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The Role of Arbuscular Mycorrhizal Fungi for Plant from the Symbiotic Perspective

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Abstract:

The symbiotic relationships between Arbuscular Mycorrhizal Fungi (AM) and plant roots not only enhance the symbiotic plant significantly uptake of key nutrients (such as phosphorus and nitrogen) in poor soils but also have a vital role in local and global ecosystems. After AM extends to deep soil through a network of myceliums, it can not only cooperate and promote the absorption of nutrient elements for plants but also affect the weathering process of soil and rock through its unique chemical and physical mechanism. In response to changes in local soil nutrients and geological structure, AM, as a natural "Carbon sink" for carbon storage, also can secrete several macro-molecules of carbon into the soil, which increases the carbon content of the soil, making the soil more cohesive. This further shows its great potential in improving the ecological environment by improving soil health. Therefore, this article will take arbuscular mycorrhizas as a mutualistic relationship highly studied by the academic community as an example, analyze the biological mechanism of each symbiotic relationship, its impact on the host and its contribution to the host-pathogen defense, and deeply study the effects of AM and plant symbiosis on soil absorption, rock weathering and carbon storage, which will not only help to reveal their ecological functions, but also help to reveal their ecological functions. It also provides new ideas for environmental protection and sustainable development in the future.

Keywords: Arbuscular mycorrhizas, host plant, symbiosis.

1. Introduction

Over the past billion years, life has emerged from the ocean and evolved to spread and colonize the surface of the Earth. As species evolved into a diverse community, complex interactions gradually formed and evolved within this community. In addition to the basic food web and predator-prey relationships, the concept of symbiosis also developed. Symbiosis is known as a long-term relationship between two species. At one-point, occasional symbiotic relationships among prokaryotes gave rise to a new kingdom—the eukaryotes. The evidence of this symbiotic relationship was inherited by living cells, mitochondria run

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as power stations to provide energy, while chloroplasts produce sugar from photosynthesis. Symbiosis has been foundational to the diverse world. A vivid example of symbiotic relationships in our world can be observed through microorganisms, which are the largest, oldest, and most diverse group of organisms on Earth. These tiny organisms are found worldwide, from Arctic icebergs to hot springs near volcanoes. Despite microorganisms being so small them, their existence supports all plants and animals on the Earth. For example, microorganisms in our bodies, particularly in the digestive system, help humans to process and absorb food, and they can also regulate intestine health. There are an estimated 39 trillion microbial cells living in individual bodies and had a ratio of 10:1 to cells, and genes have deliberately created an environment in the large intestine for growing these beneficial bacteria. Aside from animals, which require a digestive system, autotrophs like plants have also developed tight symbiotic relationships with microorganisms throughout evolution. The plant-microbe symbiosis in the past million years, including mutualistic symbiosis and pathogenic have affected the evolution and population of the host plants [1]. In modern agriculture, this relationship has become an important factor in crop yield and quality. In soya bean farming, the symbiotic relationship with rhizobia, can highly affect its yield. The nitrogen-fixing function performed by rhizobia's symbiotic structure nodes has greatly contributed to the high protein contents in the legume. Related studies show interspecies genome exchange, infection process and heritage, and competition among different rhizobia communities [2]. Another notable example is arbuscular mycorrhizal fungi, which can also form symbiotic structures with plants and help them to absorb and transport nutrients from the soil, while plants provide carbon compounds for fungi. Despite the absence of clear sexual reproduction evidence, the fossil record of AM fungi can trace to 4.6 billion years ago, which is way beyond the time plants colonized the land [3]. Furthermore, some hypotheses have proposed the possibility of AM fungi symbiosis assisted the plant's transition to the land, and the idea was supported by the genome studies of three genes needed by AM, and analytic results show these genes might existed in the ancestor of all land-plants [4]. AM fungi symbiosis also shows its ability on soil fertility improvement and even change tolerance of the host. Also, there is evidence stating that interspecies competition driven by the symbiotic relationship in both fungi and plant communities. Since symbiosis brought huge benefits for both species in the ecosystem, the dominance and accessibility of this relationship become an important problem for the whole community. Plants hosted with AM symbiosis can have more niche competitive advantages, which can cause the spreading of host plants in the environment. The mechanism of plant-microbe symbiosis was gradually revealed, but the detailed gene-level regulation, modification and interaction were still unclear. Future research directions can target the Fungi and plant genes and proteins used in symbiosis, and more symbiotic examples are needed. This paper aims to summarize current studies on the symbiotic relationships between microorganisms and plants, focusing on symbiotic interactions, interspecies effects, and ecosystem affections. The goal is to propose potential research directions and perspectives.

2. Plant-microbe symbiotic relationship

A lot of symbiosis relationships have been undergoing millions of years in the environment and formed their unique and diverse interacting pathways. However, there are also a few of them being highly interested by scientists due to their potential benefits for human society. The following text will take arbuscular mycorrhizal as a highly studied mutualistic symbiotic relationships in academia as examples to analyze the biological mechanisms of each symbiotic relationship, their impact on the host, and their contributions to host pathogen defense.

2.1 The mechanism of AM fungi symbiosis

Arbuscular mycorrhizal (AM), is a symbiotic structure formed by fungi that aims to help plant root absorption. Glomeromycota fungi have usually been used in AM studies, as it is widely distributed around the world. The mechanism of the AM symbiosis is the fine-tuned process contributed by both fungi and plants, including a series of chemical communication before and after physical interaction.

At first, both plants and fungi doesn't notice the existence of each other, so constantly releasing communicate molecules are vital to both species. Then, as chemical signals be received by one symbiont, the responses will eventually lead to positive feedback, that promote both symbionts into the pre-symbiosis stages. The goal pre-symbiosis stage is to awaken the coordinated differentiation and promote growth. Phytohormones like Strigolactones (SLs), Gibberellin, auxin and so on are believed to play an important role in plant signaling. Strigolactones (SLs), as one of the key pre-symbiotic phytohormones, are released into the soil, and promote the hyphal branching by releasing short chitin. Hyphopodium is a specialized hyphal structure formed on the root epidermis, which is used for nutrient exchange with plants. Meanwhile, fungi will produce "Myc factors", that are used for arousing the root tissue for differentiation and activate the common symbiosis signaling pathway. Once the physical interaction builds up the symbiotic structure, the nutrient exchange will begin. Then, the maintenance and colonization control will become the main scenario in symbiosis. Chemicals like Gibberellin/Gibberellic acids have double roles in regulating AM colonization and arbuscule formation [5]. A high concentration of Gibberellin will suppress colonization, while low concentration will significantly inhibit colonization. In cooperation with related proteins, Gibberellin can maintain the dominant position of plants in the symbiotic relationship. The uniqueness of AMF symbiosis not only present in the detailed chemical communication pathway, but also show on its diverse beneficial affections to host.

2.2 The impact of AM on the host

The effects of AM (arbuscular mycorrhizal) fungi symbiosis on the host can be classified into niche competitive advantages, genetic influences, and potential threats to colonization. Firstly, host plants can receive extra nutrients from AM fungi, which provides significant advantages for the growth, repair and reproduction of the host. Also, studies have shown that AM symbiosis contributes essential elements that plants often struggle to uptake on their own, elements include phosphorus (P), nitrogen (N), sulfur (S) and so on in various molecular forms, which are crucial for the synthesis of proteins and DNA in plants. Research on sweet cherry rootstock and tomatoes has demonstrated the ability of AM fungi to mediate water stress effectively [6]. Several studies have highlighted that the competitive advantage provided by AM fungi can vary among different plant species and fungus types. The genes coded for AM symbiosis in each species can perform differently, which means each individual fungi species has their favored plant, and different fungi in host plant can perform a unique combination. However, AM fungi colonization can also lead to potential threats under certain conditions. Research has shown that M. polymorpha from the Glomeraceae family is one of the rare plants that cannot form a symbiotic relationship with AM fungi and may even be harmed by fungal colonization of their tissues [7], and but authors also admitted the mutualistic symbiosis is the main scenario between AM fungi and plants. Additionally, a single plant species can be infected by multiple AM fungi simultaneously, which can lead to intense competition for ecological niches in of host, and the result can be non-beneficial or even harmful to the host. Also, the mechanism of the affection of AM fungi to the response of the plant defense system to symbiosis remains unclear. As the first physical interaction happens, the host's defense system will perform a short response and followed by inhibition. The inhibition of the plant defense system is explained by the corresponding molecular signal (such as chitin) generated by AM fungi, but it is controversial about the long-term regulation of the defense system. The transient, weak response from host plants is a key mystery waiting for an explanation. One study proposed several explanations, that can be summarized as the invalid of exogenous elicitors, inactivation of defense signal molecules, regulation of hormones, potential inhibition method and suppressed expression [8]. Current research direction in this field reinforced the importance of genome sequencing of both symbionts, and clear explanation based on gene, and protein regulation to the symbiosis [9]. In summary, AM fungi symbiosis brought huge benefits for plant growth in the ecosystem from both nutritional and defensive perspectives, but the degree of affection is constrained to the genetic adaptation and communication of both symbionts, and there is still a lacks studies about the mechanism in genetic and molecular level.

2.3 Defense of AM against pathogen and infections

The defense function of AM fungi to plants can be classified as direct and indirect affections. The direct impact of AM fungi includes an increase in chemical compounds used for defense, that unusual to be produced. Other studies have widely suggested the defense-promoting functions of AM fungi in varied plant systems. Scientist summarized AM fungi's function in protecting plants from underground pathogens, nematodes and herbivory insects [10]. Studies in AM symbiosis strawberry not only shows the half-reduction of larvae when the roots are been colonize by fungi, but also the poplar seedlings against gypsy moth larvae shows an obvious reduction in larvae size, an increase in larvae duration and living rate, which indicates its key role in strengthening the pest resistance of host plants [11]. However, there still isn't a clear explanation about how AM fungi made such a contribution to the host, and target gene tracing is still needed for future research. While the indirect impacts include more nutrient supply for plants, elements like phosphorus, sulfur and nitrogen can be essential for the synthesis of hormones and chemicals used for eliminating pathogens. In addition, the symbiosis of AM fungi can promote the release of volatiles in the host plants, which can attract parasitoids, which usually prey on herbivory [10]. In conclusion, many studies have shown AM fungi symbiosis can bring obvious advantages to the plant defensive system from both direct and indirect assistance. The presence of AM fungi can reinforce the nutrient uptake of host plants and perform well in defense of the underground herbivores, but the detailed

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explanation of this pathway is still unclear.

3. The impact of symbiotic relationships on ecosystems

The symbiotic relationships between Arbuscular Mycorrhizal Fungi (AM) and plant roots also have a vital influence in their local and global ecosystems. This article will evaluate its impact on soil nutrients and geological structure, as well as examine AM's role in the global carbon cycle, particularly assessing its contribution as a carbon sink in mitigating climate change.

3.1 The Role of AM in Promoting Nutrient Absorption Efficiency in Soil

It was mentioned in the previous part of this article that AM extends into the deep soil through its mycelial network, greatly expanding the range of absorption by plant roots. This mechanism significantly improves the absorption efficiency of key nutrients such as phosphorus and nitrogen in the soil by its symbiotic plants. Studies have shown that when the supply of phosphorus fertilizer is low, the root hyphal colonization of AM fungal fascicula will significantly increase(See Figure 1-2) [12]. Figure 1 shows the abundance of fungal T-RFs under different phosphorus treatments (P0, P25, P100) and different growth stages (V6, V13, R4). Especially when P25 is applied, the abundance of AM fungi significantly increases with increasing soil depth. This further supports the positive impact of low phosphorus supply (P25) on the AM fungal population itself [12]. Figure 2 shows the effects of applying different levels of phosphorus fertilizer (CK, P25, P100) at different growth stages (V6, V13, and R4) on the composition of AMF microbiota in maize roots. In summary, it can be concluded that under low phosphorus supply conditions, AMF root colonization significantly increases (P25), which supports the conclusion that AM fungi can improve plant phosphorus uptake efficiency under lower phosphorus supply [12].

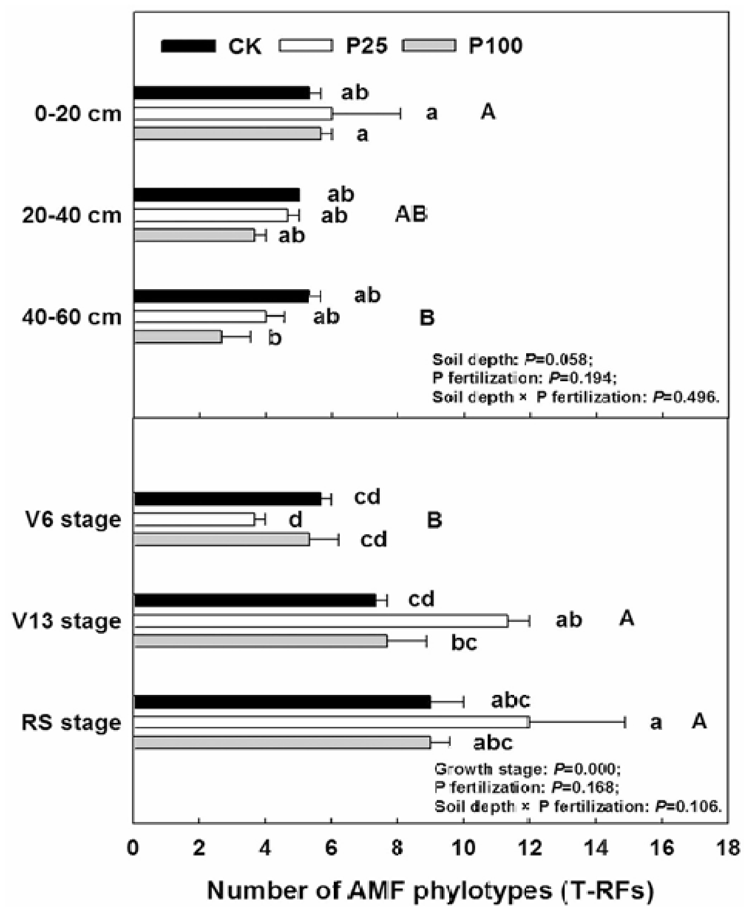

Figure 1. Abundance of AM Fungi Increases with Soil Depth Under Low Phosphorus Treatment (P25)[12]

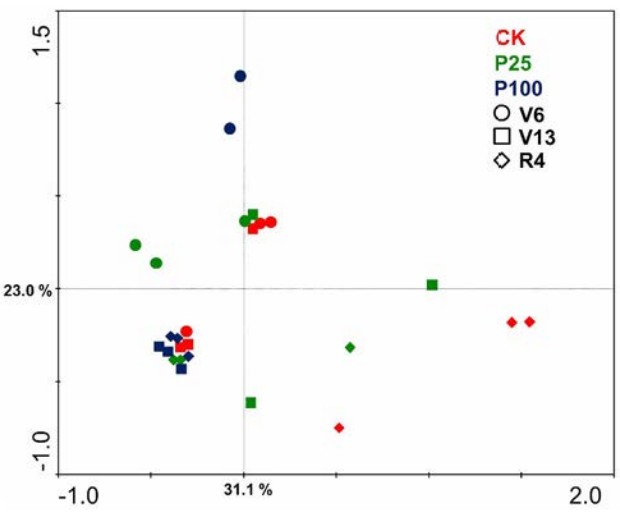

Figure 2. Low Phosphorus Supply (P25) Enhances AMF Root Colonization and Phosphorus Uptake Efficiency in Maize [12]

This type of enhancement is particularly significant in soils with poor nutrition conditions, as the AM's mycelium can reach areas inaccessible to normal plant roots, thereby absorbing more nutrients. Anderson and Cairney summarized this situation in discussing the ecological function of fungi [13], pointing out that the gain of AM's mycelial network could not simply be regarded as enhancing the nutrient absorption of plants. This enhancement simultaneously showed improvements of the recycling efficiency and availability of nutrient element in soil. In other words, when considering the entire ecosystem as a single entity, this process speeded up and enhances the 'metabolic cycles' of the local environment, enabling more distant resource joining the ecological cycle. Thereby, it indirectly participating in and enhancing the broader biogeochemical cycles in the ecosystem [13].

3.2 The Contribution of Arbuscular Mycorrhizal Fungi to Rock Weathering

AM fungi also play a role in rock weathering through their mycelial networks, as they can penetrate deep into the soil through their mycelium and come into contact with deep-seated minerals. These mycelia not only expand the absorption range of their symbiotic plant roots, but also secrete low molecular weight organic acids (LMWOAs) such as citric acid, oxalic acid, and malic acid, which promote mineral decomposition in rocks by chelating metal ions on mineral surfaces. Then, minerals such as phosphorus and calcium are then released from the decomposed rocks, providing essential elements for the plants. This process not only provides nutrients to the plants, but also improves the chemical structure of the soil and improves the fertility of the soil [14].

The study from Quirk et al. showed mycelium of AM fungi not only breaks down minerals by chemical means, but also forms trenching on the surface of minerals by physical methods, such as its continuous mechanical pressure generated during growth, which accelerates rock weathering and leads to the release of more minerals (See Figure 3) [15]. Experiments have shown that the destruction caused by these physical means of AM fungi produces more pronounced trenches on basic rocks such as basalt. These two mechanisms suggest that AM fungi play a key role in rock weathering and nutrient cycling through their mycelium networks in the ecosystem [15-16].

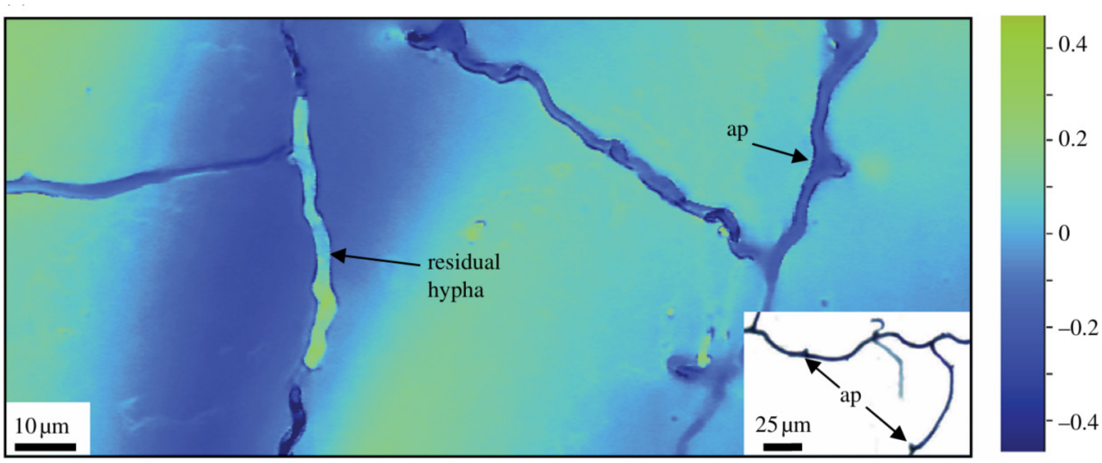

Figure 3. Trenches that the AM fungi create on the basalt surface [4]

3.3 The Role and Potential of Symbiosis of AM in Ecosystem's Carbon Storage

AM fungi promotes the photosynthetic efficiency of its symbiotic plants. Due to their symbiotic relationship, a significant portion of the photosynthetic products produced by plants through their own hyphal network will

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eventually be transferred underground, promoting the accumulation of soil organic carbon. The data from Wang et al. on the promoting effect of AM fungi on carbon sequestration further supports this theory. In their field experiment carried out in Shendong coal mining area, they inoculated four plant species along with AM fungi. It was found that net photosynthesis of plants is significantly increased after inoculation with AM fungi, and carbon storage in soil is also known to increase by 17.2% on average[17]. At the same time, AM fungi's external mycelium secretes easily extractable Glomalin-related soil protein (EE-GRSP) and total Glomalin-related soil protein (T-GRSP). These glial proteins are thought to be difficult to decompose organic matter in the soil, which can form soil aggregates, thereby reducing carbon loss[17].

4. Conclusion

In conclusion, symbiosis have played a vital role in the evolution history of Earth living organisms, because it tides up two entirely different species with a mutualistic relationship. Species with assistance from symbionts would have more advantages in niche competition, and easier to spread their population. AM fungi-plant symbiosis is a typical symbiosis example. As studies have suggested the AMF symbiosis might have lasted for hundreds million years, including helping early plant to colonize the land and spreading all over the world. Over 70% of plant species have built symbiosis with AM fungi and based on the exchanging of nutrients and carbon compounds. The complex, interspecies chemical communication has used to be difficult problems for scientists to understand the mechanism behind it, and the cause of weak defense response signal are still debatable. Though scientists have figured out some of the chemical molecules, like Strigolactones, Gibberellin and auxin in plant, there are still more questions with genetic level symbiosis regulation and chemical communication in AM fungi. The affection of AM fungi to the host are mostly beneficial effects, which includes strengthening of defense system, supply of nutrients, and increasing the drought and pest tolerance. AM fungi especially show positive affections in helping plants defend underground herbivory, like parasitic plants, nematode and moth larvae. Only one rare case of polymorpha shows the aggressive behavior of AM fungi under certain conditions, which might be valuable example in studying the limits it. AM fungi also played an important role in modifying local environment, even in global scale. When the soil is poor in phosphorus, AM fungi's hyphal extend significantly to reach more nutrients for plants, and this action promote the nutrient cycling of upper soil, which can increase the soil fertility. In addition, AM fungi can secrete organic acid to speed up the weathering of rocks, which brings more minerals to the soil and plants. Finally, as plant continuously load carbon compounds to the hyphal, large amounts of carbon are buried underground, which reduced part carbon dioxide concentration in the atmosphere. In summary, current studies about AM fungi have only revealed part of it amazing symbiosis complexity and benefits for ecosystem, and the future investigating direction can be conclude as more gene levels studies about the symbiosis communication, more studies about mechanism of its affection to host defense system, how to widely apply it in farming, and its potential in reducing global carbon dioxide concentration.

Authors Contribution

Andre Xiaoyu Song is responsible for Introduction, Part 1 and 2 in Mainbody, and Conclusion. Yitian Zhu reponsible for Part 3 in Mainbody and Abstract. All the authors contributed equally on references.

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Delaux P M, Schornack S. Plant evolution driven by interactions with symbiotic and pathogenic microbes[J]. Science, 2021, 371(6531): eaba6605.

[2] Masson-Boivin C, Sachs J L. Symbiotic nitrogen fixation by rhizobia—the roots of a success story[J]. Current Opinion in Plant Biology, 2018, 44: 7-15.

[3] Simon L, Bousquet J, Lévesque R C, et al. Origin and diversification of endomycorrhizal fungi and coincidence with vascular land plants[J]. Nature, 1993, 363(6424): 67-69.

[4] Pirozynski K A, Malloch D W. The origin of land plants: a matter of mycotrophism[J]. Biosystems, 1975, 6(3): 153-164.

[5] Liao D, Wang S, Cui M, et al. Phytohormones regulate the development of arbuscular mycorrhizal symbiosis[J]. International journal of molecular sciences, 2018, 19(10): 3146.

[6] Mohamed H. Arbuscular mycorrhizal fungi and their influence on growth and water relations of sweet cherry rootstock and tomato plants[D]. University Of Tasmania, 2015.

[7] Poveda J. Marchantia polymorpha subsp. ruderalis (Bischl. & Boissel.-Dub.)-arbuscular mycorrhizal fungi interaction: beneficial or harmful?[J]. Symbiosis, 2020, 82(3): 165-174.

[8] Song F, Song G, Dong A, et al. Regulatory mechanisms of host plant defense responses to arbuscular mycorrhiza[J]. Acta Ecologica Sinica, 2011, 31(6): 322-327.

[9] Niwa R, Koyama T, Sato T, et al. Dissection of niche competition between introduced and indigenous arbuscular mycorrhizal fungi with respect to soybean yield responses[J]. Scientific reports, 2018, 8(1): 7419.

[10] Jung S C, Martinez-Medina A, Lopez-Raez J A, et al. Mycorrhiza-induced resistance and priming of plant defenses[J].

Journal of chemical ecology, 2012, 38: 651-664.
[11] Jiang D, Tan M, Wu S, et al. Defense responses of arbuscular mycorrhizal fungus-colonized poplar seedlings against gypsy moth larvae: a multiomics study[J]. Horticulture Research, 2021, 8.
[12] Zhang, Y., Dong, S., Gao, Q., Liu, S., Zhou, H., Ganjurjav, H., ... & Li, X. (2016). Climate warming and humans played different roles in triggering Late Quaternary extinctions in east and west Eurasia. Scientific Reports, 6, 24302.
[13] Anderson, I. C., & Cairney, J. W. (2018). Ectomycorrhizal fungi: Exploring nutrient acquisition and other ecological functions. New Phytologist, 220(4), 1000-1012.
[14] Friese, C. F., & Allen, M. F. (1991). The spread of VA mycorrhizal fungal hyphae in the soil: Implications for nutrient and mineral weathering. Mycologia, 83(3), 308-313.
[15] Quirk, J., Beerling, D. J., Banwart, S. A., Kakonyi, G., Romero-Gonzalez, M. E., & Leake, J. R. (2012). Evolution of trees and mycorrhizal fungi intensifies silicate mineral weathering. Biology Letters, 8(6), 1006-1011.
[16] Bearden, B. N., & Petersen, L. (2022). Exploring the secrets of hyphosphere of arbuscular mycorrhizal fungi: Processes and ecological functions. Plant and Soil, 474(1-2), 345-358.
[17] Wang, Z.-G., Bi, Y.-L., Jiang, B., Zhakypbek, Y., Peng, S.-P., Liu, W.-W., & Liu, H. (2016). Arbuscular mycorrhizal fungi enhance soil carbon sequestration in the coalfields, northwest China. Scientific Reports, 6, 34336.