Foliar endophytic fungi as potential protectors from pathogens in myrmecophytic Acacia plants

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Abbreviations: PR-proteins, pathogenesis-related proteins; LB media broth, Luria-Bertani media; OD, optical density.

In defensive ant-plant interactions myrmecophytic plants express reduced chemical defense in their leaves to protect themselves from pathogens, and it seems that mutualistic partners are required to make up for this lack of defensive function. Previously, we reported that mutualistic ants confer plants of Acacia hindsii protection from pathogens, and that the protection is given by the ant-associated bacteria. Here, we examined whether foliar endophytic fungi may potentially act as a new partner, in addition to mutualistic ants and their bacteria inhabitants, involved in the protection from pathogens in myrmecophytic Acacia plants. Fungal endophytes were isolated from the asymptomatic leaves of A. hindsii plants for further molecular identification of 18S rRNA gene. Inhibitory effects of fungal endophytes were tested against Pseudomonas plant pathogens. Our finding supports a potential role of fungal endophytes in pathogen protection mechanisms against pathogens in myrmecophytic plants and provide the evidence of novel fungal endophytes capable of biosynthesizing bioactive metabolites.

Introduction

Plants have developed sophisticated direct defense mechanisms to deal with pathogen attack. In addition to constitutive barriers against pathogens, such as waxy epidermal cuticles and cell walls,1 plants can recognize invading pathogens and respond with inductive defenses, such as the production of reactive oxygen species,2 phytoalexins3 and pathogenesis-related (PR) protein accumulation.4 Moreover, plants can also engage the third trophic level as an indirect defense against pathogens. Recently, we found out that mutualistic ants nourished by mesoamerican Acacia plants serve to provide an indirect defense against leaf pathogens.5 And that plants would depend on the mutualistic ant partners to cope with the pathogen colonization. In addition, plants largely rely on their mutualistic interactions with microorganisms to overcome pathogen attack. Plant resistance to the pathogens commonly increases as a result of plant colonization with symbiotic microorganisms, including mycorrhizas,6,7 plant growth-promoting bacteria or fungi8 and leaf endophytic fungi.9 Thus, associations of plants with the multiple mutualistic partners occur recurrently and often provide benefits in plant protection from natural enemies.

In the obligate mutualistic interaction Acacia-Pseudomyrmex, Acacia myrmecophytic plants produce extrafloral nectar, food bodies and nesting space to house defending ants of Pseudomyrmex ferrugineus. In return, ants act as an indirect defense10 protecting plants from herbivory,11-13 pruning of neighboring plants11,13 or pathogenic microorganisms.5,14,15 Plants of the genera Acacia showed a reduced activity of PR proteins in their leaves15 which render them less able to defend themselves against pathogens. Thus, the questions how and to which extent ant-plants gain protection from microorganisms to compensate for the low abundance of PR-proteins in their leaves still remains open. Recently, we showed that the presence of mutualistic ants of P. ferrugineus on the host plant significantly reduced disease symptoms and bacterial abundance in the leaves of A. hindsii.5 Compounds secreted from the ant legs are involved in protection from pathogens in plants of A. hindsii. It seems that the ant-associated bacteria isolated from the ant legs contribute, at least partially, to the protective effect provided by mutualistic ants.5 However, other mechanisms could also be involved in the protection from pathogens in ant-Acacia plants. Chemical secretions produced by exocrine glands of the ants16 or leaf plant endosymbionts with potential inhibitory effects8 might also contribute to protection against pathogens.
The most abundant endophytes were Fusarium oxysporum and Colletotrichum gloeosporioides. Several fungal endophytes isolated from the leaves of A. hindsii have been already reported to be leaf endophytes, namely, the genus Phoma, and the species Fusarium oxysporum and Colletotrichum gloeosporioides. Inhibitory effects of the 9 morphospecies against Pseudomonas sp. (previously isolated from symptomatic leaves of A. hindsii) showed that the endophytes Colletotrichum gloeosporioides, Fusarium oxysporum, the yeast Moesziomyces bullatus and Pichia anomala were able to reduce the growth of Pseudomonas sp (Table 2). Further inhibitory bioassays showed that crude methanol extracts of the 3 most abundant endophytes were more efficient than ethyl acetate and hexane extracts (Table 2). Three methanol extracts of the above-mentioned fungal endophytes showed high antibiotic activity against the plant pathogenic bacterium Pseudomonas syringae (Fig. 1). Endophytes from the genera Colletotrichum, Phoma and Fusarium are known to be rich sources of biologically active secondary metabolites with antimicrobial activity against several pathogens. The endophytic yeast Moesziomyces bullatus was of particular interest to us as it showed the highest inhibitory effect in all our experiments and it has not been mentioned to be a plant endophyte elsewhere. Our results showed that fungal endophytes isolated from Acacia leaves might contribute through metabolites with antimicrobial activity to the protection from phytopathogens. In vitro, several studies have shown that endophytic fungi produce substances inhibiting the development of plant pathogens. Nevertheless, since the concentration of endophyte’s substances secreted in planta as well as the substantial contribution of the host plant on the in planta metabolic processes of the endophytes are unknown, it is necessary to assess in vivo the effects of fungal endophytes to their host plants.

Table 1. Identification of fungal endophytes isolated from asymptomatic leaf samples of 5 Acacia hindsii plants and their inhibitory effects against the bacterium Pseudomonas sp. The inhibition zone (mm) of Pseudomonas sp was quantified as the diameter of clear zones of growth inhibition around each endophytic fungus. Values are means ± SE (standard error) of 3 biological replicates. Dash (-) indicates no inhibition

| Endophytic fungi | Accession Number | Identity | Abundance | Pseudomonas sp. (Acacia hindsii isolate) |
|------------------|------------------|----------|-----------|-----------------------------------------|
| Cochliobolus geniculatus | JN941621.1 | 99 | 3 | — |
| Colletotrichum gloeosporioides | DQ916151.1 | 98 | 6 | 2.4 ± 0.3 |
| Colletotrichum truncatum | AJ301945.1 | 99 | 1 | — |
| Eupenicillium javanicum | JNS46126.1 | 100 | 1 | — |
| Fusarium oxysporum | KC143070.1 | 99 | 4 | 2.2 ± 0.1 |
| Moesziomyces bullatus | DQ831012.1 | 99 | 4 | 7.4 ± 0.4 |
| Paraphaeosphaeria sp | AB665311.1 | 97 | 1 | — |
| Phoma sp. | AY646226.1 | 99 | 2 | — |
| Pichia anomala | AB126679.1 | 99 | 1 | 4.1 ± 0.1 |

Here, we complement our research of the protection mechanisms in the ant-Acacia plants and provide information about the potential role of the leaf fungal endophytes as protectors from pathogens in this system.

Endophytes are microorganisms that live within host plant tissues and do not cause any apparent manifestation of disease, but rather co-exist in mutualistic association with plants for at least part of their life cycle. It is assumed that each plant in natural ecosystems hosts one or more endophytes. Plant leaves appear to be frequently infected by class II fungal endophytes, which comprise species from the phyla Ascomycota and Basidiomycota. In contrast to class I grass-fungal endophytes, class II endophytes are non-systemic, horizontally transmitted and colonize a wide range of plants in the ecosystems. Moreover, different species of class II fungal endophytes can co-occur in the same plant. Fungal endophytes may benefit host plants by promoting plant growth, improving tolerance to abiotic stress, or preventing herbivory and pathogen colonization. Endophytes have been recognized to be a novel source of bioactive compounds, because of their ability to produce a number of important bioactive secondary metabolites with antimicrobial activity that is often involved in protection from phytopathogenic microorganism.

In order to study whether asymptomatic leaves of A. hindsii are colonized by fungal endophytes, we isolated fungal endophytes by culture methods from leaflets of 5 plants of Acacia hindsii for further molecular identification of the 18S rRNA gene. Then, we tested the potential effects of A. hindsii fungal endophytes on the protection against leaf pathogens. A total of 23 isolates of endophytic fungi were obtained from the healthy leaves of A. hindsii and were identified as indicated in Table 1. The most abundant endophytes were Fusarium oxysporum, Colletotrichum gloeosporioides and the yeast Moesziomyces bullatus (Table 1). Several fungal endophytes isolated from the leaves of A. hindsii were already reported to be leaf endophytes, namely, the genus Phoma, and the species Fusarium oxysporum and Colletotrichum gloeosporioides. Inhibitory effects of the 9 morphospecies against Pseudomonas sp. (previously isolated from symptomatic leaves of A. hindsii) showed that the endophytes Colletotrichum gloeosporioides, Fusarium oxysporum, the yeast Moesziomyces bullatus and Pichia anomala were able to reduce the growth of Pseudomonas sp (Table 2). Further inhibitory bioassays showed that crude methanol extracts of the 3 most abundant endophytes were more efficient than ethyl acetate and hexane extracts (Table 2). Three methanol extracts of the above-mentioned fungal endophytes showed high antibiotic activity against the plant pathogenic bacterium Pseudomonas syringae (Fig. 1). Endophytes from the genera Colletotrichum, Phoma and Fusarium are known to be rich sources of biologically active secondary metabolites with antimicrobial activity against several pathogens. The endophytic yeast Moesziomyces bullatus was of particular interest to us as it showed the highest inhibitory effect in all our experiments and it has not been mentioned to be a plant endophyte elsewhere. Our results showed that fungal endophytes isolated from Acacia leaves might contribute through metabolites with antimicrobial activity to the protection from phytopathogens. In vitro, several studies have shown that endophytic fungi produce substances inhibiting the development of plant pathogens. Nevertheless, since the concentration of endophyte’s substances secreted in planta as well as the substantial contribution of the host plant on the in planta metabolic processes of the endophytes are unknown, it is necessary to assess in vivo the effects of fungal endophytes to their host plants.

Table 2. Inhibitory effects of methanol (MeOH), ethyl acetate (EtAc) and hexane extracts of the most abundant fungal endophytes isolated from Acacia hindsii (Fabaceae) tested on 2 bacteria Pseudomonas syringae (P.s) and Escherichia coli (E.c.). The inhibition zone (mm) of the bacteria was quantified as the diameter of clear zones of growth inhibition around each extract drop. Values are means ± SE (standard error) of 3 replicates. Dash (-) indicates no inhibition

| Endophytic fungus | Methanol extract | | Ethyl acetate extract | | Hexane extract | |
|-------------------|------------------|------------------|------------------|------------------|------------------|
|                   | P.s. | E.c.     | P.s. | E.c.     | P.s. | E.c.     |
| Colletotrichum gloeosporioides | 11.6 ± 0.24 | 12 ± 0.29 | 8.7 ± 0.21 | — | 3.5 ± 0.20 | — |
| Fusarium oxysporum | 7.1 ± 0.35 | — | 3 ± 0.20 | — | — | — |
| Moesziomyces bullatus | 13.5 ± 0.28 | 6 ± 0.20 | 6 ± 0.20 | — | — | — |
Although, it is still required to identify the substances produced by fungal endophytes in order to understand their contribution to Acacia plant protection, there is a potential for the selected endophytic fungi to produce novel bioactive compounds.

In summary, we showed that in addition to the protection mechanisms provided by the mutualistic ants and their bacteria inhabitants, foliar endophytic fungi might potentially act as a third partner involved in protection from pathogens in myrmecophytic Acacia hindsii plants. Plant-ant-fungus symbiosis has been already described in ant-plant mutualisms and it seems that mutualistic ants are responsible for the establishment and persistence of the fungus. The way how mutualistic ants shape the occurrence of endophytic fungi in Acacia leaves still requires further elucidation.

Material and Methods

Fungal endophytes were isolated from the healthy leaflets of 5 plants of Acacia hindsii according to the method described by Arnold et al. Small pieces of leaflets (2-3 mm) were placed on potato-dextrose-agar (Sigma-Aldrich). Petri plates were incubated at room temperature for several days, and the emerging colonies were subcultured to obtain pure isolates. Pure isolates were cultivated in LB media broth for 16 h at 37°C and then inoculated into LB media agar plates (100 μL of each culture bacteria with an OD₆₀₀ = 0.6 – 0.7 was used for 20 mL of agar plate). An agar slice (2 cm × 2 cm) of each fungal endophyte was placed in the center of Petri dishes containing the test bacteria. Inhibitory effects of endophytic fungi were quantified by the diameter (mm) of clear zones of growth inhibition around each isolate, which showed a good activity against the Pseudomonas sp isolate, have been extracted with 100 mL of methanol (MeOH), 100 mL of ethyl acetate (EtAc) and 100 mL of n-hexane for 6–8 hours in a shaker and used for further tests in diffusion assays. Extracted volumes were concentrated under the reduced pressure to the final volume of approximately 2 mL, and the crude extracts were tested separately in bioassays. The antibacterial activity of each fungal endophyte extract was assessed against Pseudomonas syringae var. glycinea in the disk diffusion assay. The size of the inhibition zone was determined by the diameter of the clear zone around each extract drop. The assay was performed for 3 biological replicates of each endophyte fungal.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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