (1 sp.)	Morphological	Mexico	[46]
Elaeis guineensis Jacq (Oil palm)	*Acaulospora*, *Gigaspora*, *Glomus*, and *Sclerocystis*	Morphological	Malaysia	[80]
	Twelve glomalean fungi with coarse hyphae in the oil palm rhizosphere.	Morphological	Malaysia	[81]
	Acaulospora, *Dentiscutata*, *Funneliformis*, *Gigaspora*, *Glomus*, *Scutellospora* and *Rhizophagus*	Morphological	Thailand	[64]
	Acaulospora, *Glomus*, and *Gigaspora*	Morphological	Indonesia	[68]
	Acaulospora (1 sp.)	Morphological and molecular	Indonesia	[82]
Euterpe oleracea Mart (Naidi palm)	AMF families of *Ambisporaceae*, *Claroideoglomeraceae*, *Diversisporaceae*, *Glomeraceae and Paraglomeraceae*	Morphological	Colombia	[67]
Metroxylon sagu Rottb (Sago palm)	*Acaulosporaceae*, *Ambisporaceae*, *Claroideoglomeraceae*, *Gigasporaceae*, *and Glomeraceae*	Molecular	Malaysia	[83]

Phoenix dactylifera L. (Date palm)	[6]*Glomus* (1 sp.)	Morphological	Saudi Arabia	[61]
	Acaulospora (3 spp.), [6,9,12]*Glomus* (5 spp.) and Scutellospora (2 spp.)	Morphological	Morroco	[53]
	Acaulospora (1 sp.), [4,5,8,9,10,12]*Glomus* (12 spp.), *Paraglomus* (1 sp.), *Scutellospora* (2 spp.) and *Racocetra* (2 spp.)	Morphological and molecular	Southern Arabia	[84]
	[5]*Claroideoglomus* (1 sp.), *Diversispora* (2 spp.) [12]*Funneliformis* (1 sp.) and *Septoglomus* (1 sp.)	Morphological and molecular	Oman	[85, 86]
	Acaulospora (3 spp.), [5,6,9,12]*Glomus* (9 spp.) [7]*Scutellospora* (3 spp.)	Morphological	Morocco	[87]
	Acaulospora (1 sp.), [6,9,12,13]*Glomus* (5 spp.) *Sclerocystis* (1 sp.) and *Scutellospora* (1 sp.)	Morphological	Tunisia	[88]
	Acaulospora, *Glomus*, and *Sclerocystis*	Morphological	Morocco	[89]
	Dominikia (1 sp.) *Entrophospora* (1 sp.) *Funneliformis*(1 sp.), *Rhizophagus* (1 sp.)	Morphological and molecular	Tunisia	[66]
	Acaulospora (2 spp.), [5]*Claroideoglomus* (1 sp.), *Funneliformis* (1 sp.), *Gigaspora* (3 spp.), [6]*Glomus* (3 spp.) *Racocetra* (1 sp.), *Rhizophagus* (1 sp.), [3,7]*Scutellospora* (2 spp.)	Morphological	South-eastern Algeria	[90]
	Septoglomus (2 spp.)	Morphological and molecular	Arabian Peninsula	[91]
	[5]*Albahypha* (1 sp.), [5]*Claroideoglomus* (1 sp.), *Funneliformis* (1 sp.), *Pervetustus* (1 sp.), [9]*Rhizoglomus* (1 sp.), *Septoglomus* (1 sp.)	Morphological and molecular	Morocco	[92]
Salacca zalacca (Snake fruit or Salak)	*Glomus* (3 spp.) and *Entrophospora* (1 sp.)	Morphological and molecular	Indonesia	[65]
Serenoa repens (W. Bartram) Small (Saw palmetto)	*Gigaspora* and *Glomus*	Morphological	Florida	[45]

New names of certain AMF species based on recent AMF phylogeny http://www.amf-phylogeny.com/: [1]*Acaulospora kentinensis*; [2]*Cetraspora gilmorei*; [3]*Dentiscutata nigra, D. erythropus, D. heterogama*; [4]*Diversispora eburnea*; [5]*Entrophospora etunicata, E. drummondi, E. claroidea, E. lutea*; [6]*Funneliformis mosseae, F. monosporum*;[7] *Racocetra gregaria, R. fulgida, R. coralloidea*; [8]*Rhizoglomus microaggragatum;* [9]*Rhizophagus fasiculatus, R. aggregatum, R. microaggragatum, R. intraradices, R. clarus, R. invermaius, R. irregularis*; [10]*Sclerocystis sinuosum, S. clavisporum, S. coremioides, S. liquidambaris, S. rubiformae, S. taiwanense*; [11]*Scutellospora auriglobal*; [12]*Septoglomus constrictum, S. africanum, S. viscosum*; [13]*Sieverdingia tortuosa*.

Table 2: Literature on root colonization characteristics of arbuscular mycorrhizal fungi in Palms.

Name of Palms and their common names	Root colonization characteristics: range (%), AMF structures, and pattern/ morphology	Source of roots	References
Acoelorrhaphe wrightii (Palmetto palm or Tasiste)	A, H, and V; *Arum* type	Field, nursery	[93]
	24-67%; IH and V; *Arum* type	Field	[70]
Areca catechu L. (Arecanut or Betel nut palm)	70.6%; A and V; *Arum* and *Paris* types	Field	[52]
	15-57.16%; A, H and V	Field	[54]
	50.8-77.5%; AC, H and V; *Paris* type	Field	[71]
Arenga engleri Becc. (Taiwan sugar palm or dwarf sugar palm)		Field	[48]
Astrocaryum mexicanum Liebm. Ex Mart. (Mexican forest palm)	40-50%; HC and V; *Paris* type	Field	[94]
Attalea speciosa Mart. ex-Spreng. (Babassu palms)	34.2- 49.6%	Field	[72]
Bactris gasipaes Kunth. (Peach palm)		Field	[37]
		Greenhouse	[48]
	21%; A and HC; *Arum* and *Paris* types	Field	[95]
	58-90%; IRM, V and A	Field	[13]
Bactris major Jacq.	62%; A and V	Field	[46]
Bactris mexicana Mart.	42%; A and V	Field	[46]
Brahea armata S. Watson (Mexican blue palm)	A, H, and V	Greenhouse	[96]
	AC and H; *Intermediate* type	Greenhouse	[47]
Borassus flabellifer L (Palmyra palm or toddy palm)	70.6%; A and V; *Arum* and *Paris* types	Field	[52]
Butia yatay	96%; A; *Arum* type	Field	[74]
Calamus sp.		Field	[48]
Caryota monostachya Becc. (Dwarf fishtail palm)		Field	[97]
Caryota urens L. (Jaggary Palm, solitary fishtail palm, toddy palm)		Arboretum	[48]
Chamaerops humilis L. (Dwarf Fan Palm or European Fan Palm)		Greenhouse	[48]
	A, H, and V	Greenhouse	[96]
	AC, H, and V; *Intermediate* type	Greenhouse	[47]
Coccothrinax argentata (Jacq.) L.H. Bailey (Florida Silver palm)	A, H HC, and V; *Arum* type	Field, nursery	[93]
Coccothrinax crinite (Griseb., & H.Wendl. ex C.H.Wright) Becc.(“Old man palm" or "Palma petate”)	51- 67%; A, HC and V; *Intermediate* type	Field	[77]
Cocos nucifera L. (Coconut palm)		Field	[48]
		Field	[38]

	56.8-95.2%	Nursery	[62]
	65.7%-70.6%; A and V; *Arum* type	Field	[52]
	56.4-77.2%; A, H and V	Field	[54]
	32.33%- 55.17%; A, H and V; *Arum* type	Field	[55]
		Field	[78]
	53.33-61.11%; A, IRRH and V; *Paris*-type	Field	[79]
Desmoncus orthacanthos Mart.	51%; A and V	Field	[46]
	5-34%; IRRH; *Paris* type	Field	[98]
Elaeis guineensis Jacq (African Oil palm)		Field	[48]
	32.49-52.18%	Nursery	[17]
	More than 70%; A, H, HC, and V; *Arum* and *Paris* type	Nursery	[99]
	75.8%, 82.9%	Nursery	[100]
	25-31%	Greenhouse	[171]
	58%	Nursery	[101]
	97-100%	Nursery	[102]
	36.3%; A, H and V	Nursery	[103]
	46-55%	Field, greenhouse	[56]
Euterpe edulis Mart. (Juçara, jussara açaí-do-sul or palmiteiro palm)		Field	[48]
	Field grown palms-6.5%, palm seedlings-14.3%	Field, greenhouse	[104]
Euterpe oleracea Mart. (Naidi palm)		Field	[48]
		Greenhouse	[48]
	4.3 – 10.2 %	Field	[67]
Jessenia bataua (Mart.) Burret (Pataua palm)		Greenhouse	[48]
Livistona chinensis (Jacq.) R.Br. ex-Mart. (Chinese fan palm or fountain palm)		Field	[48]
Metroxylon sagu Rottb. (Sago palm)	39.2- 73.2%; A, H and V	Field	[83]
Nypa fruticans Wurmb. (Nipa palm or Mangrove palm)	63.3%-81.0%; A and V; *Arum* and *Paris* types	Field	[52]
Oenocarpus bacaba Mart. (Turu palm)		Field	[48]
Phoenix canariensis Chabaud. (Canary Island date palm)	A, H, and V	Greenhouse	[96]
	AC, H, and V; *Intermediate* type	Greenhouse	[47]
Phoenix dactylifera L (Date palm)		Field	[48]
	90%	Field	[61]
	72%; A, IRRH and V; *Arum* type	Field	[53]
	A, H, and V	Greenhouse	[96]
	AC, IRH, and ICH; I*ntermediate* type	Greenhouse	[47]

	7- 60%; A, IRRH and V	Field	[87]
	more than 60%; A, H and V	Field	[88]
	>70%; H and V	Field	[66]
	15.7-43.8%; A, H and V	*In vitro* raised palm plantlets	[105]
	91%	Field, green house	[92]
Phoenix paludosa Roxb. (Mangrove date palm)	81%; A and V; *Arum* and *Paris* type	Field	[52]
Pseudophoenix sargentii H. Wendl. Ex Sarg. (Florida cherry palm or buccaneer palm)	A, H, and V; *Arum* type	Field, nursery	[93]
Rhapis excelsa (Thunb.) A. Henry (Broadleaf *lady palm* or bamboo palm)		Green house	[48]
Rhapis humilis Blume (Slender Lady Palm)		Green house	[48]
Roystonea elata (Bart.) F. Harper (Florida royal palm)		Field	[48]
Sabal palmetto (Walter) Lodd. ex-Schult. & Schult.f. (Cabbage palm or sabal palm)		Field	[48]
	A, H, HC, and V; *Arum* type	Field, nursery	[93]
Salacca zalacca (Gaertn.) Voss (Snake fruit or Salak)	93.33- 100%; A, H and V	Field	[65]
Serenoa repens (W. Bartram) Small (Saw palmetto)	A, HC, and V; *Arum* type	Field, greenhouse	[45]
	A, H, HC, and V; *Arum* type	Field, nursery	[93]
Syagrus romanzoffiana (Cham.) Glassman (Queen's palm)		Field	[48]
Thrinax morrisii H. Wendl. (Brittle thatch palm or critical thatch palm)	A, H, and V; *Arum* type	Field, nursery	[93]
Trithrinax campestris (Burmeist.) Drude & Griseb. (Caranday palm)	A, ICH and IRH, V; *Intermediate* type	Field	[106]
Washingtonia filifera (Lindl.) H. Wendl (California Fan Palm)		Field	[48]

A- arbuscules, H- hyphae, V- vesicles, AC- arbusculate coils, HC- hyphal coils, ICH- intercellular hyphae, IRH- intracellular hyphae, IRRH- intra-radical hyphae and IRM- intra-radical mycelium

Although **Table 2** shows that most palms are mycorrhizal, nonmycorrhizal condition is reported in particular palms such as *Areca catechu*, *Cocos nucifera*, *Jessenia bataua*, *Phoenix dactylifera*, *Phoenix roebelenii*, *Syagrus* spp. [48], *Wallichia mooreana* [97] and weak mycorrhizal condition is reported in *Syagrus romanzoffiana* [104]. Altogether about 85 species of AMF are known from currently studied palms. A similar high diversity of AMF has already been reported in medicinal plants [107] and Acacia trees [108].

Generally, AMF species associated with most tree species belong to the genera of *Glomus* and *Acaulospora* [109, 110, 111, 112, 113]. Similarly, members of the family Glomeraceae are reported as the dominant AMF per the limited literature available on AMF concerning palms, especially in cultivated palms, such as date, coconut, and oil palms. Moreover, among the 38 species of AMF so far reported in date palms, *Glomus* spp. (*Glomus* spp. are now known by different names) is the most frequent one, followed by *Acaulospora* spp. and *Rhizophagus* spp. Among the *Glomus* spp., (*Funneliformis mosseae* (T.H. Nicolson & Gerd.) C.Walker & A. Schüssler = *Glomus mosseae*) is the most frequent one so far reported in date palms (five studies among the total fifteen reports in date palms are about *Funneliformis mosseae*). Geographically, the reports (including field studies and experiments) on AMF in date palms are available from 45 countries, but information on the particular species is known from four countries (Saudi Arabia-1, Morocco-2, Tunisia-1, and Algeria-1). In contrast, *Glomus* spp., *Acaulospora* spp., and *Gigaspora* spp. are the dominant AMF associates in coconut palms. *Gigaspora decipiens* I.R. Hall & L.K. Abbott and *Glomus fasciculatum* (= *Rhizophagus fasciculatus* C. Walker & Schuessler) are the common species in coconut palm (known in three studies among the total eight studies). However, *Glomus* spp. and *Acaulospora* spp. are the dominant AMF in most of the wild and ornamental palms. Besides the commercially cultivated palms, AMF status in some palm forests is also available in the literature [73, 74, 75, 76]. Most authors report the diversity of AMF in palm forests, whereas others report root colonization or spore count and density of AMF in the palm forest fields.

The high level of AMF richness in the palm rhizosphere emphasizes the importance of AMF as a natural biological partner for the sustainable growth and production of palms. It may be noted that among the AMF investigations in 43 palms so far conducted, the absence of its association is reported in palms of certain specific fields, and the association is regarded as weak in some cases [48, 104, 114]. However, since Arecaceae, the palm family, is large (2600 species), the available studies on AMF diversity in the 43 species explored (less than 2%) may be considered nominal. Even among the available studies, despite the wide distribution and great economic importance of cultivated palms, the reports on AMF association are limited to studies of such palms in some areas of about 45 countries so far explored. AMF association in palms of not even a single country or a particular climatic region within a country or over countries is fully explored.

Moreover, reports on AMF in palms concerning palm varieties are rare, such as in coconut [62, 63] and date palms [88]. The AMF association in palm concerning palm varieties may help use it as a biological tool in the sustainable cultivation of high-yielding palms. Therefore, the task involved in exploring the diversity of AMF in palms is arduous.

Mayakrishnan et al. [115] have reported a wide occurrence of fine root endophytes, which form hyphae, hyphal coils, and fine arbuscules in the roots of six species of palms, including coconut palm, in Tamil Nadu of South India. Therefore, further investigations on the extent of fine root endophytic flora in roots have also become significant in the AMF diversity explorations in palms.

Although the significance of high throughput molecular techniques has been emphasized in exploring the biodiversity of AMF in crop fields [116], such methods are rarely applied in palm fields [65, 66, 78, 82, 83, 84, 85, 86, 91, 92]. Molecular methods of determining the diversity of specific AMF species are significant in exploring the AMF diversity of palms in wild environments. Since many wild palms are resistant to pests and diseases [117], the AMF associates of such palms are to be explored. It may provide an opportunity for experimental exploration of the same in cultivated palms to improve their resistance to diseases and pests.

AMF dependence, responsiveness, and effectiveness in palms

Along with diversity studies, the extent of dependence, responsiveness, and effectiveness of specific AMF [30] in palms are significant. Host responsiveness to AMF is influenced by the soil environment, especially soil phosphorus [118, 119]. Soil receptivity of AMF is also a significant topic of AMF application in crops [120, 121]. Another vital area of investigation on AMF in field studies is the influence of plant interactions on AMF activities in soil for mineral accumulation in host plants [122]. Therefore, in the future, AMF field diversity studies concerning soil environmental conditions will be more desirable, as emphasized in the works of Wang et al. [113]. Similarly, Wu et al. [123] emphasize the effect of AMF on leaf Nitrogen (N), Phosphorus (P), and Potassium (K) stoichiometry concerning plant life cycle, plant growth habits, and AMF types in soils, which are useful in studies for understanding the role of specific AMF in palms in the future.

Additionally, since plant mycorrhizal dependency and responsiveness and AMF effectiveness in plant roots depend on many internal (morphologic, genetic, and physiological) and external variables, intensive studies are desirable for using AMF as a biological tool in the sustainable cultivation of palms. A meta-analysis of the literature on AMF in plants has shown that enhanced nutrient uptake by plants in association with AMF depends on changes in root characteristics such as root elongation, formation and elongation of lateral roots, root hairs, root surface area, and root volume [124]. Such information on AMF's influence on root characteristics is available in some studies on AMF in a few cultivated palms such as coconut palm [125, 126], date palms [40, 127, 128, 129, 130, 131, 132, 133, 134] and oil palm [17, 39, 56, 101, 103, 135]. The details of the influences are described in **Table 3**. Therefore, emphasis on studies focusing on the impact of AMF on palm root characteristics is desirable in the future. Such studies may improve the productive application of AMF in economically significant palms.

AMF colonization pattern in palm roots

The root colonization pattern of AMF and AMF concerning root morphology or root architecture in palms per the existing literature is shown in **Table 2.** Two primary classes of mycorrhizal patterns, the *Arum* and *Paris* types, are observed in the plant roots [29, 136]. The *Arum* type with arbuscules and intercellular hyphae is the most common AMF pattern observed in the roots of cultivated crops. The *Paris*-type with extensive hyphal coils and intracellular hyphae without arbuscules is the AMF pattern found in the roots of ferns, gymnosperms, and many wild angiosperms such as forest herbs and trees [137]. However, an *intermediate* type with hyphal coils and arbuscules are characteristic features of AMF in certain Angiosperms [138].

According to the existing literature, *Arum* type, *intermediate* type, and *Arum* and *Paris* type colonization patterns are reported in the Arecaceae family. While the *Arum* and '*Arum* and *Paris*' fungal colonization is reported in most date palm roots, *Arum* and *Paris* types of root colonization is found in coconut, depending on the environmental characteristics of fields or cultivars. In the wild and ornamental palms, *Arum* type, *Paris* type, *Arum* and *Paris* type, and *intermediate* type of AM morphology are reported. Factors such as plant physiological conditions, plant phenological stages, root morphology, fungal species, and external environmental variables may concern AMF root colonization patterns, such as *Arum* or *Paris* or *Intermediate* type in plant roots [138]. Investigating factors significant to particular colonization patterns is essential in understanding the AMF activity in plants [29]. Since the studied palms show all three patterns of root colonization, such studies concerning factors controlling root colonization patterns may be desirable in palms in the future.

AMF Concerning Root Morphology and Root Architecture

AMF are generally more prevalent in monocotyledons than dicotyledons, probably due to their preference for fibrous root systems [139]. Moreover, root characteristics such as branching and the number of fine roots in plants are significant in accepting AMF as an associate [140]. However, investigations on root morphology concerning AMF association are rare in palms and have been reported in three studies alone. Fisher and Jayachandran [45] observed AMF most frequently in the thinnest roots of a palm, where the mycelia are restricted to only the outer cortex. However, Carrillo et al. [46] observed AMF in the second and third-order roots of three palms they studied, where the fungal mycelia are restricted to the inner cortex. Later, Dreyer et al. [47] observed that AMF colonization is limited to the third-order roots in the four palms they studied, with certain exceptions in *Phoenix* spp., where the root colonization is restricted to the entire root cortex. Therefore, future emphasis on AMF root colonization concerning root structure is desirable.

Additionally, roots that are colonized by AMF and that are not may be present in the same root system in certain plants. Large lateral roots' tissue composition and plasticity are responsible for a high preference for AMF for colonization [141]. For example, in rice, AMF colonization is primarily limited to large lateral roots and rarely found in crown roots, whereas it is often absent in fine lateral roots [141, 142]. Limiting certain specific branches alone to colonization can affect colonization levels in the entire root system [143]. Usually, a particular region of the root is selected by AMF, usually after a molecular dialogue between the host and symbiont [140]. Therefore, investigations on the association of AMF concerning root morphology and root architecture in palm roots are significant. It is also attributed to the differential regulation of genes controlling anatomical or physiological properties of roots [144]. Genotypic variation in AMF dependency is reported in seedlings of coconut palms [62] and oil palms [39]. Clement and Habte [145] demonstrate the existence of genotypical variations in AMF dependency in Bactris gasipaes similar to that of oil palms.

AMF association in palms with intercrops

Although many authors have found AMF colonization and spore density of mixed crop systems is higher than that of monocultures [146, 147, 148], studies on the impact of intercropping on AMF association in palm fields is limited. Rajeshkumar et al. [55] reported that in coconut, AMF spore density, species richness, and colonization rate are higher in a mixed crop system than in its monocultures. Similarly, Ambili et al. [54] observed increased spore counts in the coconut fields, concerning an increase in the number of intercrops there. In date palms, mixed cropping with sorghum has shown a significant increase in the intensity of AMF root colonization and spore count in the field [148]. However, firm generalizations are impossible with this limited number of reports. The beneficial influences of intercropping on root colonization, growth, and productivity of cultivated palms need to be standardized concerning specific intercrops, soil types, climate, and seasons for productive utilization of specific intercrops in palm fields.

Seasonal variation of AMF communities in Palms

The development of the mycorrhizal association, especially the extent of AMF root colonization, is influenced by season [149]. Root colonization usually decreases with more extreme or rapid environmental changes. Moreover, seasonal environmental changes affect plant phenological events, which can precisely influence the pattern of AMF colonization [150]. However, it may be noted that many palms, such as coconut, are perennial and reproduce continuously upon attaining maturity. The difference between the host's vegetative and reproductive growth on root colonization in such palms may be recognized by examining the difference between young and mature palms only. However, in perennial palms such as *Borassus flabellifer* Linn., which reproduce only seasonally [151] and in monocarpic palms such as *Corypha umbraculifera* Linn. which reproduces only once in lifetime [152], the difference of the influences of host's reproductive and vegetative growth on root colonization can be studied per respective seasons of vegetative or reproductive growth.

Although observations of seasonal variations in AMF root colonization in palms are plenty [46, 64, 70, 76, 78, 87, 88, 94, 95], the details of specific seasonal factors such as temperature or water availability or duration of winter or summer influencing AMF in palms are not thoroughly investigated.

Generally, the AMF root colonization in palms increases with favourable growth conditions. In date palms, root colonization rises in the wet season, and AMF spore abundance in the dry season [87]. According to these authors, root colonization is high in the wet season because of the active vegetative growth of date palms. Usually, in annual crops [153] and many trees [154], a high root colonization rate is observed in the monsoon season, whereas high spore density in the dry winter season or summer season respectively. However, a contradictory observation is available in legumes where high levels of colonization and spore density are found in the summer [155]. Compared to the number of studies on annual crops and other trees, studies on seasonal influences on AMF activities in palms are limited. Moreover, the seasonal environmental characteristics may not be identical in all geographic regions. The summer may be wet in one region but dry in another region. In general, plant growth rate and root colonization rate depend on temperature and water availability. If water availability is not hindered, root growth is most intense in palms in the warm season [156]. Therefore, seasonal fluctuation in AMF colonization needs to be assessed based on seasons concerning water availability and the extent of temperature variations over seasons.

It is well-known that a difference in the relative growth of root and AMF per season can cause a seasonal difference in the degree of root colonization in plant roots [157]. Seasonal variations in AMF root colonization may also be due to differences in plant and fungal identities and plant phenological or temporal climatic or edaphic reasons [158]. The amount of available phosphorus and soil water availability in the fields are edaphic factors affecting root colonization in the hosts. Accordingly, Zougari-Elwedi et al. [88] showed a high rate of mycorrhizal root colonization (hyphae, vesicles, and arbuscules) in the summer season, the period of its active growth in the area characterized by sporadic rains, which boost plant growth and fungus colonization. The abundance of arbuscules is an indicator of nutrient demand in the host. Moreover, the authors observe a low root colonization rate and abundant sporulation of AMF in the same palms in the winter when palms are in a dormant growth stage.

It is natural that when the fungus sporulates in the winter, they require a carbon supply from its hosts for spore formation, which negatively affect new hyphal growth in such an unfavourable season of plant growth when plants cannot share extra nutrition with the symbiont. Lara-Pérez et al. [78] observe a similar trend in the seasonal behaviour of AMF in coconut palms. In the wild palms also, the same trend is found [94]. Similar tendencies of high root colonization in the rainy or growing season and high spore density in the summer are observed for other palms, such as *Desmoncus orthacanthos*, in other studies [46, 98]. Velázquez et al. [76] report the seasonal variation of AMF spore abundance in palm forests. Palm species differ in their growth patterns; caulescent and acaulescent palms exist [159]. Accordingly, we can conclude that the season favouring plant growth (acaulescent or caulescent, depending on species) in most palms also favours AMF root colonization.

Unlike the literature reports of a high percentage of root colonization in many palms in wet seasons, as mentioned above, Auliana and Kaonongbua [64] report a low rate of mycorrhizal colonization percentage in oil palms in the rainy season. They attribute the low colonization rate to the low adaptation level of mycorrhizal spores in soils in the rainy season. Fabian et al. [70] reports the highest percentage of AMF root colonization at the beginning of the dry season in the roots of a palm, *Acoelorraphe wrightii*, but the highest number of AMF spores at the onset of the rainy season. According to them, the species richness of AMF in the palm rhizosphere is controlled by the dispersion mechanisms of AMF. Moreover, surrounding vegetation and high environmental heterogeneity also affect AM fungal species richness in the field. Similarly, root colonization and spore density in the roots of *Bactris gasipaes* (peach palm) in the monoculture systems were high in the dry seasons [95]. Therefore, it may also be concluded that seasonal variations of AMF activity in palms depend on factors other than soil moisture content or temperature of a season. The lack of correlation between mycorrhizal colonization and rhizospheric spore density in most studies suggests that spore count depends on differential seasonal influences on the host and the symbiont. However, proper generalization of seasonal impacts on AMF in palms is impossible based on the currently available limited studies. Therefore, AMF root colonization patterns and growth responses in palms concerning seasonal variations of environmental factors, including water and nutrient availability and temperature from diverse climatic zones, have become desirable for determining a generalized optimum soil and other ecological conditions for the best AMF activity in palms.

The beneficial role of AMF in palms

The thick roots without fine root hairs in palms [160] limit the absorption of nutrients from the soil. According to Baylis' hypothesis [161], trees such as palms having root systems with coarse, little-branched, and hairless terminal roots have a high mycorrhizal association with mineral nutrition, even in fertile soil. Experimental studies have confirmed the beneficial roles of AMF in date palms, oil palms, and coconuts [56, 162, 163]. The variations in the extent of the positive impacts of AMF in different palms, as expressed in the literature, are depicted in **Figure 3**.

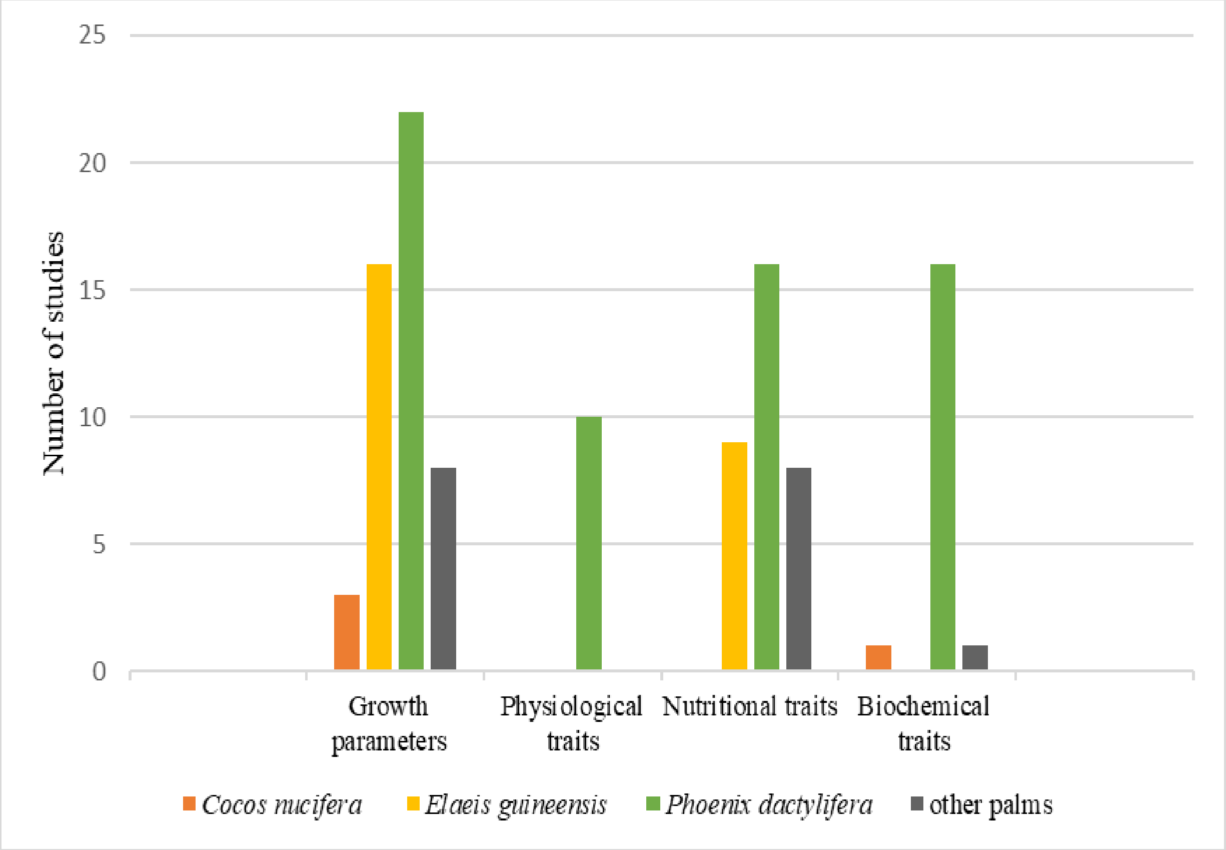

Fig. 3 Diagrammatic representation of mycorrhizal benefits in diverse palms so far discussed in the literature.

It is clear from **Figure 3** that the existing literature on AMF in palms substantiates its positive, beneficial role in promoting vegetative growth, productivity, and overcoming environmental stress in palms. The literature on the valuable roles of the application of AMF in palm growth and productivity is summarized in **Table 3**.

Table 3: Literature on the beneficial role of the application of arbuscular mycorrhizal fungi individually or in consortia with other AMF or beneficial microbes in palm growth and productivity

Palms	**AMF/consortia/ PGPR**	**Beneficial roles (positive impacts) observed**	**References**
Acoelorrhaphe wrightii	AMF inoculum[1]	Increase growth parameters and mineral nutrition	[164]
Archontophoenix alexandrae	AMF consortium[2]	Increase growth parameters and biochemical traits.	[165]
Bactris gasipaes	*Glomus aggregatum*[6]	Increase biochemical traits	[145]
Coccothrinax argentata	AMF inoculum[1]	Increase growth parameters and biochemical traits.	[164]
Cocos nucifera	AMF consortium[3]	Increase growth parameters	[125]
	AMF consortium[4] with NPK fertilizer	Increase growth parameters and biochemical traits.	[126]
	Native AMF consortium with 13 species; Commercial AMF mix of *Rhizophagus intraradices* and *Acaulospora colombiana*	Increase growth parameters	[163]
Desmoncus orthacanthos	AMF inoculum[5]	Increase growth parameters and biochemical traits	[98, 166]
		Increase growth parameters and P uptake.	[167]
Elaeis guineensis	Indigenous AMF spp.	Increase growth parameters and mineral nutrition.	[39]
	Glomus sp.	Increase in fertilizer use efficiency in palm seedlings	[168]
	Glomus manihot[6] *Entrophospora columbiana*[1] *Acaulospora mellea* *Acaulospora appendicula*[2]	Increased growth parameters and nutrient uptake reduced the mortality rate of oil palm clones.	[169]
	AMF species belong to the *Gigaspora* and *Glomus* genera	Increase growth parameters and mineral nutrition	[31]
	Glomus etunicatum[4]	Increase growth parameters and leaf K content	[17]
	Glomus intraradices[6]	Increase growth parameters	[99]
	Glomus etunicatum[4]	Increase growth parameters	[170]
	Isolates of *Entrophospora* sp. and *Glomus* sp.	Increase growth parameters	[100]
	Gigaspora sp. MV16, *Glomus* sp. MV7, *Gigaspora* sp. MV16 isolate + *Glomus* sp. MV7	Increase growth parameters	[171]
	Glomus sp.; Mixture of *Gigaspora* sp.+ *Entrophospora* sp.	Increase growth parameters and nutrient uptake	[42]
	Glomus etunicatum[4] with *Trichoderma harzianum*	Increase growth parameters	[101]
	Indigenous mycorrhizae (*Glomus* sp.16) + organic	Increase growth parameters and nutrient uptake	[102]

	fertilizer (cow manure)		
	Glomus spp. + P fertilizers	Increase growth parameters	[172]
	AMF consortium[6]	Increase growth parameters	[135]
	AMF consortium[7]	Increase growth parameters	[103]
	Rhizophagus intraradices, *Rhizophagus clarus* + Endophytic bacteria (*Pseudomonas aeruginosa*)	Increase growth parameters and nutrient uptake	[56]
Euterpe edulis	MF consortium[2]	Increase growth parameters and biochemical traits.	[165]
	Rhizophagus clarus; AMF Consortium[8]	Increase growth parameters and mineral nutrition	[41]
Euterpe oleracea	*Scutellospora* gilmorei[3], *Acaulospora* spp., *Gigaspora margarita* *Entrophospora colombiana*[1]	Increase growth parameters and nutrient uptake	[173]
Phoenix dactylifera	*Glomus deserticola*[7]	Increase mineral absorption	[174]
	Glomus monosporus[5], *Glomus clarus*[6] *Glomus deserticola*[7], Aoufous consortium[9]	Increase growth parameters	[175]
	Glomus spp.	Increase growth parameters and nutrient uptake.	[40]
	Glomus intraradices[6]; Native Complex Aoufous (stains of *Glomus mossese*)	Increase growth parameters	[176]
	Glomus verriculosum[5], *Glomus fasciculatum*[6], *Glomus intraradices*[6]	Increase growth parameters and biochemical traits	[127]
	Aoufous consortium[10], *Glomus monosporus*[5], *Glomus clarus*[3]	Increase growth parameters, biochemical traits, physiological traits, and nutrient uptake.	[177]
	Aoufous consortium[10], *Glomus monosporus*[5], *Glomus clarus*[6]	Increase growth parameters, physiological traits, and mineral nutrition.	[178]
	Aoufous consortium[10], *Glomus monosporus*[5], *Glomus clarus*[6]	Increase growth parameters	[179]
	Glomus iranicum + compost; *Glomus iranicum*	Increase growth parameters, biochemical traits, and mineral nutrition	[180]
	Glomus mosseae[5] + some strains of phosphate-solubilizing bacteria (PSB)	Increase growth parameters and nutrient uptake	[129]
	Rhizophagus intraradices	Increase growth parameters, biochemical traits, and nutrient uptake	[128]
	Rhizoglomus irregulare, AMF consortium[2] + PGPR + Compost	Increase growth parameters, biochemical traits, physiological traits, and nutrient uptake.	[131]
	Rhizoglomus irregulare + Seaweed extract (SWE)	Increase growth parameters, biochemical traits, physiological traits, and nutrient uptake.	[132]
	Rhizoglomus irregulare + compost	Increase growth parameters, biochemical traits, physiological	[133]

		traits, and nutrient uptake.	
	Complex Aoufous (CAF)[11]	Increase growth parameters, physiological traits, and nutrient uptake	[181]
	Aoufous mycorrhizal consortium (AMC)[10]	Increase growth parameters, biochemical traits, physiological traits, and nutrient uptake.	[130]
	Mycorrhizal Aoufous Consortium (MAC)[10] + compost	Increase growth parameters, biochemical traits, physiological traits, and nutrient uptake.	[182]
	Diversispora aurantia	Increase growth parameters	[91]
	AMF consortium + indigenous PGPR+ Compost	Increase growth parameters, biochemical traits, physiological traits, and nutrient uptake.	[162]
Sabal palmetto	AMF inoculum[1]	Increase growth parameters and nutrient uptake.	[164]
Senenoa repens	AMF inoculum[1]	Increase growth parameters and nutrient uptake.	[164]

No. 1 to 11: Details of AMF consortia mentioned in the table: (1) heavily colonized root fragments and many AMF spores belong to the genus *Gigaspora, Scutelospora* and *Glomus*; (2) mixture of *Acaulospora koskei, Scutellospora heterogama, Gigaspora albida* and *Rhizophagus clarum*; (3) mycorrhizal hyphae, infected root bits and viable spores of fungi belong to the genera *Acaulospora, Gigaspora, Glomus* and *Scutellospora*; AMF consortium (4) *Glomus* sp., *Funneliformis* sp., *Acaulospora* sp., *Gigaspra* sp., *and Scutellospora* sp.; (5) infected root bits, spores and extraradical mycelium; (6) mixture of *Glomus* sp., *Entrophospora* sp. *and Gigaspora* sp.; (7) mixture of *Glomus* sp., *Gigaspora* sp., *Acaulospora* sp., *and Entrophospora sp.*; (8) *Rhizophagus clarus and Claroideoglomus etunicatum; Aoufous consortium* (9) Mixture of native species of *Glomus* sp., *Sclerocystis* sp., *Scutellospora* sp. and *Acaulospora* sp.; (10) Aoufous consortium - mixture of native species of *Glomus, Sclerocystis* and *Acaulospora*; (11) Complex Aoufous (CAF) mixture of native species of *Glomus clarum, Glomus deserticola* and *Glomus monosporus*.

New names of the AMF species according to the current taxonomy: [1]*Acaulospora* coloumbiana*;* [2]*Ambispora appendicula;* [3]*Cetraspora gilmorei;* [4]*Entrophospora etunicata;* [5]*Funneliformis monosporus, F. mosseae, F. verruculosus;* [6]*Rhizophagus aggregatum; R. clarus; R. fasiculatus; R. intraradices; R. manihotis;* [7]*Septoglomus deserticola*.

In general, the AMF has a multifunctional role in the growth and production of plants, especially by enhancing nutrient uptake such as phosphorus [183, 184], which is the limiting resource for plants [185, 186, 187] in many soils. It is evident from **Table 3** that AMF plays a significant role in the accumulation of major and minor nutrients in palms. However, unlike other crops, AMF role in palms is reported from AMF-inoculated palm seedlings in acquiring high amounts of nitrogen, potassium, phosphorus, zinc, and copper from the soil [31, 39, 40]. The early AMF symbiosis in palms may be decisive in the palm's later survival and growth [44, 91]. However, monitoring studies on the early root colonization of AMF in palm seedlings to later stages of palm growth and productivity are not available in the literature. Since several species of palms are long-lived perennials requiring a high demand for nutrients for growth and fruit production [44, 188], such studies have become significant. Moreover, the beneficial effects of AMF on palm growth and productivity are based on experimental investigations in the seedlings of a few cultivated palms, such as date palms, followed by oil and coconut palms alone.

Janos [189] examined the influence of the seed size on AMF association in many species of plants and found that plants with large seeds have developed an extensive root system with the support of a high amount of seed reserves for later higher or better AMF association in them than the small-seeded plants. According to him, obligate-mycorrhizal tropical species, in general, are large-seeded. Although further studies on the influence of seed size on the beneficial roles of AMF in palms are not available in the literature, later studies in other plants show that annuals and perennials do differ in AMF association concerning seed size [190]. In legumes, large-seeded plants are less likely to have AMF association than small-seeded plants [191]. However, in commercially cultivated palms such as coconut, the available literature is insufficient to reveal the exact beneficial role of AMF on palm productivity.

The beneficial roles of mycorrhiza can be best explained by plant dependency and responsiveness to mycorrhizal inoculations. Mycorrhizal dependency is a constitutive property of plant species or genetically fixed plant traits, whereas mycorrhizal responsiveness and effectiveness are emergent properties dependent on plant and fungal species [30]. According to the author, dependency refers to the inability of a plant to grow without mycorrhiza below a critical level of P in soils. In contrast, responsiveness refers to a plant's growth rate with and without mycorrhiza at any level of P in soil. The cultivated palm varieties, especially in coconut, may differ in their dependencies as it is a genotype character. However, responsiveness depends on the kind of AMF species colonized in the roots and soil and other environmental characteristics where the palm grows. The slow growth of palms is one of the bottlenecks in assessing their mycorrhizal dependency or responsiveness through measuring morphometric growth parameters. Since mycorrhizal assistance in growth enhancement mainly comes from enhancing P uptake in the host, P content in the leaves can be a good indicator of mycorrhizal association in plants [123]. Therefore, variations in P levels in palm leaves concerning different palms or varieties of a single palm in identical soil and climatic conditions with or without mycorrhiza may reveal dependency because mycorrhiza-dependent species will have the least P content in leaves without mycorrhiza. In contrast, a change in the P level in the leaf of a particular species of a variety of palm under different soil or climate conditions with identical and different AMF species may show a difference in responsiveness.

Overall, AMF studies in palms concerning different soils, seasons, and agroclimatic zones are required. The role of specific AMF in palm productivity under diverse soil environments is also a significant theme to explore, especially in using AMF as a biological tool in the sustainable cultivation of palms. However, there are positive roles of AMF application in the seedling stage for seedling survival [189] and at tree maturity in *Litchi chinensis* Sonn. [192], but such investigations have not yet been done in palms. Therefore, long-term monitoring investigations on the beneficial roles of AMF in palms are more desirable.

Moreover, several studies suggested that indigenous AMF are suitable for development as palm biofertilizers [102, 163]. However, such beneficial indigenous species may not exist in all the fields because of unfavourable agricultural practices or other soil conditions in many cultivated fields. Therefore, further focus on exploring the diversity of AMF in economically beneficial palms in wild unaffected environments has become desirable. Exploration of the valuable roles of indigenous AMF from undisturbed natural soils and AMF root associates of unexplored species of palms, especially wild palms, have also become important in identifying the valuable indigenous species for cultivated palms. Such studies may enable us to distinguish between the weedy and the desirable indigenous species of AMF in palms. Soil conditions favouring the indigenous AMF in palm groves must also be understood. Experimental studies are required to understand the valuable environmental and other variables concerning the optimum benefits of AMF in palms in cultivated fields. However, since AMF sometimes acts negatively on certain plants, especially in manganese (Mn) absorption [193], intensive experimentation of specific AMF in palms has become desirable before general recommendations of indigenous or other specific AMF in typically cultivated palms of specific soil environmental conditions.

Many reports explain the beneficial role of AMF in the establishment of an in vitro culture of palm plantlets. Schultz [169] reported the positive effects of AMF, such as improvement in the survival rate, growth parameters, and mineral nutrition in micro-propagated oil palm seedlings. According to Sundram [17], *Glomus etunicatum* Błaszk., B.T. Goto, Magurno, Niezgoda & Cabello is the most successful single species inoculum in establishing a symbiotic association in oil palm seedlings at the nursery stage, positively affecting their vegetative growth. Galindo-Castaneda and Romero [99] reported that *Glomus intraradices* C. Walker & Schuessler potentially increased the seedling vigour at the early stages of oil palm seedlings when transplanted to the main nursery. According to Kartika et al. [102], inoculation of indigenous mycorrhizae mixed in cow manure increased the growth of oil palm seedlings under pre-nursery conditions. Rini et al. [103] report that the application of AMF can reduce the dose of fertilizer requirement for oil palm seedlings in nurseries. Ilangamudali and Senarathne [125] confirmed the utility of AMF-based biofertilizers in the early growth of coconut seedlings, especially in producing high-quality coconut seedlings with well-developed root systems for good field establishment. According to Sulistiono et al. [126], the combined application of AMF with NPK fertilizer can increase root growth and nitrate reductase activity in transplanting coconut seedlings, especially at their early growth stage. Gomez-Falcon et al. [163] reported the beneficial role of native AMF species in the growth and survival of micro-propagated coconut plantlets. Kinany et al. [180] reported AMF *Glomus iranicum's* (= *Rhizophagus iranicus*) positive role in improving the growth and nutrition of micro-propagated date palm plantlets. Hilali et al. [105] said the beneficial role of AMF *Rhizophagus irregularis* (Blaszk., Wubet, Renker and Buscot) C. Walker and A. SchuBler = *Glomus intraradices* in-vitro cultured date palm plantlets, especially in developing a more extensive root system. Besides these cultivated palms, the valuable role of AMF in the field establishment of palms like *Desmoncus orthacanthos* [166, 167], *Archontophoenix alexandrae* and *Euterpe edulis* [41, 165] are also available in the literature.

The AMF association enables palms to overcome diverse environmental stresses such as drought and salinity. In general, AMF in the soil can enhance the stabilization of soil aggregates, increase nutrient availability and water uptake [33, 103, 194], and thereby help palm growth and productivity. In general, water scarcity and salinity adversely affect the yield and productivity of palms [195, 196, 197]. However, only limited studies are available on the beneficial role of AMF in palms under such stressed environmental conditions. Most such studies are related to date palms, followed by oil palms. A critical summary of the limited experimental studies using AMF to alleviate the detrimental effects of drought and salinity in palms is summarised in **Table 4**. In general, such positive influences of AMF are attributed to a general improvement in the vigour of hosts by increasing growth parameters, mineral nutrition, water relations, stomatal conductance, synthesis of antioxidants, pigments, and similar stress-resistant secondary metabolites, and alleviation of free radical accumulation in the hosts [198, 199].

Table 4: Literature on the beneficial role of the application of AMF individually or in consortia or with other beneficial microbes for alleviating various abiotic stresses in Palms.

Name of Palms	**AMF species**	**Type of soil**	**Beneficial influence**	**References**
Elaeis guineensis (Oil palm)	^{3}AMF consortium		Increase growth parameters	[135]
Phoenix dactylifera (Date palm)	^{2}Complex Aoufous (CAF)	Sand	Increase growth parameters, mineral nutrition, and water relations	[181]
Elaeis guineensis (Oil palm)	^{2}*Glomus intraradices*	Loamy soil	Increase growth parameters and physiological traits	[176]
	^{1}Aoufous consortium ^{1}*Glomus monosporus* ^{2}*Glomus clarus*	Sandy soil	Increase growth parameters, biochemical traits, water relations, and nutrient uptake.	[177]
	^{1}Aoufous consortium ^{1}*Glomus monosporus* ^{2}*Glomus clarus*	Sandy soil	Increase growth parameters, Water parameters, and Mineral nutrition	[178]
	Rhizophagus intraradices	Sand and Soil	Increase growth parameters, biochemical traits, and nutrient uptake	[128]
	^{1}Aoufous consortium ^{1}*Glomus monosporus* ^{2}*Glomus clarus*	Sandy soil	Increase growth parameters and water relations	[179]
	Rhizoglomus irregulare, ^{1}AMF	A mixture of sand, clay,	Increase growth parameters, biochemical traits, physiological	[131]

	consortium +PGPR + Compost	and loam soil	traits, and nutrient uptake.	
	AMF complex+ PGPR	Sand	Increase biochemical and traits, physiological traits	[200]
	Aoufous consortium + PGPR+ organic amendments		Increase growth parameters, biochemical traits, water relations, and nutrient uptake.	[162]
Elaeis guineensis (Oil palm)	AMF+*Talaromyces pinophilus*	Saline soil	Increase growth parameters and P uptake	[201]
Phoenix dactylifera (Date palm)	[2]*Glomus fasciculatum* [2]*Glomus intraradices*	Sandy	Increase growth parameters and biochemical traits	[127]
	[1]*Glomus mosseae* + PGPR (in the presence of Putrescine)	Reclaimed saline soil	Increase growth parameters and biochemical traits	[202]
	[1]Aoufous consortium [1]*Glomus monosporus* [2]*Glomus clarus*	Sandy	Increase growth parameters and physiological traits	[179]
	Aoufous mycorrhizal consortium (AMC)[1]	Sand	Increase growth parameters, biochemical traits, physiological traits, water parameters, and nutrient uptake.	[130]
	[1]Mycorrhizal Aoufous Consortium (MAC) + compost	Sand	Increase growth parameters, biochemical traits, physiological traits, water parameters, and nutrient uptake.	[182]
	Rhizophagus irregularis [1]Aoufous consortium (PGPR+ Compost)		Increase growth parameters, biochemical traits, and physiological traits	[203]
	AMF complex	Sandy	Increase growth parameters, biochemical traits, and nutrient uptake	[197]

[1] Mixture of *Glomus* sp., *Entrophospora* sp., *and Gigaspora* sp.; [2] Complex Aoufous - mixture of native species of *Glomus clarum, Glomus deserticola*, and *Glomus monosporus*; [3] Aoufous consortium - mixture of native species of *Glomus*, *Sclerocystis* and *Acaulospora*. **New names of AMF species according to the current taxonomy**: [1] *Funneliformis monosporus; F. mosseae; F. verruculosus;* [2] *Rhizophagus clarus; R. intraradices*; *R. fasiculatus*; [3] *Septoglomus deserticola*.

The combined application of AMF as a consortia or along with other beneficial microbes and fertilizers enables palms to overcome drought and salinity. It is well-known that combined AMF and microbial symbionts can boost palm growth under drought and saline conditions and potentially alleviate the detrimental effect of these stresses on palm growth. However, a specific study concerning the role of AMF in overcoming the damaging effects of drought and salt stress in palms is not available in the literature except for a study on coconut [63]. Therefore, investigations on the particular role of specific AMF in palms in overcoming environmental stress need to be put into emphasis in the future.

Different diseases and pests considerably affect palm growth and productivity [204, 205, 206]. AMF helps reduce the disease severity, and some AMF species can even protect plants from various diseases [207, 208, 209] and root pathogens [210]. All the research reports showing the positive influence of AMF in palms against diseases are summarised in **Table 5**.

Table 5: Literature on the beneficial role of the application of arbuscular mycorrhizal fungi individually or in consortia with other beneficial microbes in palms as biocontrol agents

Name of Palms	**Active against diseases**	**AMF/ AMF consortia or with other microbes**	**Beneficial role**	**References**
Elaeis guineensis (Oil palm)	Basal stem rot (BSR) caused by *Ganoderma boninense*	*Glomus intraradices*[2] and *Glomus clarum*[2] + endophytic bacteria (EB)	Reduce disease development (used as a biocontrol agent)	[211, 212]
		AMF + *Trichoderma* spp.	Reduce disease severity	[213]
		AMF spp.	Controlling disease	[214]
Phoenix dactylifera (Date palm)	Bayoud disease [*Fusarium oxysporum f.* sp. *albedinis* (Foa)]	*Glomus monosporus*[1] *Glomus clarus*[2] Aoufous consortium[1]	Reduce disease severity Increase shoot height, biomass, and leaf number Stimulate the activities of Défense-related enzymes Reduce mortality rate	[175]
		Glomus monosporus[1] *Glomus deserticola*[3] *Glomus clarus*[2] Aoufous consortium[1]	Improve defense responses by stimulating the accumulation of hydroxycinnamic acid derivatives.	[215]
		Aoufous consortium[1] *Glomus monosporus*[1] *Glomus clarus*[2]	Improve tolerance by improving, Water parameters Biomass production Mineral nutrition (P, Ca, Mg, K, Mn, Na, and Cu) Reduce mortality rate	[178]
		Aoufous consortium[1] *Glomus monosporus*[1] *Glomus clarus*[2]	Improve growth parameters under disease conditions Reduce mortality rate	[179]
		Aoufous consortium[1]	Induce resistance by enhancing nutrient contents, phenolic compounds, and peroxidase activities. Reduce mortality rate	[216]
		Glomus mosseae[1]+ *Trichoderma harzianum*	Enhance palm resistance to Foa by stimulating the peroxidase activities.	[217]

AMF consortium mentioned in the table: [1]Aoufous consortium - mixture of native species *of Glomus* sp., *Sclerocystis* sp., *Scutellospora* sp., *and Acaulospora* sp.; **Name of AMF species according to the current taxonomy**: [1]*Funneliformis monosporus; F. mosseae;* [2]*Rhizophagus clarus; R. intraradices;* [3]*Septoglomus deserticola*.

It is evident from **Table 5** that AMF positively influences an increase in the palm's resistance to diseases. Such symbiotic supports include AMF's positive influence on mineral nutrition and water relations [162, 178], increasing the vigour or resistance of host plants against diseases [214, 218], and stimulating the activity of enzymes and antioxidants [213, 216]. Several studies reveal that AMF is helpful against insect attacks on plants [219, 220] by improving their vigour. AMF are also beneficial to plants in resisting soil-borne plant pathogens

[221, 222]. Although palms are resistant to pests [117], specific studies on the role of AMF association concerning pest control on palms are not available in the existing literature. Researchers generally suggest using AMF as a biocontrol agent in date palm and oil palm, especially in controlling Bayoud disease and basal stem rot diseases. However, no studies are yet available on the role of AMF in preventing some severe infections currently prevailing in coconuts, such as root wilt disease.

Additionally, although AMF are identified as an essential natural biological partner in plants for alleviating heavy metal toxicities [223] and overcoming soil degradations of diverse kinds [224] such reports explaining AMF's influence on alleviating environmental toxicities in palms or roles of AMF in overcoming soil degradations in palm groves are not available in the literature. It may be noted that nowadays, palms are cultivated using treated wastewater [225], where the stress from toxic or stressful minerals in the wastewater may be overcome using suitable AMF. Therefore, experimental studies on wastewater treatment in palm fields combined with suitable AMF species have become desirable.

Overall, a critical literature analysis on various beneficial roles of AMF in palms reveals that AMF can contribute to palm-sustainable cultivation by avoiding environmental degradation from excessive agrochemical applications in palm fields. However, the availability of literature in this regard is limited when compared to palm diversity and the diversity of agroclimatic regional variations in palm cultivation. Therefore, intensive field and experimental investigations on the specific role of AMF in reducing the application of chemicals in palm groves, especially by improving pest and disease resistance in palms, have become desirable. Moreover, field surveys have become significant on variables concerning specific AMF for identifying their disease-controlling roles in palms under specific climatic and soil conditions.

Studies on the effect of environmental and other variables concerning AMF in palms

The nature and intensity of AMF association in plants can vary depending on the plant species characteristics (root structure, seed weight, life history), fungal species, and environmental factors such as habitat type, soil fertility, soil pH [190], nutrient and water availability [226, 227]. The growth response of plants to AMF colonization [30] may be either beneficial mutualism or harmful parasitism [226, 228], but often a mutualism-parasitism continuum [229]. The factors influencing the success of AMF symbiosis or proper root colonization for beneficial influence in plants may be categorized into internal (symbiont) and external environmental variables. In palms, direct studies emphasizing factors influencing AMF association are unavailable, but some indirect mentions are available in the existing literature. They are as follows;

Internal variables

Internal variables such as host-specific plant phenological and genetic characteristics and fungal species-specific characteristics control the success of AMF association in plants. Therefore, the internal variables can be categorized into plants and fungal variables [230].

Plant variables

Plant variables such as root structure, genotype, and phenology significantly affect successful AMF symbiosis [230] in palms. Generally, plants with graminoid finely branched roots with a dense cover of long root hairs respond to mycorrhizae only in phosphorus-deficient soil. However, St. John's [231] re-examining Baylis's hypothesis with tropical trees suggested that *magnolioid* trees devoid of root hairs are moderately or heavily infected with mycorrhizal fungi. Janos [30] explains how plant responsiveness and dependence on mycorrhizas are decisive in beneficial AM symbiosis. Depending on the morphological (root structure) or physiological traits, plants show a wide range of growth responses to AMF. Later, Liu et al. [232] found that tree species with thick and poorly branched roots respond more to AMF symbiosis than trees with finer roots. According to the authors, plant species vary in their plasticity to root morphological or architectural patterns concerning NPK in soils, affecting mycorrhizal crops' effectiveness because plants favour roots over mycorrhizal fungi in nutrient-rich soils. Reports also suggest that domestication has reduced crop responsiveness to AMF over the years, and breeding programs may address this [233]. However, a positive correlation between root hair density and AM root colonization in trees is also known [234].

Many authors describe the root architecture of palms, mainly oil palms, in detail [235, 236, 237, 238]. According to these authors, the first-order (R1) roots belong to primary (radicle or embryonic) and adventitious types, which are ortho-gravitropic or dia-gravitropic. The primary embryonic (R1) roots do not last, but the R1 adventitious roots continuously arise for years. Lateral roots constantly emerge from the first-order roots (R1), called second-order roots (R2), with vertical upward, downward, or horizontal growth. The lateral roots of the R2 are the R3 roots, and further branching of the R3 forms the R4 roots, which are agravitropic. In general, all the studied palms show more or less a similar root architecture. A critical analysis of the existing literature revealed that the AMF structures, such as the hyphal coils, vesicles, and arbuscules, are most frequently observed in the thinnest and second and third-order roots of palms [45, 46, 47]. According to them, such roots are more susceptible to AMF colonization, and the root colonization is restricted to the inner cortex of such roots. However, studies regarding the influence of root structure and AMF colonization are reported only in a few palms by the authors, as mentioned above.

The host plant's phenological stage is another internal variable influencing most plants' AMF community structure [239, 240]. However, such studies regarding the palm phenological stage are available in date palms only [87]. According to the authors, the plant growth stage strongly influences AMF colonization in date palms. Besides the root structure and phenology, the genotype of the host crop also influences the AMF symbiosis in the roots of most plants [241, 242, 243]. In palms, such studies regarding the influence of host genotype are very few and are mainly reported in coconut [54, 62, 63]. Such studies reveal that root colonization and spore abundance in the soils of the native tall cultivars of coconuts is higher than that of dwarf and hybrid varieties. The above critical analysis of the current literature on palm plant factors influencing AMF symbiosis reveals that more emphasis is required on the theme in research in the future.

Fungal variables

Internal fungal variables such as the type of fungal species, its genetic diversity, and its characteristics significantly influence AMF symbiosis's success with plants [230, 244, 245]. In palms, the studies regarding the influence of different types of AMF species on the success of AMF symbiosis in palms are nominal and are mainly reported in date and oil palms [17, 100, 128, 171, 176, 177, 178, 179].

External variables

In addition to internal host-specific and fungal-specific characteristics, local edaphic factors on plant responsiveness to AMF have been emphasized continuously [113] in research. Soil environmental conditions such as soil structure also influence root growth and, thus, indirectly affect mycorrhizal association in plant roots [32]. In addition, external variables such as other plants in the field and other microbes in the soil can also affect AMF association in crops, which are called external biological variables [230]. Therefore, the external variables can be categorized into environmental and biological variables.

Environmental variables

The environmental variables that influence AMF in plants include soil and climatic factors. The soil factors include physicochemical soil characteristics such as soil texture, structure, pH, water content, and soil mineral nutrients. The climatic factors can include temperature, precipitation, photoperiod, length of summer, winter, rain, and humidity. However, the environmental factors act not in isolation but as a complex.

In the current literature on AMF in palms, some studies are available on the influence of specific edaphic and climatic factors on AMF symbiosis in date, coconut, and oil palms. In date palms, the intensity of AMF colonization and spore density is influenced by soil pH, soil moisture, electrical conductivity, temperature, humidity, mineral concentrations (P, N, Mg, K, and Na), organic matter, and organic carbon [66, 87, 88, 89, 90]. Similarly, in coconut and arecanut palms, the AMF spore count and the extent of root colonization are influenced by soil pH, EC, soil nutrients (N, P, K,) and organic carbon [54, 55, 71, 126, 163]. Moreover, the concentration of nutrients in the host tissue also decides the extent of the AMF species colonizing the plant. Thus, the dose of fertilizer applied directly affects the mycorrhizal activity, which may vary with host-fungus combinations [60]. The soil pH and P concentrations influence AMF biodiversity in oil palms [64, 168]. Drought and salinity also affect palm root colonization intensity and AMF spore count. Such studies regarding the influence of salinity and drought on AMF symbiosis are reported mainly in date palms [66, 130, 131, 177, 178, 179, 182, 197, 203].

Biological variables

Among the biological and environmental variables, indigenous mycorrhizal species play a significant role in the success of AMF association in crops. In a soil environment, coadapted symbionts also influence mycorrhizal effectiveness in the field [228]. In the current literature, some studies are available on the influence of other microbes and fertilizers on AMF association in date palms [129, 132, 133, 180, 182, 203] and oil palms [64, 101, 211].

Additionally, reports on the influence of anthropogenic factors, such as various cropping systems and cultivation practices, on AMF activity in palms are available in the existing literature. Anthropogenic factors play a significant role in AMF colonization in palms such as date palms [88, 89], coconut palms [54, 55] and other palms [71, 94, 95]. Therefore, emphasis may be placed on analysing the role of plant-specific characteristics such as root traits, AMF-specific characteristics such as local strains and other beneficial symbionts in their natural soil environment, and soil conditions on AMF activities in palms. It may enable the development of AMF as an ecotechnological tool alternative to chemicalized means in the sustainable cultivation of palms.

4. Conclusion

The current, thorough, critical analysis of the literature on AMF concerning palm provides the following significant findings.

1. Although a diversity of about 85 species of AMF is known from 43 studied palms, AMF concerning specific cultivated palm varieties of many of their cultivating zones is yet to be explored. AMF in the majority of ornamental and wild palms yet remains unknown.
2. The current literature on AMF concerning palms includes AMF diversity in palm rhizosphere, root colonization, spore abundance and spore density in palm fields, seasonal variations in AMF characteristics in palms, AMF beneficial roles including nutritional and stress overcoming in palms, and some environmental and other variables concerning AMF activity in palms.
3. The AMF root colonization patterns in palms include *Arum*, *intermediate*, and *Arum* and *Paris*, which are reported in date palm roots. However, *Arum* and *Paris* types of root colonization are found in coconut concerning the cultivars' field environmental characteristics or varieties.
4. Studies on AMF association in palms concerning root morphology and root architecture are limited to only three studies. The available studies suggest the restriction of root colonization to second or third-order roots; in such roots, mycelia can be restricted to the inner or outer cortex.
5. Seasonal variations in the percentage of root colonization and rhizosphere spore density are visible in the palms. Generally, root colonization is high in the rainy season, whereas spore density is high in summer. However, reports contradictory to the above general findings, particularly on palms, are also available in the literature.
6. Since Janos's first report on the beneficial role of AMF in palms [37], about 47 such studies have shown the positive influence of AMF on the growth parameters of palms. The most helpful role of AMF in palms is suggested to be the enhancement of mineral nutrition, followed by water availability and biochemical production in palms. All such studies in palms are conducted as experiments with seedlings.
7. About 18 studies explain the beneficial roles of AMF in palms for overcoming environmental stresses such as drought and soil salinity. Moreover, about ten studies show the valuable roles of AMF in enhancing disease resistance in palms.
8. Researchers have observed that internal variables such as plant phenological stages, root structure, host genotype, and genetic diversity of AMF, and external variables such as soil pH, soil moisture, soil organic carbon, electrical conductivity, mineral composition, and temperature and humidity have a significant influence on AMF activity in palms.
9. Specific experiments have not yet been done to examine the extent of diverse environmental and other variables for desirable AMF activity in palms.

Since imagination and deduction are significant in advancing mycorrhizal research [246] in plants, especially in perennial palms, some of the following suggestions are presented for the critical attention of researchers in their future studies on AMF concerning palms:

1. Overall, an intensive global effort on AMF concerning palms may be raised for applying AMF as an ecotechnological tool to ensure palm cultivation's sustainability. Such actions contribute to attaining the UN's SDGs.
2. AMF diversity in wild palms and cultivated palms of unexplored zones is essential for accounting for the actual AMF diversity concerning palms.
3. The mycorrhizal dependency, responsiveness, and effectiveness in specific palms, receptivity of specific AMF in particular soils, and the mycorrhizal patterns in palms (*Arum* or *Paris* or *intermediate* types) concerning all the internal and external variables need specific attention of researchers.
4. Since studies on AMF root colonization in palms concerning root morphology and architecture are limited, specific studies focusing on colonization patterns in diverse palms concerning such root aspects are desirable.
5. Since some studies show that AMF contributes to resistance to diseases and pests in plants, including

palms, and since wild palms are resistant to diseases and pests, experimental investigations on the role of AMF associates of wild palms in cultivated palms are significant.

6. Research on internal and external variables concerning beneficial AMF activity in specific palm species and soil environments is desirable.
7. Since the current experimental studies on the beneficial influence of AMF in palms are limited to seedling studies, future thrust may be on long-term monitoring of the benefits of such seedling inoculation in the productivity of palms later in the fields.
8. Since monitoring growth parameters is challenging to account for positive AMF influence in many of the perennial palms, monitoring leaf P in palms with and without AMF association may be helpful to extract the AMF dependency, responsiveness, and beneficial influence in palms.
9. Experiments on the role of diverse AMF individually and in the consortia of other AMF and other beneficial microbes for achieving various beneficial effects in palms, including disease and pest resistance, are desirable.
10. Experiments on the role of AMF in alleviating environmental stress, such as increased temperature, low humidity, drought, and salinity, also deserve research attention, especially in the sustainable cultivation of economically significant palms as preparedness for anticipating climate changes.
11. The influence of AMF in alleviating the stress of wastewater irrigation in palms needs further emphasis in research because the use of wastewater to cultivate palms is increasing in many arid regions.
12. Specific intercrops' influence on specific AMF in palms needs further intensive experimentation because multi-cropping patterns are more accepted forms of agriculture in ensuring sustainability and enhanced carbon sequestration in field soils.
13. The utility of AMF in conserving endemic, rare, and endangered palms also need emphasis in future research.

Overall, since the success in the use of AMF as a biological tool depends on the environmental complex within which they operate, experimental studies with AMF activity concerning various external ecological, biological, and internal variables affecting AMF association in all varieties of palms have become desirable, especially to achieve sustainability in palm cultivations and palm-based industries.

Abbreviations and Acronyms

A: arbuscules, AC- arbusculate coils AMF- Arbuscular mycorrhizal fungi H- hyphae HC- hyphal coils ICH- intercellular hyphae IRH- intracellular hyphae IRM- intra-radical mycelium IRRH- intra-radical hyphae V- vesicles

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

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