Soil salinization in agricultural areas of the Caribbean region and agroecological recovery strategies. Review

Salinización de suelos en áreas agrícolas de la región Caribe y estrategias agroecológicas de recuperación. Revisión

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Abstract

Introduction— In Colombia, 45% of the continental and insular surface presents some degree of susceptibility or propensity to soil degradation due to salinization. The high concentration of salts negatively affects the biologicals of the soil, causing a decrease in crop productivity.

Objective— The bibliographic information available on the factors associated with the salinization of soils in agricultural areas of the Caribbean region and different strategies for the recovery of saline soils was reviewed.

Method— A literature review was carried out in which the biophysical and anthropic factors of the salinization of soils and the associated consequences are documented. Additionally, a review was made of international and national scientific articles that address different strategies for the recovery of saline soils in which it was analyzed which ones have been more successful from the environmental point of view.

Results— The salinity of the soils was related to the climatic conditions, irrigation with poor quality water, chemical fertilization, the scarce use of vegetal covers and the low contents of organic matter in the soils. Soil washing is a viable alternative if good quality water is available. The most feasible alternative was the use of organic fertilizers

Conclusions— The salinity of the soils was related to the use of irrigation water with high saline content, little plant cover, low content of organic matter in the soil and the use of fertilizers. The most viable recovery strategy is the application of organic fertilizers and amendments.

Keywords— Salinity; irrigation water; compost; vermicompost; salt washing

Resumen

Introducción— En Colombia, el 45% de la superficie continental e insular presenta algún grado de susceptibilidad o propensión a la degradación de suelos por salinización. La alta concentración de sales afecta negativamente las biológicas del suelo, causando una disminución de la productividad de los cultivos.

Objetivo— Se revisó la información bibliográfica disponible sobre los factores asociados con la salinización de suelos en áreas agrícolas de la región Caribe y diferentes estrategias de recuperación de suelos salinos.

Metodología— Se llevó a cabo una revisión de literatura en la que se documentan los factores biofísicos y antrópicos de la salinización de los suelos y las consecuencias asociadas. Adicionalmente, se hizo una revisión de artículos científicos internacionales y nacionales que abordan diferentes estrategias de recuperación de suelos salinos en los que se analizó cuáles han sido más exitosas desde el punto de vista ambiental

Resultados— La salinidad de los suelos se relacionó con las condiciones climáticas, el riego con aguas de mala calidad, la fertilización química, el escaso uso de coberturas vegetales y los bajos contenidos de materia orgánica de los suelos. El lavado de los suelos es una alternativa viable siempre que se dispongan de aguas de buena calidad. La alternativa más factible fue el uso de abonos orgánicos.

Conclusiones— La salinidad de los suelos se relacionó con el uso de aguas de riego con alto contenido salino, escasa cobertura vegetal, bajos contenidos de materia orgánico en el suelo y uso de fertilizantes. La estrategia de recuperación más viable es la aplicación de abonos y enmiendas orgánicas.

Palabras clave— Salinidad; aguas de riego; compost; vermicompost; lavado de sales

I. Introduction

In Colombia, 45% (51 270 290 ha) of the continental and insular surface presents some degree of susceptibility or propensity to soil degradation due to salinization, being La Guajira the department with the largest extension of its territory (90%) with some degree of degradation due to accumulation of salts, followed by the departments of Atlántico, Magdalena, Cesar, and Valle del Cauca [1].

Physiographically, the coastline of the department of Magdalena is divided into two large provinces: the region of the external delta of the Magdalena River in the western part (Parque Nacional Natural Isla de Salamanca-PNNIS) and the mountainous coasts to the east, where the Sierra Nevada de Santa Marta-SNSM. The coastal climate is considered warm, most of which is classified as semi-arid and includes halophytic (mangrove) and xerophytic (cactus and thorny shrubs) vegetation on the island of Salamanca and around Santa Marta. More dense forests with a more humid climate are to the east [2].

The natural vegetation has been highly modified by subsistence agriculture, agribusiness, and the construction of tourist complexes. Agricultural development focuses on the cultivation of bananas for export and domestic agribusiness. Livestock production is one of the most important lines and is based on goat, sheep, horse, and bovine livestock. On the other hand, the peasant economy is made up of commercial and subsistence agriculture; that is, a part to sell and another for family support, highlighting miscellaneous crops of cassava, banana, corn, sorghum, coconut, yam, vegetables, and fruit trees such as orange, papaya, medlar, lemon, tangerine, sapote, suckling pig, plums, and mango, among the most representative; spreading along the entire coast [2]-[3].

The natural ecosystems of the Caribbean region have suffered irreversible changes in their original structure due to human activities. The ecosystems of the departments of Atlántico and Cesar have undergone a transformation of over 80%, while the livestock departments of Córdoba, Magdalena and Sucre have an ecosystem transformation of over 70%, while Guajira shows the least ecosystem alteration [4].

One of the major problems that are evident in coastal agricultural areas is the salinization of soils, these problems are induced or produced using saline waters that are used for irrigation, marine intrusion, surface rise of the subsoil salts and the use of chemical fertilizers [5].

In Colombia, IDEAM developed a map of susceptibility to soil degradation due to salinization at a scale of 1:100 000. According to the information, 45% of the continental and insular surface of the country presents some degree of susceptibility or propensity to soil degradation due to salinization. 2.4% of this percentage show very severe and severe degradation; 7.8% with moderate degree and 2.1% with slight degradation by salts. 42% of the Caribbean hydrographic area presents processes of degradation of soils due to salinization, of which 6.6% are severe and very severe; next is the Magdalena-Cauca hydrographic area with 30.7%, severity is 6.7%; to a lesser extent is the Pacific hydrographic (11.8%, with a severity of 2.4%). When analyzing by departments, Magdalena, Atlántico, Cesar, and La Guajira present the highest percentage of soils with very high degradation due to salinization [1].

The effects of excessive salinity indicate a reduction in crop yield; the growth stage directly influences salt tolerance; that is, the more developed the plant is, the more tolerant it is to salts; most fruit trees are more sensitive to salts than vegetable and forage crops [6].

Salinity generates a negative socioeconomic impact due to the reduction of the productivity of crops in saline lands, leading to poverty due to loss of income, farmers abandon their lands and migrate from rural to urban areas, which generates unemployment, high costs for soil recovery, where possible, loss of good quality soil (organic matter and nutrients) requires more inputs, such as fertilizers, which generates greater financial pressure on farmers [7].

From an environmental point of view, fragmentation of the ecosystem occurs, poor growth and poor vegetation cover lead to greater soil degradation (erosion), increased particulate matter (dust), sand invades productive areas, storage capacity of water reservoirs is reduced due to eroded soil material, contamination of groundwater with high levels of salts occurs [8].

One of the causes that are accentuating the problems of salinity of the soils in these areas has been the use of inappropriate agricultural production techniques [9]. The high concentration of salts negatively affects the physical and chemical properties and microbial activity of the soil, causing a decrease in soil productivity. There is also a decrease in the growth of the vegetation due to the toxicity of the salts, resulting in a lower entry of carbon (C) in these soils [10].

The physical, chemical, and biological deterioration of the soil do to of the salinization of coastal agricultural areas at the national level leads to a decrease in their productivity and consequently to food production, thus threatening food security and reducing livelihoods of the populations that are in coastal areas and that depend on it as another means of subsistence [4].

Among the recovery strategies for saline soils is the addition of organic fertilizers, the use of chemical amendments of highly soluble calcium salts, the washing of soluble salts with low salinity waters, the construction of drainage works contributes to the rehabilitation of the soil, reincorporation of native perennial species in agricultural systems, revegetation with halophytic species inoculated with symbiotic organisms, and phytoremediation [11].

In accordance with the salt problems present in different regions of Colombia, especially in departments such as Magdalena, the objective of this work was to review scientific articles related to the biophysical and anthropic factors responsible for the salinization of agricultural soils in coastal areas, as well as a comparative analysis of the recovery strategies for saline soils to specify which ones have been the most successful from the environmental point of view.

II. Methodology

An extensive bibliographic review of scientific articles, books, book chapters of the last 10 years published in national and international indexed scientific journals was carried out. For this, bibliographic sources available in electronic databases were used such as: Science Direct, Springer Link, Scopus, Multilegis, Ambientalex, Mc Graw Hill, Pearson, Web of Science, among others. The most relevant scientific articles, books, institutional documents directly related to recovery strategies such as irrigation and hedge management available on Google, Web of Science, were also reviewed and selected, etc.

The articles were classified and selected based on the topic addressed. To analyze the situation of salinization of soils in the Caribbean region, studies that reported data on soil use, pH, electrical conductivity, organic matter were considered, where salinization problems especially associated with agricultural activities were evidenced. Additionally, a review of strategies for the recovery of degraded soils due to salinity was made for agricultural soils. The information was organized in a table considering the type of strategy used, country in which it was implemented, type of experimentation (laboratory, field, or greenhouse) and reference consulted. Strategies such as use of irrigation, drainage, coverage management, plant breeding, use of microorganisms, application of chemical and organic amendments, among others, were reviewed, analyzed, and compared. A distribution was made of the types of studies carried out at the laboratory, greenhouse, field, or review level between the years 2010-2020. Finally, a comparison and analysis of the potentialities and limitations of each strategy was made to identify the most successful and feasible to implement at the field level.

III. Results and Discussion

Table 1 shows some of the results of works that have been carried out in agricultural areas of the Caribbean region, including the Magdalena, Atlántico, and Guajira departments. The type of soil use, pH and electrical conductivity, responsible factor and consequences of soil salinization can be seen in the table.

Table 1.
Investigations carried out in the department of Magdalena with soils degraded by salts.

Area or region	Land use		pH	EC dS m-1	Responsible factor	Consequence	Source
Santa Marta, Magdalena	Forest		8.03	0.56	Agricultural use under conventional intensive management, irrigation, and fertilization for more than 25 years.	Salinization, decrease in organic carbon, compaction.	[12]
	Agricultural Systems	Mango	8.15	1.02			
		Green manures	8.26	1.11			
		Vegetables	7.90	0.42			
	Green areas		7.99	0.48			
Cerrejón, La Guajira	Rehabilitation of soils for mining use with management of coverage and irrigation		7.5 - 8.5	0.4 - 1.8	Semi-arid conditions	Salinization	[5]
Repelón, Caribe	Different agricultural uses (Neem trees and ground cover, resting areas, rice, grass, banana with ground cover, cassava, beans with ground cover, corn, pin, squash)	Rainy season			Irrigation water, chemical fertilization	Increase in salinity in a localized way. Improvements in soil properties due to the type of management given to crops.	[13]
		Zone 1	7.54	0.72			
		Zone 2	7.14	0.21			
		Zone 3	6.95	0.41			
		Zone 4	6.79	0.29			
		Dry season					
		Zone 1	7.03	2.29			
		Zone 2	7.10	1.95			
		Zone 3	7.05	0.22			
		Zone 4	6.43	0.20			
Northeast department of Magdalena	Zone 1		5.6	NR	Land use type	Low content of organic carbon in the soil	[14]
	Zone 2		6.3				
	Zone 3		6.5				
	Zone 4		7.1				
	Zone 5		7.1				
	Zone 6		8.6				
Mouth of river Sinú, Córdoba	Agricultural use, irrigated rice, African palm, corn, cassava, and vegetables	Dry season	EC (dS m^{-1})		Seawater intrusion in dry season, high evapo-transpiration, clay content	Increase in electrical conductivity due to capillary rise of Na, Cl, SO and Mg ions to the surface horizons.	[15], [16]
			< 2 (28 % NS)				
			2-4 (23 % LS)				
			4-8 (26 % MS)				
			8-16 (17 % FS)				
			> 16 (6.2 % ES)				
		Rainy season	< 2 (55 % NS)				
			2-4 (25 % LS)				
			4-8 (13 % MS)				
			8-16 (5 % FS)				
			> 16 (2 % ES)				
Santa Marta, Magdalena	Natural vegetation	Dry season	Promedio 8.3		Not reported	Limited absorption of nutrients	[17]

Zone 1: Coffee with shade and tropical humid forest; *Zone* 2: Tropical humid forest, African palm cultivation for more than 20 years, currently with organic management and alternates with legumes as ground cover; *Zone* 3: Secondary tropical dry forest and plowed soil at the time of sampling for banana planting, previously planted with rice; *Zone* 4: Tropical dry forest and traditional banana cultivation, formerly tropical dry forest; *Zone* 5: Mango cultivation for more than 15 years, secondary tropical dry forest and fruit crops of warm climate with traditional management, previously tropical dry forest; *Zone* 6: Very dry tropical forest, warm climate vegetables, previously planted with corn and sorghum, and very dry tropical forest. % *NS*: percentage of non-saline soils; % *LS*: percentage of slightly saline soils; % *DM*: percentage of moderately saline soils; % *FS*: percentage of strongly saline soils; % *ES*: percentage of extremely saline soils.
Source: Own elaboration

The intensive agricultural use given to soils in the study conducted in Santa Marta (Colombia) has led to a progressive increase in pH and electrical conductivity. The decrease in organic matter caused a reduction in soil porosity and was reflected in a progressive increase in compaction and saline conditions in this type of arid and semi-arid ecosystems. When comparing the agricultural use with the management under grass vegetation and natural forest, the role that organic matter plays in maintaining the quality of the soils and preventing their degradation is highlighted [12].

At the Cerrejón mine in the department of La Guajira (Colombia), the presence of saline soils with pH values ranging from 7.5 to 8.5 and electrical conductivity between 0.4 dS/m and 1.8 dS/m was reported, the cause of which is associated with the semi-arid conditions typical of the area, which are accentuated by the lack of soil cover [5]. On the other hand, in the Repelón Irrigation District located in the department of Atlántico, the soils were naturally characterized as saline. However, in the cases where salinity was higher, it was attributed to the use of fertilizers and the poor quality of irrigation water in the area. Despite this, the soils cultivated with corn, guava, pin, rice, squash, yucca, and plantain, etc., had a low degree of affectation until now, which was associated with good management. Additionally, in areas with no agricultural activity, better physicochemical properties and greater natural fertility of the soils were observed [13].

In a more generalized study to the northeast of the department of Magdalena, mean pH values in cultivated soils of 6.9 and 7.1 for forests were found, being zone 1 (tropical humid forest and shade coffee) the one that presented the values lower pH, which was associated with the higher humidity, as well as the higher contribution of vegetation, have led to a decrease in soil pH. In zone 6, average pH values of 8.6 were observed for soils cultivated with vegetables from a warm climate and 8.7 for soils under very dry tropical forest. This was attributed to a high saturation of bases in the complex of change of the soils studied, with calcium (Ca) being the dominant cation that conditions numerous physicochemical processes typical of that area. Similarly, the low content of organic carbon had a marked effect on the pH of the soils in this region [14].

In soils of the delta of the river Sinú, department of Córdoba, it was evidenced that the salinity conditions of the soils vary depending on the time of year and the characteristics of the soils. In this regard, it was found that during the rainy period the areas of non-saline soils increased compared to the dry period, while the areas with strong and extremely saline soils decreased when compared to the dry period. The highest values of electrical conductivity were observed during the dry season coinciding with a greater intrusion of brackish waters to the continent due to the increase in tides, the reduction of the water flow of the Sinú River and a more intense potential evapotranspiration, exposing consequently, the maximum salinity values. An increase in electrical conductivity was also observed due to capillary ascent to the surface horizons, of the Na^{+}, Cl^{-}, SO and Mg^{+2} ions, which are mainly responsible for salinization [15]-[16].

In the experimental farm of the University of Magdalena, Santa Marta (Colombia), pH values of the soils were found between slightly alkaline and alkaline, with a maximum of 9.7 (very alkaline), an extremely limiting situation for the adequate development of the crops. On the other hand, it was observed that soils with pH values close to neutrality presented higher organic matter contents. As a result of, these authors suggest increasing the levels of organic matter as a management strategy that allows to attenuate the negative effect of the salinity of the soils in this area [17].

According to the cases reviewed, the salinity of the soils is influenced by climatic conditions, with arid areas being those with the highest salinity, especially those near sea level, where the intrusion of seawater during the dry season, the rise in the water table and the high evapotranspiration accentuate the salinity problems. The especially practical crop management conditions such as the use of irrigation with poor quality water, chemical fertilization, the scarce use of plant covers and the low contents of organic matter in the soils influence an increase in the levels of salts in the soils.

There are various strategies for the recovery of soils affected by salts, among them the use of irrigation with good quality water, washing the soils, plant breeding, application of chemical amendments and organic fertilizers, nutritional improvements of crops, bacteria promoters of growth, mycorrhiza, coverage management, etc. Table 2 presents a compilation of international and national scientific studies with the different strategies that have been implemented in the recovery of saline soils.

Table 2.
International and national studies on the evaluation of strategies for the recovery of saline soils

No.	Strategy type	Country	Type of work	References
Irrigation and coverage management				
1	Optimization of irrigation and drainage, combination of amendments, soil conditioners, waste management.	México	Review	[18]
2	Irrigation with treated sewage, sewage sludge.	Brasil	Greenhouse conditions	[19]
3	Coverage management, irrigation.	Colombia	Field conditions	[5]
Plant breeding and use of microorganisms				
4	Plant breeding, molecular biology, growth promoting bacteria, rhizospheric bacteria.	Australia	Review	[20]
5	Growth promoting bacteria.	India	Review	[21]
6	Halophilic bacteria.	Colombia	Greenhouse conditions	[22]
7	Biofertilizers, gypsum, sulfur, biocompost, biopolymers, electromagnetism, mycorrhiza.	Colombia	Greenhouse conditions	[23]
8	Selenium supplementation.	United States	Laboratory conditions	[24]
Chemical and organic amendments				
8	Compost, vermicompost.	México	Field conditions	[25]
9	Compost, solid vermicompost, fresh lemongrass, phosphogypsum.	Venezuela	Greenhouse conditions	[26]
10	Organic materials, plants, biochar.	India	Review	[27]
11	Vermicompost.	Venezuela	Field conditions	[28]
12	Bovine manure, gypsum, sulfuric acid, soil washing under controlled conditions.	México	Greenhouse conditions	[29]
13	Organic amendments (effluent from washing pens and urine and feces from confined animals).	Argentina	Greenhouse and field conditions	[30]
14	Chemical amendments (Gypsum).	Túnez	Laboratory conditions	[31]
15	Forage species.	Colombia	Review	[32]
16	Compost, sewage sludge.	Brasil	Field conditions	[33]

Source: Own elaboration.

When analyzing the recovery strategies for soils affected by salts presented in Table 2, it can be highlighted that techniques such as optimization of irrigation and drainage, the combination of amendments, the use of conditioners and waste management can contribute to the reduction significant effect of soil salinity with the consequent increase in crop yield [18]. Additionally, it was found that the application of irrigation with water from treated wastewater plus the additional supply of water, decreased the exchangeable Na^{+} content in the soil and increased Ca^{+2}. According to these results, the continuous use of treated effluents together with organic fertilization with biosolids based on composted sewage sludge or mineral fertilizer can be used to meet the water and nutritional needs of crops without apparent risk of salinity or sodicity. provided that these materials do not contain high content of salts and / or sodium [19].

Other strategies for the use of saline soils rather than recovery that appear indicated in the literature and that it is valuable to show are plant breeding, molecular biology techniques and soil bacteria that promote plant growth. In this regard, it was found that the genetic improvement of plants for tolerance to saline conditions, together with the inoculation of soils with rhizospheric and growth-promoting bacteria are more promising techniques that would mitigate the adverse effects of soil salinity on crop productivity [20].

In an analysis of the impact of salinity on crop yields and the best recovery strategies it was found that the salinization of the soils was responsible for the reduction between 20% and 50% of the yields; noting that the problem may be further aggravated due to climate change. Therefore, the adoption of mitigation strategies to face such impacts, the efficient management of resources and the improvement of crops and livestock can bring favorable impacts, and, in this way, better results can be obtained to overcome salinity stress. In this sense, microorganisms of the rhizoplane, the rhizosphere, endophytic bacteria, and symbiotic fungi associated with plants can confer resistance to abiotic stress through a variety of mechanisms such as triggering the osmotic response, providing growth hormones and nutrients, acting as biological control agents and induction of new genes in plants [21].

In this context, the development of stress-tolerant crops through genetic engineering and plant breeding is essential, but it is a long and expensive process, while microbial inoculation to relieve stress in plants could be a more profitable ecological option. that could be available in a shorter period. For example, the isolation of moderately halophilic bacteria with high potential for the capture and mobilization of sodium in cultivated soils has shown a decrease in the electrical conductivity of soils, going from moderate salinity to very light salinity, together with tomato plants that grew in the soils inoculated with this type of bacteria showed improvements in growth compared to the control without inoculation [22].

It was also found that the use of microorganisms, especially those of the genus *Thiobacillus*, generated a positive response in the plant due to its role in the oxidation of sulfur from its elemental form to sulfuric acid. It was similarly evidenced that the use of mycorrhizae and other rhizosphere mutualists such as *Rhizobium* and *Azospirillum* represent a very promising microbiological element in the recovery of saline soils, especially because these fungi help in the establishment and growth of plants in saline soil conditions. In addition, they protect the roots against diseases [23].

Other strategies found in the literature is the supply of Selenium (Se) to plants for the management of tolerance to saline stress conditions. However, the results were not very encouraging because the protection and transformation mechanisms of Se in plants are not yet clear, in addition to the fact that most of the experiments have been carried out under hydroponic conditions, which could be overestimating the absorption and Na^+ translocation within the plant. The experiments that have been carried out in soils have been short-term, raising questions about the potential of Se to remediate soils affected by salts in the long term. Therefore, well-planned, comprehensive, and long-term field experiments are needed to verify the productivity and economic feasibility of Se-based improvements of saline soils, in addition to considering the high cost of Se-based fertilizers [24].

The use of organic amendments, especially compost, vermicompost and biofertilizers, have been the most frequently and successfully implemented strategies. In a study developed in the municipality of Munitepec de Madero in Tlahuelilpan (Mexico) under experimental field conditions, it was found that the application of organic amendments favored the recovery of saline-sodium soils. By using compost and vermicompost as organic amendments, a greater stability of the colloidal suspensions was achieved than in the initial soils, the Electrical Conductivity (EC) decreased, and it was possible to corroborate an inverse correlation with respect to the variation of pH and EC [25]. In another study carried out under controlled greenhouse conditions, it was found that the use of phosphogypsum was not effective, while the application of vermicompost at 1.5% was highly effective [26].

Given concerns about the continued global expansion of salt-affected lands and the focus on carbon sequestration (C) processes, a review was found that evaluated current knowledge about salt-affected soils and their remediation with organic materials and plants. According to what the authors point out, there are important gaps in knowledge that limit the current understanding of the rehabilitation of soils affected by salts with organic amendments, especially biochar and the associated carbon dynamics [27].

Similar results were reported in an agricultural area under arid conditions in a saline-sodium soil in the Miranda municipality, Falcón state (Venezuela), in which the use of vermicompost made with Californian red worm (*Eisenia foetida* Sav.) proved to be a good strategy. for the integral recovery of saline-sodium soils in the study region since the electrical conductivity, pH, and the percentage of exchangeable sodium in the soils significantly decreased [28].

In the irrigation district 086, Jiménez, Tamaulipas (Mexico), a work was carried out to rehabilitate saline-sodium soils through the application of amendments such as bovine manure, gypsum, sulfuric acid and washing of potted soils under controlled conditions. It was found that washing with water of low saline concentration reduced salinity and sodium to satisfactory levels for conventional crops, with and without the application of bovine manure, gypsum, and sulfuric acid. The use of soil improvers was unnecessary, so they conclude that the rehabilitation of said saline-sodium soils could only be achieved with the application of washing, even if the change in soil pH is small [29].

In a greenhouse experiment developed in the northwestern region of the Arenosa Pampa (Argentina), a study was carried out in which different strategies for the recovery of soils affected by excess salts were evaluated. In accordance with the experiences obtained, these authors recommend preserving the surface vegetation cover, especially the native species typical of saline habitats adapted to these conditions, and they also suggest incorporating inter-seeding or direct seeding practices of perennial forage species tolerant to saline-sodium conditions. of the soils, combined in turn, with the addition of organic fertilizers that can be incorporated with the hoof of the animals to improve the physical and chemical conditions of the soil [30].

It has been shown that the use of organic materials promotes the increase of the saturated hydraulic conductivity of the soil due to the increase of macroporosity, this in turn, allows the removal of sodium from the exchange complex. In this regard, in a study carried out in a loamy-silty soil affected by salts in Sebkha Solimán (northeast of Tunisia), the effect of compost and sewage sludge was evaluated, and a positive effect was found on the physical properties, chemical and biological activity of the soil. The organic amendments improved the biological quality of the soil, while with the use of sewage sludge the effect was less beneficial, possibly attributed to the increase in salinity or the presence of trace elements [31]. In a documentary review on the methods of restoration of saline soils, with influence in the Usochicamocha irrigation district, department of Boyacá (Colombia), it was possible to identify that phytoremediation with halophyte species was the least expensive, most efficient strategy (with removal efficiencies of salts of 80% and 90%) and more environmentally sustainable, but it is the one that requires the most time since it depends on the life cycle of the chosen halophyte species, the quality of the seed, the sowing and harvesting cycles to guarantee the removal at low levels of salinity and electrical conductivity. Regarding the use of chemical and organic amendments, it was found that the removal efficiency with amendments such as the mixture between calcium sulfate and fresh or composted organic waste and vermicompost, ranged between 75% and 90%. The impact with this last strategy was positive and was evidenced in the improvement of the physicochemical properties of the soil, its structure flocculated by calcium, the decrease in sodium in the exchange complex, increase in permeability, improvement in drainage, infiltration. and hydraulic conductivity, water availability, decrease in osmotic pressure, rhizosphere development and increase in native microbial populations; all of which translates into increased soil productivity [32].

Knowledge about the application of biochar in soils affected by salts is scarce and, to date, most studies have evaluated the use of biochar only in soils not affected by salts. In this sense, the use of biochar should be taken with caution due to its effect of increasing the pH of the soil. This was evidenced in a study in which it was found that the application of biochar led to an increase in the Electrical Conductivity of the Saturation Stratum (ECse), the pH, the concentrations of Na and K, in the Sodium Absorption Ratio (SAR) and in the Exchangeable Sodium Percentage (ESP), especially in the first 10 cm of soil. Even though some studies have found decreases in pH values, salt concentration and sodium, in this and other studies the results have been totally contrary and not very consistent. Such differences have been attributed to factors such as the great variation in the composition of the raw material used to produce and the diversity of soils used in the different studies. In addition, more long-term field experiments are needed to verify the results obtained under controlled conditions [33].

A. *Comparison of the different recovery strategies for saline soils based on environmental parameters*

According to the articles consulted, it was found that the strategy that has been most studied in the recovery of saline soils is irrigation with waste and non-wastewater, either through literature review or through field and greenhouse trials. Secondly, regarding the works consulted, it was the application of vermicompost, compost and gypsum in field and / or greenhouse experiments and, on the other hand, the use of forage plant species was found as a strategy for evaluating adapted plants. to saline soil conditions. Third, the use of growth-promoting bacteria and rhizospheric bacteria was found, whose use has focused on improving cultivation conditions so that plants can better adapt and tolerate saline stress conditions (Fig. 1).

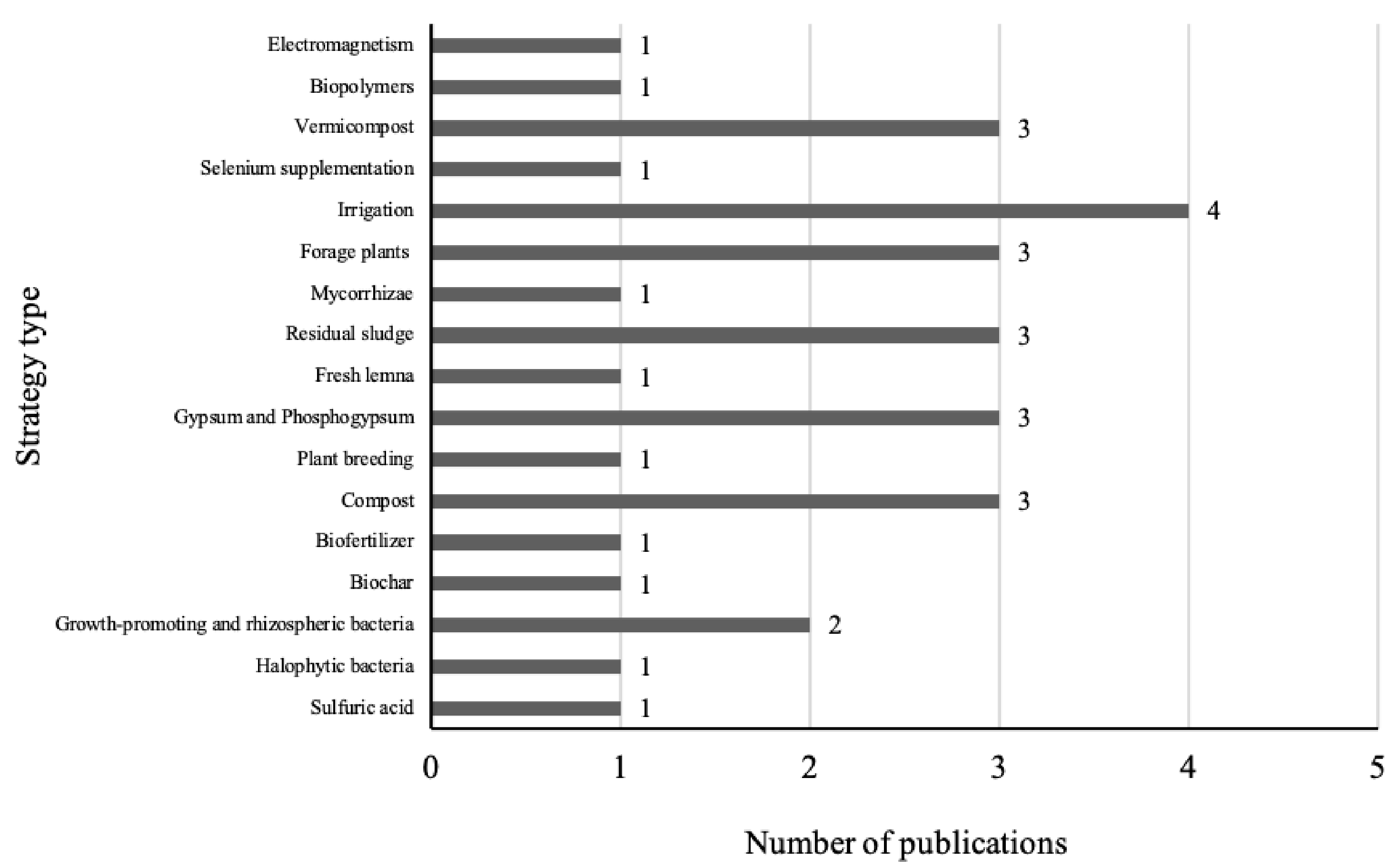

Fig. 1. Type of strategy used according to the review of articles corresponding to the years 2010-2020.
Source: Own elaboration.

Of the strategies reported in the literature, the most successful in terms of salt removal corresponds to plant breeding, however, as expressed in the analysis, its implementation is more expensive and requires more time to obtain results. Soil washing is a viable alternative if good quality water is available because in the worst case it could worsen the soil salinity problem. The use of biochar as a strategy to desalinate soils has been little studied and the results obtained have not been satisfactory.

Chemical amendments such as gypsum, sulfuric acid was not successful especially when compared with organic amendments (compost, vermicompost and biofertilizers), which were the most successful because they improved the physical, chemical, and biological conditions of the soils and provided nutrients to the plants. The use of microorganisms in the soil such as bacteria and fungi provided the plants with better conditions to cope with saline stress. Regarding the use of residual sludge, the analyzed works indicate that it can be an excellent alternative if it is do not contain high contents of heavy metals.

Fig. 2 shows that of the 17 articles consulted, six of them were works carried out at the greenhouse level, five were carried out under field conditions, four correspond to literature reviews from years prior to 2010 and two studies were carried out at laboratory level.

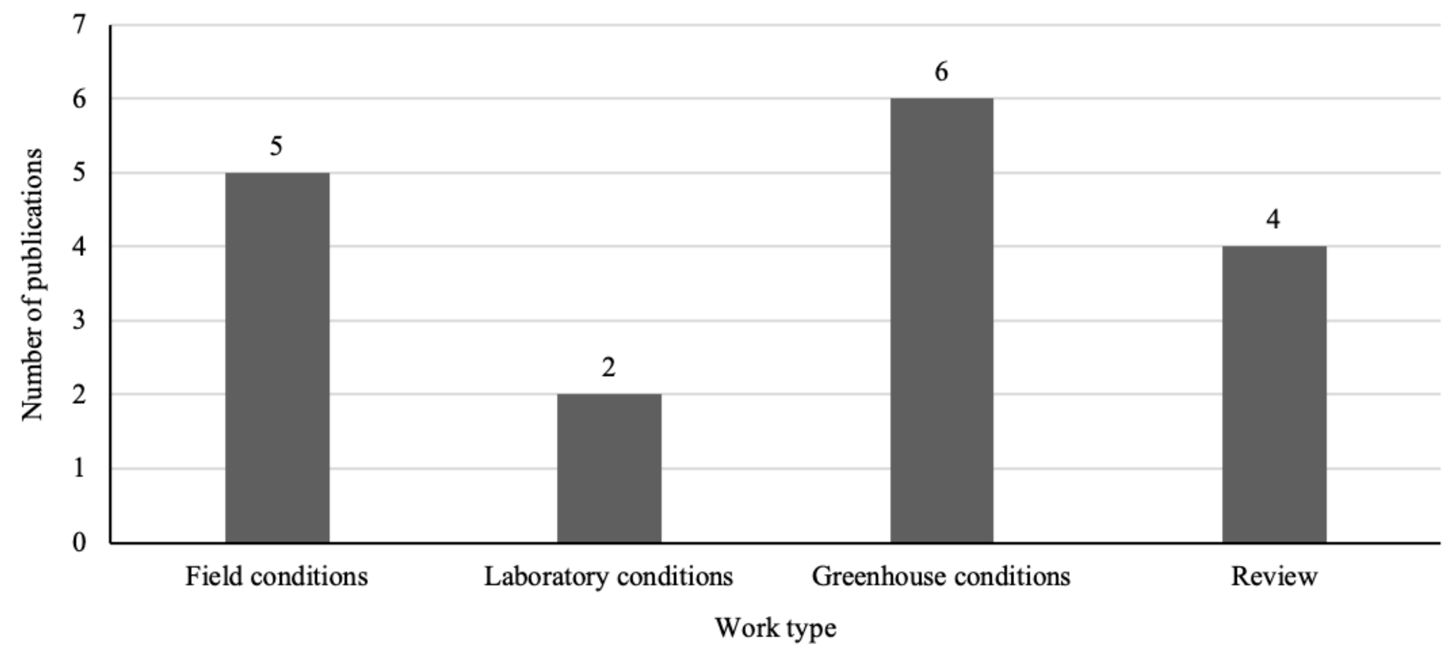

Fig. 2. Distribution of the types of studies carried out at the laboratory, greenhouse, field, or review level between the years 2010-2020.
Source: Own elaboration.

The largest number of articles found in terms of strategies used in saline soils was in Colombia with four works, three of them experimental and a literature review presented as a master's thesis in which works from years prior to 2010 are analyzed. It is followed by Mexico in number of articles reported and in third place was Venezuela, India, and Brazil (Fig. 3). It is important to note that these articles consulted correspond to a 2010-2020 window. Before 2010, more articles were found, but they were not considered in this review.

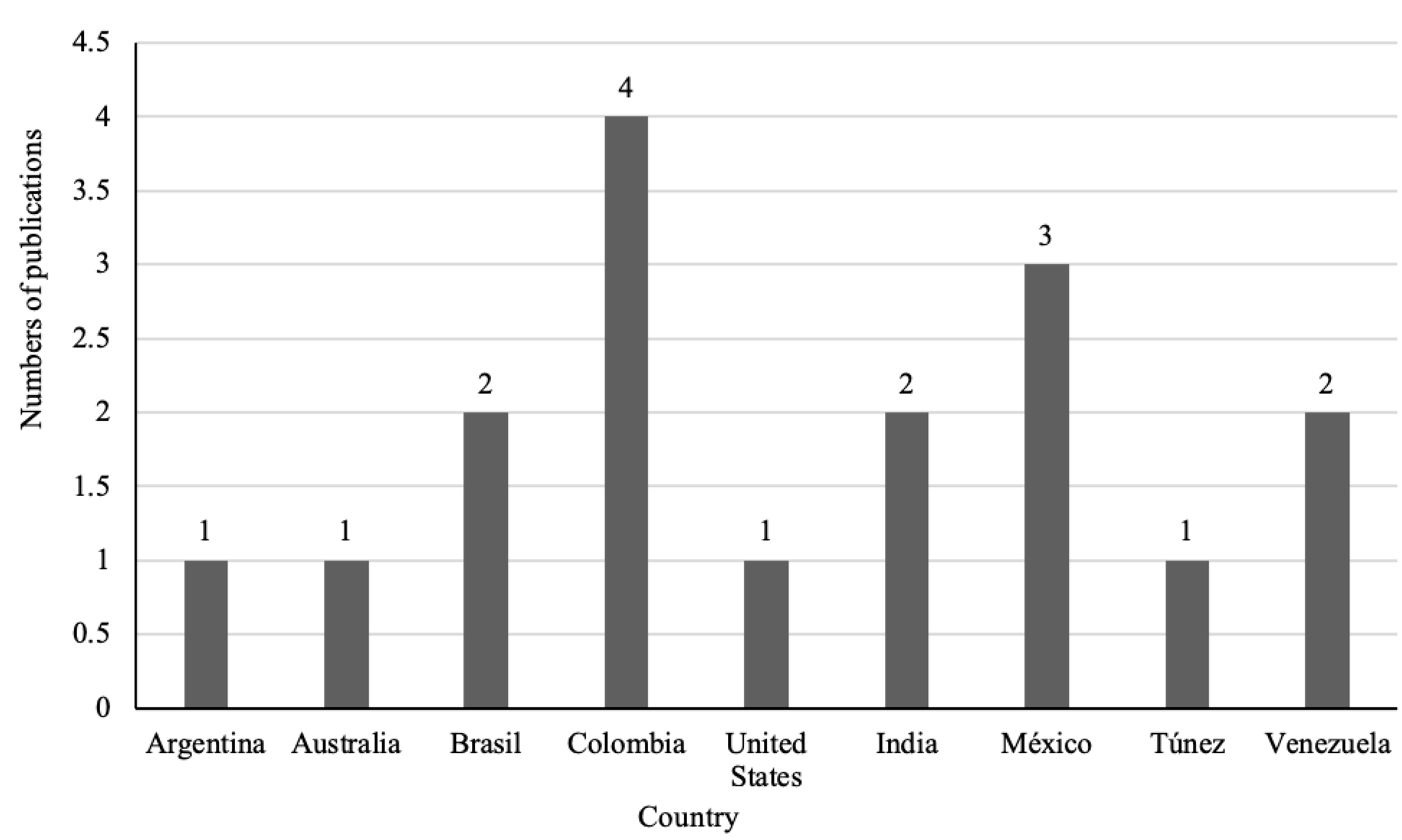

Fig. 3. Distribution of articles published by country during the years 2010-2020.
Source: Own elaboration.

IV. Conclusions

Not much literature published at the national level was found that evidence the problem of salinization in coastal soils and the productivity of crops, so it is necessary to develop more studies in this area.

The main sources of salinization reported in coastal soils were the use of irrigation waters with a high content of salts, high levels of natural salinity in the Magdalena area (Colombia), scarce vegetation cover, low content of organic matter in the soil and the use of fertilizers.

Phytoremediation was the most successful strategy followed by the application of organic soil amendments while the application of gypsum was less successful.

Few studies have been implemented for the recovery of saline soils in the Magdalena area (Colombia).

Recommendations

More research is required to address the problem of soil salinization in coastal agricultural areas of the Magdalena department, since the information available at the national level is very scarce.

It is necessary to monitor the salinization levels of coastal soils due to its effect on the agricultural productivity of the department.

It is recommended to continue delving into the strategies that have been proven to be the most successful and that can also be implemented by farmers due to their low cost and easy implementation.

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