Chapter 6
Endophytic Fungi of *Baccharis*

Yumi Oki, Lucas Arantes-Garcia, Renata Maia, Michel Stórquio Belmiro, Isabela Maria Nascimento, Ary Correa Junior, and G. Wilson Fernandes

Abstract Endophytic fungi are important mediators in the structure and dynamics of terrestrial plant communities and their relationships with associated fauna. Although endophytic fungi are found in all living plants, only 1% of all *Baccharis* species (*Baccharis artemisioides*, *B. coridifolia*, *B. dracunculifolia*, *B. megapotamica*, and *B. trimera*) have had their endophytic mycota studied. To date, 28 genera of endophytic fungi have been identified in association with species of *Baccharis*. Analysis of the enzymes and metabolites produced by this mycota indicates that these endophytes have numerous properties that may be related to better performance and resistance of their *Baccharis* host to several stressors and natural enemies. Many of these endophytes have properties that can be exploited for the development of beneficial applications in the fields of agronomy, pharmacology, and conservation, making them a particularly important group for the development of biotechnological products.

Keywords Antimicrobial activity · Bioprospecting · Fungal endophyte diversity · Plant performance · Secondary metabolites

1 Introduction

Endophytic fungi are a group of fungi that live inside plant tissues without causing harm to the host (Faeth and Fagan 2002; Hyde and Soytong 2008). They produce a variety of enzymes and secondary compounds, which favor nutrient cycling (Sun et al. 2011; Behie and Bidochka 2014), improve plant performance and resistance to adverse conditions such as droughts and high temperatures (Rodriguez et al.

Y. Oki (✉) · L. Arantes-Garcia · R. Maia · M. S. Belmiro · I. M. Nascimento · G. W. Fernandes
Ecologia Evolutiva & Biodiversidade, Departamento de Genética, Ecologia & Evolução/ICB, CP 486, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil

A. C. Junior
Departamento de Microbiologia, ICB, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil

G. W. Fernandes et al. (eds.), *Baccharis*,
https://doi.org/10.1007/978-3-030-83511-8_6

2004; Hubbard et al. 2014; Bilal et al. 2020), and minimize damage caused by herbivores and pathogenic microorganisms (Breen 1992, 1993, 1994; Fernandes and Price 1992; Hammon and Faeth 1992; Faeth and Hammon 1997; Raps and Vidal 1998; Faeth 2002; Meister et al. 2006; Oki et al. 2008, 2021; Grunseich et al. 2020). These cryptic organisms have been ignored for a long time, and their importance in species interactions and to biodiversity has been rarely studied until recently (Oki et al. 2016). According to a survey of the Web of Science database, it wasn't until the 1990s that scientific articles started to regularly use the term "endophytic fungi" (Fig. 6.1). Although the number of studies on endophytic fungal communities has progressively increased since then, there were still only 557 publications in the first decade of the twenty-first century. Approximately 75% of all the articles about endophytes retrieved by the survey (3043 articles published from 1945 to 2019) were published in the last 10 years (2279 articles between 2010 and 2019). The discovery of the importance of endophytes in nature has captured the attention of researchers and brought a wide prospective for research and applied perspectives.

Although scientific knowledge about these microorganisms is relatively recent, investigations have highlighted their remarkable diversity and wide distribution. Hundreds of species of endophytic fungi may inhabit a given host plant, with their richness being influenced by the phylogeny, ontogeny, and organs, among other factors, of the host species (Arnold et al. 2000; Cannon and Simmons 2002; Arnold and Herre 2003; Arnold and Lutzoni 2007; Banerjee 2011; Oki et al. 2016; Griffin and Carson 2018). The high diversity of endophytes indicates a wide variety of

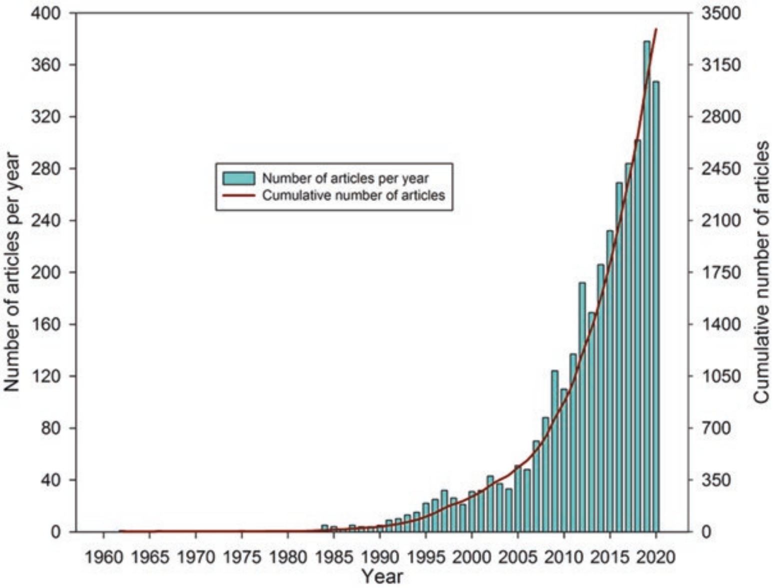

Fig. 6.1 Number of articles found in the Web of Science database (1945 to 2020) published with the term "endophytic fungi" per year and cumulatively

relationships with host plants and possibly a large number of ecological functions as well (Caruso et al. 2020). In this chapter we focus on the diversity and distribution of endophytic fungi found in association with species of *Baccharis*, a genus of shrubs and herbs that occupy many different habitats and ecosystems in their native range in the Americas, and highlight their ecological and economic potential.

2 Distribution and Diversity of Endophytic Fungi of Species of *Baccharis*

Despite there being 422 described species in the genus *Baccharis*, the associated endophytic fungal community is known for only 5: *Baccharis artemisioides*, *B. coridifolia*, *B. dracunculifolia*, *B. megapotamica*, and *B. trimera* (Table 6.1) (Heiden and Pirani 2016, see also Chap. 2 in this book). Nevertheless, 31 genera of endophytic fungi have already been reported from these 5 species: *Alternaria*, *Aureobasidium*, *Acremonium*, *Aspergillus*, *Biscogniauxia*, *Ceratopicnidium*, *Cercospora*, *Chaetomium*, *Cladosporium*, *Cochliobolus*, *Colletotrichum*, *Coriolopsis*, *Cylindrocladium*, *Diaporthe*, *Epicoccum*, *Eutypella*, *Fusarium*, *Glomerella*, *Myrothecium*, *Nigrospora*, *Penicillium*, *Phoma*, *Phomopsis*, *Podospora*, *Preussia*, *Rhizoctonia*, *Talaromyces*, *Trichoderma*, *Scopulariopsis*, *Sporormiella*, and *Xylaria* (Table 6.1). Even though none of these fungus genera were reported in all five *Baccharis* species, there are similarities among these plant species. *Baccharis dracunculifolia* and *B. trimera* were found to have the most similar endophytic fungi communities, sharing the following seven genera (Jaccard Index = 33%): *Chaetomium*, *Diaporthe*, *Nigrospora*, *Phoma*, *Phomopsis*, *Preussia*, and *Xylaria* (Fig. 6.2). Of the genera of endophytic fungi known for species of *Baccharis*, only 24 taxa have been identified to the species level: *Aureobasidium pullulans*, *Aureobasidium melanogenum*, *Aspergillus versicolor*, *Aspergillus spinulosporus*, *Ceratopicnidium baccharidicola*, *Cladosporium cladosporioides*, *Cladosporium halotolerans*, *Cladosporium endophytica*, *Cochliobolus lunatus*, *Coriolopsis rigida*, *Diaporthe phaseolorum*, *Epicoccum nigrum*, *Eutypella scoparia*, *Myrothecium verrucaria*, *Myrothecium roridum*, *Penicillium citrinum*, *Preussia africana*, *Preussia pseudominima*, *Talaromyces muroii*, *Trichoderma reesei*, *Xylaria adscendens*, *Xylaria apiculata*, and *Xylaria venosula*. Thus, the possibility exists for the description of unknown fungal species associated with *Baccharis* spp. and evidence of coevolution events.

Currently, the most studied species of *Baccharis* is *B. dracunculifolia*, with 24 endophytic fungus genera reported in 5 published studies: *Aureobasidium*, *Acremonium*, *Aspergillus*, *Biscogniauxia*, *Cercospora*, *Chaetomium*, *Cladosporium*, *Colletotrichum*, *Coriolopsis*, *Cylindrocladium*, *Diaporthe*, *Eutypella*, *Fusarium*, *Glomerella*, *Nigrospora*, *Penicillium*, *Phoma*, *Phomopsis*, *Preussia*, *Rhizoctonia*,

Table 6.1 Taxa of endophytic fungi found among species of *Baccharis*.

Endophytic genera	Endophytic taxa	Host plants	References
Alternaria	*Alternaria* sp.	*Baccharis trimera*	Vieira et al. (2014)
Aureobasidium	*Aureobasidium pullulans*	*Baccharis dracunculifolia*	Oki et al. (2009, 2020)
Acremonium	*Acremonium* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
	Acremonium sp. strain D5-FB	*Baccharis dracunculifolia*	Onofre and Steilmann (2012)
Aspergillus	*Aspergillus* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
	Aspergillus sp. strain D2-NC	*Baccharis dracunculifolia*	Onofre and Steilmann (2012)
Biscogniauxia	*Biscogniauxia* sp.	*Baccharis dracunculifolia*	Fernandes et al. (2018)
Ceratopicnidium	*Ceratopicnidium baccharidicola*	*Baccharis coridifolia*	Rizzo et al. (1997)
	Ceratopicnidium baccharidicola	*Baccharis artemisioides*	Rizzo et al. (1997)
Cercospora	*Cercospora* sp. strain D7-FB	*Baccharis dracunculifolia*	Onofre and Steilmann (2012)
Chaetomium	*Chaetomium* sp.	*Baccharis trimera*	Vieira et al. (2014)
	Chaetomium sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
Cladosporium	*Cladosporium cladosporioides*	*Baccharis dracunculifolia*	Oki et al. (2009)
	Cladosporium halotolerans	*Baccharis dracunculifolia*	Fernandes et al. (2018)
Cochliobolus	*Cochliobolus lunatus*	*Baccharis trimera*	Vieira et al. (2014)
Colletotrichum	*Colletotrichum* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
	Colletotrichum sp. strain D4-FB	*Baccharis dracunculifolia*	Onofre and Steilmann (2012)
Coriolopsis	*Coriolopsis rigida*	*Baccharis dracunculifolia*	Fernandes et al. (2018)
Cylindrocladium	*Cylindrocladium* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
	Cylindrocladium sp. strain D8-FB	*Baccharis dracunculifolia*	Onofre and Steilmann (2012)

(continued)

Table 6.1 (continued)

Endophytic genera	Endophytic taxa	Host plants	References
Diaporthe	*Diaporthe phaseolorum*	*Baccharis trimera*	Vieira et al. (2014)
	Diaporthe sp.	*Baccharis trimera*	Vieira et al. (2014)
Epicoccum	*Epicoccum nigrum*	*Baccharis trimera*	Vieira et al. (2014)
	Epicoccum sp.	*Baccharis trimera*	Vieira et al. (2014)
Fusarium	*Fusarium* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
	Fusarium sp. strain D3-FB	*Baccharis dracunculifolia*	Onofre and Steilmann (2012)
Glomerella	*Glomerella* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
Myrothecium	*Myrothecium verrucaria*	*Baccharis coridifolia*	Jarvis et al. (1987)
	Myrothecium roridum	*Baccharis coridifolia*	Jarvis et al. (1987)
	Myrothecium roridum	*Baccharis megapotamica*	Jarvis et al. (1987)
Nigrospora	*Nigrospora* sp.	*Baccharis trimera*	Vieira et al. (2014)
	Nigrospora sp.	*Baccharis dracunculifolia*	Oki et al. (2009)
	Nigrospora sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
Penicillium	*Penicillium* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
	Penicillium sp.	*Baccharis dracunculifolia*	Oki et al. (2009)
Pestalotiopsis	*Pestalotiopsis* sp.	*Baccharis trimera*	Vieira et al. (2014)
Phoma	*Phoma* sp.	*Baccharis trimera*	Vieira et al. (2014)
Phomopsis	*Phomopsis* sp.	*Baccharis dracunculifolia*	Oki et al. (2009)
	Phomopsis sp.	*Baccharis trimera*	Vieira et al. (2014)
	Phomopsis sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
	Phomopsis sp. strain D10-NC	*Baccharis dracunculifolia*	Onofre and Steilmann (2012)
Podospora	*Podospora* sp.	*Baccharis trimera*	Vieira et al. (2014)

(continued)

Table 6.1 (continued)

Endophytic genera	Endophytic taxa	Host plants	References
Preussia	*Preussia africana*	*Baccharis dracunculifolia*	Oki et al. (2009); Fernandes et al. (2018), Oki et al. (2021)
	Preussia africana	*Baccharis trimera*	Vieira et al. (2014)
	Preussia pseudominima	*Baccharis trimera*	Vieira et al. (2014)
	Preussia sp.	*Baccharis trimera*	Vieira et al. (2014)
	Preussia sp.	*Baccharis dracunculifolia*	Fernandes et al. (2018)
Rhizoctonia	*Rhizoctonia* sp.	*Baccharis dracunculifolia*	Oki et al. (2009)
Trichoderma	*Trichoderma* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
	Trichoderma reesei	*Baccharis dracunculifolia*	Onofre et al. (2014)
Scopulariopsis	*Scopulariopsis* sp.	*Baccharis dracunculifolia*	Cuzzi et al. (2012)
Sporormiella	*Sporormiella* sp.	*Baccharis trimera*	Vieira et al. (2014)
Xylaria	*Xylaria* sp.	*Baccharis dracunculifolia*	Oki et al. (2009)
	Xylaria sp.	*Baccharis dracunculifolia*	Fernandes et al. (2018)
	Xylaria sp.	*Baccharis trimera*	Vieira et al. (2014)
	Xylaria apiculate	*Baccharis dracunculifolia*	Fernandes et al. (2018)
	Xylaria venosula	*Baccharis dracunculifolia*	Oki et al. (2009), Fernandes et al. (2018), Oki et al. (2021)

Talaromyces, *Trichoderma*, *Scopulariopsis*, and *Xylaria*. The species of endophytic fungi known for *B. dracunculifolia* are *Aureobasidium pullulans*, *Aureobasidium melanogenum*, *Aspergillus versicolor*, *Aspergillus spinulosporus*, *Cladosporium cladosporioides*, *Cladosporium halotolerans*, *Cladosporium endophytica*, *Coriolopsis rigida*, *Diaporthe phaseolorum*, *Eutypella scoparia*, *Penicillium citrinum*, *Preussia africana*, *Talaromyces muroii*, *Trichoderma reesei*, *Xylaria adscendens*, *Xylaria apiculata*, and *Xylaria venosula* (Figs. 6.3 and 6.4). Many of these species (e.g., *A. pullulans*, *P. africana*, and *X. venosula*) play important ecological roles such as improving their hosts' defenses against herbivores and phytopathogens.

All together, these results indicate that the taxonomic diversity of endophytic fungi associated with species of *Baccharis* is enormous and likely underestimated. The array of functions associated with interactions between endophytic fungi and

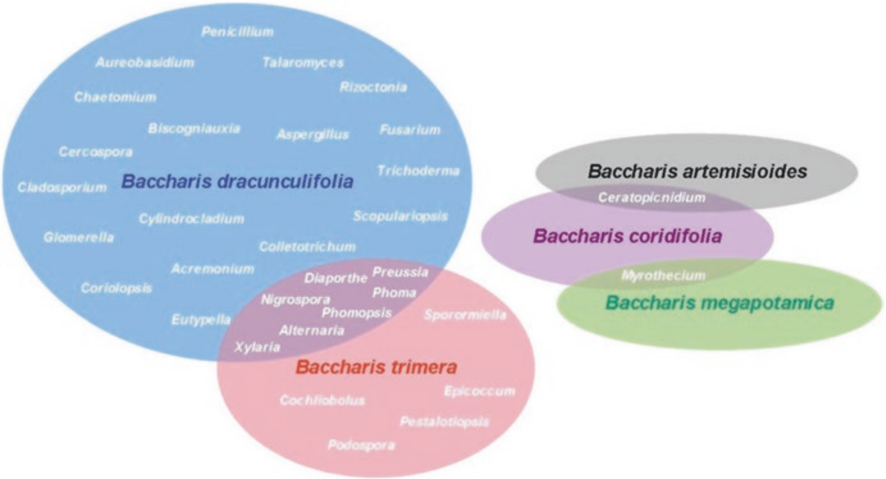

Fig. 6.2 Diagram showing fungal genera associated and shared among *Baccharis dracunculifolia, Baccharis trimera, Baccharis artemisioides, Baccharis coridifolia, and Baccharis megapotamica*

Baccharis hosts is also expected to be very large. Thus, there is a broad perspective for future studies to address, besides their biotechnological importance, the phylogenetic relationships of endophytes and hosts and the evolution and stability of associations across species and habitats.

3 Leaf Age, Plant Sex, and the Endophytic Fungus Community

The richness of endophytic fungi found among *Baccharis* spp. varies according to plant organ (Oki et al. 2009; Jia et al. 2016) and organ age (Arnold and Herre 2003; Fernandes et al. 2011; Sanchez-Azofeifa et al. 2012; Nascimento et al. 2015; Christian et al. 2019). For instance, endophytic fungus richness in mature leaves of *B. dracunculifolia* was seven times higher than that of leaves of intermediate age growing at high altitudes of Serra do Cipó, Brazil. No endophytic fungi were found in young leaves (Oki et al. 2008).

Another relevant factor that can affect the composition of endophytic mycota, particularly in the genus *Baccharis*, is host plant gender. The endophytic fungi found exclusively in female plants of *B. dracunculifolia* did not develop from

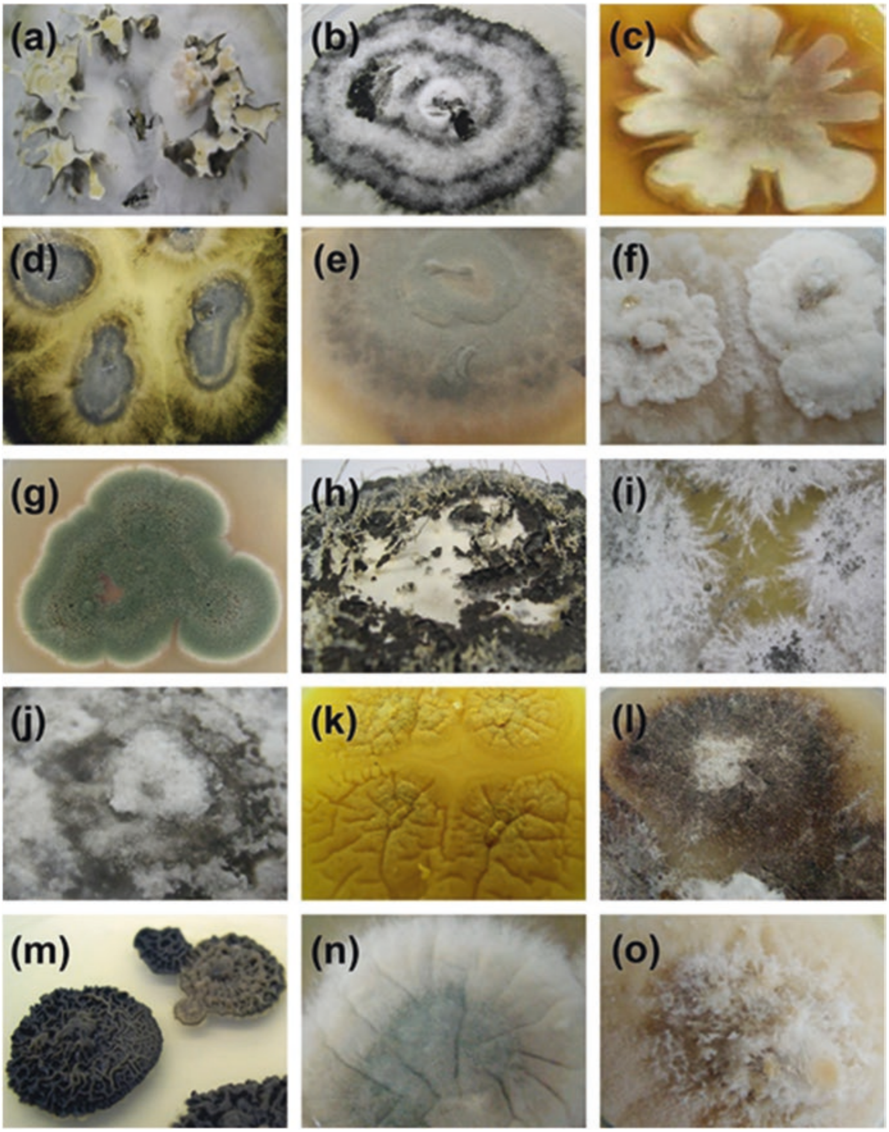

Fig. 6.3 Endophytic fungus genera found for *Baccharis dracunculifolia* (Asteraceae): (**a**) *Xylaria adscendens* (Xylariaceae); (**b**) *Biscogniauxia* sp. (Xylariaceae); (**c**) *Preussia africana* (Sporormiaceae); (**d**) *Aureobasidium pullulans* (Dothioraceae); (**e**) *Cladosporium endophytica* (Cladosporiaceae); (**f**) *Phomopsis* sp. (Diaporthaceae); (**g**) *Penicillium citrinum* (Trichocomaceae); (**h**) *Xylaria venosula* (Xylariaceae); (**i**) *Diaporthe phaseolorum* (Diaporthaceae); (**j**) *Nigrospora* sp. (Trichosphaeriaceae); (**k**) *Phoma* sp. (Didymellaceae); (**l**) *Fusarium* sp. (Nectriaceae); (**m**) *Aureobasidium melanogenum* (Dothioraceae); (**n**) *Aspergillus versicolor* (Trichocomaceae); (**o**) *Acremonium* sp. (Hypocreaceae)

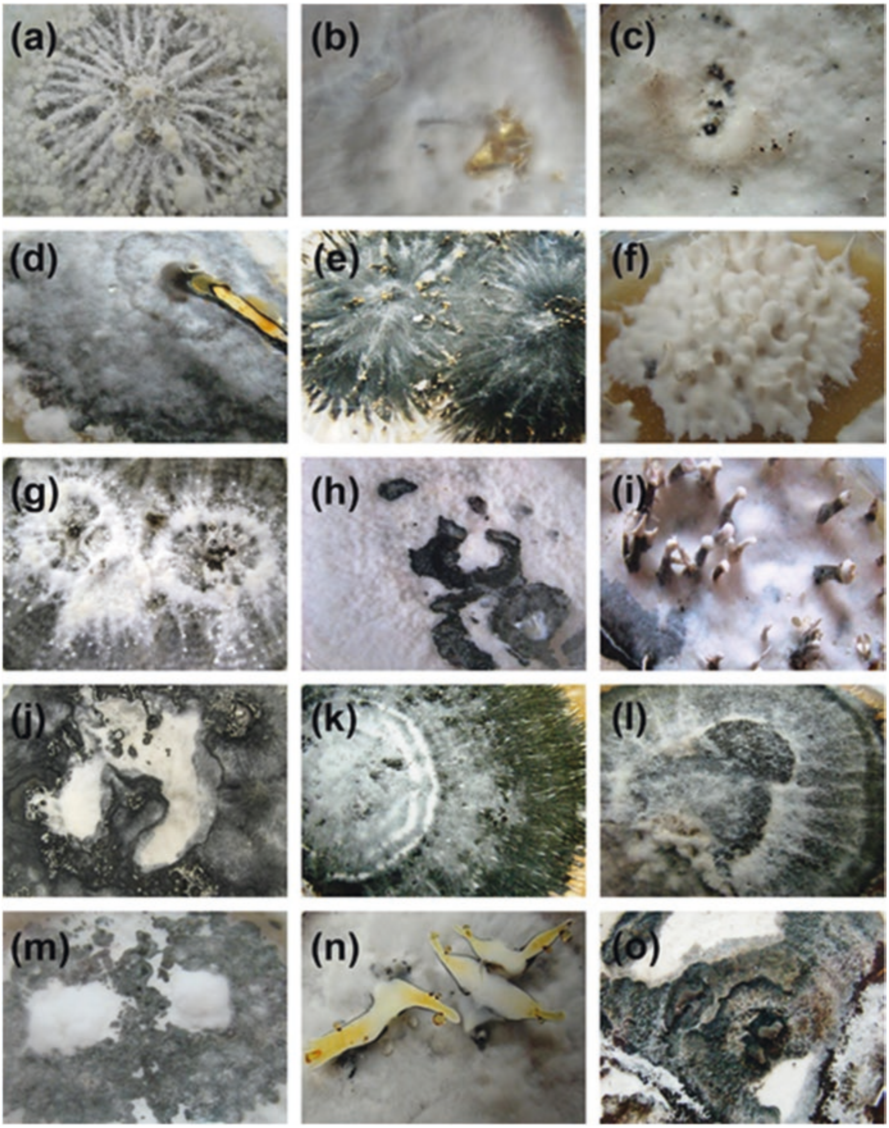

Fig. 6.4 Endophytic fungi of the family Xylariaceae found in leaves of *Baccharis dracunculifolia* (Asteraceae)

extracts from male individuals of the same species (Fernandes et al. 2018). It is likely that chemical differences between female and male plants (Darwin 1877; Wallace and Rundel 1979; Van Etten et al. 2008) determine the endophytic species that are capable of co-inhabiting these plants. Generally, female plants invest less in growth and more in resistance against herbivory than male plants (Wallace and

Rundel 1979; Herms and Mattson 1992; Van Etten et al. 2008) (but see Chap. 4). Nonetheless, these questions remain to be fully addressed in this system.

4 Untapped Potential of Endophytic Fungi: Enzymes and Bioactive Compounds

Enzymes

Despite the high diversity of endophytic fungi found among species of *Baccharis*, knowledge regarding their enzymatic makeup is scarce. This knowledge gap undermines a better understating of the physiological relationships between endophytes and their hosts (Sun et al. 2011) and their potential for industrial application (Côrrea et al. 2014). Endophytic fungi, such as species of the genus *Xylaria*, have a high production of enzymes such as cellulases and ligninases, which can degrade important components of plant cell walls (e.g., cellulose and lignin) (Carroll and Carroll 1978). These enzymes could assist in the decomposition of fallen leaves and promote nutrient cycling in nature. The accumulation of endophytic fungi themselves in leaves as age progresses (e.g., Fernandes et al. 2011; Sanchez-Azofeifa et al. 2012; Nascimento et al. 2015; Christian et al. 2019) seems to be important and in need of further evaluation, as well as the relevance of these fungi to key ecosystem functions such as decomposition.

The endophyte *Aureobasidium pullulans* found in *B. dracunculifolia* can produce lipases that belong to the class of serine hydrolases and do not need the presence of cofactors in order to act, unlike most extracellular enzymes of microbial origin (Nascimento 2010). The biological function of lipases is to hydrolyze triglycerides to form free fatty acids, mono- and diacylglycerols and glycerol (Kwon and Rhee 1986; Berger and Schnelder 1992; Bornscheuer 1995; Carvalho et al. 2003). Currently, lipases are of great interest to food (e.g., aroma improvement, food conservation, reduction of saturated fat), agricultural (e.g., herbicide synthesis), energy (e.g., biodiesel and hydrocarbon production), pharmaceutical (e.g., digestive aid), and cosmetics (e.g., active ingredient in the formulation and synthesis of specific cosmetics) industries, among others (Höfelmann et al. 1985; Cortez et al. 2017). Lipases can also play an important role in plant defense since lipids and lipid metabolites released in plant membranes function as signal molecules in the activation of plant defense responses (Shah 2005).

Recent studies have also indicated that some strains of endophytic fungi, such as *Fusarium* sp. and *Cercospora* sp. in *B. dracunculifolia*, can produce phenoloxidases that are capable of degrading phenolic compounds such as petroleum hydrocarbons and industrial effluents (Onofre and Steilmann 2012). These are important findings for bioremediation initiatives since these contaminants can be found at ca. 35 million metric tons per year in the oceans (Rosenberg and Ron 1996). These contaminants severely impact marine biodiversity over a time span of decades and even centuries (Goldberg and Bertine 2000; Pinheiro et al. 2019; Magris and Giarizzo 2020). Much of this contamination comes from oil in municipal and industrial waste and runoff, leaks in pipelines and storage tanks, and sewage and ballast water discharge (Telli Karakoç and Ediger 2020; Pokazeev et al. 2021).

Many endophytic fungi have proven to be excellent bioremediators of heavy metals that can harm human health, such as arsenic. Some of these endophytes are resistant to arsenic and arsenate and possess the ability to transform them into volatile arsenic gases (Páez-Espino et al. 2009). *Aspergillus, Cladosporium, Fusarium, Penicillium*, and *Trichoderma* are some of the endophytic fungus genera known for their bioremediation potential. They are frequently found in plants that have tolerance to, or the ability to bioaccumulate, heavy metals (Deng et al. 2014). Coincidentally, these fungus genera are also found among species of *Baccharis*, mainly *B. dracunculifolia*. *Baccharis dracunculifolia* has been shown to have great phytostabilization potential for areas contaminated with arsenic (Gilberti et al. 2014). This phytostabilization potential is likely associated with the endophytic fungi in this species; however, no studies have evaluated this relationship.

Endophytic Fungi as a Source of Bioactive Compounds

Endophytic fungi represent a promising source of natural bioactive products. Researchers around the world have been intrigued by the diversity of secondary compounds produced by endophytic fungi and by the similarity between the metabolites produced by endophytic fungi and their host plants (Kusari et al. 2013). This similarity in the production of secondary compounds may be due to several factors, including (1) host plant metabolism being induced by the fungus; (2) fungus metabolism being induced by the host plant; (3) fungus sharing specific biosynthesis pathways with the host plant; and (4) host plant being able to metabolize substances of fungal origin or vice versa (e.g., Ludwig-Müller 2015).

Among the best-known examples of bioactive compounds produced by endophytic fungi is palictaxel (commercialized as Taxol) produced by *Taxomyces andreanae* from the medicinal tree *Taxus brevifolia* (Stierle et al. 1993). Palictaxel is one of the most effective chemotherapeutic compounds used in the treatment of various types of cancer (i.e., ovary, breast, and lung) (Stierle et al. 1993, see Chap. 18). Before this discovery, the supply of this diterpenic substance was limited to the slow-growing barks of *T. brevifolia* that grow in moist soils close to lakes and rivers in some regions of the Pacific Northwest (Guchelaar et al. 1994). Thus, the possibility of extracting palictaxel from *T. andreanae* significantly reduced the production costs of this compound and increased its supply and availability. In addition, other species of endophytic fungi have also been reported to produce palictaxel in plant species of the genera *Taxus* and *Podocarpus* and even in *Ginkgo biloba* (Zhao et al. 2010; Naik 2019). One of these endophytic fungi is *Cladosporium cladosporioides* isolated from *Taxus media* (Zhang et al. 2009), which, coincidentally, is also found in *B. dracunculifolia*, although there is no information on whether it produces palictaxel. Future studies could attempt to propagate this fungus species from *B. dracunculifolia* and isolate its products to evaluate if the chemotherapeutic palictaxel is also produced by *C. cladosporioides* when it occurs in different host plant species. Such studies would generate a cascade of interesting and innovative investigations of major economic and medical relevance.

Among the endophytic fungi most frequently found among species of *Baccharis*, the genera *Xylaria* and *Preussia* deserve to be highlighted with regard to their metabolism. Species of *Xylaria* are known to produce several chemical constituents of the terpene class (Smith et al. 2002), xanthones (Healy et al. 2004), cyclopeptides (Huang et al. 2007), and xyloketals (Lin et al. 2001), among others. Species of this genus are found in other plant species of the family Asteraceae and are known for their inhibitory activity against phytopathogens such as *Penicillium expansum* (Bleicher and Bernardi 1985; Costa and Veiga 1996) and *Aspergillus niger* (Lock 1962; Santos et al. 2010). Furthermore, species of the genus *Preussia* are known to produce the metabolite preussomerin A, which is active against pathogens (Chen et al. 2009). A variety of substances produced by *Preussia* spp. have been identified in the last 10 years, including coumarins (Gonzalez-Menendez et al. 2017), anthraquinones (Gonzalez-Menendez et al. 2017), chronomes (Zhang et al. 2012; Gonzalez-Menendez et al. 2017), and preussochromones (Zhang et al. 2012). Some preussochromones have shown activity against lung cancer cell lines (Zhang et al. 2012).

Unfortunately, knowledge about the metabolites produced by endophytic fungi of species of *Baccharis* is still incipient and restricted to the endophytes found in *B. megapotamica*, *B. coridifolia*, and *B. dracunculifolia*. For instance, *B. megapotamica* and *B. coridifolia* produce certain macrocyclic trichothecenes, which are also produced by their endophytic fungi *Myrothecium verrucaria* and *Myrothecium roridum* (Jarvis et al. 1987, see Chaps. 14 and 15). These substances have been responsible for causing the death of cattle through necrosis of their ruminal epithelium and some lymphoid tissues (Varaschin et al. 1998, see also Chap. 15). On the other hand, some of these trichothecenes have been reported as effective in the treatment of lymphocytic leukemia (Kupchan et al. 1976; Jarvis et al. 1987, Carvalho et al. 2016, see also Chap. 14).

Among the endophytic fungi found in *B. dracunculifolia*, *A. pullulans* and *Xylaria venosula* stand out for the production of phenols and triterpenes, while *Preussia africana* for fatty acids (Oki et al. 2016, 2021). Chromatographic analysis showed that a group of triterpenes found in extracts from *A. pullulans* was similar to those found in *B. dracunculifolia*.

In addition, host plant metabolism can induce endophytic fungi of different genera and classes to produce similar secondary compounds (Ludwig-Müller 2015). A study with endophytic fungi of species of *Baccharis* revealed that a group of triterpenes present in extracts of *A. pullulans* was similar to those found in extracts of *X. venosula* (Oki et al. 2021). This similarity in the production of secondary compounds between different genera of endophytic fungi from the same plant species indicates a synergistic biochemical relationship between fungus species. Explanations for these findings include (1) endophytes sharing specific biosynthesis pathways with the host plant, and (2) endophytes producing the same secondary compounds as the host plant (see Ludwig-Müller 2015; Stierle and Stierle 2015). *Aureobasidium pullulans* is also used in the production of aureobasidin A, a cyclic peptide substance that has antifungal properties (Takesako et al. 1993). This fungus also releases volatile organic compounds that are capable of suppressing the growth of phytopathogens (Don et al. 2020).

Due to its arsenal of secondary metabolites, *A. pullulans* has been considered an effective biological control agent against several phytopathogenic fungi that affect numerous agricultural crops, including *Alternaria alternata* (Don et al. 2020), *Botrytis cinerea* (Di Francesco et al. 2015; Don et al. 2020; Oki et al. 2021), *Colletotrichum acutatum* (Di Francesco et al. 2015; Oki et al. 2021), *Neofusicoccum parvum* (Rusin et al. 2019), *Penicillium digitatum* (Di Francesco et al. 2015; Oki et al. 2021), *Penicillium expansum* (Di Francesco et al. 2015), *Penicillium italicum* (Di Francesco et al. 2015), and *Rhizoctonia solani* (Di Francesco et al. 2020). *Aureobasidium pullulans* is also highlighted for stimulating the growth of beans and soybean (Di Francesco et al. 2020), which may be attributed to improving host plant nitrogen fixation or a greater release of hormones such as auxins, gibberellins, and cytokinins by *A. pullulans* (Ali et al. 2019). Furthermore, this fungus can improve plant resistance in soil with heavy metals through the release of enzymes that assist in reducing metal absorption and enhance the plant's antioxidant system (Ali et al. 2019).

5 Endophytic Fungi-*Baccharis*-Herbivore Interaction

Some endophytic mycota (i.e., *A. pullulans*, *P. africana*, and *X. venosula*) from *B. dracunculifolia* can produce secondary compounds that reduce the survival of herbivores such as the aphid *Uroleucon erigeronensis* (Oki et al. 2021). On the other hand, a study with *B. dracunculifolia* leaf buds indicated that herbivory can be a gateway for endophytic fungi through horizontal transmission (Fernandes et al. 2018).

Although herbivores often favor the infection of the host plant with endophytic fungi, this was not found to be the case for galling insects on *Baccharis reticularia*. Individuals of *B. reticularia* with and without galls showed no difference in endophytic fungus richness (Formiga 2013). However, a higher richness of endophytic fungi was found in gall samples that had a higher content of nitrogen and potassium (Formiga 2013). Nevertheless, a relationship between endophytic fungus richness and nitrogen and phosphorus content was not observed. These results suggest that endophytes can increase the nutritional status of galled plants by improving plant vigor and reducing the effects of gall infestation (Formiga 2013). This mutualistic relationship has not been reported so far in the literature and certainly needs further studies.

All together, these findings suggest that although endophytic fungi are often imperceptible inside plants, they are important mediators in the relationships between herbivores and their host plants and apparently very important among species of the genus *Baccharis*.

6 Climate Change and Endophytic Fungus Diversity

Growing concerns about the impacts that climate change will have on endophytes have increased research interest in this group with searches for strategies that could mitigate these effects. Recent studies on the endophytes of *B. dracunculifolia* and *Baccharis platypoda* grown under increased CO_2 concentration did not find differences in mycota richness (Oki et al. 2020). On the other hand, endophytic community composition changed by 50% when compared to individual plants developed under conditions of ambient CO_2 (Oki et al. 2016). Thus, several species of endophytic fungi that play fundamental roles in plant performance and resistance may disappear or be replaced by other species of unknown functional roles. These changes in species composition are associated with structural and chemical changes (Sanchez-Azofeifa et al. 2012) that may occur in plants under increased CO_2 concentration, such as increased biomass, greater leaf thickness, and higher phenolic content, among other aspects (Oki et al. 2020). Despite these recent studies of endophytic fungi under conditions of predicted climate change, there is still no clear long-term notion of the impacts that increased atmospheric CO_2 concentration might exert on the symbiosis between endophytic fungi and their host plants.

7 Final Considerations and Ways Forward

Despite the limited number of studies on endophytic fungus communities of species of *Baccharis*, this chapter has shown how relevant these microorganisms are to ecological relationships, as well as their great potential in industrial research and developments involving their bioactive compounds. Further investigations into the diversity of endophytic fungi among species of *Baccharis* are needed to better understand the phylogenetic, ecological, and metabolic relationships among them, as well as their prevalence under certain environmental conditions. The relationship between endophyte and host attributes is also of major relevance, and the *Baccharis* system represents an interesting system to be evaluated in this regard. Some of these aspects could be intrinsic to the host plant (e.g., genetics, sex, age, resistant/susceptibility) or of the environment (e.g., seasonality, microhabitat conditions, climate change influence). The association between a host plant and its endophytes may be subject to certain genetic expressions that can vary seasonally and/or spatially (Faeth 2002, Mejía et al. 2014). Another relevant aspect yet to be studied in detail is the ability of endophytic fungi to signal one another triggering silent biosynthetic pathways (Scherlach and Hertweck 2009). Understanding these very interesting relationships and their intrinsic and extrinsic factors would certainly contribute to solidifying knowledge of endophytic fungi and contribute to better exploration of their potential uses for industrial/pharmaceutical purposes.

Acknowledgments We thank for CNPq, FAPEMIG, Planta and CAPES for grants and scholarships to the authors.

References

Ali A, Bilal S, Khan AL, Mabood F, Al-Harrasi A, Lee IJ (2019) Endophytic *Aureobasidium pullulans* BSS6 assisted developments in phytoremediation potentials of *Cucumis sativus* under Cd and Pb stress. J Plant Interact 14:303–313. https://doi.org/10.1080/17429145.2019.1633428

Arnold AE, Herre EA (2003) Canopy cover and leaf age affect colonization by tropical fungal endophytes: ecological pattern and process in *Theobroma cacao* (Malvaceae). Mycologia 95:388–398. https://doi.org/10.1080/15572536.2004.11833083

Arnold AE, Lutzoni F (2007) Diversity and host range of foliar fungal endophytes: are tropical leaves biodiversity hotspots? Ecology 88:541–549

Arnold AE, Maynard Z, Gilbert GS, Coley PD, Kursar TA (2000) Are tropical fungal endophytes hyperdiverse? Ecol Lett 3:267–274

Banerjee D (2011) Endophytic fungal diversity in tropical and subtropical plants. Res J Microbiol 6:54–62

Behie SW, Bidochka MJ (2014) Nutrient transfer in plant–fungal symbioses. Trends Plant Sci 19:734–740. https://doi.org/10.1016/j.tplants.2014.06.007

Berger M, Schnelder MP (1992) Enzymatic esterification of glycerol II. Lipase-catalyzed synthesis of regioisomerically pure 1 (3)-rac-monoacylglycerols. J Am Oil Chem Soc 69:961–965

Bilal S, Shahzad R, Imran M, Jan R, Kim KM, Lee IJ (2020) Synergistic association of endophytic fungi enhances *Glycine max* L. resilience to combined abiotic stresses: heavy metals, high temperature and drought stress. Ind Crop Prod 143:1–10. https://doi.org/10.1016/j.indcrop.2019.111931

Bleicher J, Bernardi J (1985) Podridões da maçã e seu controle na pós-colheita. Technical Bulletin. Empresa Catarinense de Pesquisa Agropecuária (EMPASC), Florianópolis, 24 p

Bornscheuer UT (1995) Lipase-catalyzed syntheses of monoacylglycerols. Enzym Microb Technol 17:578–586

Breen JP (1992) Temperature and seasonal effects on expression of *Acremonium* endophyte-enhanced resistance to *Schizaphis graminum* (Homoptera: Aphididae). Environ Entomol 21:68–74. https://doi.org/10.1093/ee/21.1.68

Breen (1993) Enhanced resistance to three species of aphids (Homoptera: Aphididae) in *Acremonium* endophyte-infected turf grasses. J Econ Entomol 86:1279–1286. https://doi.org/10.1093/jee/86.4.1279

Breen JP (1994) *Acremonium* endophyte interactions with enhanced plant resistance to insects. Annu Rev Entomol 86:401–423. https://doi.org/10.1146/annurev.en.39.010194.002153

Cannon PF, Simmons CM (2002) Diversity and host preference of leaf endophytic fungi in the Iwokrama Forest Reserve, Guyana. Mycologia 94:210–220

Carroll GC, Carroll FE (1978) Studies on the incidence of coniferous needle endophytes in the Pacific NorthWest. Can J Bot 56:3034–3043. https://doi.org/10.1139/b78-367

Caruso G, Abdelhamid MT, Kalisz A, Sekara A (2020) Linking endophytic fungi to medicinal plants therapeutic activity. A case study on Asteraceae. Agriculture 10:1–23. https://doi.org/10.3390/agriculture10070286

Carvalho PDO, Campos PRB, Noffs MDA, Oliveira JGD, Shimizu MT, Silva DMD (2003) Application of microbial lipases to concentrate polyunsaturated fatty acids. Quim Nova 26:75–80

Carvalho MP, Weich H, Abraham WR (2016) Macrocyclic trichothecenes as antifungal and anticancer compounds. Curr Med Chem 23:23–35. https://doi.org/10.2174/0929867323666151117121521

Chen X, Shi Q, Lin G, Guo S, Yang J (2009) Spirobisnaphthalene analogues from the endophytic fungus *Preussia* sp. J Nat Prod 72:1712–1725. https://doi.org/10.1021/np900302w

Christian N, Herre EA, Clay K (2019) Foliar endophytic fungi alter patterns of nitrogen uptake and distribution in *Theobroma cacao*. New Phytol 222:1573–1583. https://doi.org/10.1111/nph.15693

Corrêa RCG, Rhoden SA, Mota TR, Azevedo JL, Pamphile JA, Souza CGM, Polizeli MLTM, Bracht A, Peralta RM (2014) Endophytic fungi: expanding the arsenal of industrial enzyme producers. J Ind Microbiol Biotechnol 41:1467–1478. https://doi.org/10.1007/s10295-014-1496-2

Cortez DV, Castro HFD, Andrade GS (2017) Potencial catalítico de lipases ligadas ao micélio de fungos filamentosos em processos de biotransformação. Quim Nova 40:85–96

Costa IFD, Veiga P (1996) Inibição do desenvolvimento de *Penicillium expansum* (Link) Thom. por fungicidas, in vitro. Ciênc Rural 26:357–360. https://doi.org/10.1590/S0103-84781996000300002

Cuzzi C, Link S, Vilani A, Sartori C, Onofre SB (2012) Endophytic fungi of the “vassourinha” (*Baccharis dracunculifolia* D. *C.* – Asteraceae*)*. Rev Bras Bioci 10:135–139

Darwin C (1877) The various contrivances by which orchids are fertilised by insects. John Murray

Deng Z, Zhang R, Shi Y, Hu L, Tan H, Cao L (2014) Characterization of Cd-, Pb-, Zn-resistant endophytic Lasiodiplodia sp. MXSF31 from metal accumulating *Portulaca oleracea* and its potential in promoting the growth of rape in metal-contaminated soils. Environ Sci Pollut Res 21:2346–2357

Di Francesco A, Ugolini L, Lazzeri L, Mari M (2015) Production of volatile organic compounds by *Aureobasidium pullulans* as a potential mechanism action against postharvest fruit pathogens. Biol Control 81:8–14. https://doi.org/10.1016/j.biocontrol.2014.10.004

Di Francesco A, Zajc J, Gunde-Cimerman N, Aprea E, Gasperi F, Placì N, Caruso F, Baraldi E (2020) Bioactivity of volatile organic compounds by *Aureobasidium* species against gray mold of tomato and table grape. World J Microb Biotechnol 36:1–11. https://doi.org/10.1007/s11274-020-02947-7

Don SY, Schmidtke LM, Gambetta JM, Steel CC (2020) *Aureobasidium pullulans* volatilome identified by a novel, quantitative approach employing SPME-GC-MS, suppressed *Botrytis cinerea* and *Alternaria alternata in vitro*. Sci Rep 10:4498. https://doi.org/10.1038/s41598-020-61471-8

Faeth SH (2002) Are endophytic fungi defensive plant mutualists? Oikos 98:25–36. https://doi.org/10.1034/j.1600-0706.2002.980103.x

Faeth SH, Fagan WF (2002) Fungal endophytes: common host plant symbionts but uncommon mutualists. Integr Comp Biol 42:360–368. https://doi.org/10.1093/icb/42.2.360

Faeth SH, Hammon KE (1997) Fungal endophytes in oak trees: long-term patterns of abundance and associations with leafminers. Ecology 78:810–819

Fernandes GW, Price PW (1992) The adaptive significance of insect gall distribution: survivorship of species in xeric and Mesic habitats. Oecologia 90:14–20

Fernandes GW, Oki Y, Sanchez-Azofeifa A, Faccion G, Amaro-Arruda HC (2011) Hail impact on leaves and endophytes of the endemic threatened *Coccoloba cereifera* (Polygonaceae). Plant Ecol 212:1687–1697. https://doi.org/10.1007/s11258-011-9941-z

Fernandes GW, Oki Y, Belmiro MS, Resende FM, Correa AC Jr, Azevedo JL (2018) Multitrophic interactions among fungal endophytes, bees, and *Baccharis dracunculifolia*: resin tapering for propolis production leads to endophyte infection. Arthropod Plant Interact 12:329–337. https://doi.org/10.1007/s11829-018-9597-x

Formiga A (2013) Distribuição temporal e respostas celulares de *Baccharis reticularia* DC. (Asteraceae) a interações bióticas. PhD Thesis, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil

Gilberti L, Menezes A, Rodrigues AC, Fernandes GW, Berbara RLL, Marota HB (2014) Effects of arsenic on the growth, uptake and distribution of nutrients in the tropical species *Baccharis dracunculifolia* DC (Asteraceae). J Toxicol Sci 2014:1–18

Goldberg ED, Bertine KK (2000) Beyond the mussel watch—new directions for monitoring marine pollution. Sci Total Environ 247:165–174

Gonzalez-Menendez V, Martin J, Siles JA, Gonzalez-Tejero MR, Reyes F, Platas G, Tormo JR, Genillour O (2017) Biodiversity and chemotaxonomy of *Preussia* isolates from the Iberian Peninsula. Mycol Prog 16:713–728. https://doi.org/10.1007/s11557-017-1305-1

Griffin EA, Carson WP (2018) Tree endophytes: cryptic drivers of tropical forest diversity. In: Pirttilä A, Frank A (eds) Endophytes of Forest trees. Springer, pp 63–103. https://doi.org/10.1007/978-3-319-89833-9_4

Grunseich JM, Thompson MN, Aguirre NM, Helms AM (2020) The role of plant-associated microbes in mediating host-plant selection by insect herbivores. Plan Theory 9:1–23. https://doi.org/10.3390/plants9010006

Guchelaar HJ, Ten Napel CHH, De Vries EGE, Mulder NH (1994) Clinical, toxicological and pharmaceutical aspects of the antineoplastic drug taxol: a review. Clin Oncol 6:40–48

Hammon KE, Faeth SH (1992) Ecology of plant-herbivore communities: a fungal component? Nat Toxins 1:197–208. https://doi.org/10.1002/nt.2620010307

Healy PC, Hocking A, Tran-Dinh N, Pitt JI, Shivas RG, Mitchell JK, Kotiw M, Davis RA (2004) Xanthones de um microfungus do gênero *Xylaria*. Phytochemistry 65:2373–2378. https://doi.org/10.1016/j.phytochem.2004.07.019

Heiden G, Pirani JR (2016) Novelties towards a phylogenetic classification of *Baccharis* (Asteraceae, Astereae). Phytotaxa 289:285–290. https://doi.org/10.11646/phytotaxa.289.3.9

Herms DA, Mattson WJ (1992) The dilemma of plants: to grow or defend. Q Rev Biol 67:283–335

Höfelmann M, Hartmann J, Zink A, Schreier P (1985) Isolation, purification, and characterization of lipase isoenzymes from a technical *Aspergillus niger* enzyme. J Food Sci 50:1721–1725. https://doi.org/10.1111/j.1365-2621.1985.tb10574.x

Huang H, She Z, Lin Y, Vrijmoed LLP, Lin W (2007) Cyclic peptides from an endophytic fungus obtained from a mangrove leaf (*Kandelia candel*). J Nat Prod 70:1696–1699. https://doi.org/10.1021/np0605891

Hubbard M, Germida JJ, Vujanovic V (2014) Fungal endophytes enhance wheat heat and drought tolerance in terms of grain yield and second-generation seed viability. J Appl Microbiol 116:109–122. https://doi.org/10.1111/jam.12311

Hyde KD, Soytong K (2008) The fungal endophyte dilemma. Fungal Divers 33:163–173

Jarvis BB, Comezoglu SN, Amomon HL, Breedlove CK, Miller RW, Woode MK, Streelman DR, Sneden AT, Dailey RG, Kupchan SM (1987) New macrocyclic trichothecenes from *Baccharis megapotamica*. J Nat Prod 50:815–828. https://doi.org/10.1021/np50053a008

Jia M, Chen L, Xin HL, Zheng CJ, Rahman K, Han T, Qin LP (2016) A friendly relationship between endophytic fungi and medicinal plants: a systematic review. Front Microbiol 7:906. https://doi.org/10.3389/fmicb.2016.00906

Kupchan SM, Uchida I, Branfman AR, Dailey RG, Fei BY (1976) Antileukemic principles isolated from Euphorbiaceae plants. Science 191:571–572. https://doi.org/10.1126/science.1251193

Kusari S, Pandey SP, Spiteller M (2013) Untapped mutualistic paradigms linking host plant and endophytic fungal production of similar bioactive secondary metabolites. Phytochemistry 91:81–87. https://doi.org/10.1016/j.phytochem.2012.07.021

Kwon DY, Rhee JS (1986) A simple and rapid colorimetric method for determination of free fatty acids for lipase assay. J Am Oil Chem Soc 63:89–92

Lin Y, Wu X, Feng S, Jiang G, Luo J, Zhou S, Vrijmoed LLP, Jones EBG, Krohn K, Steingröver K, Zsila F (2001) Five unique compounds: xyloketals from mangrove fungus *Xylaria* sp. from the South China Sea coast. J Org Chem 66:6252–6256. https://doi.org/10.1021/jo015522r

Lock GW (1962) Sisal: twenty-five years sisal research. Longmans, London, 355p

Ludwig-Müller J (2015) Plants and endophytes: equal partners in secondary metabolite production? Biotechnol Lett 37:1325–1334

Magris RA, Giarrizzo T (2020) Mysterious oil spill in the Atlantic Ocean threatens marine biodiversity and local people in Brazil. Mar Pollut Bull 153:1–11

Meister B, Krauss J, Härri SA, Schneider MV, Muller CB (2006) Fungal endosymbionts affect aphid population size by reduction of adult life span and fecundity. Basic Appl Ecol 7:244–252. https://doi.org/10.1016/j.baae.2005.06.002

Mejía LC, Herre EA, Sparks JP, Winter K, García MN, Van Bael SA, Stitt J, Zi S, Shang Y, Guiltinan MJ, Maximova SN (2014) Pervasive effects of a dominant foliar endophytic fungus on host genetic and phenotypic expression in a tropical tree. Front Microbiol 5:1–17. https://doi.org/10.3389/fmicb.2014.00479

Naik BS (2019) Developments in taxol production through endophytic fungal biotechnology: a review. Orient Pharm Exp Med 19:1–13. https://doi.org/10.1007/s13596-018-0352-8

Nascimento IM (2010) Avaliação da atividade antipatogênica e enzimática de três fungos endofíticos de *Baccharis dracunculifolia* (Asteraceae). Monograph. Pontifícia Universidade Católica de Minas Gerais. 36p

Nascimento TL, Oki Y, Lima DMM, Almeida-Cortez JS, Fernandes GW, Souza-Motta CM (2015) Biodiversity of endophytic fungi in different leaf ages of *Calotropis procera* and their antimicrobial activity. Fungal Ecol 14:79–86. https://doi.org/10.1016/j.funeco.2014.10.004

Oki Y, Fernandes GW, Corrêa Júnior A (2008) Fungos: Amigos ou inimigos? Ciênc Hoje 42:64–66

Oki Y, Soares NR, Belmiro MS, Correa-Junior A, Fernandes GW (2009) The influence of the endophytic fungi on the herbivores from *Baccharis dracunculifolia* (Asteraceae). Neotrop Biol Conserv 4:83–88. https://doi.org/10.4013/5119

Oki Y, Goto BT, Jobim K, Rosa LH, Ferreira MC, Coutinho ES, de Xavier JHA, Carvalho F, de Souza MFM, Berbara RLL, Fernandes GW (2016) Arbuscular mycorrhiza and endophytic fungi in ruspestrian grasslands. In: Fernandes GW (ed) Ecology and conservation of mountaintop grasslands in Brazil. Springer, Switzerland, pp. 157–179

Oki Y, Arantes-Garcia L, Costa MB, Nunes BC, Silveira BR, Gélvez-Zúñiga I, Franco A, Fernandes GW (2020) CO_2 fertilizer effect on growth, polyphenols, and endophytes in two *Baccharis* species. Braz Arch Biol Technol 63:e20190302. https://doi.org/10.1590/1678-4324-2020190302

Oki Y, Nascimento IM, Costa NB, Maia RA, Takahashi JA, Ferraz V, Fernandes GW (2021) Effectiveness of endophytic fungi from *Baccharis dracunculifolia* against sucking insects and fungal pathogens. In: Rosa LH (ed) Neotropical endophytic fungi. Springer. pp.337–349

Onofre SB, Steilmann P (2012) Phenoloxidases produced by endophytic fungi isolated from *Baccharis dracunculifolia* D. C. (Asteraceae). Resour Environ 2:271–274. https://doi.org/10.5923/j.re.20120206.04

Onofre SB, Bonfante T, Santos ZMQ, Moura MC, Cardoso AF (2014) Cellulase production by endophytic strains of *Trichoderma reesei* from *Baccharis dracunculifolia* DC (Asteraceae). Adv Microbiol 4:275–283. https://doi.org/10.4236/aim.2014.45034

Páez-Espino D, Tamames J, Lorenzo V, Canovas D (2009) Microbial responses to environmental arsenic. Biometals 22:117–130. https://doi.org/10.1007/s10534-008-9195-y

Pinheiro HT, Teixeira JB, Francini-Filho RB, Soares-Gomes A, Ferreira CEL, Rocha LA (2019) Hope and doubt for the world's marine ecosystems. Perspect Ecol Conser 17:19–25

Pokazeev K, Sovga E, Chaplina T (2021) Main natural and anthropogenic sources of pollution of the Black Sea, its shelf zones and small water reservoirs. In: Pokazeev K, Sovga E, Chaplina T (eds) Pollution in the Black Sea. Springer Oceanography. Springer, Cham. https://doi.org/10.1007/978-3-030-61895-7_9

Raps A, Vidal S (1998) Indirect effects of an unspecialized endophytic fungus on specialized plant-herbivorous insect interactions. Oecologia 114:541–547. https://doi.org/10.1007/s004420050478

Rizzo I, Varsavky E, Haidukowski M, Frade H (1997) Macrocyclic trichothecenes in *Baccharis coridifolia* plants and endophytes and *Baccharis artemisioides* plants. Toxicon 35:753–757. https://doi.org/10.1016/S0041-0101(96)00149-3

Rodriguez RJ, Redman RS, Henson JM (2004) The role of fungal symbioses in the adaptation of plants to high stress environments. Mitig Adapt Strateg Glob Chang 9:261–272

Rosenberg E, Ron EZ (1996) Bioremediation of petroleum contamination. In: Crawford RL, Crawford DL (eds) Bioremediation: Principles and applications. Cambridge University Press, Cambridge, pp 100–124

Rusin C, Di Francesco A, Di Foggia M, D'Aquino S, Rombolà A, Tugnoli V, Bothelo RV, Baraldi E (2019) An emerging problem affecting apple production: *Neofusicoccum parvum*. *Aureobasidium pullulans* Le 1 and L8 strains as an alternative control strategy. Biol Control 134:157–162. https://doi.org/10.1016/j.biocontrol.2019.04.015

Sanchez-Azofeifa A, Oki Y, Fernandes GW, Ball RA, Gamon J (2012) Relationships between endophyte diversity and leaf optical properties. Trees 26:291–299. https://doi.org/10.1007/s11829-018-9597-x

Santos MB, Santos CY, Almeida MA, Santos CRS, Sant'Anna HLS, Santos OSN, Silva F, Martins GN (2010) Efeito inibitório in vitro de extrato vegetal de *Allium sativum* sobre *Aspergillus niger* Tiegh. Rev Bras Pl Med 12:13–17. https://doi.org/10.1590/1983-084X/12_150

Scherlach K, Hertweck C (2009) Triggering cryptic natural product biosynthesis in microorganisms. Org Biomol Chem 7:1753–1760. https://doi.org/10.1039/B821578B

Shah J (2005) Lipids, lipases and lipid modifying enzymes in plant disease resistance. Annu Rev Phytopathol 43:229–260. https://doi.org/10.1146/annurev.phyto.43.040204.135951

Smith CJ, Morin NR, Bills GF, Dombrowski AW, Salituro GM, Smith SK, Zhao A, MacNeil DJ (2002) Novel sesquiterpenoids from the fermentation of *Xylaria persicaria* are selective ligands for the NPY Y5 receptor. J Org Chem 67:5001–5004. https://doi.org/10.1021/jo011054+

Stierle AA, Stierle DB (2015) Bioactive secondary metabolites produced by the fungal endophytes of conifers. Nat Prod Commun 10:1671–1682. https://doi.org/10.1177/1934578X1501001012

Stierle A, Strobel G, Stierle D (1993) Taxol and taxane production by *Taxomyces andreanae*, an endophytic fungus of Pacific yew. Science 260:214–216. https://doi.org/10.1126/science.8097061

Sun X, Guo LD, Hyde KD (2011) Community composition of endophytic fungi in *Acer truncatum* and their role in decomposition. Fungal Divers 47:85–95. https://doi.org/10.1007/s13225-010-0086-5

Takesako K, Kuroda H, Inoue T, Haruna F, Yoshikawa Y, Kato I, Uchida K, Hiratani T, Yamaguchi H (1993) Biological properties of aureobasidin a, a cyclic depsipeptide antifungal antibiotic. J Antibiot 46:1414–1420. https://doi.org/10.7164/antibiotics.46.1414

Telli Karakoç F, Ediger D (2020) Oil pollution of the surrounding waters of Turkey. In: The handbook of environmental chemistry. Springer, Berlin/Heidelberg. pp. 1–26. https://doi.org/10.1007/698_2020_477

Van Etten ML, Prevost LB, Deen AC, Ortiz BV, Donovan LA, Chang SM (2008) Gender differences in reproductive and physiological traits in a gynodioecious species, *Geranium maculatum* (Geraniaceae). Int J Plant Sci 169:271–279. https://doi.org/10.1086/524109

Varaschin MS, Barros CS, Jarvis BB (1998) Intoxicação experimental por *Baccharis coridifolia* (Compositae) em bovinos. Pesq Vet Bras 18:65–68. https://doi.org/10.1590/S0100-736X1998000200006

Vieira ML, Johann S, Hughes FM, Rosa CA, Rosa LH (2014) The diversity and antimicrobial activity of endophytic fungi associated with medicinal plant *Baccharis trimera* (Asteraceae) from the Brazilian savannah. Can J Microbiol 60:847–856. https://doi.org/10.1139/cjm-2014-0449

Wallace CS, Rundel PW (1979) Sexual dimorphism and resource allocation in male and female shrubs of *Simmondsia chinensis*. Oecologia 44:34–39. https://doi.org/10.1007/BF00346394

Zhang P, Zhou PP, Yu LJ (2009) An endophytic taxol-producing fungus from Taxus media, *Cladosporium cladosporioides* MD2. Curr Microbiol 59:227–232

Zhang F, Li L, Niu S, Si Y, Guo L, Jiang X, Che Y (2012) A thiopyranchromenone and other chromone derivatives from an endolichenic fungus, *Preussia africana*. J Nat Prod 75:230–237. https://doi.org/10.1021/np2009362

Zhao J, Zhou L, Wang J, Shan T, Zhong L, Liu X, Gao X (2010) Endophytic fungi for producing bioactive compounds originally from their host plants. In: Méndez-Vilas A (ed) Current research, technology and education topics in applied microbiology and microbial biotechnology. Formatex Research Center, Badajoz, pp 567–576