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Research Article

Arbuscular Mycorrhizal Fungi Associated with *Myrciaria dubia* in the Amazonia Region, Peru

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Myrciaria dubia (Kunth) McVaugh (camu-camu) is a shrub native to the Amazon region that produces fruits with a high content of vitamin C and various bioactive compounds, making it a functional food with antioxidant, anti-inflammatory, and antimicrobial properties. However, it is unknown which microorganisms are associated with its root system and can influence its growth and productivity. Arbuscular mycorrhizal fungi (AMF) are associated with most plants and are essential for their establishment, survival, and productivity since they facilitate their nutrition, increase water absorption, and improve soil structure. Although the AMF association is already known in some species of *Myrciaria*, no report is available on its association in *M. dubia*. This study presents, for the first time, the symbiotic association between AMF and *M. dubia* from the INIA San Roque experimental station located in the Amazon region, Peru. For the morphological and molecular analyses of the AMF, samples of rhizospheric soil and roots from two native accessions of the National Germplasm Bank of *M. dubia* were collected. Eighteen AMF morphospecies were identified in rhizospheric soil, belonging to nine genera *Acaulospora*, *Ambispora*, *Entrophospora*, *Diversispora*, *Gigaspora*, *Glomus*, *Paraglomus*, *Funneliformis*, and *Sclerocystis*, being the first one the most frequent. The roots of *M. dubia* showed high colonization by AMF (mean = 91%), and characteristic structures of arbuscular mycorrhizae, such as vesicles, hyphae, and arbuscules, could be observed. Likewise, the molecular analysis detected the presence of genetic material (rDNA) corresponding to AMF in the roots of both accessions. Our results evidenced the symbiotic association between AMF and *M. dubia*, which encourages further investigation of the functional potential of these microorganisms in this economically crucial agricultural plant in Peru.

1. Introduction

Myrciaria dubia (Kunt) McVaugh, popularly known as camu camu, is native to the Amazon region of Peru, Brazil, Venezuela, and Colombia [1], and its most prominent natural population is located in the eastern Peruvian Amazon [2]. It is a shrub species found naturally in flooded environments near streams or rivers in the Amazon region [3–5]. However, it is cultivated in agricultural areas (nonflooded lands) in association with other crops [6], demonstrating good adaptive capacity [7].

The pulp of the *M. dubia* fruit has a tremendous nutritional potential that lies in the high concentration of ascorbic acid (vitamin C), higher than other fruits such as acerola, lemon, and orange [8]. This fruit is consumed worldwide as a beverage, frozen pulp, or extract [1, 9]. Likewise, it presents antioxidant [10], anti-inflammatory [1], and photoprotective [11] properties. Consequently, almost all research on this species has focused on its nutraceutical, pharmaceutical, and cosmetological properties, with few studies on the diversity of microbial communities present in the rhizosphere of this plant.

Among the microbial communities, the arbuscular mycorrhizal fungi (AMF) stand out [12], which are associated with approximately 80% of plant species in almost all terrestrial ecosystems [13, 14]. This association is defined as an obligatory mutualistic symbiotic relationship that inhabits the root cells of the host plant [15], improving the uptake of P, N, S, K, and various microelements (Fe, Cu, Zn, and many other minerals) [16]. Likewise, it provides resistance against pathogens and unfavorable environmental conditions and improves soil quality [17].

Root colonization by AMF is characterized by presenting fungal structures, such as mycelium, auxiliary cells, arbuscules, vesicles, and spores [18, 19], being this vast structure it is most important for its correct identification using the morphological approach [18–22]. Currently, in the Peruvian Amazon, some studies have recorded a great diversity of AMF [23–27]. New species were identified in different crops [23, 28–38] using morphological and molecular tools [39–41], and molecular analyses of the SSU-ITS-LSU region of rDNA [42].

In this context, to know the symbiotic association between AMF and *M. dubia*, we evaluated: (i) the presence of intraradical fungal structures typical of AMF symbiosis: vesicles, hyphae, and arbuscules; (ii) the presence of AMF rDNA inside the roots of *M. dubia*; and (iii) diversity of AMF species present in *M. dubia* rhizospheric soil in the Amazonas region, Peru.

2. Materials and Methods

2.1. Soil Collection and Conservation. The sampling was carried out in two elite accessions (which exhibited the best agronomic qualities, such as percent pulp, fruit weight, ascorbic acid content, and yield. These accessions gave rise to the first variety of *M. dubia* "INIA 395-Vitahuayo," https://www.gob.pe/institucion/inia/noticias/349846) of the National Germplasm bank of *M. dubia* of the Agrarian Experimental Station "San Roque" Iquitos, National Institute of Agrarian Innovation (INIA) (Figure 1). This station is located at 25 km of the Iquitos–Nauta highway (03°57'17" S, 73°24'55" W, 112 m of elevation) and has a sandy loam texture soil, pH = 4.10, M.O = 1.63%, and P = 3.01 ppm (*Supplementary 1*). The *M. dubia* accessions were introduced from plant material collected from native populations located in the Loreto region (Table 1). The biological samples were composed of 1.5 kg of rhizospheric soil and 10 g of root tissue, which were extracted from three random plants for each accession. From each plant, subsamples were collected from three equidistant points around the main stem from 0 to 20 cm deep, which were mixed and stored in polyethylene bags in a cooler at 4°C and then transported to the biology and molecular genetics laboratories at the National University of San Martín (Tarapoto, Peru). In the laboratory, the roots and soil were separated. The roots were pooled in a sample composed of each accession, washed, dried with paper, cut into 1–2 cm pieces, and homogenized in water. Two 200 mg aliquots were frozen at −80°C for molecular analysis. The remaining roots were kept in ethanol at 70° to determine mycorrhizal colonization. Soil samples were also mixed for each accession, dried at room temperature for 48 hr, and sieved through a 5-mm mesh to remove root debris and stones. Finally, they were stored in airtight bags and kept at 4°C until use.

2.2. Morphological Analyses. The isolation and specimen preparation were performed according to Corazon-Guivin et al. [34]. For the morphological identification of AMF, the classification proposed by Oehl et al. [39] was followed, and the taxonomic organization of orders, families, and genera suggested by Blaszkowski et al. [40] and Wijayawardene et al. [41] was followed.

2.3. Fungal Intraradical Colonization. Approximately 5 g from the roots of each accession were stained, according to Vierheilig et al. [43]. Once stained, the roots were cut into 1 cm segments, mounted on slides, and examined in a compound microscope (20x) by intersection method [44].

2.4. Molecular Analysis. DNA was extracted from 100 mg fine roots (a mix of the three plants for each accession) using the cetyltrimethylammonium bromide (CTAB) protocol. Subsequently, a two-step PCR (using gDNA) was conducted to amplify the ribosomal fragment of AMF consisting of partial SSU, ITS1, 5.8S, ITS2, and partial LSU rDNA using the primers SSUmAf/LSUmAr and SSUmCf/LSUmBr, consecutively [42]. The PCR was carried out according to Corazon-Guivin et al. [23, 28–34]. PCR products from the second round of amplifications (∼1500 bp) were separated by electrophoresis on 1.2% agarose gel, stained with Diamond™ Nucleic Acid Dye (Promega), and revealed by UV illumination.

2.5. Comparative Analysis. Sørensen index was used to assess the similarity of AMF species among accessions. The Venn diagram was constructed using the calculate and draw custom Venn diagrams tool available online (http://bioinformatics.psb.ugent.be/webtools/Venn/).

3. Results and Discussion

According to the morphological and molecular analyses, the mutualistic symbiotic relationship between AMF and *M. dubia* was evidenced for the first time. Likewise, we report the taxonomic diversity of AMF associated with two accessions from the National Germplasm Bank of *M. dubia*, Peru. Previous studies showed that species of the genus *Myrciaria* establish symbiosis with AMF. For example, a study evaluated *M. cauliflora* plants in the field and reported 40% root colonization [45]. In the same way, it was observed that *M. glomerata* seedlings, under controlled conditions, showed similar results [46]. In our study, AMF root colonization reached a mean value of 91%. We were able to observe the presence of different typical AMF

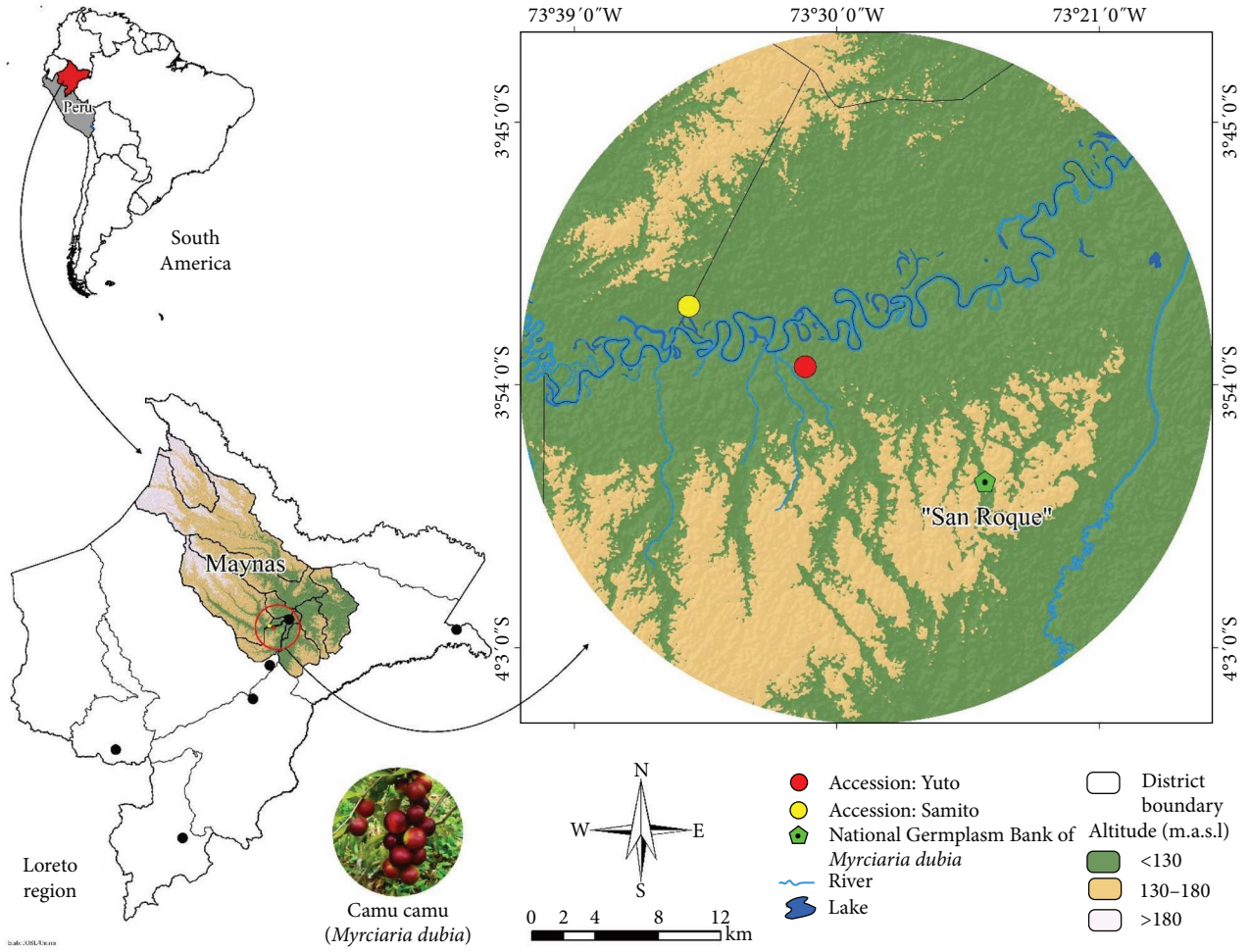

Figure 1: Spatial location of the National Germplasm Bank of *M. dubia* (Kunth) McVaugh at the Agrarian Experimental Station "San Roque" in Loreto Region, National Institute of Agrarian Innovation (INIA).

Table 1: Origin sites of the elite accessions from the National Germplasm Bank of *M. dubia* (Kunth) McVaugh at the Agrarian Experimental Station "San Roque" in Iquitos, National Institute of Agrarian Innovation (INIA), Peru.

Department	Province	District	Basin	Location	Codnac	Codentban	Coordinates
Loreto	Maynas	San Juan Bautista	Nanay	Samito	PER1000394	MD-014	3°51'18.3" S 73°35'4.5" W
				Yuto	PER1000395	MD-015	3°53'22.9" S 73°31'5.0" W

structures, i.e. hyphae, vesicles, and intraradical arbuscules (Figure 2). Also, we provide molecular evidence on the presence of AMF in roots of *M. dubia* (Figure 3). This analysis was carried out using the primers SSUmAf/LSUmAr and SSUmCf/LSUmBr [38], which amplify a much more informative region of rDNA than is typically used for root-level molecular analysis [47].

We found a total of 18 AMF species belonging to nine genera and seven families in the rhizospheric soil of two *M. dubia* accessions (*Supplementary 2*). *Acaulospora* is the most dominant genus, with five species: *A. mellea*, *A. morrowiae*, *A. undulata*, and two unidentified species. Diversispora followed it with four species: *D. aurantia*, *D. eburnea*, *D. invermanium*, *and D. tortuosa*, and *Ambispora* with three species: *A. appendicula*, *A. reticulata*, and an unidentified one. Furthermore, *Funneliformis geosporus*, *Glomus macrocarpum*, *Sclerocystis sinuosum*, *Entrophospora etunicata*, *Gigaspora margarita*, and *Paraglomus* sp. were found (Figure 4). The presence of possible unidentified new species could be related to the fact of an area not yet characterized and a poorly studied plant species. Thus, our research group recently recently reported 11 new AMF species in the Peruvian Amazon such as *Funneliglomus sanmartinensis*, *Microkamienskia peruviana*, *Acaulospora*

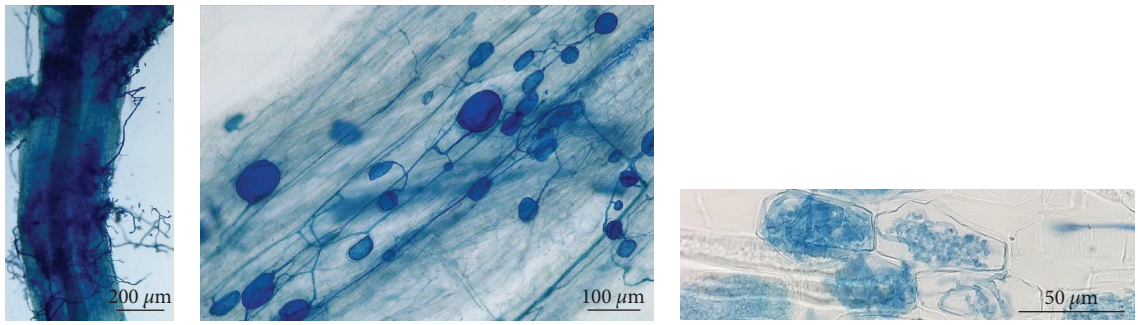

Figure 2: Arbuscular mycorrhizal colonization in *M. dubia* (Kunth) McVaugh: (a) extraradical hyphae of arbuscular mycorrhizal; (b) vesicles in roots; and (c) branched arbuscles.

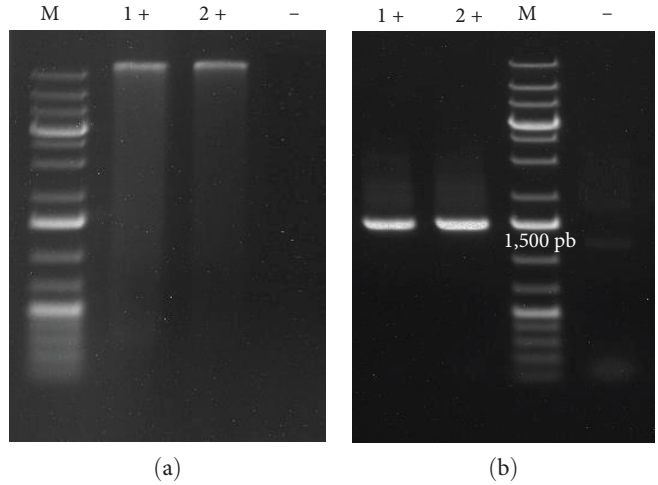

Figure 3: Gel electrophoresis. (a) Carril 1: (M) 1 kb molecular marker (Invitrogen, USA), Carril 2−3: (1+, 2+) AMF genomic DNA, Carril 4: (−) negative control, no DNA was added; (b) PCR reaction, Carril 1−2: (1+, 2+) 1,500 bp fragment of AMF DNA, Carril 3: (M) 1 kb molecular marker (Invitrogen, USA), Carril 4: (−) negative control reaction, no DNA was added.

aspera, *Nanoglomus plukenetiae*, *Rhizoglomus variabile*, *Paraglomus occidentale*, *Acaulospora flava*, *Paraglomus peruvianum*, *Acaulospora flavopapillosa*, *Rhizoglomus cacao*, and *Diversispora alba* [28–38]. A study conducted in three agroecosystems associated with *Theobroma cacao* in the Peruvian Amazon rainforest reported 46 AMF species [48]. Meanwhile, another study carried out in the Colombian Amazon rainforest reported 18 AMF species, similar to the species richness found in our study [49].

Approximately, 65% of the soils of the Amazon lowlands in Peru are classified as ultisols, characterized by being extraordinarily acidic and having low availability of phosphorus [50]. The pH can exert a fundamental influence on the composition and diversity of bacteria and fungi living in the soil, owing to its direct impact on the regulation and mobilization of several essential nutrients [23, 51]. In this context, AM symbiosis constitutes a key strategy to help plants efficiently take up phosphorus from the soil [52]. In this type of ecosystem, it has been reported that the genus *Acaulospora* is abundant [48], similar to our study, where the sampling area is classified as ultisol. In this regard, Veresoglou et al. [53] and Coutinho et al. [54] mentioned that the genus *Acaulospora* is adapted to an acid soil pH (<5.0). Likewise, the absence of species from the *Rhizoglomus* genus in our study could be influenced by pH, as certain limitations in the growth of some species of this genus in slightly acidic soil have been reported [55].

Among the 18 AMF species identified, two were found exclusively in the rhizospheric soil of Samito, six species in the rhizospheric soil of Yuto, and 12 AMF species were shared between both accessions (Figure 5). The high percentage of similarity (67%) of AMF species can be attributed to the proximity of both accessions within the Germplasm bank, exhibiting similar edaphoclimatic properties. In their study, Vieira et al. [56] demonstrated a higher percentage of similarity of AMF species in two ecosystems that shared similar soil properties. Furthermore, the presence of certain AMF species exclusively in the rhizospheric soil of one accession and not the other could indicate that the genotype of each accession might have an influence. In this regard,

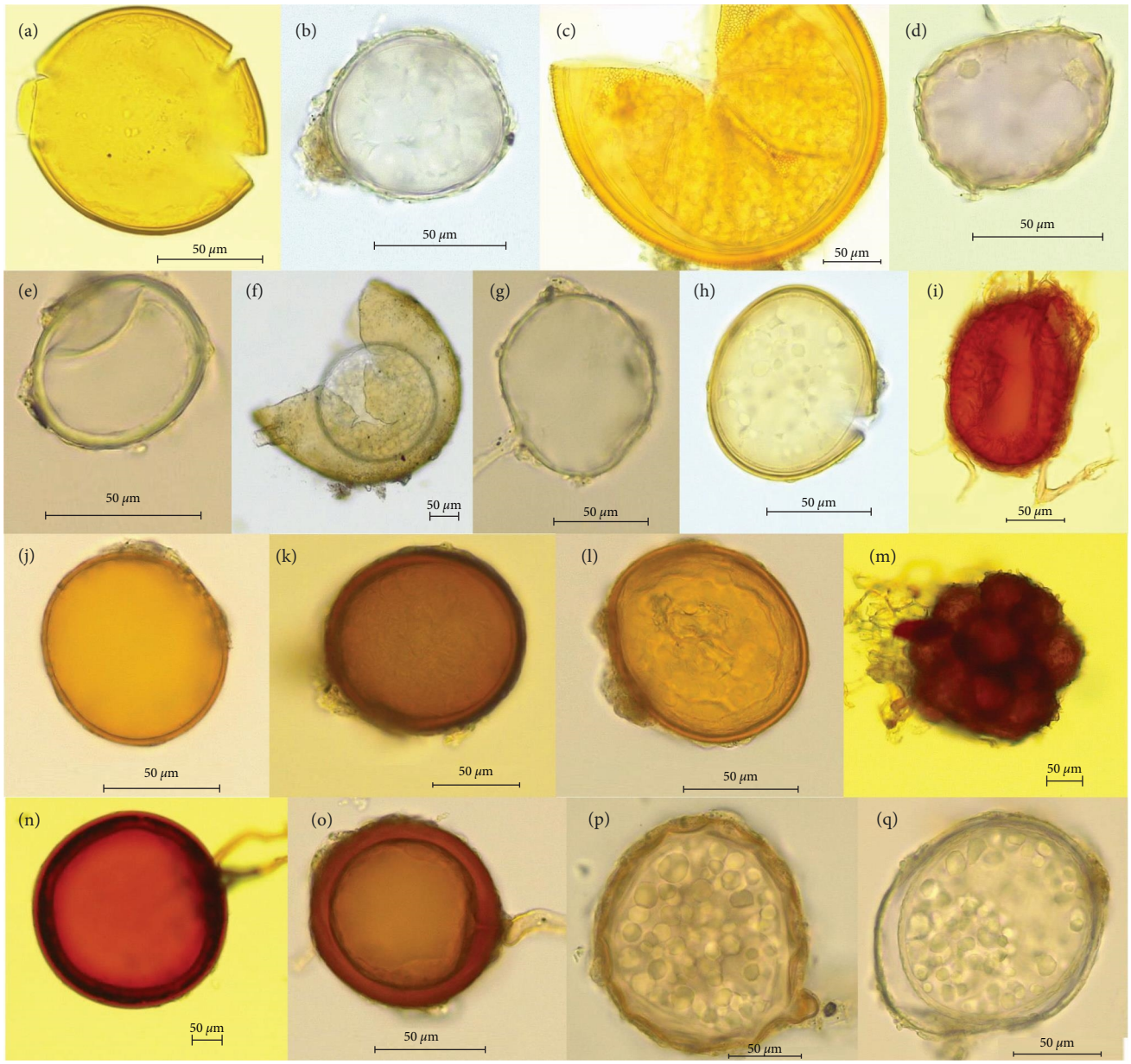

Figure 4: AMF species in *M. dubia* (Kunth) McVaugh: (a) *Entrophospora etunicata;* (b) *Acaulospora morrowiae* (c) *Acaulospora* sp1.*; (d) *Acaulospora* sp2.*; (e) *Paraglomus* sp.; (f) *Ambispora appendicula;* (g) *Diversispora eburnea;* (h) *Acaulospora mellea*, (i) *Diversispora tortuosa;* (j) *Diversispora aurantia;* (k) *Diversispora invermanium;* (l) *Funneliformis geosporum;* (m) *Sclerocystis sinuosum;* (n) *Gigaspora margarit;* (o) *Glomus macrocarpum;* (p) *Ambispora* sp.*; (q) *Ambispora reticulata*. (*) still unidentified.

Carrascosa et al. [57] also demonstrated that purslane genotypes from different geographical areas can significantly influence the composition of microbial communities in their rhizospheres.

4. Conclusions

Our study reports and describes, for the first time, the interaction between AMF and *M. dubia* through the observation of structures such as hyphae, vesicles, and arbuscules in the root system of this plant. Likewise, molecular techniques allowed the confirmation of the presence of AMF in *M. dubia* roots, at the time of sampling. On the other hand, in soil samples, it was possible to identify a high diversity of AMF associated with the rhizosphere of *M. dubia*, the *Acaulospora* genus being the richest in morphospecies. Our results indicate that AMF may play a very important role in the establishment, nutrition, and productivity of *M. dubia* cultures, which is why it is important to carry out research to elucidate the functional role of these fungi in the flow of nutrients

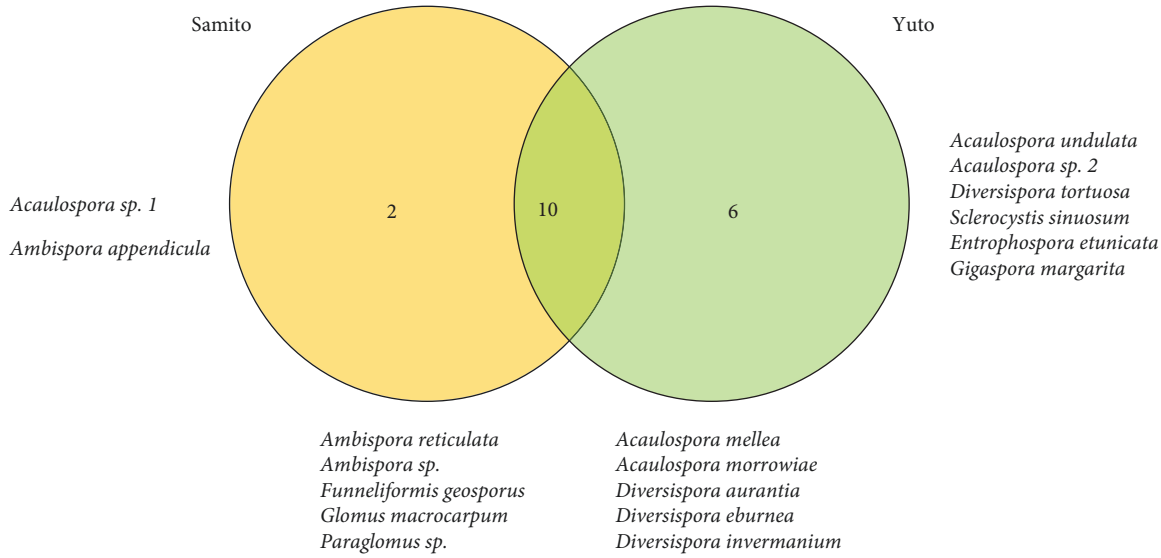

Figure 5: Venn diagram showing the AMF species richness (exclusive and shared) in the rhizospheric soil of the Samito and Yuto accessions of *M. dubia* (Kunth) McVaugh.

between the soil and plant. This will help to propose better strategies for the use, management, and formulation of inoculants that promote sustainable production of *M. dubia* crops in Peru.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author and co-authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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Supplementary Materials

Supplementary 1. Table 1: physical–chemical soil properties of the National Germplasm Bank of *M. dubia* (Kunth) McVaugh at the Agrarian Experimental Station "San Roque" in Loreto Region, National Institute of Agrarian Innovation (INIA).

Supplementary 2. Table 2: abundance, richness of species, and colonization of arbuscular mycorrhizal fungi in the rhizospheric soil of two elite accessions from the National Germplasm Bank of *M. dubia* (Kunth) McVaugh of the Agrarian Experimental Station "San Roque" Iquitos, of the National Institute of Agrarian Innovation (INIA).

References

[1] P. C. Langley, J. V. Pergolizzi Jr., R. Taylor Jr., and C. Ridgway, "Antioxidant and associated capacities of camu camu (*Myrciaria dubia*): a systematic review," *Journal of Alternative and Complementary Medicine*, vol. 21, no. 1, pp. 8–14, 2015.

[2] E. Arellano-Acuña, I. Rojas-Zavaleta, and L. Paucar-Menacho, "Camu-camu (*Myrciaria dubia*): fruta tropical de excelentes propiedades funcionales que ayudan a mejorar la calidad de vida," *Scientia Agropecuaria*, vol. 7, no. 4, pp. 433–443, 2016.

[3] L. Azevedo, P. F. de Araujo Ribeiro, J. A. de Carvalho Oliveira et al., "Camu-camu (*Myrciaria dubia*) from commercial cultivation has higher levels of bioactive compounds than native cultivation (Amazon forest) and presents antimutagenic effects *in vivo*," *Journal of the Science of Food and Agriculture*, vol. 99, no. 2, pp. 624–631, 2018.

[4] M. Fidelis, J. S. Santos, G. B. Escher et al., "*In vitro* antioxidant and antihypertensive compounds from camu-camu (*Myrciaria dubia* McVaugh, Myrtaceae) seed coat: a multivariate structure-activity study," *Food and Chemical Toxicology*, vol. 120, no. 1, pp. 479–490, 2018.

[5] A. Fujita, V. Souza, L. Daza, C. Fávaro-Trindade, D. Granato, and M. Genovese, "Effects of spray-drying parameters on *in vitro* functional properties of camucamu (*Myrciaria dubia* Mc. Vaugh): a typical Amazonian fruit," *Journal of Food Science*, vol. 82, no. 5, pp. 1083–1091, 2017.

[6] M. Pinedo Panduro, C. Linares Bensimón, H. Mendoza Zuñiga, and R. Anguiz, *Plan de Mejoramiento Genético de Camu Camu*, Instituto de Investigaciones de la Amazonia Peruana, Iquitos, Perú, 2004.

[7] C. Abanto-Rodriguez, M. Pinedo-Panduro, E. Alves-Chagas et al., "Relation between the mineral nutrients and the vitamin C content in camu-camu plants (*Myrciria dubia*) cultivated on high soils and flood soils of Ucayali," *Scientia Agropecuaria*, vol. 7, no. 3, pp. 297–304, 2016.

[8] L. K. O. Yuyama, J. P. L. Aguiar, K. Yuyama et al., "Teores de elementos minerais em algumas populações de camu-camu," *Acta Amazônica*, vol. 33, no. 1, pp. 549–554, 2003.

[9] M. Hermann, "The impact of the european novel food regulation on trade and food innovation based on traditional plant foods from developing countries," *Food Policy*, vol. 34, no. 6, pp. 499–507, 2009.

[10] D. Fracassetti, C. Costa, L. Moulay, and F. A. Tomás-Barberán, "Ellagic acid derivatives, ellagitannins, proanthocyanidins and other phenolics, vitamin C and antioxidant capacity of two powder products from camu-camu fruit (*Myrciaria dubia*)," *Food Chemistry*, vol. 139, no. 1–4, pp. 578–588, 2013.

[11] V. Doroteo, C. Terry, C. Díaz, A. Vaisberg, and R. Rojas, "Compuestos fenólicos y actividades antioxidante, antielastasa, anticolagenasa y fotoprotectora *in vitro* de *Myrciaria dubia* (camu camu) y *Caesalpinia spinosa* (tara)," *Revista de la Sociedad Química del Perú*, vol. 78, no. 4, pp. 254–263, 2012.

[12] M. C. Brundrett and L. Tedersoo, "Evolutionary history of mycorrhizal symbioses and global host plant diversity," *New Phytologist*, vol. 220, no. 4, pp. 1108–1115, 2018.

[13] J. Taylor, T. Helgason, and M. Öpik, "Molecular community ecology of arbuscular mycorrhizal fungi," in *The Fungal Community: Its Organization and Role in the Ecosystem*, J. Dighton and J. F. White, Eds., pp. 1–26, CRC Press Taylor & Francis, Fourth edition, 2017.

[14] F. F. Martín, J. J. Molina, E. N. Nicolás et al., "Application of arbuscular mycorrhizae *Glomus iranicum* var. *tenuihypharum* var. *nova* in intensive agriculture: a study case," *Journal of Agricultural Science and Technology*, vol. 7, pp. 221–247, 2017.

[15] S. Ivanov, J. Austin II, R. H. Berg, and M. J. Harrison, "Extensive membrane systems at the host-arbuscular mycorrhizal fungus interface," *Nature Plants*, vol. 5, no. 2, pp. 194–203, 2019.

[16] P. Teotia, M. Kumar, R. Prasad, V. Kumar, N. Tuteja, and A. Varma, "Mobilization of micronutrients by mycorrhizal fungi," in *Mycorrhiza—Function, Diversity, State of the Art*, A. Varma, R. Prasad, and N. Tuteja, Eds., pp. 9–26, Springer, Cham, 2017.

[17] V. Säle, J. Palenzuela, C. Azcón-Aguilar et al., "Ancient lineages of arbuscular mycorrhizal fungi provide little plant benefit," *Mycorrhiza*, vol. 31, pp. 559–576, 2021.

[18] S. Stürmer, "A history of the taxonomy and systematics of arbuscular mycorrhizal fungi belonging to the phylum Glomeromycota," *Mycorrhiza*, vol. 22, pp. 247–258, 2012.

[19] E.-H. Lee, J.-K. Eo, K.-H. Ka, and A.-H. Eom, "Diversity of arbuscular mycorrhizal fungi and their roles in ecosystems," *Mycobiology*, vol. 41, no. 3, pp. 121–125, 2013.

[20] C. Thonar, A. Erb, and J. Jansa, "Real-time PCR to quantify composition of arbuscular mycorrhizal fungal communities—marker design, verification, calibration and field validation," *Molecular Ecology Resources*, vol. 12, no. 2, pp. 219–232, 2011.

[21] P. Kohout, R. Sudová, and M. Janoušková, "Comparison of commonly used primer sets for evaluating arbuscular mycorrhizal fungal communities: is there a universal solution?" *Soil Biology and Biochemistry*, vol. 68, pp. 482–493, 2014.

[22] T. Thapa, U. De, and B. Chakraborty, "Association and root colonization of some medicinal plants with arbuscular mycorrhizal fung," *Journal of Medicinal Plants Studies*, vol. 3, no. 2, pp. 25–35, 2015.

[23] M. Corazón-Guivin, A. Vallejos-Tapullima, and S. Rengifo-Del Aguila, "Influence of substrate properties on communities of arbuscular mycorrhizal fungi isolated from agroecosystems in Peru," *Journal of Soil Science and Plant Nutrition*, vol. 22, pp. 4784–4797, 2022.

[24] S. Rengifo-Del Aguila, A. De la Sota-Ricaldi, M. Corazon-Guivin, and Á. López-García, "Phylogenetic diversity of arbuscular mycorrhizal fungal communities increases with crop age in *Coffea arábica* plantations," *Journal of Soil Science and Plant Nutrition*, vol. 22, no. 1, pp. 3291–3303, 2022.

[25] N. Diagne, M. Ngom, P. Djighaly, D. Fall, V. Hocher, and S. Svistoonoff, "Roles of arbuscular mycorrhizal fungi on plant growth and performance: importance in biotic and abiotic stressed regulation," *Diversity*, vol. 12, no. 10, Article ID 370, 2020.

[26] A. M. de la Sota Ricaldi, S. Rengifo Del Águila, R. Blas Sevillano, Á. López-García, and M. A. Corazon-Guivin, "Beta diversity of arbuscular mycorrhizal communities increases in time after crop establishment of Peruvian sacha inchi (*Plukenetia volubilis*)," *Journal of Fungi*, vol. 9, no. 2, Article ID 194, 2023.

[27] B. Luis-Alaya, M. Toro, R. Calsina et al., "Evaluation of the presence of arbuscular mycorrhizae and cadmium content in the plants and soils of cocoa plantations in San Martin, Peru," *Diversity*, vol. 15, no. 2, Article ID 246, 2023.

[28] M. A. Corazon-Guivin, A. C. Mendoza, J. C. Guerrero-Abad et al., "*Funneliglomus*, gen. nov., and *Funneliglomus sanmartinensis*, a new arbuscular mycorrhizal fungus from the Amazonia region in Peru," *Sydowia*, vol. 71, pp. 17–24, 2019.

[29] M. Corazon-Guivin, A. Cerna-Mendoza, and J. Guerrero-Abad, "*Nanoglomus plukenetiae*, a new fungus from Peru, and a key to small-spored Glomeraceae species, including three new genera in the "*Dominikia* complex/clades"," *Mycological Progress*, vol. 18, pp. 1395–1409, 2019.

[30] M. Corazon-Guivin, A. Cerna-Mendoza, J. Guerrero-Abad, A. Vallejos-Tapullima, G. Silva, and F. Oehl, "*Acaulospora aspera*, a new fungal species in the Glomeromycetes from rhizosphere soils of the inka nut (*Plukenetia volubilis* L.) in Peru," *Journal of Applied Botany and Food Quality*, vol. 92, pp. 250–257, 2019.

[31] M. Corazon-Guivin, A. Cerna-Mendoza, and J. Guerrero-Abad, "*Microkamienskia* gen. nov. and *Microkamienskia peruviana*, a new arbuscular mycorrhizal fungus from Western Amazonia," *Nova Hedwigia*, vol. 109, no. 3-4, pp. 355–368, 2019.

[32] J. Song, J.-F. Liang, M. Mehrabi-Koushki, I. Krisai-Greilhuber, and B. Ali, "Fungal systematics and evolution: FUSE 5," *Sydowia*, vol. 71, pp. 141–245, 2019.

[33] M. A. Corazon-Guivin, A. Cerna-Mendoza, J. C. Guerrero-Abad et al., "*Paraglomus occidentale*, a new arbuscular mycorrhizal fungus from the sources of the Amazon river in Peru, with a key to the Paraglomeromycetes species," *Sydowia*, vol. 72, pp. 85–94, 2020.

[34] M. A. Corazon-Guivin, A. Vallejos-Tapullima, A. M. de la Sota-Ricaldi et al., "*Acaulospora flava*, a new arbuscular mycorrhizal fungus from *Coffea arabica* and *Plukenetia volubilis* plantations at the sources of the Amazon river in Peru," *Journal of Applied Botany and Food Quality*, vol. 94, pp. 116–123, 2021.

[35] M. A. Corazon-Guivin, A. Vallejos-Tapullima, A. M. de la Sota-Ricaldi et al., "*Acaulospora flavopapillosa*, a new fungus in the Glomeromycetes from a coffee plantation in Peru, with an updated key for the identification of Acaulosporaceae species," *Journal of Applied Botany and Food Quality*, vol. 95, pp. 6–16, 2022.

[36] M. Corazón-Guivin, G. Vallejos-Torres, A. Vallejos-Tapullima et al., "*Rhizoglomus cacao*, a new species of the Glomeraceae from the rhizosphere of *Theobroma cacao* in Peru, with an updated identification key for all species attributed to Rhizoglomus," *Nova Hedwigia*, vol. 115, pp. 99–115, 2022.

[37] R. Lebeuf, A. Paul, Y. Lamoureux et al., "Fungal systematics and evolution: FUSE 8," *Sydowia*, vol. 74, pp. 193–249, 2022.

[38] R. Lebeuf, J. Landry, J. F. Ammirati et al., "Fungal systematics and evolution: FUSE 9," *Sydowia*, vol. 75, pp. 313–377, 2023.

[39] F. Oehl, E. Sieverding, J. Palenzuela, K. Ineichen, and G. A. da Silva, "Advances in *Glomeromycota* taxonomy and classification," *IMA Fungus*, vol. 2, no. 2, pp. 191–199, 2011.

[40] J. Błaszkowski, M. Sanchez-Garcia, P. Niezgoda et al., "A new order, Entrophosporales, and three new *Entrophospora* species in Glomeromycota," *Frontiers in Microbiology*, vol. 13, pp. 1–25, 2022.

[41] N. N. Wijayawardene, K. D. Hyde, L. K. T. Al-Ani et al., "Outline of fungi and fungus-like taxa," *Mycosphere*, vol. 11, no. 1, pp. 1060–1456, 2020.

[42] M. Krüger, H. Stockinger, C. Krüger, and A. Schüßler, "DNA-based species level detection of *Glomeromycota*: one PCR primer set for all arbuscular mycorrhizal fungi," *New Phytologist*, vol. 183, no. 1, pp. 212–223, 2009.

[43] H. Vierheilig, A. P. Coughlan, U. Wyss, and Y. Piché, "Ink and vinegar, a simple staining technique for arbuscular-mycorrhizal fungi," *Applied and Environmental Microbiology*, vol. 64, no. 12, pp. 5004–5007, 1998.

[44] T. P. McGONIGLE, M. H. Miller, D. G. Evans, G. L. Fairchild, and J. A. Swan, "A new method which gives an objective measure of colonization of roots by vesicular-arbuscular mycorrhizal fungi," *New Phytologist*, vol. 115, no. 3, pp. 495–501, 1990.

[45] M. Bhuiyan, M. Banu, and M. Rahman, "Assessment of arbuscular mycorrhizal association in some fruit and spice plants of Rangamati hill district," *Bangladesh Journal of Agricultural Research*, vol. 42, no. 2, pp. 221–232, 2017.

[46] R. F. da Rui, S. C. Santos, E. R. P. Lourente, S. de Paula Quintão Scalon, D. M. Dresch, and J. A. Schiavo, "Mudas de *Myrciaria glomerata* (o. berg) com fungos micorrízicos arbusculares e fósforo: crescimento e dependência micorrízica," in *Tecnologia de Produção em Fruticultura*, pp. 32–49, Atena Editors, 2020.

[47] M. Öpik, A. Vanatoa, E. Vanatoa et al., "The online database Maarj *AM* reveals global and ecosystemic distribution patterns in arbuscular mycorrhizal fungi (Glomeromycota)," *New Phytologist*, vol. 188, no. 1, pp. 223–241, 2010.

[48] K. Rojas-Mego, C. Elizarbe-Melgar, M. Gárate-Díaz, D. Ayala-Montejo, R. Pedro, and E. Sieverding, "Hongos de micorriza arbuscular en tres agroecosistemas de cacao (*Theobroma cacao* L.) en la amazonía peruana," *Folia Amazónica*, vol. 23, no. 2, pp. 149–156, 2014.

[49] C. Peña-Venegas, G. Cardona, J. Arguelles, and A. L. Arcos, "Micorrizas arbusculares del sur de la amazonia colombiana y su relación con algunos factores fisicoquímicos y biológicos del suelo," *Acta Amazónica*, vol. 37, pp. 327–336, 2007.

[50] P. Ruiz, K. Rojas, and E. Sieverding, "La distribución geográfica de los hongos de micorriza arbuscular: una prioridad de investigación en la Amazonía peruana," *Espacio y Desarrollo*, vol. 1, no. 23, pp. 47–63, 2011.

[51] Y. Ma, H. Zhang, D. Wang et al., "Differential responses of arbuscular mycorrhizal fungal communities to long-term fertilization in the wheat rhizosphere and root endosphere," *Applied and Environmental Microbiology*, vol. 87, no. 17, pp. 1–13, Article ID e0034921, 2021.

[52] L. Wang, L. Zhang, T. S. George, and G. Feng, "A core microbiome in the hyphosphere of arbuscular mycorrhizal fungi has functional significance in organic phosphorus mineralization," *New Phytologist*, vol. 238, no. 2, pp. 859–873, 2023.

[53] S. Veresoglou, T. Caruso, and M. Rillig, "Modelling the environmental and soil factors that shape the niches of two common arbuscular mycorrhizal fungal families," *Plant and Soil*, vol. 368, pp. 507–518, 2013.

[54] E. S. Coutinho, G. W. Fernandes, R. L. L. Berbara, H. M. Valério, and B. T. Goto, "Variation of arbuscular mycorrhizal fungal communities along an altitudinal gradient in rupestrian grasslands in Brazil," *Mycorrhiza*, vol. 25, no. 8, pp. 627–638, 2015.

[55] M. C. Arocha-Rodríguez, E. Pérez-Ortega, K. Fernández-Suárez, and G. Haesaert, "Efecto del pH del medio de cultivo en el crecimiento presimbiótico de *Rhizoglomus irregulare*," *Cultivos Tropicales*, vol. 40, pp. 1–12, 2019.

[56] L. C. Vieira, D. K. A. Silva, I. E. C. Escobar et al., "Changes in an arbuscular mycorrhizal fungi community along an environmental gradient," *Plants*, vol. 9, no. 1, Article ID 52, 2020.

[57] A. Carrascosa, J. A. Pascual, A. López-García et al., "Different functional and taxonomic composition of the microbiome in the rhizosphere of two purslane genotypes," *Agronomy*, vol. 13, no. 7, Article ID 1795, 2023.