CHAPTER
174

Endophytic fungi and their compounds of agronomic interest

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ABSTRACT
INTRODUCTION: Endophytic fungi are microorganisms that live inside plants for at least part of their life cycle without causing any harm. They can stimulate dormancy breakdown by producing metabolites that act on the embryo that stimulate seed germination and potentially growth promoters with symbiotic interactions between plants. The compounds produced have diverse effects, such as: stimulators of growth and development of plants, increased mineralization and availability of nutrients, producing stimulating compounds releasing phytohormones and breakdown of dormancy. MATERIAL AND METHODS: Selected several articles that were collected in the scientific databases in Portuguese and English. RESULTS AND DISCUSSION: Articles were selected for the elaboration of a table reporting the main compounds in the promotion of growth and breakdown of dormancy. CONCLUSION: Endophytes can contribute to the discovery of new biomolecules for various biotechnological applications and the development of sustainable agriculture.

Keywords: Endophytic fungi, Interactions, Metabolic, Plants, Agriculture

1 INTRODUCTION

New production alternatives to feed the world population and its livestock are becoming increasingly necessary with ecologically correct, economic and stable agropractices to ensure food security (POVEDA, et al., 2021; CHOUHAN, et al., 2022; BARON and RIGOBELO, 2022).

In this context, improving agricultural technologies and crop varieties has been the main driver for increasing agricultural productivity during the last century, but to ensure an environmentally sustainable and socially responsible food supply, the development of new agricultural practices that focus on minimizing soil environmental degradation, environmental pollution and the adverse effects of climate change is needed, basically, environmentally friendly biological strategies (IQ; EGIDI; LIU; KAUR; Singh, 2019). Plants interact with microorganisms at all trophic levels adapting to growth and there is symbiosis between them (YAN, Lu et al., 2019). These microorganisms may be beneficial to their host plants through mutualistic symbiosis (JIA, M. *et al*., 2016). Among the important microorganisms for sustainable agriculture we have endophytic fungi (BACON, 2000).

Etymologically, the term 'endophyte' means 'within the plant' (endon: inside, phyton: plant) (BARON and RIGOBELO, 2022). Endophytic fungi are microorganisms that reside inside the internal tissues in plants without causing damage to living plants (BACON, 2000).

Endophytic fungi can be classified according to their ecology, diversity with the mode of reproduction by sexual or asexual spores (BAMISILE et al., 2018). They can be strictly linked to plants and complete an important part or even their entire life cycle within plants (HARDOIM, et al., 2015).

Almost all vascular plants examined to date harbor endophytes that are believed to originate from the rhizosphere and phyllosphere and enter the host plant through natural openings or wounds (GRABKA, et al., 2022).

Successful colonization by endophytes depends on many variables, including plant tissue type, plant genotype, microbial taxon and strain type, and biotic and abiotic environmental conditions (HARDOIM, et al., 2015).

Also the recognition of the plant as a host requires the activation of virulence mechanisms for colonization and the triggering of the host's defenses by these events. As long as there is a balance in this interaction, the fungus survives on the nutrients of the host plant and, in return, offers benefits (BAMISILE et al., 2018).

Endophytes can infect host plants vertically and/or horizontally. In vertical transmission the systemically diffused fungus is passed to the descendants via seeds of the host plant. The transmission of the fungus carried out through spores of asexual and sexual origin is said to be horizontal (SAIKKONEN et al., 2004).

Endophytic fungi can be classified into four groups: (a) Class I are Clavicipitaceous fungi (resides in grasses with vertical transmittance), (b) Class-II-IV are non-clavicipitaceous fungi (Ascomycota and Basidiomycota), in which Class II endophytes inhabit roots, shoots, and rhizomes and transmit through seeds or rhizomes (i.e., both horizontally and vertically), (c) Class III inhabits leaves/shoots (transmitted horizontally), and (d) Class IV are ascomycetes typical, form conidia and reside in the roots (transmitted horizontally) of plants (RODRÍGUEZ et al., 2009; HARTLEY AND GANGE, 2009).

Fungal species release several secondary metabolites, including plant growth promoters (KADDES et al., 2019; YADAV, et al., 2023, SCHMALTZ, et al., 2023; QIN et al., 2023).

Endophyte fungi form mutualistic interactions and beneficial relationships with their host plants (RODRIGUEZ et al., 2009), which can not only stimulate plant growth, but also promote the accumulation of secondary metabolites in the plant (MURTHY et al., 2014). They can produce a wide range of compounds associated with defense, communication and interaction with host plants, nutrient absorption (BRADER et al., 2014). These carbon-based compounds are known as volatile organic compounds (VOCs) (KADDES et al., 2019).

Volatile organic compounds VOCs are hydrophobic organic molecules with low molecular weight (<300 Da) and high vapor pressure (≥0.01 kPa at 20 °C) (PAGANS; FONT; SÁNCHEZ, 2006). VOCs are typically secondary metabolites belonging to terpenoids, phenylpropanoids, benzenoids, fatty acids, and amino acid derivatives. Due to their small size and high vapor pressure, VOCs can diffuse easily through the atmosphere and soil (DUDAREVA, et al., 2006).

The bioactive potentials of endophytic VOCs include inter- and intraspecific signaling and synthesis of growth-promoting metabolites by host plants (GOMES et al., 2015).

The regulation of secondary metabolism in fungi is complex, involving multiple proteins and complexes that respond to various environmental and host stimuli. Major inroads have been made in understanding these processes in the model fungus, Aspergillus nidulans. The functional characterization of homologues of Aspergillus proteins such as LaeA in other fungi should lead to many discoveries. Recently detailed metabolic pathways have been constructed on a whole-genome scale for A. nidulans (DAVID, Helga et al., 2008).

2 MATERIAL AND METHODS

The present work, of a descriptive nature, was a bibliographic review, developed from the accomplishment of a bibliographic survey carried out with searches of articles in national and international journals, in databases and specialized sites (Google Scholar, SciELO, PubMed). That deals with endophytic fungi that can contribute to a more sustainable agriculture.

3 RESULTS AND DISCUSSION

The symbiosis of endophytic fungi largely promotes plant growth, producing several secondary metabolites (JAIN and PUNDIR, 2017).

They act as reservoirs of new bioactive secondary metabolites such as bezopyranones, alkaloids, phenolic acids, quinones, steroids, saponins, tannins and terpenoids. Due to the impact of endophytes on the host plant, increasing its growth or increasing its fitness (NAZIR and RAHMAN, 2018; MATHUR, et al., 2021).

And plant hormones such as gibberellins, jasmonates, abscisic acid and many others play a role in plant growth (STRANSKA, et al., 2022). Cosmopolitan endophytic fungi act as biostimulants to produce certain bioactive compounds, phytohormones, phosphate solubilization factors (VERMA, et al., 2022).

These microbial groups of plants have potential functions that can help with germination and growth (ZAMAN, et al., 2023).

Delgado-Sánchez, et al. (2010) tested the effects of four species of fungi *Penicillium chrysogenum,* Phoma *sp.*, *Trichoderma harzianum* and *T. koningii* on breaking the dormancy of *Opuntia leucotricha seeds that* have physiological dormancy. They detected that the seeds inoculated with the four fungi achieved the highest germination index than the control, opening new insights into the effect of fungi on the breakdown of seed dormancy.

The isolate FS2 (Talaromyces sp.) promoted the growth of several plant species such as Brassica campestris, Arabidopsis thaliana, Phaseolus vulgaris , Nicotiana benthamiana and Cucumis sativus, when it was applied, not only in the soil (in contact with the plants), but also when it was not in contact with the plants in the same plastic chamber. This last case means that the volatile compounds emitted by this fungus can participate in the promotion of plant growth (YAMAGIWA, et al. 2011).

The production of volatile compounds by these microorganisms results in a gain in plant mass, in addition to improving the nutrition and protection mechanism of these plants, as shown in Table 1 (LIU et al., 2015).

TABLE 1 - Secondary Metabolisms Produced by Endophytic Fungi

ENDOPHYTIC FUNGI	BIOACTIVE COMPOUNDS	FUNCTION	BIBLIOGRAPHIC REFERENCE
Talaromyces sp. nov.	b-cariofileno	Promotion of plant growth	YAMAGIWA, et al. 2011
Aspergillus carbonarius, *A. ochraceus*	2-phenylethanol	Vegetative Growth	Farbo,. 2018
Trichoderma sp.	6-pentil-2H-pyrane-2-one (6-PP)	alters root organogenesis by modulating ethylene signaling and auxin transport	Zin & Badaluddin, 2020
Laccaria bicolor	(-)-tujopseno	responsible for changes in the root architecture of plants	DITENGOU, Franck A. et al., 2015
Trametes gibbosa	1-octen-3-ol	semiochemical insects	Thakeow et al.,2008
Muscodor albus	1-butanol, 3-methyl-	Antimicrobials	STROBEL, et al., 2001
Induratia	Pyrimidine 2-chloro-4-ethyl-6-methyl-, Cycloactive, Tricycle[4.3.1.1(3,8)] undecan-3-methoxy-, 4-Amino-3,5-diethylpyridine, Imidazo [5,1-f][1,2,4]triazine-2,7-diamine, Dimethyl-[4-[2-(3-methylisoxazol-5-yl)vinyl]phenyl]amine, 4(1H)-Pyrimidinone, 2,3-dihydro-1-methyl-6-(4-pyridinyl)-2-thioxo-, 2-Phenyl-6-chloro-benzofuran, 1-Methyl-2-nitro-4-(1,2,2-trimethyl-cyclopentyl)-benzene	Biological control of toxicogenic fungi	GOMES, et al., 2023
Aspergillus niger	Benzoic acid	Promoting growth	MATHUR, Parikshana et al., 2023.
Geotrichum candidum	ethyl isovalerate, isoamyl acetate and 2-phenylethanol	Broad-spectrum bioactivity against stored grain pathogens	MITRA, et al, 2023.
Lasiodiplodia theobromae	β-resorcylic acid, (15 S)-O--methyllasiodiplodine, 1 , (14S , 15S) -14-hydroxy-of--Methyllasiodiploldine, 2 and 2,4-dihydroxy-6-(8-hydroxy-heptyl) ethyl benzoate	(bio-)herbicides	MACÍAS-RUBALCAVA; GARRIDO, 2022.
Aspergillus sp, Penicillium sp, Trichoderma sp, Chaetonium sp e Colletotrichum sp.	Dimethylamine, ethylamine, formamide and Formic acid, ethyl ester	Breakdown of dormancy of seeds of *Andropogon* L. grass	DE SOUZA FERREIRA, et al., 2023.

Source: Prepared by the authors

The use of endophytic fungi is an alternative of great potential in the areas of biocontrol, biostimulation and biofertilization (BARON and RIGOBELO, 2022).

In the emerging field of agriculture, fungal endophytes have been considered as potential "biostimulants" that can facilitate the commercial bioprospection of high-value secondary metabolites from upper and lower groups of cultivable and non-cultivable plants in the most sustainable and mutualistic way (DAS, et al., 2022; Adeleke et al., 2022; DE SOUZA FERREIRA, et al., 2023).

4 FINAL CONSIDERATIONS

This review denoted the importance that fungal microorganisms have for the interspecific relationship between microorganisms and plants. In this sense, find strategies to shape the endophytic microbiome for agricultural use in order to promote sustainability. Thus, endophytes have great potential for the bioprospection of sustainable compounds that can replace or mitigate the indiscriminate use of pesticides and chemical fertilizers with integrated practices aimed at the cultivation of plants important for Brazilian agriculture.

However, the need for research using genetic tools, the main genes involved in the biosynthetic pathways of VOCs can be identified and overexpressed for the large-scale production of these compounds that are abundant and have high genetic diversity, the identification and characterization of new VOCs for global sustainable development.

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