Original Article

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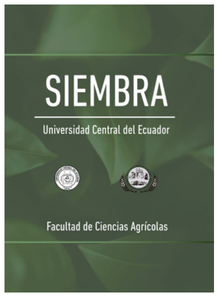

Hongos asociados al cultivo de banano (Musa spp.) con potencial biotecnológico para el desarrollo de inoculantes

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Abstract

Bananas are the most widely consumed tropical fruit worldwide. Its production is an important source of economic income in Latin American and Caribbean countries. Recently, banana crops have been affected by the attack of overly aggressive pathogens such as *Fusarium oxysporum* and *Mycosphaerella fijiensis*. Chemical control is a widely used strategy, which has led to the excessive use of agrochemicals in banana production. There is great concern worldwide about the state of banana crops, which makes environmentally friendly alternatives necessary to cope with the actual threats. Ecuador is one of the main banana producers in the world, so it is essential to innovate production systems by implementing biologically sustainable alternatives to minimize environmental impacts and warranty productivity. This review aims to consolidate key information on banana-associated fungi, including isolation and introduction techniques of endophytic fungi. Finally, relevant research on biotechnological strategies based on endophytic and mycorrhizal fungi to improve banana production is included. We expect this review will provide insights into experimental investigations in the design of fungal inoculants.

Keywords: banana, production, sustainable crops, endophytic fungi, mycorrhizal fungi.

Resumen

El banano es la fruta tropical de mayor consumo mundial. Su producción es un importante ingreso económico en países de Latinoamérica y el Caribe. Recientemente, el cultivo de banano se ha visto afectado por el ataque de patógenos muy agresivos como *Fusarium oxysporum* y *Mycosphaerella fijiensis*. El control químico es una estrategia ampliamente utilizada, que ha llevado al uso excesivo de agroquímicos en la producción bananera. Existe una gran preocupación mundial por el estado de los cultivos de banano, siendo necesario encontrar alternativas amigables con el medio ambiente. Ecuador es uno de los principales productores de banano en el mundo, por lo que es fundamental innovar el sistema de producción mediante la implementación de alternativas biológicamente sostenibles para minimizar el impacto ambiental y garantizar la productividad. La presente revisión pretende consolidar información clave sobre los hongos asociados al banano, incluyendo técnicas de aislamiento e introducción de endófitos. Finalmente, se incluyen investigaciones re-

levantes sobre estrategias biotecnológicas basadas en hongos endofíticos y micorrízicos para mejorar la producción de banano. Nuestro objetivo es que esta revisión proporcione información para la investigación experimental en el diseño de inoculantes fúngicos.

Palabras clave: banano, producción, cultivos sostenibles, hongos endófitos, hongos micorrízicos.

1. Introduction

1.1. General information on bananas

1.1.1. Characteristics of the banana tree

Musa spp. (banana) is a group of perennial herbaceous plants belonging to the Kingdom Plantae, class Angiosperma, subclass Monocotyledon, order Zingiberales, family Musaceae, genus Musa (Sabio et al., 1999). Banana comes from Southeast Asia, normally cultivars are the product of natural hybridization between two species: *Musa balbisiana*, native to the east coast of India, and *Musa acuminata*, native to Thailand, Malaysia and Myanmar (Mejía Calderón, 2018).

The banana plant consists of a pseudostem, leaves, inflorescence, fruits and root. The pseudostem is formed by a set of overlapping leaf sheaths that can reach 3 to 6 m in height. The leaves are large, approximately 2 to 4 m long by 0.50 m wide. The leaves' size allows to determine the stage in which the crop is, depending on the shapes presented by them (Mejía Calderón, 2018). Additionally, the inflorescence presents a complex structure supported by a true stem, located in the highest part of the pseudostem. It has female flowers from which the fruit clusters emerge, and -as they develop-, the distal portion of the inflorescence becomes male flowers, producing fertile or infertile pollen (Vézina & Baena, 2020).

The fruit is an elongated, curved berry approximately 10-15 cm long. The skin is thick, smooth, and green, yellow or red in color, depending on the variety (Infoagro, 2022). Each 100 g of ripe, fresh fruit contains: water (~74 g), protein (~1.1 g), total lipids (~0.3 g), carbohydrates (~21.8), dietary fiber (~2.0 g), sodium [Na] (~1.0 mg), potassium [K] (~385.0 mg), calcium [Ca] (~8.0 mg), magnesium [Mg] (~30 mg), phosphorus [P] (~22 mg), iron [Fe] (~0.42 mg), copper [Cu] (~0.11 mg), zinc [Zn] (~0.18 mg), manganese [Mn] (~0, 2 mg), β-carotene (~68.0 µg), vitamin E ~0.29 mg), vitamin C (~11.7 mg), thiamine (~0.04 mg), riboflavin (~0.07) and niacin (~0.61 mg) (Casallas Malaver, 2010), the amount of nutrients will depend on the type of genome, variety, altitude and climatic conditions of the crop (Blasco López & Gómez Montaño, 2014; Dipta et al. , 2021; Kookal & Thimmaiah, 2018).

Moreover, the root supports the plant and allows water and nutrients to be transported through the root hairs toward the entire plant structure. The root system consists of primary, lateral, secondary and tertiary roots, whose number depends on the limitations and damage caused during the growth process. Under normal conditions, banana roots can reach 5 to 10 m in length, this allows the plant to take up a greater volume of soil (López & Espinoza, 1995). The nutrients absorbed in large quantities through the banana root system are: K, P and nitrogen [N]; while, Mg, Ca, Zn, Fe, Cu, Na, sulfur [S], boron [B], molybdenum [Mo] and chlorine [Cl] are absorbed in smaller quantities (Turner & Rosales, 2003).

1.1.2. Banana growing worldwide

Banana is the fourth most important exported fruit worldwide, its cultivation covers approximately 5,029,997 ha, with more than 1,000 banana varieties worldwide (Ancasi-Espejo et al., 2016), representing 20.2 million tons of annual exports (Food and Agriculture Organization of the United Nations [FAO], 2020). Its production is mostly concentrated in African countries (73%), Latin America and the Caribbean (25%), while only 2% is found in Asian nations. In Latin America and the Caribbean, specifically, the largest banana producers are Ecuador, Colombia, Panama, Venezuela, Costa Rica and Peru (Ancasi-Espejo et al., 2016).

Ecuadorian bananas are particularly recognized worldwide for their quality and flavor. Their export represents the country's third highest income, after oil and shrimp (Banco Central del Ecuador [BCE], 2021). Banana exports represent 2% of the national GDP (Ministerio de Comercio Exterior, 2017). International demand is such that 30% of the bananas consumed in the world come from Ecuador, consolidating this country as one of the main banana producing and exporting countries worldwide (Fierro Ulloa & Villacres Rojas, 2014).

During 2020, the banana plantation area in Ecuador was 160,600 ha. The cultivated areas at the national level are mainly distributed in coastal provinces such as Los Ríos, El Oro and Guayas, which account for 86.0% of national exports, while in the Andean region banana plantations account only for 9.7%. The most popular and most exported varieties in Ecuador are Cavendish, baby banana and red banana, the latter being the variety of great demand in the international market, because of its size, color and flavor (Instituto Nacional de Estadísticas y Censos [INEC], 2020).

The main regions and countries where Ecuadorian bananas are exported are the European Union (27%), Russia (20.13%), Middle East (13.89%), United States (9.96%), Southern Cone (6.79%), Eastern Europe (6.89%), Africa (6.72%), East Asia (5.30%), United Kingdom (1.28%), Oceania (0.91%), and Norway (0.47%) (Asociación de Comercialización y Exportación de Banano [ACORBANEC], 2021).

2. Fungal-plant relationship

2.1. Soil micro-ecology

Soil is a complex mixture of minerals, organic matter, water and living organisms (van Konijnemburg, 2006). Its quality plays a fundamental role in maintaining the balance between carbon dioxide [CO_2] production and consumption in the biosphere (Garcia de Salamone, 2011). As part of living organisms, microbial communities are the most important functional component of soil biota (Orduz Tovar et al., 2021), as they participate in the decomposition of organic matter, fixation of atmospheric N2, mineralization of organic N-, solubilization of P and S (Garcia de Salamone, 2011). In addition, microorganisms collaborate in the production of antibiotics and formation of symbiotic associations to improve nutrient absorption in plants, protection of plants against pathogens and decomposition of pollutants, among others (Pfenning & Magalhães de Abreu, 2012).

The presence or absence of edaphic microflora is a useful biological marker to evaluate the general state of the soil (Silberman et al., 2013). The product of the metabolic process of these microorganisms on organic matter is related to the optimum physicochemical conditions of the soil (Ramos & Zúñiga, 2008). That is, changes in the structure and function of the microbial community are linked to the alteration of the terrestrial system, as a result of the emission of greenhouse gases (CO2, NO or N2O) and the loss of nitrogen by leaching (García de Salamone, 2011). Therefore, on many occasions soil microorganisms determine the availability of nutrients, being considered as tools for soil management and plant nutrition (Murillo Cuevas et al., 2019).

The presence of microorganisms in the soil is variable; thus, microbial diversity decreases at greater depth. Similarly, microbiological communities vary among soils, specifically due to differences in the amount and type of organic matter, pH, climatic factors, vegetation, nutrient availability and mineralogy (Osorio-Vega, 2009).

It is estimated that 10^6 to 10^8 bacteria, 10^6 to 10^7 actinomycetes, 10^4 to 10^5 fungi, 10^3 to 10^6 algae, and 10^3 to 10^5 protozoa can be found in one gram of dry soil (Osorio-Vega, 2009). Although the most abundant microorganisms in the soil are bacteria, fungi, due to their larger size, represent ~70% of the biomass (Calvo Vélez et al., 2008).

Fungi play various roles in the ecosystem, according to the environment in which they grow they can be: saprophytes responsible for transforming organic and inorganic matter (Barrios & Sandoval, 2018); parasitic fungi, which cause damage to the host (cell death); mutualistic symbiont fungi that associate with other organisms for a balanced benefit, without causing any immediate negative effect (lichens, endophytes, mycorrhizae) (Lutzoni et al., 2004; Marín, 2018).

2.2. Endophytic fungi

Endophytic fungi are filamentous fungi associated with most plant species, distributed from the Arctic to the tropics, both in natural ecosystems and in modified ecosystems (agricultural fields) (Cepero de García et al., 2012; Paris, 2016). They are localized in intercellular and intracellular spaces of plant vascular bundles (Giusiano et al., 2019). The largest proportion of this group belongs to the phyla Ascomycota, Basidiomycota, Zygomycota and Glomeromycota (Sánchez-Fernández et al., 2013).

Depending on their role in the ecosystem, endophytic fungi are organized into decomposers, parasitic and mutualistic (Giusiano et al., 2019). This will depend on the environmental and genetic conditions of both the fungus and the host plant. In the case of pathogenic microorganisms, they remain unexpressed in the plant until environmental conditions are favorable to induce disease. While saprophagous fungi absorb nutrients from the host until they cause its death (Silva-Valenzuela et al., 2020). On the other hand, mutualistic fungi are characterized by having a symbiotic relationship with the host plant. That is, plant provides photosynthates from photosynthesis to the fungus (Sánchez-Fernández et al., 2013). Meanwhile, endophytic fungi produce secondary metabolites to induce plant growth, increase tolerance to abiotic factors (water stress, salinity, drought, high temperatures), and favor the solubilization and mineralization of organic and inorganic P, zinc (Zn), among others (Abello & Kelemu, 2006; Hobbie & Horton, 2007; Peteira Delgado et al., 2021; Wang et al., 2014).

Plant protection by mutualistic endophytic fungi occurs through direct (enzyme production), indirect (strengthening host defenses) and biological (occupation of the ecological niche) mechanisms (Aragón & Beltrán-Acosta, 2018; Pulido Agudelo & Nino Moreno, 2015). It is important to note that the fungus-plant antagonist relationship will depend on the infective capacity of the fungus, plant status, environmental factors and stage of development of the organisms involved (Salgado Salazar & Cepero de García, 2005).

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2.3. Mycorrhizae

The term mycorrhiza was coined in 1885 by the German biologist Albert Frank, from the Greek *mycos* which refers to fungus and the Latin *rhiza* which means root (Grageda-Cabrera et al., 2012). Mycorrhiza is defined as the association between soil fungi and plant roots (Smith & Read, 2008, Villegas Ríos & Cifuentes, 2004).

Mycorrhizae are classified according to the fungal species that interacts with plants and the nutritional strategy of the fungus (Honrubia, 2009). The most relevant groups are ectomycorrhizas that act by forming a mantle on the root to penetrate the cells of the cortex, and arbuscular mycorrhizas that invade the root without the need to form a mantle (Camargo Ricalde et al., 2012), the latter group being the most predominant, since they have the capacity to establish a symbiotic relationship with approximately 80% of plant species (Camarena-Gutiérrez, 2012), as they contribute to nutrient absorption and disease resistance in plants (Sarabia Ochoa et al., 2010).

2.3.1. Arbuscular mycorrhizae

It is a mutualistic symbiotic relationship between fungi of the phylum Glomeromycota and the root system of vascular plants, such association occurs through the formation of arbuscules, mycelia, vesicles and branched absorbing structures in the external and internal part of the root cortex (Cuenca et al., 2007). Arbuscular mycorrhizal fungi [AMF] differ from necrotrophic pathogenic fungi because the former do not produce enzymes that degrade carbon compounds (Rillig et al., 2016).

Arbuscules are the most important structures of AMF because they are involved in nutrient exchange between the plant and the fungus (Cuenca et al., 2007). On the one hand, AMF help plants in the uptake of low mobility elements (P, Cu and Zn), in increased water absorption (Lovera & Cuenca, 2007), in protection against root pathogens, and also increase tolerance to heavy metals present in soil and extreme pH conditions (Belezaca et al., 2019). AMF also favor the transfer of nutrients between nearby plants through the formation of hyphal bridges (Barrera Berdugo & Rodríguez López, 2010). On the other hand, plants contribute approximately 20% of photosynthetic products to the fungus (Parniske, 2008).

3. Studies and biotechnological strategies for the utilization of endophytic fungi in bananas

3.1. Isolation methods of endophytic fungi associated with banana root

The isolation phase of endophytic fungi must have a precise surface disinfection stage of plant tissues to avoid unintentional isolation of epiphytic fungi (Sinno et al., 2020). Therefore, for the isolation of endophytic fungi from banana root, a sterilization method suggested by Pocasangre et al. (2000) is followed, which consists of washing the plant material with running water, followed by rinsing with a solution of sodium hypochlorite (5%) for 5 min, then washing the samples in triplicate with sterile water and allowing them to air dry on a sterilized paper towel, and finally peeling off the outer layer of the root with a scalpel. This method has been validated by multiple studies, being considered in many cases a traditional method for the isolation of banana endophytic fungi, despite the slight modifications that some authors have used (Cao et al., 2002; Méndez-Castillo et al., 2017; Nuangmek et al., 2008; Pocasangre et al., 2000; Savani et al., 2021; Ting et al., 2008; Xia et al., 2011; Zakaria et al., 2016).

Once the roots have been sterilized, the root is cut into fragments approximately 1-1.5 cm long and placed in Petri dishes with a solid medium specific for fungi, such as potato dextrose agar [PDA], supplemented with antibiotics. The isolates are left to incubate in the dark for several days at 25-30 °C. To verify the effectiveness of the sterilization procedure, aliquots of water from the final sterilization rinse are placed in Petri dishes with the same culture medium as a negative control, and in case of growth of microorganisms, the sample is discarded (Cao et al., 2002).

Zapata Henao et al. (2019) propose an alternative method of disinfection, which consists of placing the sample in an airtight container for 30 min in a gaseous atmosphere (chlorine gas, Cl_2), caused by the reaction of 100 ml of 6.25% sodium hypochlorite [NaClO] and 5 ml 37% hydrochloric acid [HCl]. The tissues obtained are seeded on PDA with 150 ppm streptomycin and incubated at 25 °C for 8-10 days to obtain pure isolates.

Tests contrasting the protocols of the traditional method proposed by Pocasangre et al. (2000) versus the alternative method of Zapata Henao et al. (2019) showed that sterilization with Cl2 is the most efficient method for removing contaminants from the root surface, since it was possible to obtain a greater heterogeneity of taxonomic groups of endophytic fungi than with the traditional method.

3.2. Banana endophytes

Over the last few years, several isolation and characterization studies of endophytic fungi associated with banana have been carried out in different regions of the world, succeeding in isolating and identifying different taxonomic groups of endophytic fungi through molecular techniques and/or morphological characters of pure cultures (Cao et al., 2002; Gnanasekaran et al., 2015; Méndez-Castillo et al., 2017; Nuangmek et al., 2008; Núñez-Trujillo et al., 2013; Pocasangre et al., 2000; Savani et al., 2021; Shitole et al., 2019; Souza Junior et al., 2018; Thangavelu & Gopi 2015; Ting et al., 2008; Xia et al., 2011; Zakaria et al., 2016; Zapata Henao et al., 2019). The results obtained from these investigations are shown in Table 1, considering the species with the highest frequency of occurrence.

3.3. Biotechnological strategies for banana cultivation

The increase in world population puts pressure on natural resources to meet food demand (Alori et al., 2017; Yadav et al., 2021). Specifically, in order to increase crop yields, the use of agrochemicals has been adopted (Ahmad et al., 2018). However the increasing and continuous application of these products have contributed to air pollution and to the deterioration of soil productive capacities (increased salinity and pH imbalance) (Adesemoye et al., 2017; Sharma et al., 2021). For this reason, innovative and environmentally friendly alternatives have been sought to reduce the use of chemical fertilizers (Guevara et al., 2014; Rashid et al., 2016). Within this context, microbial inoculation could be considered as a potential strategy to promote agricultural productivity and sustainability (Garcia et al., 2021).

Microbial inoculants are formulations based on one or several strains of live, soil-derived microorganisms (plant growth-promoting rhizobacteria, mycorrhizal fungi and rhizobia). Their application, either alone or in combination, on seeds, plants and soil, facilitates plant growth, improves crop adaptation and promotes resistance to environmental factors (drought). Additionally, they increase the nutrient availability of the host plant through biophysical and biochemical activities performed by these microorganisms on the soil surface (Alori et al., 2017; Jack et al., 2021; Restrepo Franco et al., 2015).

The development of biological inoculants, mainly those of fungal origin, require a specific procedure, since their functionality and persistence depend on the interaction with other organisms present in the rhizosphere (competition, parasitism, or cooperation), and the environment. Thus, correct methods and tools for isolation, formulation and subsequent administration must be taken into account (Pozo et al., 2021). Biotechnological strategies applied in soil management and associated organisms could contribute to crop sustainability (Bejarano Perona & Cano Vidal, 2007). According to, Rashid et al. (2016) endophytic fungi are capable of producing secondary metabolites, which promote plant growth and improve their resistance to abiotic and biotic factors.

In the case of banana, it has been confirmed that there is a great diversity of endophytic fungi, especially in the root (Gómez-Lama Cabanás et al., 2021). Despite this, Srivastava and Singh (2019) mention that, for the development of inoculants in banana, an initial evaluation of the mycorrhizal strain must be carried out to match the dose and type of inoculant appropriate for each crop of *Musa* spp. For this reason, Ochieno (2020) proposes a protocol for the analysis of endophytes in banana (Figure 1).

Table 1. Endophytic fungi isolated from bananas.

Species	Type of sample	Country of investigation	Identification technique	References
Aspergillus spp.	Corm Root Rhizosphere	Brazil China India Spain Thailand	Identification through morphological characters Molecular identification (rDNA)	Cao et al. (2002); Sikora et al. (2003); Núñez-Trujillo et al. (2013); Souza Junior et al. (2018); Shitole et al. (2019)
A. oryzae	Corm	Spain	Molecular identification (rDNA)	Núñez-Trujillo et al. (2013)
A. niger	Root	India	Identification through morphological characters.	Gnanasekaran et al. (2015); Shitole et al. (2019)
A. creneus *A. funiculosus* *A. itaconicus*	Root	India	Identification through morphological characters.	Gnanasekaran et al. (2015);
A. flavus	Corm	India Spain	Identification through morphological characters. Molecular identification (rDNA)	Gnanasekaran et al. (2015); Núñez-Trujillo et al. (2013)
A. versicolor	Leaf	Brazil	Molecular identification (rDNA).	Souza Junior et al. (2018)
Corndana sp. *Nodulisporium* spp.	Leaf Root	Thailand	Identification through morphological characters.	Nuangmek et al. (2008)
Chaetonium spp.	Corm	Spain	Molecular identification (rDNA)	Núñez-Trujillo et al. (2013)
Fusarium spp.	Corm Racquis	Colombia Spain Thailand	Molecular identification (rDNA)	Pocasangre et al. (2000); Sikora et al. (2003); Núñez-Trujillo et al. (2013); Méndez-Castillo et al. (2017)
Fusarium oxysporum	Root	India Malaysia Thailand	Molecular identification (rDNA)	Sikora et al. (2003); Ting et al.(2008); Zakaria et al. (2012)
Fusarium solani	Root Root	Malaysia Thailand	Molecular identification (rDNA)	Sikora et al. (2003); Zakaria & Rahman (2011)
Fusarium proliferatum *Rhizopus oryzae* *Rhizopus stolonifer* *Rhizoctonia solani*	Root	Malaysia	Molecular identification (rDNA).	Zakaria et al. (2012)
Hypocreales spp. *Nigrospora zimmermanii* *Peroneutypa scoparia*	Leaf	Brasil	Molecular identification (rDNA)	Souza Junior et al. (2018)
Penicillium spp.	Root Leaf Corm	España China	Molecular identification (rDNA)	Cao et al. (2002); Sikora et al. (2003); Núñez-Trujillo et al. (2013); Cosoveanu et al. (2016).
Penicillium radicum	Corm	Spain	Molecular identification (rDNA)	Núñez-Trujillo et al. (2013)

Species	Type of sample	Country of investigation	Identification technique	References
Penicillium solitum	Raquis	Colombia	Molecular identification (rDNA)	Méndez-Castillo et al. (2017)
Verticillium spp.	Corm Leaf	Colombia Honduras Guatemala	Identification through morphological characters	Zapata Henao et al.(2019); Pocasangre et al. (2000)
Trichoderma spp.	Corm Pseudostem	Colombia	Identification through morphological characters	Pocasangre et al. (2000); Zapata Henao et al.(2019)
T. asperellum	Root	China	Molecular identification (rDNA)	Xia et al. (2011)
T. atroviride	Root	Malaysia China	Molecular identification (rDNA)	Xia et al. (2011); Zakaria et al. (2016).
T. reesei	Root	India	Molecular identification (rDNA) Molecular identification (rDNA)	Savani et al. (2021)
T. viride	Root	India	Identification through morphological characters	Shitole et al. (2019)
T. harzianum	Root Root Corm Raquis	India Colombia	Microscopic identification and morphological characters Molecular identification (rDNA)	Thangavelu & Gopi (2015); Méndez-Castillo et al. (2017); Shitole et al. (2019)
T. koningii	Root Corm	India	Identification through morphological characters	Gnanasekaran et al. (2015); Thangavelu y Gopi (2015)
T. pseudokoningii	Root Corm	India	Microscopic identification and morphological characters	Thangavelu y Gopi (2015)

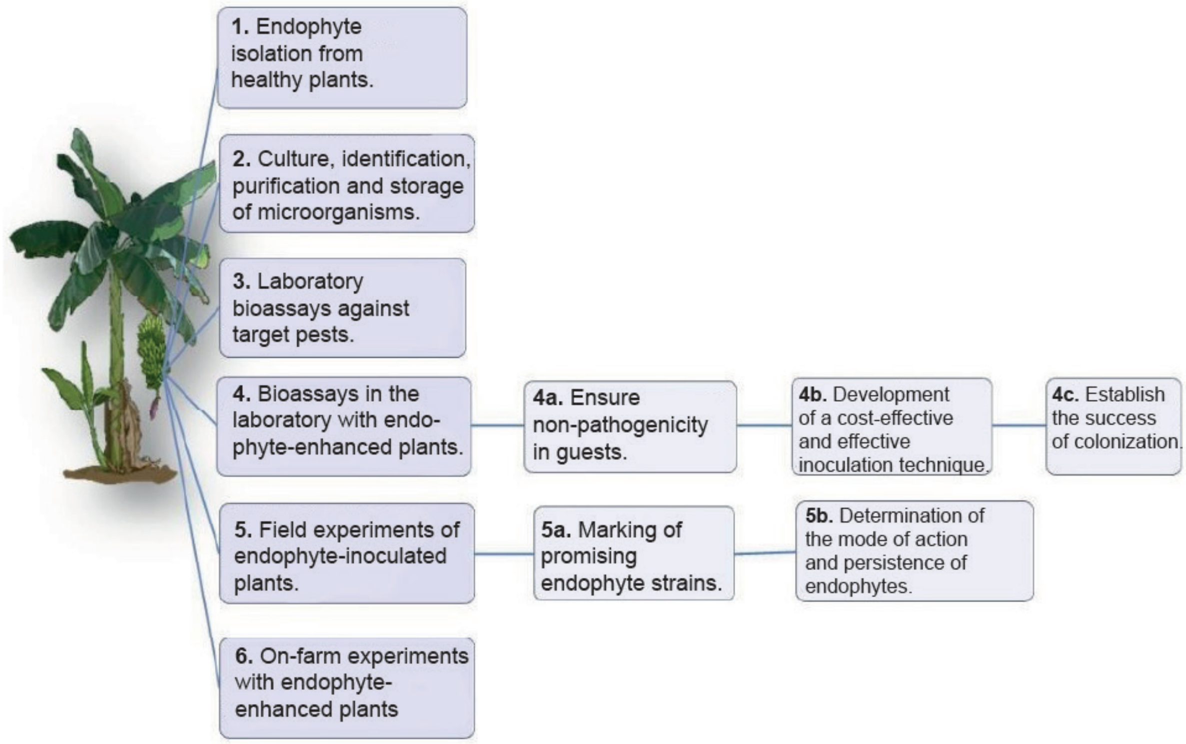

Figure 1. Research protocol for the development of inoculants from banana endophytic fungi (Adapted from Ochieno, 2020).

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3.3.1. Methods for the application of fungal inoculants in bananas

Colonization of endophytic fungi in banana crops can be done using inoculation techniques such as: foliar spraying, soil spraying, root dipping or injection (Vega, 2018).

Foliar spraying is based on the administration of a microbial formulation on leaves with appropriate spraying equipment (Preininger et al., 2018). Whereas soil spraying involves the application of conidial suspensions around the root zone of seedlings (Bamisile et al., 2018). The root dipping technique is based on breaking the banana root tip and dipping in a conidial suspension for a given time, prior to planting seedlings (Chaves et al., 2009). Finally, the injection process consists of applying a conidial formulation through a syringe into the banana pseudostem or corm (Ibarra, 2019; Kavino & Manoranjitham, 2018).

Akello et al. (2007) conducted a study for the introduction of *Beauveria bassiana* on banana, comparing three inoculation methods: root and rhizome immersion in a conidial suspension, injection of conidia into the plant, and inoculation of a mixture of conidia with solid substrate. It was shown that immersion of roots and rhizomes in conidial suspensions was the most suitable inoculation method for banana.

3.3.2. Benefits of the application of endophytic fungi in bananas

The application of fungal inoculants endemic to bananas such as: *Fusarium oxysporum*, *Paecilomyces lilacinus*, *Penicillium* spp., *Fusarium* spp., *Trichoderma harzianum*, *Trichoderma asperellum*, *Talaromyces pinophilus*, either alone or in combination, improve the development of Musa spp. (Castillo et al., 2019; Chaves et al. 2016; Dubois et al. 2004; Mwaura et al. 2010; Patel et al. 2021; Pérez Vicente et al. 2009; Ting et al. 2008). Several studies have reported that endophytic fungi isolated from Musa species have the potential to promote plant growth, and also improve disease resistance (Zapata Henao et al., 2019; Mwaura et al., 2010; Waweru et al., 2014).

Fusarium oxysporum has been shown to act as a biocontrol agent against eggs of *Cosmopolites sordidus* and *Radopholus similis* (Dubois et al. 2004). Likewise, the joint application of *F. oxysporum* and *Serratia marcescens* inhibited the accelerated wilt caused by *Fusarium oxysporum* f. sp. *cubense* race 4 (Foc R4T) infection, and promoted the development of healthy and diseased plants (Ting et al. 2008). Also, it has been shown that fungi such as *Paecilomyces lilacinus*, *Penicillium* spp. and *Fusarium* spp., from banana leaves deposited in the soil with the presence of Sigatoka, control the spread of the fungus *Mycosphaerella fijiensis*, due to its ability to take advantage of the chitin present in the pseudothecia of the pathogen (Carr-Rodríguez, 2009). Other studies have confirmed that a non-pathogenic strain of *Fusarium oxysporum* causes the death and paralysis of the endoparasite *Helicotylenchus multicinctus*, which causes superficial lesions of the banana root (Delgado Párraga, 2012; Mwaura et al. 2009). Individual administration of *Trichoderma harzianum* and *Trichoderma asperellum* in the root system and soil significantly reduced the incidence and severity of Foc TR4 (Chaves et al. 2016; Pérez Vicente et al. 2009). Likewise, the introduction of *T. harzianum* and arbuscular mycorrhizae acted as a biological control against Foc TR4, and significantly increased plant height, pseudostem diameter, and banana root weight (Castillo et al., 2019). Finally, the fungus *Talaromyces pinophilus*, isolated from the banana rhizosphere, decreased the presence of *Aspergillus niger* by secreting β-glucanase and chitinase, and stimulated the growth of banana plantations through the production of banana plantations through the production of siderophores, indole-3-acetic acid (IAA), and phosphate solubilization (Patel et al., 2021).

3.3.3. Benefits of Arbuscular Mycorrhizal Fungi (AMF) in Bananas

In recent years, several studies have been carried out focused on the introduction of AMF in bananas, to test its effects on crop yields. Some of these AMF have been isolated from asymptomatic banana plants, including *Rhizophagus irregularis* (formerly *Glomus intrarradices*), *Acualospora scrobiculata*, *Glomus* spp., *Glomus etunicatum*, *Gigaspora margarita, Funneliformis mosseae* (anteriormente *Glomus mosseae*) and *Glomus microcarpum* (Elsen et al., 2008; Gbongue et al., 2019; Lin et al., 2021; Oye Anda et al., 2015; Rufyikiri et al., 2000; Srivastava & Singh, 2019).

The introduction of *Rhizophagus irregularis* induced the resistance of *Radopholus similis* and *Pratylenchus coffeae*, reducing the presence of nematodes by up to 84% (Elsen et al., 2008). It delayed the symptoms caused by *M. fijiensis* (black Sigatoka) and significantly increased the presence of Si, P, and Ca in banana shoots and roots (Gbongue et al., 2019; Oye Anda et al., 2015). It strengthened the root cell wall through the production of lignin (Lin et al., 2021). In a similar fashion, water absorption in banana plants increased under aluminum stress (Rufyikiri et al., 2000). The application of *Acualospora scrobiculata* associated with *R. irregularis*, positively favored root development under conditions of water stress and the assimilation of photosynthates in the leaves, in addition to increasing the absorption of water and nutrients in bananas (Srivastava & Singh, 2019).

In a similar fashion, the introduction of *Glomus etunicatum* in conjunction with *Gigaspora margarita* intensified P, N and K levels in bananas (Mwashasha et al., 2011). Likewise, it has been shown that *G. margarita* promotes the growth of banana seedlings and promotes protection against FocR4T (Borges et al., 2007). On the other hand, the inoculation of *Glomus clarum* (native to bananas) and *G. etunicatum* in banana seedlings enhanced Ca concentration and tolerance to salt stress (Yano-Melo et al., 2003), while the addition of *Glomus* spp. and *G. proliferum* increased pseudostem height, leaf surface area, and root dry weight, and decreased root necrosis index (Declerck et al., 2002). Finally, the association of *Funneliformis mosseae* and *Glomus microcarpum* increased the content of foliar chlorophyll and nutrients such as N, P and K in bananas (Kammadavil Sahodaran et al., 2019).

4. Perspectives

Ecuador is one of the main banana producing countries worldwide (FAO, 2021). Bananas, like other crops, are not exempt from problems, limitations, and challenges. The application of chemical fertilizers and pesticides on a large scale has not changed over time in the Ecuadorian banana sector. Therefore, it is necessary to improve or renew strategies in the banana production system, implementing alternative technologies that involve biological processes, not only to reduce environmental impact, but also to increase productivity and minimize production costs (Dawson, 2016; Elbehri et al., 2015). After learning about the importance of microorganisms in various production systems, perception changed towards maintaining the productivity of the desired crops (Hazarika et al., 2015). As a consequence, in recent years, the inoculation of endophytic fungi as a biological strategy in agriculture is gaining interest in the scientific community (Yashavantha Rao et al., 2020). This is mainly due to the fact that the ability of fungi to promote plant growth, control pathogens, and increase resistance to stress (water and saline) has been widely proven (Ripa et al., 2019; Silva-Valenzuela et al., 2020).

It has been shown that bananas harbor a highly variable microbial community of fungi and bacteria (Gómez-Lama Cabanás et al., 2021). Despite this, to date, research focused on the inoculation of endophytic fungi in Musa spp. as a biotechnological strategy, is still very limited worldwide. A large part of these trials have focused mainly on biocontrol against pests ((Foc R4T, M. *fijiensis*) (Carr-Rodríguez, 2009; Castillo et al., 2019; Chaves et al., 2016; Gbongue et al., 2019; Pérez Vicente et al., 2009; Ting et al., 2008) and parasites (*R. similis*) (Dubois et al., 2004; Elsen et al., 2008). However, these studies have been carried out in vitro, so it is necessary to carry out field tests to understand the mechanisms that favor or hinder endophytic colonization in plants, particularly in adverse climatic conditions, and in this way design options that allow the optimal functioning of microorganisms in the growth, health and nutrition of bananas. Another little-explored application is the development of inoculants with endemic banana fungi that have a growth-promoting effect. Consequently, field studies and development of inoculants with potential for biotization are promising topics that open paths for innovation in the agricultural system and deserve to be investigated in more detail to take advantage of the potential of fungi associated with banana roots.

5. Conclusions

It was possible to collect relevant information on the isolation and characterization of endophytic fungi related to bananas with biotechnological potential, a large part of these studies have been carried out in various countries in Asia and Europe. Various studies have proven that bananas, mainly the roots, harbor a highly variable community of fungi, of which the genera Fusarium and Trichoderma are the groups with the highest appearance in bananas. In view of this, many studies with a biotechnological focus are aimed at the biocontrol of pests (Foc TR4, *M. fijiensis*) and parasites (*R. similis*), using bioinputs based on microorganisms.

Contributor roles

- Betty Peregrina Acaro Reyes: investigation, writing – original draft.
- Stefania Cevallos: conceptualization, validation, writing – review & editing.

Ethical implications

Ethics approval not applicable.

Conflict of interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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