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Soil Inoculation with Cyanobacteria: Reviewing Its' Potential for Agriculture Sustainability in Drylands



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Abstract

In the last decades, there has been a huge expansion of intensive agriculture crops to attend the enormous demand of food needs with increasing population. Intensive agriculture is highly dependent on chemicals, which has caused numerous environmental problems such as contamination of aquifers, soils and air, with serious consequences on human health. A challenge in the next decades will be the development of economically viable methods to enhance productivity, at the same time that conservation of natural resources, protection of environment and production of healthy agricultural products are ensured. Sustainable agriculture requires management of a healthy living soil. Use of microorganisms such as cyanobacteria appears as a real alternative to achieve more sustainable managements. In this review, we briefly discuss the roles of cyanobacteria in the improvement of soil stability, soil nutrient and moisture status, organic matter content, microbial activities, and the growth and productivity of crops. Application of cyanobacteria is especially promising in croplands from dryland regions where high tolerance of these organisms to harsh environmental conditions converts them into viable alternatives or complements to more widespread conservation practices based on vegetation covers.

Keywords: Biocrust; Fertility; Carbon sequestration; Soil erosion; Cropland

Introduction

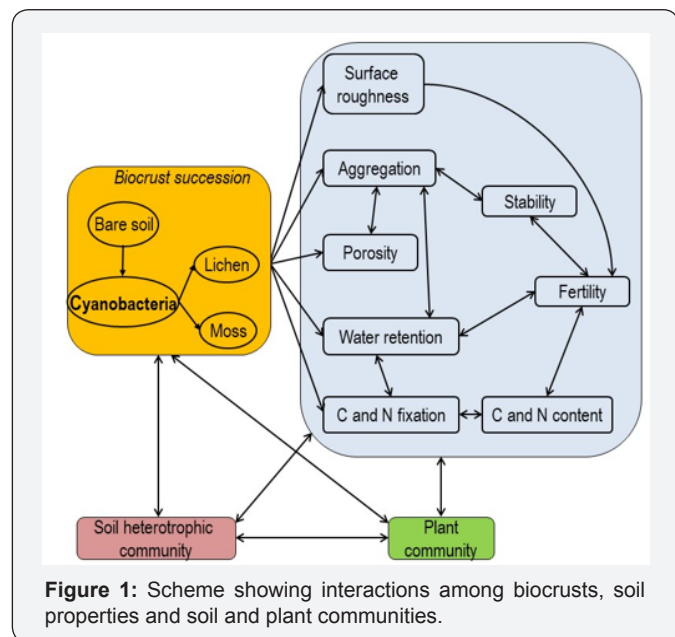
The increase of world's population and subsequent increase in food demand has led to a significant expansion of the cultivated land. Global cropland cover represents around 1370 million hectares or 12% of ice-free land [1]. Traditional agriculture including intensive tillage, removal of herbaceous cover, use of chemical fertilizers and pesticides have led to several environmental problems such as contamination of water bodies, damage to soil structure, accelerated oxidation of organic matter, loss of nutrients, high erosion rates, and loss of diversity [2]. Ultimately, these problems reduce the ability of the agro-system to provide vital ecosystem services and reduce the soil capacity for C sequestration [3]. It has been estimated an average SOC loss of 22% in 50 years due to agricultural erosion [4] and some scenarios predict that agriculture could become the main source of CO₂ released in the atmosphere by 2050 (IIASA's Integrated Assessment Modeling Framework project). Effects could be even more dramatic in the Mediterranean basin, where the predicted increase in aridity [5] due to climatic change impacts are expected to have important consequences on crop productivity and will have direct social, economic and ecological consequences, such as increase in poverty and food insecurity, land degradation and

depletion of natural resources [6]. As an example, an estimated 12 million hectares of agricultural land, which could potentially produce 20 million tons of grain, are lost every year due to land degradation. This urgently demands for interventions to transform current food production systems into sustainable and climate-resilient systems that ensure food supply and at the same time that mitigate our impact on the Earth system. To sustain agricultural productivity and environmental quality, the presence of a healthy living soil with improved quality, able to support vegetation and microbial communities and to provide basic regulation services is required [7].

Why cyanobacteria? Their role in the environment

Cyanobacteria are prokaryotic oxygenic phototrophs, which have the ability to colonize very diverse environments thanks to their extraordinary resilience to stressful environmental conditions such as extremes of temperature, UV irradiance, drought, salinity and rapid hydration/dehydration cycles [8,9]. Cyanobacteria play a number of important roles in the environment [10] (Figure 1). Cyanobacteria increase soil stability and reduce erosion by water and wind [11], increase surface moisture by holding large amounts of water [12], and fix carbon (C) and nitrogen (N), thus

increasing soil fertility (Figure 1) [13]. In arid and semiarid environments, cyanobacteria are one of the most important microorganisms forming biological soil crust communities [14], which are recognized to have major roles in hydrological, erosion, biogeochemical and ecological processes [15] and to provide critical services to society [16]. Due to these recognized roles, soil inoculation with cyanobacteria or cyanobacterisation is proposed as a sustainable technique to improve soil quality and combat degradation processes in drylands [17].



Cyanobacteria for improvement of soil water status

Cyanobacterial biocrusts are able to affect all components of the soil water balance (infiltration and runoff, evaporation, soil moisture, dewfall deposition) by modifying soil properties such as roughness, albedo, hydrophobicity, porosity and water retention [18-20]. In general, cyanobacteria increase water availability by increasing infiltration and maintaining surface moisture longer compared to bare soils [21]. Their role in soil moisture is largely due to the ability of polysaccharide sheaths to absorb up large amounts of water. Besides, exopolysaccharides can trap airborne particles, leading to the accretion of new sand and clay layers that increase the sorptivity of the soil helping water infiltration [22]. A stable soil moisture potential down to 20% water content has been found in natural crusts, while a decrease of soil moisture potential at 80% water content has been found after removal of cyanobacterial-EPS from the soil [12].

Cyanobacteria as soil stabilization agents

The importance of cyanobacteria in enhancing the stability of soil aggregates has been widely described [23]. This is especially significant within the first millimeters of the soil surface and strongly improving soil's resistance to both wind and water erosion [11,18,24,25]. Two are the main mechanisms of cyanobacteria for soil particle binding:

- i. Mechanically, by entangled filaments thus forming a network in the upper soil layers that greatly enhances aggregate stability;
- ii. Chemically, by the sticky polysaccharides binding soil particles, and favouring soil aggregation [26].

Several studies have demonstrated enhanced aggregation when soils are inoculated with cyanobacteria [25,27,28]. This effect in soil stability has important implications on the reduction of water, sediment and nutrient losses by erosion and consequent effects in the reduction of water eutrophication, maintaining of fresh water pools, reduction of soil C losses and release of CO₂ and other greenhouse gases to the atmosphere, thus improving soil C levels.

Cyanobacteria as regulators of biogeochemical cycles

Cyanobacteria also play important direct roles in CO₂ fixation and C cycling in soils. Cyanobacteria produce extracellular polymers of diverse chemical composition, especially exopolysaccharides that can represent 75% of the carbohydrates synthesized by biocrusts [13]. Organic matter is incorporated into the soil from the decay of cyanobacteria biomass and exopolysaccharides, thus also increasing the humus content. It has been shown the increase in soil organic C content after soil inoculation with cyanobacteria [29]. However, less studied has been the effect of cyanobacteria inoculation on soil CO₂ fluxes. In a recent experiment in China, soils inoculated with cyanobacteria showed 3.3 times higher C fixation rates than non-inoculated soils [30].

Cyanobacteria, especially the N-fixers cyanobacteria, increase the N content in natural desert soils. This fixed N is either released to the surrounding environment and make it available to plants [31], or either released to the atmosphere in the form of N₂O, or NO and HONO, which influence ozone and OH reactivity at the atmosphere [32]. Phosphorus is the second important nutrient after N for plants and microorganisms. Cyanobacteria influence the availability of P to plants as they have the ability to transform non-usable forms of inorganic-P to a usable form through biological processes [33]. Inoculation of the soil surface with different heterocystous and non-heterocystous cyanobacteria has been reported to enhance total N, available N, and available P [34].

Cyanobacteria as promoters of diversity and facilitators for other organism colonization

Due to the improved effects on soil structure and stability, nutrient content and soil moisture availability, cyanobacteria improve the microhabitat for the soil heterotrophic community [31,35,36] and facilitate the colonization of other organisms such as lichens and mosses, and the establishment and survival of annual and vascular plants in dry environments [37,38]. The enriched organic C substrate provided by cyanobacteria also becomes the support of a more abundant and diverse population of soil microfauna [39]. Hence, biocrusts, and especially well-developed ones as those dominated by cyanobacteria, are used as indicators of biodiversity and soil health [40].

Direct effects of cyanobacteria on plant growth from crops have been also reported due to the production of a great number of substances such as growth-promoting regulators, vitamins, amino acids, polypeptides, biotin, metabolites that act as allelochemical agents, proteins, total soluble sugars, antibacterial and antifungal substances that exert phytopathogen biocontrol, and polymers, especially exopolysaccharides that improve soil structure and exoenzyme activity [41].

Use of cyanobacteria in agriculture: current and future perspectives

Recent studies demonstrate the viability of inoculating soils with cyanobacteria (or cyanobacterisation) as a strategy to artificially induce the formation of a biocrust and combat desertification processes in drylands [17,30]. However, their use to reduce soil erosion and increase soil fertility and C sequestration in agricultural lands from drylands has been scarcely explored.

In the field of agriculture, cyanobacteria have been mainly used as biofertilizers due to their role as nutrient supplements [42]. Investigations have mainly focused on the use of aquatic species as for example *Anabaena azollae* in the fertilization of rice paddies throughout Asia [43]. To a much lesser extent, inoculation of diverse N-fixing cyanobacteria species as *Nostoc*, *Calothrix*, *Tolypothrix*, and *Scytonema* in non-waterlogged soils has also shown beneficial effects in terms of improvement of quality of soil properties and enhancement in plant growth in a number of crops such as tomato, wheat, maize, and lettuce [44,45]. Together with their recognized functions as natural fertilizers, cyanobacteria provide a number of ecological roles that open the range for their application in agriculture. The use of cyanobacteria in agricultural systems from drylands is especially promising given the extreme resistance that these organisms present to the abiotic stresses that characterize these regions such as low rainfall, high radiation levels and long periods of drought. Application of cyanobacteria in arid croplands is expected to have a major effect in the maintenance of adequate levels of soil organic matter, improvement of soil fertility and reduction of sediment and nutrient losses by water erosion, which is one of the most common processes accelerating soil degradation in agricultural lands from drylands. Besides, inoculation of soils with cyanobacteria can provide valuable solutions for sequestration of CO₂ and other gases involved in global warming. So far, the use of vegetation covers has been the main conservation practice in rainfed and irrigated crops from drylands in order to combat soil degradation processes and prevent the mineralization of organic matter and the loss of soil structure and soil fertility in crops [46]. While these techniques are known to have an important effect on the increase of soil organic C levels, improvement of soil enzymatic activity and CO₂ sequestering, they have the disadvantage of higher water requirements and, in some cases, competition for resources with crops. Application of cyanobacteria, isolated or in combination with cover crops, could provide very interesting results in terms of reduction of soil erosion and increase of soil fertility, at the same time that reduce water demands.

Up to now, there has been a low development of these techniques due to lack of knowledge regarding the factors involved in the success and failure of establishment of inoculated cyanobacteria under field conditions. Development of these sustainable biotechnological techniques requires efforts of both basic and applied research to move from laboratory or indoor conditions to their application in the field. Research involves the selection of suitable cyanobacteria species that ensures successful survival, establishment and performance in the field, as well as optimization of the conditions for cyanobacteria culture in order to maximize biomass productivity, while minimizing production costs. To this regard, it has been shown the possibility of culturing cyanobacteria using eutrophicated water sources as culture media to sequester the nitrates and phosphorus excess from polluted water and their subsequent recycling as biofertilizer for plant growth [47]. This would represent an extremely green low-cost technology, contributing on one hand to bioremediation of wastewaters and, on other hand, to supply one of the most limiting nutrients for crop productivity, i.e. P, as a biofertilizer. Efforts made in the last years have contributed to important advances in the application of cyanobacteria as inoculants for dryland soil restoration. Further research will allow broadening the range of applications, including their use to advance towards a more sustainable agriculture in the 21st century, especially challenging in dryland regions under current climate change context.

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