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Article

Eco-intensification of agricultural systems as the potential of soil microorganisms. A meta-analysis

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Abstract

Agricultural eco-intensification is based on the optimal management of all components of the agroecosystem. One of the components most sensitive to changes is the soil, where the role of microorganisms present in the rhizosphere is fundamental. That is why this work aims to analyze the potential of using microorganisms as a basis for eco-intensification in agricultural systems. This potential was analyzed with a meta-analysis of 203 publications in the period from 2015 to 2022, whose collection was subjected to a frequency analysis of keywords and thematic axes and a cluster analysis (level 3) of the nodes identified using the Nvivo software. The results indicate that only 5.9% analyzed highlight the importance of soil microbiology in agricultural eco-intensification. It is concluded that agricultural eco-intensification promotes fewer inputs, low production costs, and optimal incomes while conserving the soil, improving water content and quality, restoring soil and habitat health, and reducing the emission of greenhouse gases in the agroecosystem. The strengthening of soil microorganisms as an element of eco-intensification represents a niche to improve agroecosystems' ecology, productivity, and profitability, taking advantage of and maximizing the ecosystem services they offer. This involves deepening research into these interactions to encourage their adoption by farmers.

Keywords:

agriculture, ecology, environmental, sustainability.

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Introduction

The effects derived from the conventional intensification of agriculture based on the high use of chemical inputs are clearly unsustainable. This intensification offers a set of practices based on the use of synthetic inputs for large areas of monoculture. The productivist model based on the high use of inputs had its origin in the industrial revolution; that is, at a time when the volume of the human population represented less than 15% of the current one and in which the unsustainability of productive systems was not so evident (Montoya *et al*., 2022).

Currently, the great challenge of world agriculture is raising its economic, social, and environmental sustainability. Among the targets proposed in the Agenda of the Sustainable Development Goals (SDGs) for 2030, the purposes of 'ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture' can be highlighted (UN, 2022). These goals have determined changes in the way intensification processes are implemented so that the priorities of the sector are met without overexploitation of the land (Creus, 2017).

In this regard, Lal (2019) states that it is precisely in this context where the importance of eco-intensification can be insisted on for a much-needed paradigm shift, understanding that practices that improve soil quality and functionality will positively impact the activity and diversity of biota species, where microorganisms play a fundamental role; thanks to their ecosystem services, they are an essential part of a successful transition to sustainable agricultural systems.

This approach was developed since the beginning of the twentieth century in northern Europe under the concept of ecological agriculture, where they were already distancing themselves from the trends aimed at increasing yields in conventional agriculture (Calderón, 2004).

By virtue of this Ayan *et al*. (2021) argue that the use of beneficial microorganisms constitutes a strategy to develop more sustainable agricultural systems and reduce the negative impact of chemicals for agronomic management (nutrition, pests, and diseases). In addition, plant-associated microbial communities improve plants' tolerance to environmental stress, favor nutrient uptake and contribute to their growth (Santoyo *et al*., 2021).

Based on these considerations, this work aimed to analyze the potential of using microorganisms as a basis for eco-intensification in agricultural systems. To this end, a meta-analysis was carried out considering the assumption that, in agricultural systems, eco-intensification does not weigh the benefits of managing microorganisms consciously to maximize productivity.

Materials and methods

The compilation of the scientific literature was carried out from January to March 2022, the period in which the research was conducted, documents published between 2015 and 2022 were used; in the case of eco-intensification concepts, publications that allowed understanding the construction of the concept were analyzed. Websites specialized in academic search engines were used, such as Google Scholar, ResearchGate, Science Direct, Scopus, and Web of Science, which allowed the search in: Agrosystems, Elsevier, Emerald, IOP, Nature, Oxford, Springer, and in the Mexican journals of Science and Technology of the National Council of Humanities, Sciences, and Technologies (CONAHCYT, for its acronym in Spanish), of free access.

Searches were conducted in Spanish and English. The main keywords used in the search were: 1) intensification/intensification; 2) ecological/ecological; 3) microorganisms/ microorganisms; 4) agroecology and 5) agriculture.

All publications found were managed and stored with the free access program (Zotero, 2018). The documents were exported in RIS format to a computer storage folder. The files were imported into the Nvivo trial version program, where a frequency analysis of words with at least nine characters was performed. This number of characters was selected since keywords or phrases related to the topics of the publications contain at least these characters.

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The frequency analysis of words allowed the identification of the most representative keywords of each document, that is, all the words that were found within the first quartile (25%). These keywords allowed the selection of the publications that contained the highest percentage of information on the key research topics. The selected publications were subjected to a cluster analysis to identify the relationship between research topics through the Nvivo program through the classification parameters called nodes.

The nodes were coded with the first quartile (25%) of keywords. The cluster analysis allowed the determination of the frequency of studies for each topic and the relationship between them, the results of which generated three discussion approaches to analyze the potential of microorganisms in eco-intensification in agricultural systems.

Results and discussion

The frequency test of words with at least nine characters generated six words that represent 25% of the total words (in Spanish and English): intensification, ecological, microbial, agriculture, environmental, and agroecology, which are represented in the image of the most frequent words considering the 203 references analyzed (Figure 1).

Figure 1. Distribution of the most frequent words in publications and documents related to the eco-intensification of agricultural systems.

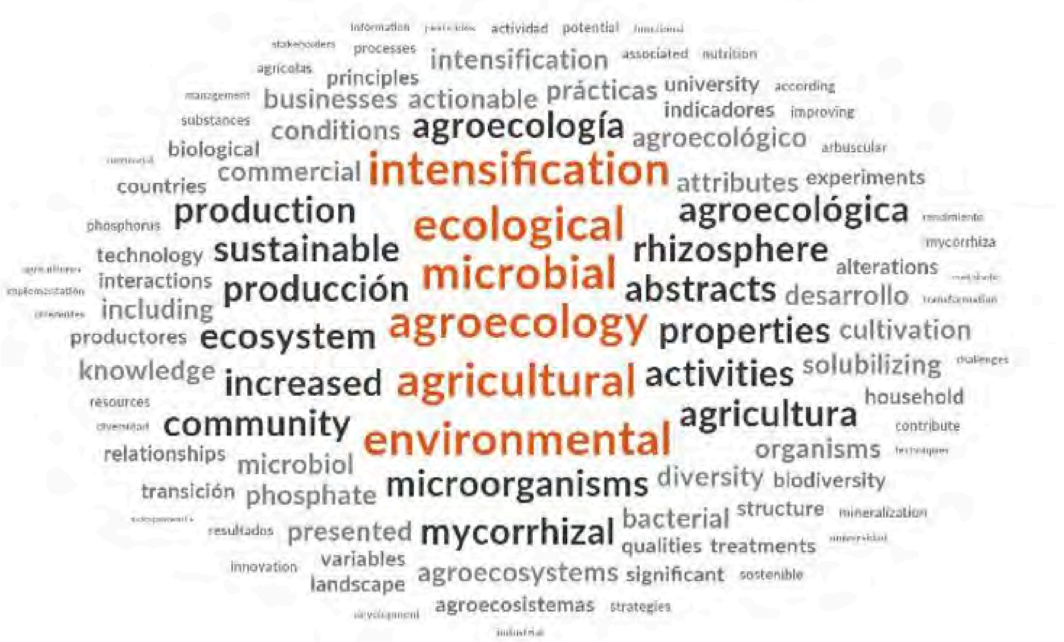

Figure 1 shows the words of a length of at least nine characters most representative in the sample of scientific information selected, which shows the relationship that exists in the bibliographic collection with respect to the objective of this work. Of the total articles analyzed in the Nvivo software, only 12 (Table 1) relate the keywords: 1) intensification; 2) ecological; and 3) microorganisms.

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Table 1. Documents that addressed topics related to the keywords intensification, ecological, and microorganisms.

Authors	Title
Gaba *et al*. (2014)	Managing biotic interactions for ecological intensification of agroecosystems
Giagnocavo *et al*. (2022)	Reconnecting farmers with nature through agroecological transitions: interacting niches and experimentation and the role of agricultural knowledge and innovation systems
Altieri *et al*. (2017)	Technological approaches to sustainable agriculture at a crossroads: an agroecological perspective
Omotayo and Babalola (2021)	Resident rhizosphere microbiome's ecological dynamics and conservation: towards achieving the envisioned sustainable development goals, a review
Bajsa *et al*. (2013)	The effect of agricultural practices on resident soil microbial communities: focus on biocontrol and biofertilization
Bargaz *et al*. (2018)	Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system
Trivedi *et al*. (2016)	Response of soil properties and microbial communities to agriculture: implications for primary productivity and soil health indicators
Montoya *et al*. (2022)	Beneficial microorganisms in sustainable agriculture: harnessing microbes' potential to help feed the world
Santoyo *et al*. (2021)	Plant growth stimulation by microbial consortia
García (2015)	Agriculture in the Southern Cone, what is known, what is left to know?
Lozano *et al*. (2015)	Arbuscular mycorrhiza-forming fungi and their effect on soil structure in farms with intensive agroecological management
Creus (2017)	Microbial inoculants: pieces of a puzzle that still needs to be assembled

In this sense, it can be stated that despite the relationship that exists between ecological processes in agriculture and soil microorganisms, it is visualized that of the 203 publications, only 5.9% relate ecological intensification processes with the use of soil microorganisms. The rest had a majority focus on the importance for soil health, comparison with other technologies (conventional and sustainable intensification), crop association and rotation, biodiversity, and carbon sequestration, among others.

Ecological agriculture, according to Trivedi *et al*. (2016), is based on improving the ecosystem services provided by biodiversity, these depend on the degree of (agro)biodiversity at the field, farm, and landscape level, and they call it biodiversity-based agriculture, while other authors call it 'ecologically intensive agriculture'. Its main objectives are to reduce negative environmental impacts and raise production limits of production-oriented agriculture, and it is known as 'efficiency/substitution-based agriculture', while others call it 'ecological intensification'. Through the meta-analysis, this study shows the relationship between eco-intensification, as a synonym for 'ecological intensification', with the ecosystem processes of agroecosystems, specifically with soil microorganisms.

Figure 2 and Table 2 show the results of the multivariate analysis of clusters (the farther apart the elements, the less related they are) and Pearson's correlation coefficients (coefficients close to one indicate a strong relationship between the variables and values close to zero indicate that there is no relationship between the two variables; values less than 0 indicate negative association), these indicate that there is a non-significant relationship between the studies that address the topic of intensification in agriculture with important components in agroecosystems,

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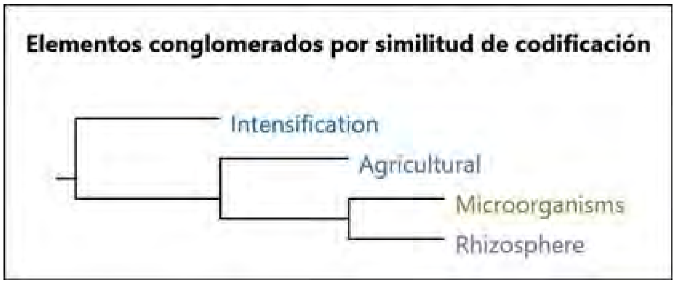
such as microorganisms present in the rhizosphere, according to the documents analyzed. This shows that there is a niche for research and intensive agricultural production based on maximizing ecological processes with soil microorganisms in agroecosystems.

Figure 2. Diagram of the cluster analysis of the topics analyzed level 3.



The correlation according to the Pearson test (Table 2) indicates that the relationship between codes is not significant, with a degree of significance of $p \leq 0.05$; in the case of the relationship of the Rhizosphere code with Intensification, there is a significant relationship; nevertheless, it is negative, which allows us to understand that the publications address the topics with an inversely proportional relationship.

Table 2. Pearson's correlation coefficient between the topics analyzed. To analyze the relationships that exist between the nodes.

Code A	Code B	Coefficient
Rhizosphere	Microorganisms	0.58
Microorganisms	Intensification	0.18
Microorganisms	Ecological	0.16
Rhizosphere	Intensification	-0.005
Agriculture	Intensification	0.17

Significance level ($p \leq 0.05$).

These results allow the publications to be separated into three thematic axes: 1) ecological intensification or eco-intensification (EI) of agricultural systems; 2) potential of soil microorganisms in eco-intensification; and 3) ecosystem services provided by microorganisms in eco-intensified agricultural systems.

Eco-intensification (EI) of agricultural systems

The term 'ecological intensification' is relatively recent, and there is still no generally accepted meaning (Gaba *et al*., 2014). As a synonym, eco-intensification (EI) refers to the use of ecological processes to increase productivity in agricultural production systems simultaneously with ecosystem services (García, 2015). In this sense, Aubin *et al*. (2019); Giagnocavo *et al*. (2022) declare that EI is a new concept in agriculture that addresses the double challenge of maintaining a level of production sufficient to meet the needs of human populations while respecting the environment to conserve the natural world and the quality of human life.

This concept is used by institutions such as FAO (2011), which, since that year, declared the importance of the paradigm shift in agricultural intensification processes, and authors such as González *et al*. (2020), who confirmed the importance of intensification to promote sustainability in agricultural systems.

Other authors Gaba *et al*. (2014); Lal (2019) define EI as the intensification of biological processes that sustain ecosystem services in the medium term (efficiency of management

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options) and the long term (sustainability of management options). While for Xie *et al*. (2019), EI is understood as a means to increase agricultural production (food, fiber, agrofuels, and environmental services) while reducing the use and need for external inputs (agrochemicals, fuels, and plastics), capitalizing on the ecological processes that sustain and regulate primary productivity in agricultural agroecosystems. Lal (2019) emphasizes that EI was designed to restore soil organic carbon (SOC) and soil inorganic C (SIC) stocks of degraded soils.

It should be noted that other forms of intensification have been studied, such as sustainable intensification (SI) (González *et al*., 2020). Where there are notable differences in concepts, management, productivity, and environmental impact, but it is not the objective of this paper to highlight the differences between these terms and forms of production (Lal, 2019).

However, agroecosystems must also be relevant for climate change adaptation and mitigation, the improvement of water quality and renewal capacity, the improvement of biodiversity, and the advance in achieving the United Nations SDGs (Lal, 2019). The needs to maximize food production per unit area and meet other demands of the increasingly prosperous society must be met by adopting land-use and soil/crop/animal management systems that also restore the health of the soil and other natural resources.

Eco-intensification manages the agricultural system but with a priority on ecological processes in the agroecosystem and emphasizes the systems approach, in addition to strongly considering social and cultural perspectives. Rather than an objective *per se*, eco-intensification seeks to become a necessary process to achieve the broader objectives of agroecology: food security and sustainability (Altieri *et al*., 2017; Bargaz *et al*., 2018).

At this point, it is appropriate to define that agricultural eco-intensification is considered to be characterized by its system approach, addresses the benefits derived from ecological processes, and considers socioeconomic relations in its management. It is pertinent to mention that it will allow the increase of the efficiency of the existing natural resources according to the socio-ecological characteristics of the system.

As common agricultural practices, organic waste is recycled and incorporated into the system, the use of chemical inputs is balanced with organic inputs, intensive use of the soil is made in time and space (rotation strategies and crop associations), the most suitable crops and varieties to promote according to the consumption and edaphoclimatic characteristics of the regions are identified while enhancing native species; water use is optimized (efficient irrigation techniques), integrated pest and disease management strategies are promoted and productive diversity in agroecosystems is achieved.

An important component of most agricultural production systems are soil microorganisms for all the benefits (biochemical transformations, nutrient cycles, production of antibiotics and vitamins, etc.) they provide, so introducing this component in eco-intensification production approaches will be a fundamental factor to achieving sustainability since they provide an important accumulation of benefits in these systems.

Understanding the biogeochemical processes that occur in the soil, especially in the rhizosphere, is essential to analyze the variations that exist in the soil, such as those induced by nutrient cycles, biological dynamics, and soil-plant relationships, and thus be able to manage crop systems in order to optimize existing resources and maximize the outputs of agroecosystems.

Potential of soil microorganisms in eco-intensification

EI is a system based on agricultural production and sustainable management of soil quality and functionality. Nevertheless, to achieve this, it is vital to understand the microorganism-soil-plant relationships that are becoming more relevant every day since the functionality of agroecosystems is essential for human well-being as there are beneficial relationships that can be used to optimize agricultural production (Bajsa *et al*., 2013; Omotayo and Babalola, 2021). These contributions that nature provides to human society are known as ecosystem services (ESs).

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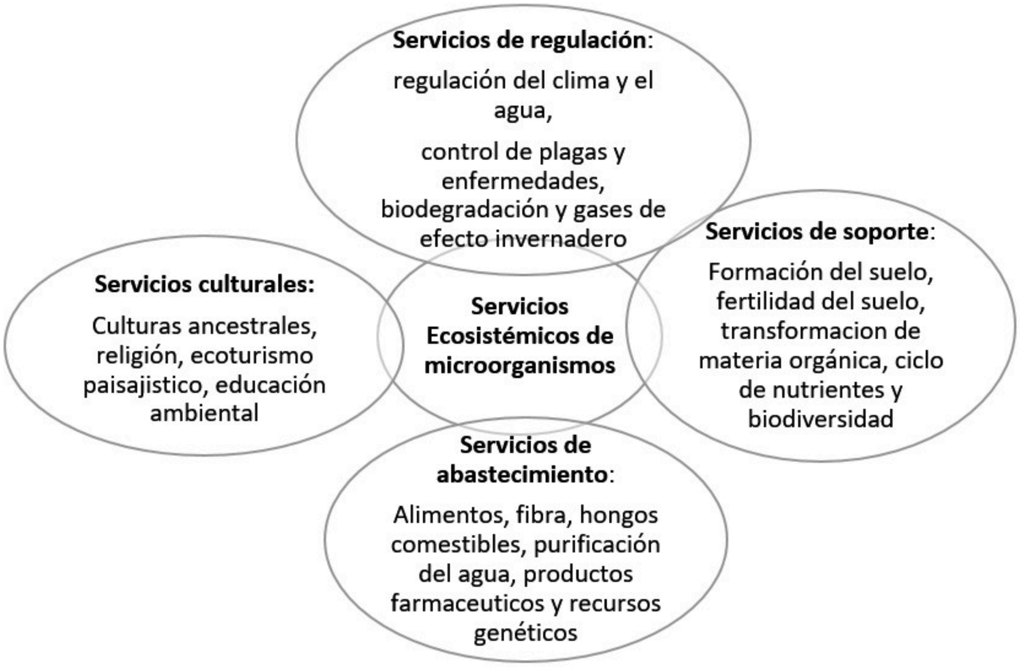
According to Rojas and Hernández (2021), ESs integrate tangible and intangible benefits derived from nature for the benefit of human beings and that, according to certain criteria, can be economically valued for their conservation and management. Saccá *et al*. (2017) established that ESs originate from the interaction of biotic and abiotic processes in the agroecosystem.

Therefore, it is essential to understand the ecosystem benefits that soil microbial activity can provide in agroecosystems. Soil microorganisms play several key regulatory roles in biogeochemical cycles, soil fertility, and resilience. They increase the density of nutrients by the decomposition of organic matter or by the solubilization of elements. Because of this, these microorganisms are called functional groups (Thiour *et al*., 2019; Ayan *et al*., 2021).

It is recognized that the functional diversity of soil microorganisms can improve the stability of agroecosystems and the provision of ecosystem services, but there is a need to link existing knowledge on understanding the functionality of agroecosystems in the rhizosphere to fully explain the connection between diversity, stability, and function in agricultural systems (Santoyo *et al*., 2021). In a general sense, Figure 3 specifies the main ecosystem services to which soil microorganisms contribute.

Figure 3. Main ecosystem services provided by soil microorganisms. Modified from Saccá *et al*. (2017); Chen *et al*.(2019).



Ecosystem services provided by microorganisms in eco-intensified agricultural systems

The meta-analysis allowed us to identify 12 publications corresponding to 5.9% of the total analyzed, which deepen the importance of soil microorganisms in eco-intensified agricultural systems to provide ecosystem services; the main ecosystem services with their respective authors are shown below.

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Regulatory ecosystem services

Climate regulation

Climate regulation is one of the most important ecosystem services provided by soil microorganisms, as bacteria and fungi play a key role in the exchange of carbon (C) between land and the atmosphere. On the other hand, the temperature-induced acceleration of heterotrophic microbial activity rates generates positive feedback on climate change (Cavicchioli *et al*., 2019).

Water purification and bioremediation

The soil acts as a purifying filter for water by passing through the unsaturated zone and storing it for plants. Some microorganisms participate in the purification of water as it passes through the soil, which is mainly due to their ability to degrade various contaminants through bioremediation (Lin *et al*., 2021).

Pest and disease control

The microorganisms that inhabit terrestrial ecosystems play a primary role in maintaining ecosystem health. Among this microbiota, a particular set called plant growth-promoting microorganisms (PGPM) were found, which directly or indirectly favor vegetative growth, generate tolerance to abiotic and biotic stress in the plant, facilitate plant nutrition, and antagonize phytopathogens in host plants. Among the most studied microbial genera of this group are: *Pseudomonas*, *Enterobacter*, *Bacillus*, *Variovorax*, *Klebsiella*, *Burkholderia*, *Azospirillum*, *Serratia*, *Azotobacter* and *Trichoderma* (Valenzuela *et al*., 2020).

Ecosystem support services

Soil formation

Lozano *et al*. (2015); Heredia (2020) mention that soil aggregates are structural units between elementary particles formed through abiotic and biotic interactions. Among the biotic components that interact are roots, fungi (saprophytes and mycorrhizal), mesofauna, and bacteria. Some of these fungi not only participate in this process but also intervene directly and indirectly in various aspects of soil formation and structure and in the formation of habitats for other species and in the nutrient cycle.

Soil fertility

Microorganisms are key players in many ecosystem processes, including improving soil fertility. They mediate biogeochemical cycles for the availability of soil mineral nutrients, such as nitrogen, phosphorus, and sulfur, which are the main nutrients that promote plant growth, use organic carbon as an energy source to drive the recycling process and also decompose organic matter to maintain soil fertility, favoring the growth and sustainable productivity of plants (Basu *et al*., 2021).

The use of microbial inoculants is usually a profitable practice for the farmer, which is achieved using inoculants of proven activity and purity that ensure an adequate specific number by species, guaranteeing quality and, therefore, confidence. Because of this potential of soil microorganisms, their optimal management would be greatly beneficial in agricultural EI processes, which implies the need for further research on the benefits and costs of using microbial inoculants in EI to encourage their adoption.

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Conclusions

Only 5.9% of the total publications analyzed highlight the importance of soil microbiology in agricultural eco-intensification; this opens a new line of research, which is the study of the potential of soil microorganisms and the impact of ecosystem services on eco-intensified agricultural systems.

The strengthening of soil microorganisms as an element of eco-intensification undoubtedly represents a niche to improve agroecosystems' ecology, productivity, and profitability, taking advantage of and maximizing the ecosystem services they offer.

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