BIOFERTILIZATION WITH CHLOROPHYTA AND CYANOPHYTA: AN ALTERNATIVE FOR ORGANIC FOOD PRODUCTION

Biofertilización con clorofitas y cianofitas: una alternativa para la producción de alimentos orgánicos

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ABSTRACT
Chlorophyta and Cyanophyta are photosynthetic organisms characterized by their biochemical plasticity, which has allowed them to develop in different environments and have a faster growth rate than plants. Depending on the species and environmental conditions, these organisms can produce nitrogenous enzymes, for atmospheric nitrogen fixation; phosphatases, that solubilize phosphorus; phytohormones, that promote plant growth; and hygroscopic polysaccharides, that prevent erosion and improve soil characteristics. In this sense, the aim of this review was to analyze the available information on the use of Chlorophyta and Cyanophyta as biofertilizers and their potential application in organic food production. Multiple studies and researches were found demonstrating the advantages of these microorganisms when being used to improve plants productivity, and also at the same time, leading to sustainable agriculture that is respectful to the environment. However, their high production cost has become a limiting factor for their commercialization.

Keywords: Biofertilizers, cyanobacteria, green algae, organic agriculture.

RESUMEN
Clorófitas y cianófitas son organismos fotosintéticos que se caracterizan por su plasticidad bioquímica, lo que les ha permitido desarrollarse en diferentes ambientes y tener una tasa de crecimiento más rápida que las plantas. Dependiendo de la especie y las condiciones ambientales, estos organismos pueden producir enzimas nitrogenadas para la fijación del nitrógeno atmosférico; fosfatasas que solubilizan el fósforo; fitohormonas que promueven el crecimiento de las plantas; y polisacáridos higroscópicos que evitan la erosión y mejoran las características del suelo. En este sentido, el objetivo de esta revisión fue analizar la información disponible sobre el uso de cianófitas y clorófitas como biofertilizantes, y su posible aplicación en la producción de alimentos orgánicos. Multiples estudios e investigaciones fueron encontrados demostrando las ventajas del uso de estos microorganismos para mejorar la productividad de las plantas, y que a su vez conducen a una agricultura sostenible respetuosa con el medio ambiente. Sin embargo, su alto costo de producción se ha convertido en un factor limitante para su comercialización.

Palabras clave: Agricultura orgánica, algas verdes, biofertilizantes, cianobacterias.
INTRODUCTION

Chlorophytes and cyanophytes are photosynthetic organisms characterized by their biochemical plasticity, which has allowed them to develop in different environments and have a faster growth rate than plants. Both chlorophytes and cyanophytes, do not have tissue-specific biochemistry activity, meaning that each cell produces all the necessary substances for photosynthesis, development, and reproduction. Therefore, interest in the biotechnological potential of these organisms has increased, given their adaptability to large-scale production technologies. Some of these microalgae main biotechnological applications are high nutritional value and healthy food production, hydrogen production as biofuel, ecosystem restoration, and crop biofertilization (Guedes et al., 2011; Berg et al., 2014; Nyberg et al., 2015; Verseux et al., 2016; Chamizo et al., 2018).

According to the species and environmental conditions, these organisms can produce nitrogenous enzymes, for atmospheric nitrogen fixation; phosphatases, for phosphorus solubilization; phytohormones similar to cytokinins for plant growth, such as iso-pentenyladenine and zeatin; and, hygroscopic polysaccharides that prevent erosion and improve soil characteristics (Osman et al., 2010; Lu and Xu, 2015; de Siqueira Castro et al., 2017). These features have awakened interest in chlorophytes and cyanophytes investigation as alternatives for organic crops fertilization. Multiple laboratory and field experiments had evaluated these organisms’ application in crops like rice, corn, wheat, tomatoes, and others, especially in countries with limited access to chemical fertilizers (Coppens et al., 2016; Renuka et al., 2016; Chittapun et al., 2018; Dineshkumar et al., 2018; Dineshkumar et al., 2019). Thus, this review aims to analyze the available information on chlorophytes, and cyanophytes use as biofertilizers for organic food production, being an alternative to products obtained from chemical syntheses, such as conventional fertilizers and pesticides.

BIOFERTILIZATION WITH CHLOROPHYTA AND CYANOPHYTA AS AN ALTERNATIVE IN AGRICULTURE

Soil fertilization is a relevant and limiting factor for crops growth and productivity due to crops that extract large amounts of nutrients, and agricultural practices that decrease organic matter (OM) content, which is essential for soil structure, soil biodiversity, buffer capacity, thermal conductivity and soil fertility (Nain et al., 2010; Lin et al., 2013); and can also affect soil’s water retention (Lehmann and Kleber, 2015; Schlatter et al., 2017). Research has shown that soil processes related to phosphorus, carbon and nitrogen cycles, and also soil quality indicators such as arbuscular mycorrhizal fungi, community-level physiological profiles, alkaline phosphatase, and dehydrogenase activities, are very sensitive to the indiscriminate use of chemical fertilizers causing serious consequences such as lower nutritional quality, soil structure degradation, and change in the physical, chemical and biological soil conditions as its microbiota is altered (Souza et al., 2016; Malik et al., 2017; Nivelle et al., 2018).

As an alternative to commercial fertilizers, a series of biofertilization techniques had been developed, like composting use, organic and biological fertilizers, all of them aiming to promote sustainable agricultural practices favorable to the environment and that generate higher nutritional quality products (Vandana et al., 2017; Helmy, 2018). Biofertilizers are substances that contain alive microorganisms and improve the plant’s development. The difference between these products and chemical fertilizers consist in the biofertilizer’s gradual nutrients and phytoestimulants supply, that improves soil characteristics and provides optimal plant growth (Carvajal-Muñoz and Carmona-Garcia, 2012; Mosa et al., 2015). Biofertilization stimulates soil properties by increasing OM content, facilitating cation-exchange capacity (CEC), raising water retention, promoting aggregates formation, and improving soil’s buffering capacity, through the presence of polysaccharides and mucilaginous substances that provide the cohesiveness for binding soil mineral particles and thereby help in soil structure formation (Carvajal-Muñoz and Carmona-Garcia, 2012; Vitousek et al., 2013; Ghosh, 2018).

Owing to its ion retention capacity, OM preserves nitrogen, and phosphorus by diminishing these nutrients leaching, and favors microorganisms root colonization and prevents phytopathogens development (Lehman et al., 2015). Therefore, microbial inoculants have been used in sustainable agriculture to maintain high productivity and crop quality with lower costs compared to chemical fertilizers (Sarma et al., 2015; Li et al., 2017; Vandana et al., 2017).

Furthermore, biofertilizers are an alternative to improve agricultural productivity in erosion susceptible soil, which can be caused by the lack of OM, due to its particle aggregating effect (Cotrufo et al., 2015; Lehman et al., 2015). A strategy to increase OM and soil nutrient levels consist in adding microorganisms that produce mucilaginous polysaccharides (intracellular and extracellular), which are hygroscopic and have adhesive properties that act as soil particle aggregating agents, thus, increasing soil’s porosity and improving its structure (Colica et al., 2014; Rossi and de Philippi, 2015). These effects in the soil can last for several months, and afterward, during the degradation of polysaccharides, plants receive those nutrients gradually (Park et al., 2017; Li et al., 2018). Some chlorophytes and most cyanophytes have a high production of these polysaccharides and mucilage, as they are components of the cell wall (Ghosh, 2018). Recent research uncovered their many possible applications not only in agriculture but also in biomedicine due to their antibacterial, antiviral, antifungal, and anticoagulant activity (Guo et al., 2015; Berri et al., 2016; Faggio et al., 2016).
Chlorophytes and cyanophytes are fast-growing photoautotrophic organisms with the ability to adapt to different environmental conditions, which allows them to be established in small areas and regions non-suitable for crops (Sorochkina et al., 2018). Cyanophytes are primary colonizers during soil’s successional processes, and can even grow over volcanic ashes (Kerfahi et al., 2017). It is estimated that there are between 22,000 and 26,000 species, of which only a few are used for commercial purposes, including Spirulina, Chlorella, Nostoc, Anabaena, Haematococcus, Dunaliella, Botryococcus, Porphyridium, Scenedesmus, Nitzchia, Isochrysis, Schyzochytrium, and Phaeodactylum (Lu and Xu, 2015; Galarza et al., 2016; Hagemann and Hess, 2018).

In chlorophytes and cyanophytes, mucilage synthesis is considered a strategy to tolerate various types of environmental stress caused by dehydration, mechanical damage, UV radiation, and high temperatures. Mucilage acts as a metal ions chelator, approaching plant’s cell wall and facilitating its absorption. Also, it favors the specialized microbial interactions between different microenvironments and biomineralization processes (de los Ríos et al., 2015; Fimbres-Olivarria et al., 2018). Cyanophytes can improve desert soil characteristics due to their mucilaginous polysaccharides and other metabolites production, that increase soil levels of nitrogen and carbon, and capture water from the atmosphere, allowing the development of vascular plants like Coleogyne ramosissima, Stipa hymenoides, Streptanthella longirostris, Lepidium montanum var. jonesii, Agriophyllum squarrosum, Agropyron mongolicum, Artemisia ordosia, and Elymus dahuricus (Wierzchos et al., 2015; Rasuk et al., 2016).

The use of chlorophytes and cyanophytes as biofertilizers is called “algalization”, a term developed by G.S. Venkataraman in the 1970s. Research on this topic has focused on the use of chlorophytes and cyanophytes to offer nitrogen in crops. However, as seen in Figure 1,

**Figure 1.** Effects of cyanophytes and chlorophytes as microalgal biofertilizers. In soil, they produce mucilage, hygroscopic polysaccharides, phosphatases, phytohormones, nitrogenous enzymes, antipathogen, and antioxidant compounds that enhance nutrient uptake and growth and protect the roots. In the plant, there is an improvement in rooting, germination, growth and development, yield and nutritional value of the final consumption product.
Besides nitrogen fixation they can also improve soil physical properties, increase the nutrients available to plants, and produce substances that promote plant development (Dash et al., 2016; Rossi et al., 2017; Helmy, 2018). Indeed, the presence of cytokines had been described in cyanophytes like Calothrix sp, Nostoc sp, and Phormidium animale (Frébortová et al., 2017). This type of phytohormones is responsible for increasing productivity in crops fertilized with cyanophytes, which do not necessarily correspond to higher nitrogen soil levels, but a major cell division and differentiation caused by the stimulating of plant growth (Haque et al., 2017).

**BIOFERTILIZATION WITH CYANOPHYTES**

Several investigations have shown the viability of cyanophytes use as biofertilizers in plants (See Table 1), especially in rice, providing nitrogen through N₂ atmospheric fixation, and large amounts of polysaccharides that immobilize water on the soil surface during the dry season (Iyovo et al., 2010). This retained water remains available to plants, prolonging their growing season and significantly increasing their yields (Odjadjare et al., 2017). Moreover, polysaccharides can also prevent wind erosion during the dry season, due to their aggregation effect on the surface soil particles (Dash et al., 2016; Padhy et al., 2016; Chittapun et al., 2018).

In rice crop, the nitrogen balance depends on microalgae as they participate in nitrogen fixation and mineralization. For this reason, paddy rice crops are fertilized with cyanophytes mixtures in numerous countries such as China, India, Indonesia (Shahane et al., 2015; Rossi et al., 2017; Yao et al., 2018), Spain and some of South America (Ranjan et al., 2016; Jhala et al., 2017). In rice, Nostoc and Anabaena strains, both nitrogen fixers, are predominant, reducing the use of chemical fertilizers up to 15 %, and contributing to the biological fixation of approximately 20-30 kg of nitrogen per hectare, in each growing season (Chittapun et al., 2018; Singh et al., 2018).

Biofertilization with cyanophytes has also been evaluated in other crops such as wheat (Li et al., 2017; Di Salvo et al., 2018), legumes (Sonkoly et al., 2017; Muñoz-Rojas et al., 2018), and green peas, where cyanophytes from Nostoc genus stimulated plant growth and increased seed germination, reducing the use of chemical fertilizers by 50 % (Osman et al., 2010). Furthermore, Maqubela et al. (2009) evaluated fertilization in maize also with Nostoc sp, finding that plants had between 40-49 % more dry weight and 14-23 % more N in their tissue. Similarly, Grzesik and Romanowska-Duda (2014) biofertilized maize, using cyanophytes strains from Microcystis aeruginosa and Anabaena sp, finding not only improvements in biomass and nutrient uptake, but also in percentage, dynamics, and mean time of germination. The authors associated these events with a high concentration of different bioactive compounds included in Cyanobacteria that stimulate physiological pathways inside the plant, like the assimilation of atmospheric nitrogen, increases in chlorophyll content in leaves, activity of net photosynthesis, transpiration, stomatal conductance, intercellular CO₂ concentration, activity of acid and alkaline phosphatase, RNase, total dehydrogenase, and a decrease in electrolyte leakage from leaves, which indicates lower permeability of cytomembranes under the application of Cyanobacteria (Grzesik and Romanowska-Duda, 2014). Later, the same authors confirmed those finding using willow plants (Grzesik et al., 2017).

Overall, several authors had concluded that the species of Cyanophyta mentioned above can be an alternative replacement for chemical fertilization in different crops and that it is compatible with organic agriculture, including horticulture (Chamizo et al., 2018). Additionally, it has been observed that Cyanophyta also stimulates microbial activity in soils damaged by fire and in arid and semi-arid soils, reducing water and wind erosion (Nisha et al., 2018).

**BIOFERTILIZATION WITH CHLOROPHYTES**

Cyanophytes use is widely known, but its applications are limited by some species possibility of producing toxic compounds (Kaushik et al., 2019). Since chlorophytes do not have this disadvantage, they offer interesting possibilities given their ease and speed of growth, as well as, for their nutrient content that includes Ca, Mg, Zn, Fe, P, K and Mn (Carvajal-Muñoz and Carmona-Garcia, 2012).

Moreover, Chlorophytes can produce polysaccharides and some phytohormones, which could favor soils recovery, improve nutrient content, and enhance plants growth (Grzesik et al., 2017; Schreiber et al., 2018). For instance, irrigation of wheat and rice crops with chlorophytes suspensions, as well as the immersion of seeds in those suspensions, had shown numerous benefits, such as an increase in germination and productivity rates (Galarza et al., 2016; Huang et al., 2016; da Silva Ferreira and Sant’Anna, 2017; de Siqueira Castro et al., 2017; Dineshkumar et al., 2018).

Out of all microalgae, Chlorella genus has been most used for biofertilization so far and was the first microalga to be cultivated (Wijffels et al., 2013). Chlorella is a unicellular, non-mobile Chlorophyta with 2-10 μm diameter. It is known for its food potential, given its high content of proteins and other nutrients. The use of Chlorella vulgaris, for instance, is widely known. Eman et al. (2008) used extracts of C. vulgaris on grape cultivations by adding them in concentrations of 25 % and 100 %, causing a positive effect on productive bulbs percentage when comparing to the control treatment. Other characteristics like leaf area, stem length, and leaves and buds number, were too positively affected. Moreover, they observed a slight increase in the productivity of the vines expressed in the number of bunches, the weight of the grapes, the fruits quality, a reduction in the ripening time,
Table 1. Use of Chlorophyta and Cyanophyta as biofertilizers in different crop and non-crop plants.

| Plant                  | Organisms               | Application                                                                 | Effect                                                                 | Country | Reference          |
|------------------------|-------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------|---------|--------------------|
| Williams banana        | Chlorella vulgaris       | Spray four times during growing season at 0.0, 25, 50, 75 and 100 %         | Improvements: yield, bunch and hand weight, and chemical properties      | Egypt   | Eman et al., 2008  |
| (Musa cavendishii)     | (Chlorophyta)            | (total soluble solids % and total sugars, decrease in % of starch and total acidity). |                                                                      |         |                    |
| Maize (Zea mays)       | Nostoc sp. (Cyanophyta)  | 1 g dry weight/L suspension on soil (dry biomass: 6 g/m²).                  | Improvements: soil’s C, N and EPS content, and aggregate stability.     | South Africa | Maqubela et al., 2009 |
| Pea (Pisum sativus)    | Oscillatoria argustissima (Cyanophyta) | Fresh weights: 0.5, 1 and 1.5 g dissolved in 100 mL of distilled water each (OD: 0.95 at 700 nm) added to the soil (3 Kg soil/pot). | Improvements: germination percentage, growth parameters (root depth, shoot length, dry weight, leaf area, and number), pigments content (chlorophyll a and b, carotenoid), carbohydrate, total N and P, and protease and amylase activities. | Egypt   | Osman et al., 2010  |
| Maize (Zea mays)       | Microcystis aeruginosa   | Monocultures suspended in water applied to grains up to 35 % for 2 days, and continuous moistening of the substrate (filter papers). | Improvements: germination percentage, dynamics, and mean time of germination and accelerated growth of seedlings (faster elongation of roots and leaves and enlarged fresh and dry biomass). Increase in chlorophyll content, the activity of net photosynthesis, and others. | Poland  | Grzesik and Romanowski-Duda, 2014 |
| Chlorella sp.          | Chlorophyta             | Seed watered with 2 ml of C. vulgaris solution (289×10⁻²/ml) or C. pyrenoidosa solution (11.8×10⁻⁴/ml) twice a day. | Improvements: healthier seedlings with the enhanced root system. Seedlings of cucumber and eggplants had greener and bigger leaves. Cucumber seedlings were disease resistant. Higher chlorophyll a and b content, except in rice. | Dubai, UAE | Elhafiz et al., 2015 |
| Cucumber (C. sativus)  | Chlorella vulgaris       | Dry biomass (20 μg chlorophyll/g vermiculite: compost) with water. 50 g of each formulation (MC1 and MC2) was mixed with 6 Kg of soil. | Improvements: higher values of available N, P, and K in roots, shoots, and grains, and better nitrogen-fixing potential. Microbial biomass carbon significantly enhanced. Increase in plant dry and spike weight. | India   | Renuka et al., 2017 |
| Wheat (Triticum aestivum) | Chlorella sp.,          | Foliar application of suspension: 10 L/ha. | Improvements: greener, larger and healthier leaves, K and Ca content, apple weight and size. | Hungary  | Nagy, 2016        |
| Scenedesmus sp.,       | Chlorococcus sp. (Chl), |                                                                      |                                                                      |         |                    |
| Phormidium sp.,        | Chlorella vulgaris       |                                                                      |                                                                      |         |                    |
| Anabaena sp.,          | C. pyrenoidosa solution |                                                                      |                                                                      |         |                    |
| Westiellopsis sp.,     | (Chlophyta)             |                                                                      |                                                                      |         |                    |
| Copicladium sp.        | (Chlorophyta)           |                                                                      |                                                                      |         |                    |
| Rice (Oryza sativa)    | Aphanothece sp.         | 10 Kg dry weight/ha.                                                   | Improvements: grain yield and panicle number.                          | India   | Dash et al., 2016  |
| (S. melongena)         | Gloeotrichia sp.        |                                                                      |                                                                      |         |                    |
| Tomato (Solanum lycopersicum) | Ulothrix sp.   | Blended with the organic growing medium.                              | Improvements: fresh weight, sugar and carotenoid content of fruits.    | Belgium | Coppens et al., 2016 |
| Klesormidium sp.       | (Chlorophyta)           |                                                                      |                                                                      |         |                    |
| Apple (Malus domestica) | Chlorella vulgaris       | Foliar application of suspension: 10 L/ha. | Improvements: growth (shoot length, leaf area and plant dry weight), crop yield, leaf metabolic activities (chlorophyll a, catalase activity and protein-carbohydrate ratio), and soil properties (silt %, N content, and amelioration of metal contents). | Hungary  | Nagy, 2016        |
| Rice (Oryza sativa)    | Commercial packets of N-fixing of Cyanophyta | 1 Kg/m² | Improvements: growth (shoot length, leaf area and plant dry weight), crop yield, leaf metabolic activities (chlorophyll a, catalase activity and protein-carbohydrate ratio), and soil properties (silt %, N content, and amelioration of metal contents). | India   | Padhy et al., 2016 |
| Willow (Salix viminalis) | Microcystis aeruginosa  | Foliar application of monocultures (2.5×10⁷ cells/mL) three times during vegetation season, 3-week intervals. | Improvements: plant height, total shoot length, and number, FM and DM, chlorophyll levels and intensify gas exchange. Better physiological performance and crop yields, by enriching plants with growth-promoting substances. Improvement in plant health status. | Poland  | Grzesik et al., 2017 |
| Anabaena sp.           | (Cyanophyta)            |                                                                      |                                                                      |         |                    |
| Chlorella sp.          | (Chlorophyta)           |                                                                      |                                                                      |         |                    |

(Continued)
and also, an increase in the number of sugars and a decrease in the acidity. Also, in a vineyard, the use of C. vulgaris caused an increase in vegetative growth, productivity, and fruit quality (Nagy, 2016).

Similarly, extracts of C. vulgaris had a positive effect on banana crops, increasing quality and productivity (Hamouda and El-Ansary, 2017); and in lettuce, rice, cucumber, and eggplant, it was tested alongside Chlorella pyrenoidosa, reporting good result from both species as they improved growth and metabolism parameters in all plants (Elhafiz et al., 2015).

Another study conducted in Hungary by Nagy (2016), evaluated C. vulgaris use as foliar biofertilizer of apple plant (Malus domestica Borkh.). It was demonstrated that the use of this Chlorophyta as biofertilizer resulted in greener and healthier leaves. Although treatments did not have a significant effect on N, P, Mg, and micronutrients concentrations in the leaves, the use of the algal suspension did increase the K significantly and Ca leaves content. Furthermore, Pereira et al. (2018) found that the use of another Chlorella species, C. sorokiniana stimulated the in vitro rooting of the epiphytic orchid Schomburgkia crispa. This represents an alternative for its use as a supplement since it allows to obtain better yields than conventional culture media.

On the other hand, Barone et al. (2018) analyzed the effect of sulfate restriction on 53 genes and the morphology of Beta vulgaris L., under the addition of the chlorophytes C. vulgaris and Scenedesmus quadricauda. Results indicated that at the morphological level, seedlings treated with chlorophytes showed significantly higher values for root traits related to soil exploration and nutrient uptake; and at a molecular level, the Chlorophyta extract positively regulates many of the evaluated genes, thus, demonstrating the biostimulating effects of microalgae.

Differently, Schreiber et al. (2018) estimated wheat growth (Triticum aestivum L.) on two nutrient-deficient substrates: “null Erde” and sand, with and without fertilization by wet and spray-dried algae, and with a chemical fertilization control. After the wheat growth, it was recorded that the plants grown in the sand were smaller, but the fertilization with the algae led to a growth that was comparable to the chemical fertilizer one. These results showed that algae biomass and its nutrients represent an alternative to support agriculture in marginal soils.

**IS IT POSSIBLE TO APPLY MICROALGAE USE IN ORGANIC PRODUCTION?**

Organic production abstains from the use of synthetic origin agrochemicals in crops, to avoid the ecological imbalance generated by xenobiotics; instead, applies techniques that allow sustainable agricultural production (Crowder and

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Table 1. Use of Chlorophyta and Cyanophyta as biofertilizers in different crop and non-crop plants.

| Plant                | Organisms                  | Application                          | Effect                                                                 | Country  | Reference            |
|----------------------|----------------------------|--------------------------------------|------------------------------------------------------------------------|----------|----------------------|
| Maize (Zea mays)     | Chlorella vulgaris          | 3 g dry powder/Kg soil before planting. | Improvements: shoot length, leaves number, dry and fresh weight, total plant length, nutrients and pigments content and germinability of the seeds produced. | India    | Dineshku-mar et al., 2019 |
| Sugar beet (Beta vulgaris) | Chlorella vulgaris          | 2 and 4 mL/L in hydroponic solution. | Improvements: root traits and expression of genes related to nutrient acquisition. | Italy    | Barone et al., 2018    |
| Rice (Oryza sativa)  | Nostoc commune             | 6 and 12 g wet in 12 Kg of soil.    | Improvements: root length, shoot length, wet weight, and dry weight of seedlings. | Thailand | Chitapan et al., 2018 |
| Rice (Oryza sativa)  | Chlorella vulgaris          | Mixed with soil by soil drench method in concentration: 25, 50, 75 and 100 %. | Improvements: plant height, leaves number, leaf area, fresh and dry weight, seed number, weight of seeds, seed weight and yield. Increase in rice yield up to 7–20.9 %. | India    | Dineshku-mar et al., 2018 |
| Orchid (Schomburgkia crispa) | Chlorella sorokiniana      | 96×10^6 cells/mL used as suspension and supernatant in the culture medium. | Improvements: leaf and root length, shoot fresh and dry weigh, number of roots and leaves, pigmented (green) roots, shoot development and bud preparation for rooting. | Brazil   | Pereira et al., 2018 |
| Bean (Phaseolus vulgaris) | Chlorella sp.              | Foliar application (3x10^6 cells/ ml) twice a week. | Improvements: pod number and size, seed and total dry weight, root length and in crop yield. | Ecuador  | Maila, 2018            |

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A new generation of algae biofertilizers focuses on chlorophytes and cyanophytes extracts (without living cells) with lower costs. These products are especially focused on foliar nutrition, since they have high levels of vitamins, amino acids, and hydrolyzed form enzymes, that can be incorporated through stomas. These formulations are mainly oriented to crops with high added-value such as flowers or medicinal plants (Renuka et al., 2018; Rizwan et al., 2018). Colombia still needs to work on the implementation of chlorophytes and cyanophytes biofertilization alternative to improve product quality and to boost national agriculture towards adequate soil management and environmental sustainability.

CONCLUSIONS

Although application and quantities of Chlorophytes and Cyanophytes inoculum, in addition to the experimental conditions, are dissimilar in the reviewed works, an overall positive effect of these microorganisms on plant growth is established in all the research mentioned above. In this context, the main task of the scientists is to find ways to improve plants productivity, leading to sustainable agriculture that secures food production and is respectful to the environment at the same time; and it seems that the use of chlorophytes and cyanophytes as biofertilizers have a great potential to achieve this objective. Nonetheless, high production costs still represent a limitation in their commercialization, which is why the main focus of investigations from now on should be to generate new algal-based biofertilizers that focus on chlorophytes and cyanophytes extracts (without living cells) with lower costs, and to elucidate the molecular and physiological mechanisms around the plant-biofertilizer interaction, so a better understanding of its effects and how to manage them can be achieved.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Barone V, Bagliero A, Stevanato P, Brocchello C, Bertoldo G, Bertaglia M, et al. Root morphological and molecular responses induced by microalgae extracts in sugar beet (Beta vulgaris L.). J Appl Phycol. 2018;30(2):1061-1071. Doi: https://doi.org/10.1007/s10811-017-1283-3
Berg A, Lindblad P, Svensson BH. Cyanobacteria as a source of hydrogen for methane formation. World J Microbiol Biotechnol. 2014;30(2):539-545. Doi: https://doi.org/10.1007/s11274-013-1463-5
Berri M, Slugocki C, Olivier M, Hellow E, Jacques I, Salmon H, et al. Marine-sulfated polysaccharides extract of Ulva armoricana green algae exhibits an antimicrobial activity and stimulates cytokine expression by intestinal epithelial cells. J Appl Phycol. 2016;28(5):2999-3008. Doi: https://doi.org/10.1007/s10811-016-0822-7
Carvajal-Muñoz JS, Carmona-Garcia CE. Benefits and limitations of biofertilization in agricultural practices. Livest Res Rural Dev. 2012;24(3):1-8.

Chamizo S, Mugnai G, Rossi F, Certini G, De Philippis R. Cyanobacteria inoculation improves soil stability and fertility on different textured soils: gaining insights for applicability in soil restoration. Front Environ Sci. 2018;6(49). Doi: https://doi.org/10.3389/fenvs.2018.00049

Chittapun S, Limbipichai S, Amnuaysin N, Boonkerd R, Charoensook M. Effects of using cyanobacteria and fertilizer on growth and yield of rice, Pathum Thani I: a pot experiment. J Appl Phycol. 2018;30(1):79-85. Doi: https://doi.org/10.1007/s10611-017-1138-y

Colica G, Li H, Rossi F, Li D, Liu Y, De Philippis R. Microbial secreted exopolysaccharides affect the hydrological behavior of induced biological soil crusts in desert sandy soils. Soil Biol Biochem. 2014;68:62-70. Doi: https://doi.org/10.1016/j.soilbio.2013.09.017

Coppens J, Grunert O, Van Den Hende S, Vanhoutte I, Boon M, Grzesik M, Romanowska-Duda Z. Improvements in biochemical and physical pathways of litter mass loss. Nat Geosci. 2015;8(10):776–779. Doi: https://doi.org/10.1038/ngeo2520

Crowder DW, Reganold JP. Financial competitiveness of organic agriculture on a global scale. Proc. Natl. Acad. Sci. USA. 2015;112(24):7611-7616. Doi: https://doi.org/10.1073/pnas.1423674112

Dash NP, Kumar A, Kaushik MS, Singh PK. Cyanobacterial (unicellular and heterocystous) biofertilization to wetland rice influenced by nitrogenous agrochemical. J Appl Phycol. 2016;28(6):3343-3351. Doi: https://doi.org/10.1007/s10611-016-0871-y

da Silva Ferreira V, Sant’Anna C. Impact of culture conditions on the chlorophyll content of microalgae for biotechnological applications. World J Microbiol Biotechnol. 2017;33(1):20. Doi: https://doi.org/10.1007/s11274-016-2181-6

de los Ríos A, Ascaso C, Wierchhos J, Vincent WF, Quesada A. Microstructure and cyanobacterial composition of microbial mats from the High Arctic. Biodiversity Conserv. 2015;24(4):841-863. Doi: https://doi.org/10.1007/s10531-015-0907-7

de Siqueira Castro J, Calijuri ML, Peixoto Asemany P, Cecon PR, Rodrigues de Assis I, Ribeiro VJ. Microalgae biofilm in soil: Greenhouse gas emissions, ammonia volatilization and plant growth. Sci Total Environ. 2017;574:1640-1648. Doi: https://doi.org/10.1016/j.scitotenv.2016.08.205

Dineshkumar R, Kumaravel R, Gopalsamy J, Azim Sikder MN, Sampathkumar P. Microalgae as bio-fertilizers for rice growth and seed yield productivity. Waste Biomass Valori. 2018;9(5):793-800. Doi: https://doi.org/10.1007/s12649-017-9873-5

Dineshkumar R, Subramanian J, Gopalsamy J, Jayasingam P, Arumugam A, Kannadasan S, et al. The impact of using microalgae as biofertilizer in maize (Zea mays L.). Waste Biomass Valori. 2019;10(5):1101-1110. Doi: https://doi.org/10.1007/s11104-017-3548-7

Di Salvo LP, Ferrando L, Fernández-Scavino A, García de Salamone IE. Microorganisms reveal what plants do not: wheat growth and rhizosphere microbial communities after Azospirillum brasilense inoculation and nitrogen fertilization under field conditions. Plant Soil. 2018;424(1-2):405-417. Doi: https://doi.org/10.1007/s11104-017-3548-7

Elhafiz AA, Elhafiz AA, Gaur SS, Hamdany N, Osman M, Rajya Lakshmi TV. Chlorella vulgaris and Chlorella pyrenoidosa live cells appear to be promising sustainable biofertilizer to grow rice, lettuce, cucumber and eggplant in the UAE soils. Recent Res Sci Technol. 2015;7:14-21. Doi: https://doi.org/10.19071/rst.2015.v7.2919

Eman AAM, Abdullah ASE, Ahmed MA. The combined effect of some organic manures, mineral N fertilizers and algal cells extraction on yield and fruit quality of Williams banana plants. Am Eurasian J Agric Environ Sci. 2008;4(4):417-426.

Faggio C, Pagano M, Dottore A, Genovese G, Morabito M. Evaluation of anticoagulant activity of two algal polysaccharides. Nat Prod Res. 2016;30(17):1934-1937. Doi: https://doi.org/10.1080/14786419.2015.1086347

Fimbres-Olivarria D, Carvajal-Millan E, Lopez-Elias JA, Martinez-Robinson KG, Miranda-Baeza A, Martinez-Cordova LR, et al. Chemical characterization and antioxidant activity of sulfated polysaccharides from Navicula sp. Food Hydrocoll. 2018;75:229-236. Doi: https://doi.org/10.1016/j.foodhyd.2017.08.002

Frébortová J, Plíhal O, Florová V, Kokáš F, Greplová M, et al. Light influences cytokinin biosynthesis and sensing in Nostoc (cyanobacteria). J Phycol. 2017;53(3):703-714. Doi: https://doi.org/10.1111/jpy.12538

Galarza JI, Delgado N, Henríquez V. Cisgenesis and intragenesis in microalgae: promising advancements towards sustainable metabolites production. Appl Microbiol. Biotechnol. 2016;100(24):10225-10235. Doi: https://doi.org/10.1007/s00253-016-9748-z

Ghosh AK. Functions and bio-functions of soil and its restoration. Int J Res Anal Rev. 2018;5(3):672-677.

Grewe CB, Pulz O. The biotechnology of cyanobacteria. In: Whitton BA, editor. Ecology of Cyanobacteria II: Their Diversity in Space and Time. Heidelberg, New York and London: Springer Dordrecht; 2012. p. 707-739.

Grzesik M, Romanowska-Duda Z. Improvements in Germination, Growth, and Metabolic Activity of Corn Seedlings by Grain Conditioning and Root Application with Cyanobacteria and Microalgae. Pol J Environ Stud. 2014;23(4):1147-1153.
Grzesik M, Romanowska-Duda Z, Kalaji HM. Effectiveness of cyanobacteria and green algae in enhancing the photosynthetic performance and growth of willow (Salix viminalis L) plants under limited synthetic fertilizers application. Photosynthetica. 2017;55(3):510-521. Doi: https://doi.org/10.1007/s11109-017-0716-1

Guedes AC, Amaro HM, Barbosa CR, de Pereira RD, Malcata FX. Fatty acid composition of several wild microalgae and cyanobacteria, with a focus on eicosapentaenoic, docosahexaenoic and α-linolenic acids for eventual dietary uses. Food Res Int. 2011;44(9):2721-2729. Doi: https://doi.org/10.1016/j.foodres.2011.05.020

Guo M, Ding GB, Guo S, Li Z, Zhao L, Li K, et al. Isolation and antitumor efficacy evaluation of a polysaccharide from Nostoc commune Vauch. Food Funct. 2015;6(9):3035-3044. Doi: https://doi.org/10.1039/c5fo00471c

Hagemann M, Hess WR. Systems and synthetic biology for the biotechnological application of cyanobacteria. Curr Opin Biotechnol. 2018;49:94-99. Doi: https://doi.org/10.1016/j.copbio.2017.07.008

Hamouda RA, El-Ansary MSM. Potential of plant-parasitic Nematode control in banana plants by microalgae as a new approach towards resistance. Egypt J Biol Pest Co. 2017;27(2):165-172.

Haque F, Banayan S, Yee J, Chiang YW. Extraction and applications of cyanotoxins and other cyanobacterial secondary metabolites. Chemosphere. 2017;183:164-175. Doi: https://doi.org/10.1016/j.chemosphere.2017.05.106

Helmy AM. Organic and Biofertilization on Crop Production in Semiarid Regions. In: Barceló D, Kostianoy AG, editors. The Handbook of Environmental Chemistry. Switzerland: Springer Nature; 2018. p. 235-264.

Hoffman J, Pate RC, Drennen T, Quinn JC. Techno-economic assessment of open microalgal production systems. Algal Res. 2017;23:51-57. Doi: https://doi.org/10.1016/j.algal.2017.01.005

Huang Y, Xiong W, Liao Q, Fu Q, Xia A, Zhu X, et al. Comparison of Chlorella vulgaris biomass productivity cultivated in biofilm and suspension from the aspect of light transmission and microalgae affinity to carbon dioxide. Bioresour Technol. 2016;222:367-373. Doi: https://doi.org/10.1016/j.biortech.2016.09.099

Iyovo GD, Du G, Chen J. Sustainable biomethane, biofertilizer and biodiesel system from poultry waste. Indian J Sci Technol. 2010;3(10):1062-1069.

Jhala YK, Panpatte DG, Vyas RV. Cyanobacteria: Source of Organic Fertilizers for Plant Growth. In: Panpatte DG, Jhala YK, Vyas RV, Shelat HN, editors. Microorganisms for Green Revolution. Singapore: Springer Verlag; 2017. p. 253-264.

Kaushik MS, Kumar A, Abraham G, Dash NP, Singh PK. Field evaluations of agrochemical toxicity to cyanobacteria in rice field ecosystem: a review. J Appl Phycol. 2019;31(1):471-489. Doi: https://doi.org/10.1007/s10811-018-1559-2

Kerfahi D, Tateno R, Takahashi K, Cho HJ, Kim H, Adams JM. Development of soil bacterial communities in volcanic ash microcosms in a range of climates. Microb Ecol. 2017;73(4):775-790. Doi: https://doi.org/10.1007/s00248-016-0873-y

Kose A, Ozen MO, Elibol M, Oncel SS. Investigation of in vitro digestibility of dietary microalgae Chlorella vulgaris and cyanobacterium Spirulina platensis as a nutritional supplement. 3 Biotechnol. 2017;7(3):170. Doi: https://doi.org/10.1007/s13205-017-0832-4

Lehmann J, Kleber M. The contentious nature of soil organic matter. Nature. 2015;528(7580):60-68. Doi: https://doi.org/10.1038/nature16069

Lehman RM, Cambardella CA, Stott DE, Acosta-Martinez V, Manter DK, Buyer JS, et al. Understanding and enhancing soil biological health: the solution for reversing soil degradation. Sustainability. 2015;7(1):988-1027. Doi: https://doi.org/10.3390/su7010988

Li H, Su L, Chen S, Zhao L, Wang H, Ding F, et al. Physicochemical characterization and functional analysis of the polysaccharide from the edible microalgae Nostoc sphaeroides. Molecules. 2018;23(2):pii:E508. Doi: https://doi.org/10.3390/molecules23020508

Li L, Fan F, Song A, Yin C, Cui P, Li Z, et al. Microbial composition and diversity are associated with plant performance: a case study on long-term fertilization effect on wheat growth in an Ultisol. Appl Microbiol. Biotechnol. 2017;101(11):4669-4681. Doi: https://doi.org/10.1007/s00253-017-8147-2

Lin CS, Chou TL, Wu JT. Biodiversity of soil algae in the farmlands of mid-Taiwan. Bot Studies. 2013;54:41. Doi: https://doi.org/10.3390/1.3110-3110-31-41

Lu Y, Xu J. Phytohormones in microalgae: a new opportunity for microalgal biotechnology? Trends Plant Sci. 2015;20(5):273-282. Doi: https://doi.org/10.1016/j.tplants.2015.01.006

Maila MMB. Evaluación de la respuesta del fréjol (Phaseolus vulgaris L.) a la aplicación foliar de un fertilizante y un biofertilizante con base en algas (tesis de pregrado). Quito: Carrera de Ingeniería Agronómica, Facultad de Ciencias Agrícolas, Universidad Central del Ecuador; 2018. p. 89.

Malik Z, Ahmad M, Abbasi GH, Dawood M, Hussain A, Jamil M. Agrochemicals and soil microbes: interaction for soil health. In: Hashmi MZ, Kumar V, Varma A, editors. Xenobiotics in the Soil Environment. London: Springer International Publishing AG; 2017. p.139-152.

Maqubela MP, Mnkeni PNS, Malam Issa O, Pardo MT, D’Acqui LP. Nostoc cyanobacterial inoculation in South African agricultural soils enhances soil structure, fertility, and maize growth. Plant Soil. 2009;315(1-2):79-92. Doi: https://doi.org/10.1007/s11104-008-9734-x

El-Gleel Mosa WFA, Paszt LS, Frąc M, Trzcinski P. The role of biofertilization in improving apple productivity - a review. Adv Appl Microbiol. 2015;75(1):21-27. Doi: http://dx.doi.org/10.4236/aim.2015.751003
Muñoz-Rojas M, Chilton A, Liyanage GS, Erickson TE, Merritt DJ, Neilan BA, et al. Effects of indigenous soil cyanobacteria on seed germination and seedling growth of arid species used in restoration. Plant Soil. 2018;429(1-2):91-100. Doi: https://doi.org/10.1007/s11104-018-3607-8

Nagy PT. Effects of foliar biofertilization on quality parameters of apple (Malus domestica Borkh.). Ecocycles. 2016;2(2):21-25. Doi: https://doi.org/10.19040/ecocycles.v2i2.58

Nair LO, Rana AO, Joshi M, Jadhav SD, Kumar D, Shivay YS, et al. Evaluation of synergistic effects of bacterial and cyanobacterial strains as biofertilizers for wheat. Plant Soil. 2010;331(1-2):217-230. Doi: https://doi.org/10.1007/s11104-009-0247-z

Nisha R, Kiran B, Kaushik A, Kaushik CP. Bioremediation of salt affected soils using cyanobacteria in terms of physical structure, nutrient status and microbial activity. Int J Environ Sci Technol. 2018;15(3):571-580. Doi: https://doi.org/10.1007/s13762-017-1419-7

Nivelle E, Verzeaux J, Chabot A, Roger D, Chesnais Q, Ameline A, et al. Effects of glyphosate application and nitrogen fertilization on the soil and the consequences on aboveground and belowground interactions. Geoderma. 2018;311:45-57. Doi: https://doi.org/10.1016/j.geoderma.2017.10.002

Nyberg M, Heidorn T, Lindblad P. Hydrogen production by the engineered cyanobacterial strain Nostoc PCC 7120 ΔhupW examined in a flat panel photobioreactor system. J Biotechnol. 2015;215:35-43. Doi: https://doi.org/10.1016/j.jbiotec.2015.08.028

Odjadjare EC, Mutanda T, Olaniran AO. Potential biotechnological application of microalgae: a critical review. Crit Rev Biotechnol. 2017;37(1):37-52. Doi: https://doi.org/10.3109/07388551.2015.1108956

Osman MEH, El-Sheekh MM, El-Naggar AH, Gheda SF. Effect of two species of cyanobacteria as biofertilizers on some metabolic activities, growth, and yield of pea plant. Biol Fert Soils. 2010;46(8):861-875. Doi: https://doi.org/10.1007/s00374-010-0491-7

Padhy RN, Nayak N, Dash-Mohini RR, Rath S, Sahu RK. Growth, metabolism and yield of rice cultivated in soils amended with fly ash and cyanobacteria and metal loads in plant parts. Rice Science. 2016;23(1):22-32. Doi: https://doi.org/10.1016/j.rsici.2016.01.003

Park CH, Li XR, Zhao Y, Jia RL, Hur JS. Rapid development of cyanobacterial crust in the field for combating desertification. PLoS One. 2017;12(6):e0179903. Doi: https://doi.org/10.1371/journal.pone.0179903

Pereira NS, Ramires Ferreira BR, Machado de Carvalho E, Damiani CR. Application of Chlorella sorokiniana (Chlorophyceae) as supplement and/or an alternative medium for the in vitro cultivation of Schomburgkia crispa (Orchidaceae). J Appl Phycol. 2018;30(4):2347-2358. Doi: https://doi.org/10.1007/s10811-018-1441-2

Prasanna R, Sood A, Ratha SK, Singh PK. Cyanobacteria as a “green” option for sustainable agriculture. In: Sharma NK, Rai AK, Stal LJ, editors. Cyanobacteria: An Economic Perspective. Chichester, West Sussex, UK: John Wiley & Sons Inc.; 2014. p. 145-166.

Ranjan K, Priya H, Ramakrishnan B, Prasanna R, Venkatachalami S, Thapa S, et al. Cyanobacterial inoculation modifies the rhizosphere microbiome of rice planted to a tropical alluvial soil. Appl Soil Ecol. 2016;108:195-203. Doi: https://doi.org/10.1016/j.apsoil.2016.08.010

Rasuk MC, Fernández AB, Kurth D, Contreras M, Novoa F, Poiré D, et al. Bacterial diversity in microbial mats and sediments from the Atacama Desert. Microb Ecol. 2016;71(1):44-56. Doi: https://doi.org/10.1007/s00248-015-0649-9

Reganold JP, Wachter JM. Organic agriculture in the twenty-first century. Nat Plants. 2016;2(2):15221. Doi: https://doi.org/10.1038/nplants.2015.221

Renuka N, Prasanna R, Sood A, Ahlulwalia AS, Bansal R, Babu S, et al. Exploring the efficacy of wastewater-grown microalgal biomass as a biofertilizer for wheat. Environ Sci Pollut R. 2016;23(7):6608-6620. Doi: https://doi.org/10.1007/s11356-015-5884-6

Renuka N, Prasanna R, Sood A, Bansal R, Bidyaran N, Singh R, et al. Wastewater grown microalgal biomass as inoculants for improving micronutrient availability in wheat. Rhizosphere. 2017;3(1):150-159. Doi: https://doi.org/10.1016/j.rhisp.2017.04.005

Renuka N, Guldha A, Prasanna R, Singh P, Bux F. Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges. Biotechnol Adv. 2018;36(4):1255-1273. Doi: https://doi.org/10.1016/j.biotechadv.2018.04.004

Rizwan M, Mujtaba G, Memon SA, Lee K, Rashid N. Exploring the potential of microalgae for new biotechnology applications and beyond: A review. Renew Sust Energ Rev. 2018;92:394-404. Doi: https://doi.org/10.1016/j.rser.2018.04.034

Rossi F, De Philippis R. Role of cyanobacterial exopolysaccharides in phototrophic biofilms and in complex microbial mats. Life. 2015;5(2):1218-1238. Doi: https://doi.org/10.3390/life50201218

Rossi F, Li H, Liu Y, De Philippis R. Cyanobacterial inoculation (cyanobacterisation): perspectives for the development of a standardized multifunctional technology for soil fertilization and desertification reversal. Earth-Sci. Rev. 2017;171:28-43. Doi: https://doi.org/10.1016/j.earscirev.2017.05.006

Sarma BK, Yadav SK, Singh S, Singh HB. Microbial consortium-mediated plant defense against phytopathogens: readdressing for enhancing efficacy. Soil Biol Biochem. 2015;87:25-33. Doi: https://doi.org/10.1016/j.soilbio.2015.04.001

Schlatter D, Kinkel L, Thomashow L, Weller D, Paulitz T. Disease Suppressing Soils – New Insights from the Soil Microbiome. Phytopathology. 2017;107(11):1284-1297. Doi: https://doi.org/10.1094/PHYTO-03-17-0111-RW
Schreiber C, Schiedung H, Harrison L, Briese C, Ackermann B, Kant J, et al. Evaluating potential of green alga Chlorella vulgaris to accumulate phosphorus and to fertilize nutrient-poor soil substrates for crop plants. J Appl Phycol. 2018;30(5):2827-2836. Doi: https://doi.org/10.1007/s10811-018-1390-9

Shahane AA, Singh YV, Kumar D, Prasanna R, Chakraborty D. Effect of planting methods and cyanobacterial inoculants on yield, water productivity and economics of rice cultivation. J Agr Rural Dev Trop. 2015;116(2):107-121.

Silva AN, de Figueiredo CC, de Carvalho AM, dos Santos Soares D, dos Santos DCR, da Silva VG. Effects of cover crops on the physical protection of organic matter and soil aggregation. Aust J Crop Sci. 2016;11(12):1623-1629.

Singh AK, Singh PP, Tripathi V, Verma H, Singh SK, Srivastava AK, et al. Distribution of cyanobacteria and their interactions with pesticides in a paddy field: A comprehensive review. J Environ. Manage. 2018;224:361-375. Doi: https://doi.org/10.1016/j.jenvman.2018.07.039

Singh SP, Pathak J, Sinha RP. Cyanobacterial factories for the production of green energy and value-added products: An integrated approach for economic viability. Renew Sust Energ Rev. 2017;69:578-595. Doi: https://doi.org/10.1016/j.rser.2016.11.110

Sonkoly J, Valkó O, Deák B, Miglécz T, Tóth K, Radócz S, et al. A new aspect of grassland vegetation dynamics: cyanobacterium colonies affect establishment success of plants. J Veg Sci. 2017;28(3):475-483. Doi: https://doi.org/10.1111/j.1120-1229.2013.012503

Sorochkina K, Velasco Ayuso S, Garcia-Pichel FPY. Establishing rates of lateral expansion of cyanobacterial biological soil crusts for optimal restoration. Plant Soil. 2018;429(1-2):199-211. Doi: https://doi.org/10.1007/s11104-018-3695-5

Souza GP, de Figueiredo CC, Gomes de Sousa DM. Soil organic matter as affected by management systems, phosphate fertilization, and cover crops. Pesq Agropec Bras. 2016;51(9):1668-1676. Doi: http://doi.org/10.1590/S0100-204X2016000900067

Stephens E, Wolf J, Oey M, Zhang E, Hankamer B, Ross IL. Genetic engineering for microalgae strain improvement in relation to biocrude production systems. In: Moheimani NR, McHenry MP, de Boer K, Bahri PA, editors. Biomass and Biofuels from Microalgae. Switzerland: Springer International Publishing; 2015. p. 191-249.

Tafur JE, Estrada L. Tratamiento de aguas residuales in vitro por medio de la microalga Chlorella sp. en el municipio de Barrancabermeja, Colombia. Rev CITECSA. 2015;6(10):5-19.

Tasende MG, Peteco C. Explotación de las macroalgas marinas: Galicia como caso de estudio hacia una gestión sostenible de los recursos. Ambiente. 2015;111:116-132.

Vandana UK, Chopra A, Bhattacharjee S, Mazumder PB. Microbial biofertilizer: A potential tool for sustainable agriculture. In: Panpatte DG, Jhala YK, Vyas RV, Shhet HN, editors. Microorganisms for Green Revolution - Volume 1: Microbes for Sustainable Crop Production. Singapura: Springer; 2017. p. 25-52.

Verseux C, Baqué M, Lehto K, de Vera JPP, Rothlischild LJ, Billi D. Sustainable life support on Mars—the potential roles of cyanobacteria. Int J Astrobiol. 2016;15(1):65-92. Doi: https://doi.org/10.1017/S147355041500021X

Wierzchos J, DiRuggiero J, Vitek P, Artieda O, Souza-Egipsy V, Skaloud P, et al. Adaptation strategies of endolithic chlorophototrophs to survive the hyperarid and extreme solar radiation environment of the Atacama Desert. Front Microbiol. 2015;6:934. Doi: https://doi.org/10.3389/fmicb.2015.00934

Wijffels RH, Kruse O, Hellingwerf KJ. Potential of industrial biotechnology with cyanobacteria and eukaryotic microalgae. Curr Opin Biotechnol. 2013;24(3):405-413. Doi: https://doi.org/10.1016/j.copbio.2013.04.004

Yao Y, Zhang M, Tian Y, Zhao M, Zeng K, Zhang B, et al. Azolla biofertilizer for improving low nitrogen use efficiency in an intensive rice cropping system. Field Crops Res. 2018;216:158-164. Doi: https://doi.org/10.1016/j.fcr.2017.11.020