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Review
THE AGRICULTURE, SALINITY AND ARBUSCULAR MYCORRHIZAL FUNGI: A NEED, A PROBLEM AND AN ALTERNATIVE

Revisión bibliográfica
La agricultura, la salinidad y los hongos micorrízicos arbusculares: una necesidad, un problema y una alternativa

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ABSTRACT. Among the adverse conditions of farming systems, salinity is the most influential factor on the establishment of human populations. Salinity inhibits plant growth and productivity, induces osmotic imbalances relationships between soil and plants and in the metabolism of these. Stress tolerance in plants is a complex phenomenon involving many changes at the biochemical and physiological level. The mechanisms behind stress tolerance seem to be affected by the colonization of arbuscular mycorrhizal fungi, numerous studies demonstrating that inoculation with these fungi improving plant growth under salt stress, so the knowledge of the interactions between different AMF species and soil conditions leading to the establishment of better adapted populations and more effective to ensure the benefits of symbiotic association under these conditions.

Key words: biofertilizers, abiotic stress, fungi

RESUMEN. Entre las condiciones adversas de los sistemas agrícolas, la salinidad es el factor que más ha influido sobre el establecimiento de las poblaciones humanas. La misma inhibe el crecimiento de las plantas y su productividad, induce desequilibrios en las relaciones osmóticas entre el suelo y las plantas y en el metabolismo de estas. La tolerancia al estrés en la plantas es un fenómeno complejo que involucra numerosos cambios a nivel bioquímico y fisiológico. Los mecanismos detrás de la tolerancia al estrés parecen estar afectados por la colonización de los hongos micorrízicos arbusculares. Demostrando numerosos estudios que la inoculación con estos hongos mejora el crecimiento de las plantas bajo estrés salino; por lo que el conocimiento de las interacciones entre distintas especies de HMA y las condiciones edáficas lleva al establecimiento de poblaciones mejor adaptadas y más efectivas que garanticen los beneficios de la asociación simbiótica en estas condiciones.

Palabras clave: biofertilizantes, estrés abiótico, hongos

INTRODUCTION

In nature, plants are exposed to many stress conditions that retard their development and reduce yields. One of the most widespread agricultural problems is salt accumulation in soil surface (1).

Salinity completely affects a third portion of all irrigated lands in areas with water shortage, high temperatures, high evapotranspiration or when a deficient irrigation is managed by farmers. In addition, due to decrease of available water sources, the use of saline water for irrigation is almost inevitable (2).

In general, salinity inhibits plant growth and its productivity. High salinity induces unbalanced osmotic relationships between soil, plants and their metabolism. There is a group of factors that enhances plant tolerance against salinity; their application to plants can provide better resistance to salt stress and help improve crop productivity under these conditions (3, 4).

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Stress tolerance in plants is a complex phenomenon that involves numerous biochemical and physiological changes; however, the mechanisms behind stress tolerance seem to be affected by arbuscular mycorrhizal fungus (AMF) colonization (5).

Arbuscular mycorrhizal symbiosis is an obvious result from the interaction between plant roots and fungus; it is an excellent example of great morphological disorders undergone by roots to get adapted to a symbiont. AMF receives plant photosynthates; meanwhile the plant improves its ability to take up nutrients, water and enhances both its abiotic and biotic stress tolerance (6, 7).

Several studies have shown that fungal inoculation improves plant growth under salt stress conditions (4, 8). This can be attributed to an increased mineral nutrient absorption, such as phosphorus (P), zinc (Zn), copper (Cu) and iron (Fe). There is some evidence that AMF protects leaf metabolism from sodium (Na) toxicity (9, 10).

Salt stress affects plant growth and its damages on plant metabolic activity may change according to AMF use; thus, it is necessary to perform deeper studies on the selection of effective AMF strains, so as to improve plant development under such stress conditions.

SALINITY

Among all adverse farming system conditions, salinity is the most influencing factor on the establishment of human populations, as there are historical records of migrations caused by arable soil salinization (11).

Salinity is a serious problem for agriculture, mainly in arid and semi-arid regions. The total soil area affected in the world is of 831 million hectares, including 397 and 434 million hectares of saline and sodic soils, respectively (12).

Soils with salinity problems are located in places where evaporation is greater than rainfall (13); therefore, the most affected climatic areas by salts are situated in arid, semiarid and steppe areas, where evaporation is dominant.

The most influencing factors on saline soil formation are: topography, biological activity, climatic conditions, geomorphological processes of sedimentation, erosion, material redistribution and changes in surface as well as underground water, besides some human actions, such as tillage, irrigation with low water quality and use of chemicals (14-17).

Irrigation with water containing salts have an unavoidable effect on higher salt concentration in plant root zone (18), which depends on several factors, including the quantity and quality of irrigated water, irrigation method and adequate drainage (14, 19, 20).

Human activity has enlarged salinity areas by expanding irrigated lands as a result of developing great hydrological projects, which have led to changes in water and salt balance of hydrogeological systems. According to a study performed at the United Nations University, about 62 million hectares (20 %) of irrigated lands are affected in the world, exceeding 45 million hectares in the 1990s (21).

PLANTS AND SOIL SALINITY

The most common salinity effect on plants is that it reduces its development, due to a decreased osmotic potential of the medium and, consequently, of soil water potential, a specific toxicity usually associated with excessive Na^+ and Cl^- absorption, a nutritional unbalance caused by salt ion interference of essential nutrients and the above effects combined. As a result of these primary effects, other secondary stresses often occur, such as oxidative damage[A] (22).

Water absorption

One of the most obvious salt stress effects is that it reduces water absorption capacity, which may be observed through water stress effects, such as a reduced leaf expansion and loss of turgor (23).

A plant cell exposed to saline medium balances its hydric potential by losing water, resulting in a decreased osmotic potential and turgor. This situation leads to chemical signals (higher intracellular free Ca^{2+}, ABA synthesis, etc.) that trigger further adaptive responses[A].

Macroscopic changes observed under salinity conditions, such as reduced leaf area and root/aerial part relationship, among others, also show a necessary adjustment to recover water balance (24).

[A] *World losing 2,000 hectares of farm soil daily to salt damage* [en línea]. Phys.Org, 28 de octubre de 2014, [Consultado: 23 de marzo de 2016], Disponible en: <http://phys.org/news/2014-10-world-hectares-farm-soil-daily.html>.

Ion absorption

In a saline soil, high Na^+ and Cl^- or (SO_4^{2-}) concentration causes nutrient absorption interference (K^+, Ca^{2+}, NO_3^-) and prevents their uptake, meanwhile they can reach toxic cytosolic levels to cell metabolism (25).

The root, as the main water and ion absorption organ, is very important for a short or long-term response to salt stress. Abscisic acid (ABA) is synthesized there, which is one of the early stressful signs that is able to produce local (hydraulic conductivity) and distant (stomatal closure) physiological changes (26). Both anatomical and morphological root characteristics can have great influence on the adaptive ability to salinity (27, 28).

Nutritional effects

The presence of salt ions in soil solution, starting from a certain critical concentration level, causes a displacement of plant mineral nutritional balance. This effect occurs in two ways:

- ♦ Soil ionic strength has a direct effect on nutrient absorption and translocation, which is evident because salinity induces phosphorus uptake and accumulation in certain species. This is an osmotic effect that occurs regardless of the type of salt used (29).
- ♦ The most common salinity mechanism that modifies plant mineral nutrition is the direct Cl^- and Na^+ interaction on nutrient uptake and translocation within the plant (25).

Several studies show that K^+ concentration decreases in the plant when salinity or Na^+/Ca^{2+} relationship increases in the soil (14, 30-32).

The reduced K^+ absorption by Na^+ is a competitive process in the plant. Although plants have high K^+ selectivity compared to Na^+, its excessive amounts may have negative effects (33). Despite various studies indicate K^+ absorption and translocation is reduced in plants grown on substrates where Na^+ predominates, there is little evidence demonstrating that K^+ addition improves plant development under these conditions (34, 35).

Apart from this classic ion unbalance, a decreased NO_3^- concentration in plants under saline conditions has been widely studied under several experimental conditions with different plant species, such as wheat (*Triticum* spp L.), barley (*Hordeum vulgare* L.) and tomato (*Solanum lycopersicum* Mill) (36-41). However, in spite of the drastic NO_3^- concentration reduction in leaves as a response to salinity, various nitrogenous fractions increase (or at least do not decrease), such as proline content, betaines and amino acids or total soluble proteins (42).

Moreover, NaCl has also proved to induce phosphorus toxicity in some species as corn (*Zea mays* L.) (43, 44), sesame (*Sesamum indicum* L.) (45), certain soybean varieties (*Glycine max* L.) (46) and lupine (*Lupinus polyphyllus* Lindl.) (47).

Under saline conditions, there may be some problems with micronutrient availability in plants, although the influence of salinity on their concentrations depends either on the plant or the micronutrient involved (48, 49).

ARBUSCULAR MYCORRHIZAL FUNGI AND SALINITY

Arbuscular mycorrhizal fungi (AMF) are plant root symbionts that can be considered the cornerstone of mutualism in terrestrial ecosystems (50).

Mycorrhizal symbiosis is an ancient relationship. Hyphae and arbuscules have been reported in fossils derived from the early Devonian period and molecular studies suggest Glomal presence about 350-460 million years ago, which evolved along with the plants when they were conquering the Earth (51).

Arbuscular mycorrhizae have been widely described as favoring plant growth (52). Mycorrhizal colonization provokes physical, biochemical and physiological changes in roots, so that it leads to a better overall plant status and helps relief abiotic (heavy metals, salinity) and biotic (pathogen attacks, rhizosphere microbial changes) stress situations (53).

AMF has the ability to protect plants from salinity stress; however, its mechanisms are not so clear, partly because there are few studies about AMF effects on plant growth under salinity conditions and its effects upon mycorrhizal colonization. Nevertheless, some available data indicate these fungi have the potential of improving salt tolerant crop benefits when selected and combined adequately (54).

The existence of AMF under saline environments is well known, where salt tolerant plants can have a better early growth (55, 56).

It is considered that AMF improves mineral nutrient supply to plants in saline soils, especially phosphorus, which tends to be precipitated by other ions, such as Ca^{2+}, Mg^{2+} and Zn^{2+} (5, 57-59).

In addition to nutritional improvement, AMF benefits some physiological processes, as plant water absorption capacity, increases root water conductivity and promotes osmotic balance adaptation as well as carbohydrate composition (60, 61). Thus, these fungi mitigate the adverse effects of excessive salt accumulated in roots (9).

The role of mycorrhizae under saline conditions is still incomplete. A few studies have demonstrated its effects on osmotic adjustment (61, 62), but all of them have been focused on low salinity; therefore, it would be interesting to perform new experiments under different salinity situations to explain its role.

A discussion on AMF ecology under a saline environment may be confused, due to the need to distinguish between biotic and abiotic effects on fungus distribution and its relative abundance (63). No mycorrhizal colonization is observed when sodium is higher than 3 131 mg g^{-1} in the soil, but there have been root-colonized plants and arbuscular mycorrhizal fungus spores in habitats of saline soils with electrical conductivity exceeding 185 dS m^{-1} (56).

Several studies report the identification of AMF species in saline soils. The positive identification of these fungi into species is a difficult and highly specialized process that can be impossible when the material is collected in these soils (56).

Salinity effects on arbuscular mycorrhizal formation should include its influence on host plant growth. Root colonization levels are reduced when soil salinity is higher, perhaps because of physiological changes caused by direct symbiotic effects or indirect fungal effects provoked by other soil parameters, such as pH, texture, organic matter, aeration, clay content, physical and chemical soil characteristics as well as biotic factors (64).

AMF USED AS AN ALTERNATIVE FOR AGRICULTURAL PRODUCTION UNDER SALINITY CONDITIONS

Although there is evidence that mycorrhizal symbiosis affects and regulates several mechanisms involved in plant tolerance to salinity, many physiological aspects and the molecular basis of this regulation are unknown. However, the ecological significance of mycorrhizal association to plant survival and growth under salt stress conditions is widely demonstrated; therefore, it is important for agriculture under this condition.

In a study performed with AMF inoculation in pepper plants (*Capsicum frutescens* L.), a higher growth and yield was observed by reducing sodium in leaves, also increasing membrane stability and essential inorganic nutrient concentrations (65).

AMF improved harmful salinity effects on plant growth and nutrition of pepper (*Capsicum annuum* L.) at lower Na concentrations in leaf tissues and relieved salinity impact on membrane stability; besides, it delayed senescence syndrome in these plants (66).

Inoculated grapevines (*Vitis vinifera* L.) recorded significant increases of volume and root length, leaf number per plant, leaf area and dry weight, as well as chlorophyll levels compared to non-mycorrhized plants under salinity conditions (67).

In tomato plants (*Solanum lycopersicum* Mill) grafted to become more salinity resistant, the use of AMF-inoculated rootstocks increased total and commercial yield, besides improving quality parameters, such as high vitamin C and low acid contents (68).

Mycorrhized trifoliate orange (*Poncirus trifoliata*L.) seedlings showed more efficient antioxidant defense systems that provided better protection against salinity damages; in addition, malondihaldeide and hydrogen peroxide contents in leaves of mycorrhized plants were significantly lower (69).

Two leguminous crop species of *Myrica esculenta* (Buch.) and *Syzygium cumini* (L.), where the effects of different salinity levels were tested on growth, nodulation and nitrogen fixation proved that co-inoculation of rhizobia together with AMF showed the best results in all cases (70).

A greenhouse study was conducted to determine the effects of increasing salt (NaCl) concentrations on mycorrhized and non-mycorrhized leguminous crop species of *Strophostyle shelvola* (L.). Data showed evidence of significantly higher chlorophyll content, dry weight and root nodule number of mycorrhized plants than non-mycorrhized ones. High salt concentrations had a negative effect on growth, but they were partially mitigated by AMF (71).

These and other studies have reported agricultural benefits of AMF inoculation in areas affected by high salt levels and the importance of studying this fungal ecology in saline soils, in order to identify the most efficient strains for agriculture under these conditions.

CONCLUSIONS

Experimental results confirm that AMF enables to alleviate adverse salinity effects by means of improving water intake and nutrient absorption, especially P through colonized plant roots. Moreover, it is able to enhance photosynthetic efficiency reduction, gas exchange and membrane disorders by applying various mechanisms; thus, the proper AMF management has the potential to enable and improve agriculture in salinity-affected areas, using a natural process that plants have employed since the planet was colonized.

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