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The Effects of High-Carbon Plant Residues on The Plant Symbiosis of Arbuscular Mycorrhizal Fungi (AMF) In Phosphorus (P)-Limited Soils and The Role of Soil Structure in This Effect

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Abstract
This review, the addition of plant residues with a high carbon (C:N) ratio (e.g., straw, dry stalks) to phosphorus (P)-limited soils affects the symbiotic relationship between arbuscular mycorrhizal fungi (AMF) and plants, and the role of soil texture (sandy, clay, silty) in this interaction is discussed. Literature shows that the C:N ratio of organic matter sources added to the soil affects soil microbial communities and the balance between mineralization and immobilization. It has been reported that high C:N applications cause mineral N immobilization by soil microorganisms in the short term, leading to N deficiency in plants, while the application of materials with low C:N ratios to the soil accelerates net mineralization. It has been emphasized that this situation indirectly affects the symbiotic interaction between AMF spores and plant roots because the plant's nutritional status is dependent on carbon utilization.
Soil texture influences AMF development and nutrient flow mediated by AMF by affecting water retention, aeration, porosity, and organic matter decomposition rate. Indeed, while low water and nutrient retention in sandy soils make AMF associations more beneficial, P bonds and low oxygen availability in clay soils can lead to different outcomes in these associations.
According to the study results, to ensure mineral N balance in the management of high C:N materials, pre-composting or the use of low C:N mixtures is recommended, along with the development of application strategies specific to soil texture (drip irrigation and organic matter stabilization in sandy soils; shredding/composting enhancement applications in clay soils).
Keywords: *Arbuscular Mycorrhizal Fungus (AMF), C:N, soil, texture.*

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I. INTRODUCTION

Arbuscular mycorrhizal fungi (AMF) improve phosphorus (P) uptake through their symbiotic relationship with plants; this effect is critically important for agricultural productivity, soil health, and sustainable food management [9]. AMF are obligate biotrophs that obtain carbon (and, when conditions permit, carbon-lipid components) from the photosynthetic products of plants to meet their own growth and reproduction needs; because fungi cannot perform photosynthesis, they must obtain carbon from plants to sustain their life cycles. This fundamental ecological reality also demonstrates that carbon-nutrient flow in the AMF–plant symbiosis is one of the main factors determining the direction and strength of the symbiotic relationship [11, 13]. The most well-known benefit of AMF for plants is that it increases phosphorus (P) uptake; in short, fungal hyphae reaches soil volumes that plant roots cannot access, facilitating the transport of phosphate ions to the plant. However, this benefit depends on the plant being able to allocate sufficient carbon to maintain the symbiosis. One of the main factors affecting the plant's carbon budget is the nutrient status of the soil, particularly the nitrogen (N) status and the characteristics of the organic materials used. When plant residues with a high C:N ratio (e.g., straw, dry stalks) are added to the soil, the microbial N immobilization that occurs in the short term can reduce the pool of mineral N available to the plant, limiting plant growth and thus photosynthetic carbon production. As a result, the amount of carbon that the plant can allocate to AMF decreases. Consequently, AMF colonization either weakens or symbiotic benefits decrease, which becomes critical especially under P-limited conditions. The immobilization effect of high C:N sources vary depending on the material's C:N ratio, lignin/phenolic content, and environmental conditions [1, 5].

However, soil management practices (especially organic matter applications) can directly or indirectly alter the strength of the AMF-plant relationship. Plant residues with high C:N ratios are a common and economical source of OM; however, the microbial processes that occur during the decomposition of these materials can affect AMF-plant symbiosis in different ways. The physical, chemical, and biological properties of the soil can influence these processes. Understanding how texture, a very important physical property of soil, affects these interactions; and how sand, clay, and silt alter this process is of vital importance for agricultural applications. The aim of this review is to synthesize these questions in light of the current literature and present practical/research-oriented conclusions.

II. MATERIAL and METHOD

For this review article, searches were conducted using the databases of Web of Science, Scopus, PubMed/PMC, Google Scholar, and publishers (Frontiers, MDPI, Wiley, ScienceDirect) focusing on the period 2010–2025 using keywords such as "high C:N residues and mycorrhiza," "straw decomposition nitrogen immobilization," "soil texture and arbuscular mycorrhizal fungi," and "phosphorus limitation and AMF." Both experimental study results and systematic/thematic studies obtained from these searches were included. Focusing particularly on studies conducted on sandy, clayey, and silty textures, critical and current articles (high-impact factor journals and PMC open access studies between 2018–2025) were selected (selection criteria: methodological clarity, explanation of tissue/plant model, reporting of C:N and P status) and summarized.

The collected studies were evaluated and grouped according to three main themes. These are: (A) N transformations and immobilization mechanisms of high C:N inputs; (B) sensitivity of AMF colonization and function to nutrient (especially P) limitation; (C) effects of soil texture (sand, clay, silt) on OM decomposition and AMF processes. These themes were compared with findings in the literature to develop general models and practical management recommendations.

III. RESULT AND DISCUSSION

3.1 Effects of high C:N application—N immobilization and carbon-microbial dynamics

Organic waste containing high C:N ratios (e.g., straw, dry stalks) obtain the N they need from the environment as they are decomposed by soil microorganisms; this process is called immobilization. This cycle reduces the pool of mineral N (NH_4^+, NO_3^-) available to plants in the short term [2, 16]. As a result, plants enter limitation N, growth is restricted, and photosynthetic C production may decrease. This decrease directly affects the amount of carbon the plant can allocate to AMF, limiting nutrient exchange in the symbiotic relationship. Many studies have observed that high C:N inputs initially have a negative effect on growth, but over time mineralization begins and the effects diminish. The most important point here is that the intensity and duration of immobilization depend on the C:N ratio of the material in the environment, the lignin/phenol content, and the environmental temperature/relative humidity conditions [2]. N deficiency caused by high C:N inputs not only inhibit plant growth but also limits the carbon that the plant will transfer to the fungus; however, since fungi also have their own N and P uptake capacities, the processes in the symbiotic partnership may differ between species and strains [8, 13]. Understanding these dynamics is essential for improving organic matter management and the effectiveness of AMF-based bio stimulant applications.

3.2. Effects of C limitation on the AMF-plant relationship

Carbon-nutrient exchange between AMF and plants requires a stable equilibrium. When the plant's C supply decreases (e.g., due to growth inhibition caused by N stress), the amount of C allocated by the plant to the fungus may also decrease; this may lead to a decrease in fungal colonization rates as the fungus derives less benefit from this relationship [8, 9]. Furthermore, some studies have indicated that AMF itself has the potential to take up mineral N forms (especially NH_4^+), thus complicating plant-fungus competition for N [3].

To summarize schematically: high C:N → N immobilization → plant N limitation → reduced photosynthetic C → reduced C transfer (to AMF) → low colonization and/or low benefit from AMF (the events occurring at these stages vary depending on conditions).

3.3. Phosphorus (P) limitation and the role of AMF

The interaction of AMF with plants becomes particularly important under P-limited conditions. AMF hyphae can increase soluble P uptake by accessing larger volumes of soil. In some cases, these hyphae also support the availability of other micronutrients that activate enzymes that mineralize organic P [6, 8]. However, N limitations arising from high C:N inputs can weaken AMF-plant carbon exchange, as described above. In this case, the P transfer capacity of AMF may not reach the expected high levels in practice. Furthermore, in calcium-rich (calcareous) conditions, P may be fixed as Ca-phosphate, and AMF alone may not be able to rapidly solubilize this form. Therefore, AMF + phosphate-solubilizing bacteria or P fertilization at the most appropriate form and level may be recommended for P mobilization**.**

3.4. Effect of soil texture: differences between sandy, clayey, and silty soils

Soil texture determines the decomposition rate of OM, water retention, oxygen diffusion, porosity, macro-micronutrient availability, and their uptake conditions [10]. The interaction between all these factors shapes AMF and microorganism activity. The degree of influence of textures in this interaction varies. Accordingly, the following headings will clarify this situation.

3.4.1. Sandy soils and their effects

Sandy soils have large pores as a physical characteristic, causing rapid drainage, low water retention, and faster oxygen diffusion. In this case, OM decomposition in sandy soils can generally be rapid (depending on process conditions), but limited water and low organic matter content can subject the plant to water stress. Therefore, AMF can provide more significant benefits in water and P uptake by plants in this case. AMF hyphae can spread over large volumes in sandy environments, which can lead to increased P uptake [7, 8]. However, when high C:N compounds are applied to the soil, the effects of N immobilization can be observed more quickly as stress on the plant due to the low buffering capacity of sandy soils.

3.4.2. Clay soil and their effects

Clay soils have fine pores as a physical characteristic and possess high water retention, low oxygen diffusion, and high surface area. Due to these conditions, OM decomposition may be slow because microbial communities have a different composition due to the anaerobic environment. In clay soil, phosphorus tends to bind to various surfaces physiochemically, and diffusion rates are low; AMF is also beneficial here, but hyphal spread and oxygen deficiency may limit the activity of some strains. Furthermore, immobilization may take longer because the decomposition of high C:N materials added to the environment may proceed more slowly. Due to the lack of oxygen, AMF-plant interaction may be suppressed for longer periods in this wet environment [12].

3.4.3. Loamy soils (loam/silt loam) and their effects

Silty soils have moderate water retention and air balance as physical properties; they are generally suitable in terms of organic matter and nutrient availability. Loamy soils generally provide favorable conditions for AMF; OM decomposition and nutrient transformations are balanced, so N immobilization caused by high C:N inputs may not be as sudden as in sandy soils or as prolonged as in clay soils. Therefore, AMF-plant symbiosis may yield more stable results in the medium to long term [15].

3.5. Results and recommendations based on the studies

A series of studies (pot and field studies) reported that high C:N materials initially limit plant growth and can weaken AMF colonization and AMF contribution; however, this negative effect can be reduced by pre-composting or mineral N addition [6, 15]. It was found that the relative benefit of AMF to plants is more pronounced under field conditions, especially in sandy soils, while in clay soils, the benefit of AMF has yielded more complex results due to the dominant role of P chemistry. These findings point to the importance of texture-specific management strategies [14]. In line with practical studies, if high C:N ratio materials are to be applied to the soil, the C:N ratio should be reduced through pre-composting or a pre-treatment (grinding, heating the pile, etc.) that accelerates decomposition should be performed [4, 15]. The application of a measured mineral N source (e.g., urea) alongside high C:N ratio sources balances immobilization and can sustain the plant's allocation of C for AMF. Experimental studies have reported that ratios such as ~0.2 g N (pot-scale example) are effective. For field applications, this ratio should be adjusted according to the given fertilization norms. Additionally, to determine strategies based on soil texture: for sandy soils, applying OM + water-absorbing (retentive) organic mixtures (such as biochar) together with AMF inoculation is synergistic. For clay soils, finely ground/composted forms of OM and applications that increase air permeability (such as perlite, pumice) are recommended. For loamy soils, balanced OM application combined with AMF inoculation is generally appropriate.

IV. CONCLUSION

Applying plant residues with a high C:N ratio to the soil can lead to short-term N immobilization in the soil, thereby impairing plant N status; this situation can limit AMF colonization and AMF-derived benefits by reducing the carbon allocated by the plant to AMF. However, effects vary depending on material composition, environmental conditions, and soil texture. Soil texture plays a decisive role in AMF hypha density and nutrient flow by affecting OM decomposition, water-air balance, and nutrient diffusion; AMF provides more pronounced benefits in sandy soils, while in clay soils it can produce different results due to P chemistry and low oxygen.

From a management perspective, the best practice is to pre-compost the high C:N materials, supplement mineral N when necessary, implement texture-specific practices, and, when appropriate, use P-mobilizing approaches that synergize with AMF (phosphorus-solubilizing bacterial inoculation, biochar, controlled P application). These strategies are environmentally friendly practices that will increase the efficiency of AMF-plant symbiosis. However, most of the studies conducted so far are results from greenhouse/pot studies or short-term field studies. In other words, these results do not represent long-term averages. For this reason, for recommendations and suggestions to be more consistent, long-term field studies should be conducted to more clearly determine OM accumulation and its dynamics in AMF associations.

On the other hand, comparative studies on which AMF strain is more effective in which textures are limited. It is necessary to determine texture-specific AMF strains and their adaptations. In addition to the composition and ratios of C:N content in the applied organic materials, the structure and ratios of different OM components such as lignin, phenolics, and N compounds must also be known so that their specific roles in AMF-interaction can be better defined.

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