

# Chapter 11

## Marine Fungi Associated with Antarctic Macroalgae



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**Abstract** Fungi are well known for their important roles in terrestrial ecosystems, but filamentous and yeast forms are also active components of microbial communities from marine ecosystems. Marine fungi are particularly abundant and relevant in coastal systems where they can be found in association with large organic substrata, like seaweeds. Antarctica is a rather unexplored region of the planet that is being influenced by strong and rapid climate change. In the past decade, several efforts have been made to get a thorough inventory of marine fungi from different environments, with a particular emphasis on those associated with the large communities of seaweeds that abound in littoral and infralittoral ecosystems. The algicolous fungal communities obtained were characterized by a few dominant species and a large number of singletons, as well as a balance among endemic, indigenous, and cold-adapted cosmopolitan species. The long-term monitoring of this balance and the dynamics of richness, dominance, and distributional patterns of these algicolous fungal communities is proposed to understand and model the influence of climate change on the maritime Antarctic biota. In addition, several fungal isolates from marine Antarctic environments have shown great potential as producers of bioactive natural products and enzymes and may represent attractive sources of biotechnological products.

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## 11.1 Introduction

Marine ecosystems represent an unexplored environment regarding microbial life, where about one million microorganisms (Bacteria, Archaea, viruses, and fungi) are found per milliliter of seawater (Glöckner et al. 2012). In the oceans around the world, microbes are key players in the biogeochemical cycling of carbon, nitrogen, phosphorus, silica, iron, and other trace elements (Nelson et al. 1996; Moore et al. 2002; Morel and Price 2003; Voss et al. 2013). They are at the base of the trophic net as primary producers, primary consumers, and decomposers and also are associated with macroorganisms as seaweeds and animals in both beneficial and harmful ways (Richmond 2004; Ramanam et al. 2016).

The role that fungi play in marine ecosystems is not as well-known and long documented as their role in terrestrial habitats. In fact, the field of marine mycology did not flourish until the publication of the book *Fungi in Oceans and Estuaries* of Johnson and Sparrow (1961) and the work of Kohlmeyer and Kohlmeyer compiled in their book *Marine Mycology* (1979). In this last publication, marine fungi were categorized into two major ecological groups: obligate and facultative marine fungi. Obligate marine fungi are those growing and sporulating exclusively in marine or estuarine habitats, while facultative marine fungi are those from freshwater and terrestrial milieus able to grow and possibly to sporulate in the marine environment. The dimension of marine fungal diversity has been estimated at about 10,000 species (Raghukumar 2017). However, only 1112 marine species have recently been listed by Jones et al. (2015), belonging mostly to *Ascomycota* (943 species), followed by *Basidiomycota* (96 species), asexual morphs (43 species), *Chytridiomycota* (26 species), *Zygomycota* (3 species), and *Blastocladiomycota* (1 species). It is clear that marine fungi do not represent a coherent phylogenetic group. Therefore, it seems likely that fungal adaptation to marine environments was the result of multiple terrestrial-marine transitions (Richards et al. 2012).

The distribution of fungi in marine environments is not uniform and is influenced primarily by the availability of dissolved oxygen and the presence of organic matter (Kohlmeyer et al. 2004). For instance, the open ocean is considered to be a fungal desert (Kohlmeyer and Kohlmeyer 1979). In this oligotrophic environment, scarce nutrients and enzymes secreted by fungi are likely to be lost by rapid diffusion in the water column. This is why osmotrophs are not favored in liquid environments as other heterotrophic microorganisms with a phagotrophic grazing behavior are (Richards et al. 2012). Nonetheless, the non-abundant and non-diverse fungal assemblages of these vast environments of the planet are considered to be dominated by ascomycetous and basidiomycetous yeasts (Bass et al. 2007; Kohlmeyer and Kohlmeyer 1979), even though sequence-based surveys are pointing out the presence of an overlooked diversity of deep-branching fungi related to chytrids (Richards et al. 2012).

In contrast to the open ocean, coastal environments sustain diverse fungal communities of filamentous and yeast forms belonging mostly to Dikarya. Most of them are found to be associated with a wide variety of substrata, including silt sediments, sand, corals, calcareous structures produced by mollusks and barnacles, living animals, decaying leaves of mangroves, wood, intertidal grasses, and seaweeds (Hyde et al. 1998; Kohlmeyer et al. 2004). These substrates from intertidal zones can also carry dormant propagules of terrestrial or freshwater fungi that are passively washed into the marine milieu. A surface sterilization of the substrate is considered sufficient to ascertain the true obligate or facultative marine nature of the fungi recovered. Otherwise, the term “marine-derived fungi” is used (Jones et al. 2015; Raghukumar 2017).

Macroalgae are particularly abundant in well-lit coastal environments and are considered the second largest source of marine-derived fungi, after corals, in these environments (Bugni and Ireland 2004). Among them, green algae grow abundantly in the intertidal zone, while red and brown algae prefer subtidal conditions. About a hundred fungal species have been described in association with seaweeds as parasites, saprobes, or endophytes (Raghukumar 2017; Suryanarayanan 2012). These are collectively known as “algicolous fungi,” a relatively unexplored group of fungi with great metabolic potential as producers of bioactive compounds (Furbino et al. 2014; Godinho et al. 2013).

In the past decade, important efforts have been made to unveil the diversity of marine fungi from different marine Antarctic ecosystems, with a particular emphasis on those associated with Antarctic seaweeds (Furbino et al. 2014, 2017; Godinho et al. 2013; Gonçalves et al. 2013, 2017; Loque et al. 2010). These advances will be discussed below.

## 11.2 Marine Antarctic Fungi

Antarctica is considered to be one of the harshest and most pristine ecosystems in the world where low temperature, low levels of organic nutrients, low water availability, strong winds, and strong UV radiation are found (Furbino et al. 2014). Still, under these conditions, microbial communities thrive (Santiago et al. 2017), and within these communities, many fungal species have been recovered from different terrestrial and marine substrates (Ruisi et al. 2007).

There are only few reports regarding marine substrates different from algae, including wood baits, invertebrate animals, and the deep-sea and marine sediments (Table 11.1). In samples of immersed wooden baits in Penguin Bay, Grasso et al. (1997) described nontypical marine fungal species, belonging to *Ascomycota* and their anamorphs. Henriquez et al. (2014) isolated from marine sponges 100 ascomycetes and, among them, members of the genera *Pseudogymnoascus* that produced bioactive compounds of antimicrobial and antitumoral activities. Using culture-independent techniques, Bass et al. (2007) evaluated water samples from the Drake Passage at different depths (250–500 m and 200–3000 m) and concluded that fungi are relatively rare in these deep-sea habitats, recovering mostly yeasts. Gonçalves et al. (2013) sampled core sediments from 100, 500, 700, and 1100 m in the

**Table 11.1** Marine Antarctic fungi from different habitats

Region	Substrate	Fungal taxa	Reference
Penguin Bay (Adelie Cove), South Georgia	Wooden baits	<i>Trichocladium achrasporum</i>	Grasso et al. (1997)
		<i>Trichocladium lignicola</i>	
		<i>Phoma</i> sp.	
		<i>Trichocladium constrictum</i>	
Drake Passage	Water column at different depth	Uncultured fungi	Bass et al. (2007)
Bransfield Strait of Admiralty Bay, King George Island	Sediment	<i>Penicillium solitum</i>	Gonçalves et al. (2013)
King George Island	Sponges	<i>Epicoccum</i> sp.	Henriquez et al. (2014)
		<i>Phoma</i> sp.	
		<i>Trichocladium</i> sp.	
		<i>Aureobasidium pullulans</i>	
		<i>Cladosporium</i> sp.	
		<i>Pseudogymnoascus</i> sp.	
		<i>Penicillium</i> sp.	
		<i>Thelebolus</i> sp.	
		Uncultured <i>Pseudeurotium</i> sp.	
Maxwell Bay, King George Island	Oligochaete <i>Grania</i> sp.	<i>Cystobasidium slooffiae</i>	Herrera et al. (2017)
		<i>Rhodotorula glutinis</i>	
		<i>Rhodotorula mucilaginosa</i>	
Bransfield and Gerlache Straits	Seawater	<i>Acremonium</i> sp.	Gonçalves et al. (2017)
		<i>Aspergillus pseudoglaucus</i>	
		<i>Cladosporium phaerospermum</i>	
		<i>Cystobasidium slooffiae</i>	
		<i>Exophiala xenobiotica</i>	
		<i>Glaciozyma antarctica</i>	
		<i>Graphium rubrum</i>	
		<i>Lecanicillium attenuatum</i>	
		<i>Metschnikowia australis</i>	
		<i>Penicillium chrysogenum</i>	
		<i>Penicillium citreosulfuratum</i>	
		<i>Purpureocillium lilacinum</i>	
		<i>Simplicillium aogashimaense</i>	

Admiralty Bay of King George Island and recovered only isolates of *Penicillium solitum* with amylasic and esterasic activities. Herrera et al. (2017) found different species of yeasts associated with the gut of *Grania* sp., an oligochaete that lives in marine interstitial habitats feeding on the debris of seaweeds. The authors suggested a possible mutualistic relationship between them. Recently, seawater samples at different depths of the Gerlache and Bransfield Straits in the Northern Antarctic Peninsula were collected by Gonçalves et al. (2017), and different yeasts and filamentous fungi were obtained, at high densities in some places. The authors brought the attention on underwater currents as a dispersal mechanism used by marine fungi across the Antarctic Ocean.

Antarctica is being influenced by strong and rapid climate change, mainly in the Peninsula region where temperatures have risen by 3 °C in 50 years and there is also evidence that indicates a warming of the circumpolar current and a loss of ice cover, particularly in the Antarctic islands (Bridge and Spooner 2012). This raises the question on how profoundly the effects of global change could affect the marine biota of Antarctica. In this regard, following changes in the patterns of richness, dominance, and distribution of marine fungal communities could help to understand the influence of these changes. A particular emphasis on the balance between endemic, indigenous, and cosmopolitan fungal species has been given in association with Antarctic macroalgae by Furbino et al. (2014), which may represent models to analyse possible climate changes in the Antarctic Ocean. Endemic species are characterized as true psychrophilic fungi that actively grow and reproduce only in Antarctica (Ruisi et al. 2007), while indigenous species are taxa recurrently recovered from a particular substrate in Antarctica but also appear in non-Antarctic sites (Arenz et al. 2014). Finally, cosmopolitan species are those species widely distributed that are able to grow at least under Antarctic summer conditions, showing a mesophilic or psychrophilic behavior (Furbino et al. 2014). A decrease in endemic species associated with an increase of cosmopolitan taxa within the fungal communities associated with endemic macroalgae is considered to reflect the influence of climate change in the maritime Antarctic Peninsula.

### 11.3 Algaliculous Antarctic Fungi

Marine seaweeds are the key primary producers in littoral and infralittoral ecosystems of the Antarctic. Indeed, it has been suggested that algal beds cover about 30% of the bottom surface in the maritime Antarctic, with an estimate of 74,000 tons of wet biomass around Admiralty Bay alone (Nedzarek and Rakusa-Suszczewski 2004). These communities are characterized by a high degree of endemism and the presence of cold-adapted species, mostly of red and brown algae (Wiencke and Clayton 2002; Wiencke and Amsler 2012; Wiencke et al. 2014). In a recent study, Pellizzari et al. (2017) identified 104 macroalgal taxa (28 Phaeophyceae, 24 Chlorophyta, and 52 Rhodophyta) in the South Shetland archipelago, demonstrating that their diversity is probably increasing because of more efficient sampling techniques or because of changes in biogeographical distribution. All these Antarctic

seaweeds shelter a community of symbiont, saprobe, and parasitic fungi. The structure of the fungal assemblage depends not only on the algal host species, but also on other factors like geographic isolation or the capability to tolerate or detoxify the array of antifungal metabolites produced by the seaweed (Suryanarayanan 2012). In addition, macroalgae from Antarctica show a wide plasticity regarding morphofunctional groups (filamentous, balloon-like, fleshy, terete, foliaceous, and calcareous algae) that could influence the development of particular fungal lineages.

Efforts have been made to get a thorough inventory of marine fungi associated with seaweeds from the Antarctic. The list of fungi recovered is summarized in Table 11.2 in relation to their algal hosts that are shown in Fig. 11.1. Loque et al. (2010) obtained 75 fungal isolates associated with three marine algae, with the fungus *Pseudogymanoascus pannorum* and the yeast *Metschnikowia australis* as the prevalent species. Godinho et al. (2013) and Furbino et al. (2014) surveyed the diversity of fungi associated with different sets of macroalgae. Both works obtained inventories of around 50 taxa and arrived to the same conclusion that fungal assemblages from a particular host were comprised by a few dominant species and a high number of singletons. Duarte et al. (2016) obtained 25 different taxa of yeasts from 9 algal species. Finally, Furbino et al. (2017) recovered 44 fungal isolates from 7 different seaweed species, with some of the isolates displaying agarolytic and carrageenolytic activities. This led the authors to hypothesize that the Antarctic macroalgae shelter saprobes fungi capable of producing enzymes with the potential to degrade algal biomass.



**Fig. 11.1** Macroalgal species collected in Antarctica and selected as hosts to recover algicolous fungi: (a) *Palmaria decipiens*, (b) *Gigartina skottsbergii*, (c) *Georgiella confluens*, (d) *Curdia racovitzae*, (e) *Iridaea cordata*, (f) *Pyropia endiviifolia*, (g) *Ulva flexuosa*, (h) *Acrosiphonia arcta*, (i) *Monostroma hariotii*, (j) *Adenocystis utricularis*, (k) *Cystosphaera jacquinotii*, (l) *Phaeurus antarcticus*, (m) *Ascoseira mirabilis*, (n) *Desmarestia* sp., and (o) *Himantothallus grandifolius*

**Table 11.2** List of fungal taxa described in association with macroalgae from Antarctica

Island	Macroalgae group	Macroalgae host	Fungal taxa	Reference
King George Island	Phaeophyceae	<i>Adenocystis utricularis</i>	<i>Metschnikowia australis</i>	Loque et al. (2010)
			<i>Pseudogymnoascus pannorum</i>	
			<i>Antarctomyces psychrotrophicus</i>	
			<i>Oidiodendron</i> sp.	
			<i>Penicillium</i> sp.	
			<i>Phaeosphaeria herpotrichoides</i>	
			<i>Rhodotorula mucilaginosa</i>	
		<i>Ascoseira mirabilis</i>	<i>Metschnikowia australis</i>	Furbino et al. (2017)
			<i>Antarctomyces pellizariae</i>	
			<i>Leucosporidiella fragaria</i>	
			<i>Beauveria bassiana</i>	
			<i>Cladosporium</i> sp.	
			<i>Leucosporidiella muscorum</i>	
		<i>Desmarestia menziesii</i>	<i>Metschnikowia australis</i>	Godinho et al. (2013)
			<i>Penicillium</i> sp.	
		<i>Cystosphaera jacquinotii</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)
			<i>Mrakia</i> sp.	
		<i>Himantothallus grandifolius</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)
			<i>Cryptococcus carnescens</i>	
			<i>Dioszegia xingshanensis</i>	
			<i>Cryptococcus victoriae</i>	
			<i>Cryptococcus</i> sp.	
			<i>Holtermanniella festucosa</i>	
			<i>Mrakia</i> sp.	
			<i>Holtermanniella nyarrowii</i>	
			<i>Leucosporidiella fragaria</i>	
			<i>Leucosporidiella muscorum</i>	
<i>Rhodotorula glacialis</i>				

(continued)

**Table 11.2** (continued)

Island	Macroalgae group	Macroalgae host	Fungal taxa	Reference	
		<i>Desmarestia anceps</i>	<i>Pseudogymnoascus pannorum</i>	Loque et al. (2010)	
			<i>Aureobasidium pullulans</i>	Duarte et al. (2016)	
			<i>Metschnikowia australis</i>		
			Ustilaginaceae		
	Rhodophyta	<i>Palmaria decipiens</i>	<i>Metschnikowia australis</i>		Loque et al. (2010) and Furbino et al. (2017)
			<i>Rhodotorula mucilaginosa</i>	Loque et al. (2010)	
			<i>Cryptococcus carnescens</i>	Furbino et al. (2017)	
			<i>Penicillium</i> sp.		
		<i>Pyropia endiviifolia</i>	<i>Metschnikowia australis</i>		Furbino et al. (2014)
			<i>Cladosporium</i> sp.		
			<i>Pseudogymnoascus</i> sp.	Duarte et al. (2016)	
			<i>Penicillium</i> sp.		
			<i>Dipodascus australiensis</i>		
		<i>Gigartina skottsbergii</i>	<i>Metschnikowia australis</i>		
			<i>Glaciozyma litorale</i>	Furbino et al. (2014)	
			<i>Glaciozyma martinii</i>		
			<i>Mrakia</i> sp.		
			<i>Rhodotorula glacialis</i>		
	Chlorophyta	<i>Monostroma hariotii</i>	<i>Metschnikowia australis</i>	Furbino et al. (2014)	
			<i>Guehomyces pullulans</i>		
			<i>Cryptococcus albidosimilis</i>		
			<i>Rhodotorula laryngis</i>		
			<i>Cryptococcus victoriae</i>		
			<i>Pseudogymnoascus</i> sp.		
			<i>Rhodotorula mucilaginosa</i>		
			<i>Cystofilobasidium infirmominiatum</i>		
			<i>Meyerozyma guilliermondii</i>		
			<i>Cryptococcus adeliensis</i>		
			<i>Rhodotorula minuta</i>		

(continued)



**Table 11.2** (continued)

Island	Macroalgae group	Macroalgae host	Fungal taxa	Reference
		<i>Acrosiphonia arcta</i>	<i>Pseudogymnoascus</i> sp. <i>Metschnikowia australis</i> <i>Penicillium</i> sp. <i>Candida sake</i> <i>Cladosporium</i> sp. <i>Cladosporium tenuissimum</i> <i>Debaryomyces hansenii</i> <i>Mortierella</i> sp. <i>Phoma</i> sp. <i>Thelebolus globosus</i>	Godinho et al. (2013)
Deception	Chlorophyta	<i>Monostroma harti</i>	<i>Aspergillus tabacinus</i>	Furbino et al. (2014)
			<i>Pseudogymnoascus</i> sp.	
			<i>Penicillium</i> sp.	Godinho et al. (2013)
			<i>Pseudogymnoascus destructans</i>	
			<i>Meyerozyma guilliermondii</i>	
			<i>Cryptococcus</i> cf. <i>laurentii</i>	
			<i>Cordycipitaceae</i> sp.	
			<i>Helotiales</i> sp.	
			<i>Hyaloscyphaceae</i> sp.	
			<i>Mrakia</i> sp.	
	Phaeophyceae	<i>Adenocystis utricularis</i>	<i>Debaryomyces hansenii</i>	Godinho et al. (2013)
			<i>Meyerozyma caribbica</i>	
			<i>Penicillium</i> sp.	
			<i>Aspergillus conicus</i>	
			<i>Pseudogymnoascus</i> sp.	
		<i>Penicillium citrinum</i>		
Rhodophyta	<i>Iridaea cordata</i>	<i>Metschnikowia australis</i>	Furbino et al. (2017)	
		<i>Pseudogymnoascus</i> sp.		
		<i>Doratomyces</i> sp.		
		<i>Penicillium</i> sp.		
	<i>Pyropia endiviifolia</i>	<i>Penicillium</i> sp.	Furbino et al. (2014)	
		<i>Meyerozyma guilliermondii</i>		
		<i>Pseudogymnoascus</i> sp.		
		<i>Verticillium</i> sp.		
		<i>Aspergillus</i> sp.		
		<i>Lecanicillium</i> sp.		
	<i>Palmaria decipiens</i>	<i>Cryptococcus magnus</i>	Duarte et al. (2016)	
		<i>Dioszegia athyri</i>		
		<i>Rhodotorula marina</i>		
		<i>Ustilaginaceae</i>		
		<i>Tilletiopsis washingtonensis</i>		

(continued)

**Table 11.2** (continued)

Island	Macroalgae group	Macroalgae host	Fungal taxa	Reference
Elephant	Chlorophyta	<i>Monostroma harti</i>	<i>Penicillium steckii</i>	Furbino et al. (2014)
			<i>Penicillium</i> sp.	
			<i>Aspergillus</i> sp.	
			<i>Cladosporium</i> sp.	
			<i>Penicillium citrinum</i>	
			<i>Penicillium crustosum</i>	
Chlorophyta	<i>Ulva intestinalis</i>	<i>Penicillium</i> sp.	Godinho et al. (2013)	
		<i>Penicillium discolor</i>		
		<i>Antarctomyces psychrotrophicus</i>		
		<i>Cryptococcus victoriae</i>		
		<i>Engyodontium</i> sp.		
		<i>Geomyces luteus</i>		
		<i>Helotiales</i> sp.		
		<i>Mycarthris</i> cf. <i>corallines</i>		
		<i>Thelebolus globosus</i>		
		Rhodophyta		<i>Palmaria decipiens</i>
<i>Geomyces</i> sp.				
<i>Acremonium</i> sp.				
<i>Fusarium</i> sp.				
<i>Yamadazyma mexicana</i>				
<i>Aspergillus</i> sp.				
<i>Chaetomium</i> sp.				
<i>Penicillium spinulosum</i>				
<i>Pyropia endiviifolia</i>	<i>Cadophora malorum</i>		Furbino et al. (2014)	
	<i>Penicillium</i> sp.			
	<i>Pseudogymnoascus</i> sp.			
	<i>Thelebolus globosus</i>			
	<i>Aspergillus</i> sp.			
	<i>Antarctomyces psychrotrophicus</i>			
	<i>Cladosporium lignicola</i>			
<i>Aspergillus protuberus</i>				
Phaeophyceae	<i>Phaeurus antarcticus</i>	<i>Penicillium</i> sp.	Godinho et al. (2013)	
		<i>Pseudogymnoascus</i> sp.		
		<i>Aspergillus terreus</i>		
		<i>Eurotium herbariorum</i>		
		<i>Eurotium repens</i>		
		<i>Penicillium steckii</i>		

(continued)

**Table 11.2** (continued)

Island	Macroalgae group	Macroalgae host	Fungal taxa	Reference
Livingston	Rhodophyta	<i>Curdiea racovitzae</i>	<i>Metschnikowia australis</i>	Furbino et al. (2017)
		<i>Gigartina skottsbergii</i>	<i>Metschnikowia australis</i>	Furbino et al. (2017)
			<i>Penicillium</i> sp.	
Robert	Phaeophyceae	<i>Ascoseira mirabilis</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)
		<i>Adenocystis utricularis</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)
			<i>Glaciozyma litorale</i>	
			<i>Sporidiobolus pararoseus</i>	
			<i>Pseudozyma</i> sp.	
			<i>Ustilaginaceae</i> sp.	
		<i>Pseudozyma tsukubaensis</i>		
		<i>Desmarestia menziesii</i>	<i>Candida sake</i>	Duarte et al. (2016)
			<i>Metschnikowia australis</i>	
			<i>Glaciozyma litorale</i>	
	<i>Mrakia</i> sp.			
	Rhodophyta	<i>Gigartina skottsbergii</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)
			<i>Mrakia</i> sp.	
<i>Leucosporidiella muscorum</i>				
<i>Iridaea cordata</i>		<i>Metschnikowia australis</i>	Duarte et al. (2016)	
		<i>Glaciozyma litorale</i>		
Nelson	Phaeophyceae	<i>Desmarestia menziesii</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)
			<i>Mrakia</i> sp.	
Half Moon	Rhodophyta	<i>Curdiea racovitzae</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)
			<i>Sporidiobolus pararoseus</i>	
		<i>Gigartina skottsbergii</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)
			<i>Mrakia</i> sp.	
	<i>Iridaea cordata</i>	<i>Metschnikowia australis</i>	Duarte et al. (2016)	
Robert	Rhodophyta	<i>Georgiella confluens</i>	<i>Metschnikowia australis</i>	Furbino et al. (2017)
			<i>Cladosporium</i> sp.	
			<i>Coprinellus radians</i>	
			<i>Penicillium</i> sp.	
			<i>Rhodotorula mucilaginosa</i>	

Some fungal species were recovered from several algal species and appear to be endemic to the Antarctic. This is the case of the ascomycetous yeast *M. australis* that was obtained in all the abovementioned surveys associated to very different kinds of seaweeds. This particular species was also recovered from Antarctic seawater (Fell and Hunter 1968), from the stomach of the Antarctic krill *Euphausia superba* (Donachie and Zdanowski, 1998), in Antarctic freshwater and marine sediments (Vaz et al. 2011), and it was the only fungus obtained from the intravesicular liquid of *Adenocystis utricularis* (Loque et al., 2010).

*Antarctomyces* includes only two known species, which are considered endemic to Antarctica: *A. psychrotrophicus* and *A. pellizariae*. The former one has been isolated from the macroalgal species *Ascoseira mirabilis* (Furbino et al., 2017), *Ulva intestinalis* (Godinho et al., 2013), and *Pyropia endiviifolia* (Furbino et al., 2014) but also from other Antarctic environments such as soils (Stchigel et al. 2001), freshwater lakes (Gonçalves et al. 2012), and lichen thalli (Santiago et al. 2015) and as a symbiotic endophyte of the Antarctic grass *Deschampsia antarctica* (Rosa et al. 2009). *A. pellizariae* represents a new blue-pigmented species recently reported in Antarctic snow (de Menezes et al. 2017).

*Pseudogymnoascus pannorum* and its anamorphic stage *G. pannorum* are another species considered to be endemic to Antarctica (Arenz et al. 2014) that were isolated from *Adenocystis utricularis* and *Desmarestia anceps* (Loque et al., 2010). However, other species of this genus are considered indigenous because of their ubiquitous distribution in cold regions. In general, *Pseudogymnoascus* species are considered truly psychrophilic and halotolerant, being able to utilize different carbon sources, with particular cellulolytic and keratinolytic activities (Mercatini et al. 1989). Several isolates of *Pseudogymnoascus* not assigned to a particular species were isolated from other algal species in other marine Antarctic surveys (Furbino et al. 2014, 2017; Godinho et al. 2013). Other indigenous fungi associated with Antarctic seaweeds are *Cadophora malorum*, *Cryptococcus victoriae*, *Cryptococcus adeliensis*, and *Mortierella antarctica* (Furbino et al., 2014).

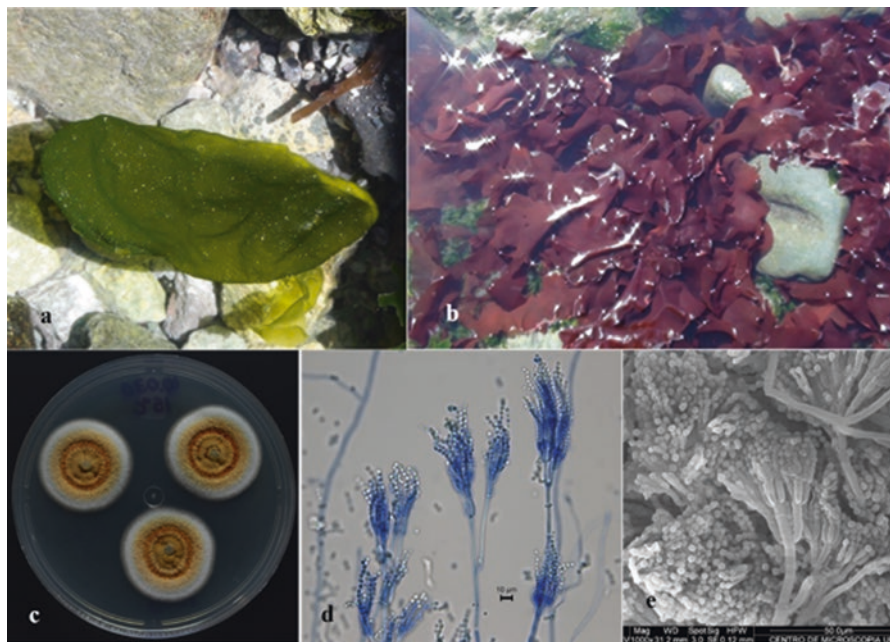
The cosmopolitan genus *Penicillium* has been recovered from several Antarctic seaweeds (Furbino et al. 2014, 2017; Godinho et al. 2013; Loque et al. 2010) but also in other Antarctic environments such as soils (Azmi and Seppelt 1998), lakes (Ellis-Evans 1996), wood (Arenz et al. 2006), marine sediments (Gonçalves et al. 2013), in permafrost (Zucconi et al. 2012). According to Bugni and Ireland (2004), *Penicillium* represents one of the most common genera isolated from macroalgae. However, the endophytic nature of the association was questioned because members of this genus are usually washed out when surface-sterilization protocols are used on the host (Zuccaro et al. 2003). Conversely, the fact that some *Penicillium* isolates associated with seaweeds displayed agarolytic and carrageenolytic activities suggests that their presence is not merely a contamination of propagules from other environments but rather indicates their possible role as latent saprobes on algal tissues (Furbino et al. 2017). Other cold-adapted cosmopolitan species associated with Antarctic seaweeds are *Cryptococcus albidosimilis*, *Guehomyces pullulans*, *Meyerozyma guilliermondii*, *Phoma herbarum*, *Rhodotorula laryngis*, *Rhodotorula mucilaginoso*, and *Rhodotorula minuta* (Furbino et al., 2014).

## 11.4 Biotechnological Potential of Antarctic Algaliculous Fungi

Algaliculous fungi are considered particularly capable of producing secondary metabolites with novel bioactivities of pharmaceutical and agricultural interest (Bugni and Ireland 2004; Suryanarayanan 2012). In fact, marine fungi associated

with diverse green, red, and brown seaweeds have been reported to produce strong antioxidants as well as antialgal, antifungal, and antiinsect metabolites. These metabolites may help in deterring colonization of algal thalli by other microbes, in warding off herbivores, and in protecting the algal host from stresses (Suryanarayanan et al. 2010, 2012).

Particular interest has been given to Antarctic fungi because their ability to survive in extremely harsh conditions was considered suggestive of the presence of unusual biochemical pathways that could lead to new bioactive compounds (Santiago et al. 2012). Despite this, only few studies were performed dealing with the metabolic capabilities of marine Antarctic fungi in general and Antarctic algicolous fungi in particular (Furbino et al. 2014; Godinho et al. 2013; Gonçalves et al. 2015). Among those studies, Godinho et al. (2013) reported the bioactive compounds produced by two distinct *Penicillium* sp. isolates recovered from the macroalgae *Monostroma harti* and *Palmaria decipiens* (Fig. 11.2). Extracts displayed high and selective antifungal activities against the plant pathogen *Cladosporium sphaerospermum* and trypanocidal activities against *Trypanosoma cruzi*, the etiological agent of Chagas disease, with NMR spectral data suggesting the presence of highly functionalized aromatic compounds. The work of Furbino et al. (2014) also showed that several algicolous isolates of *Pseudogymnoascus* spp., *Dipodascus australiensis*, *Guehomyces pullulans*, and *Metschnikowia australis* were able to



**Fig. 11.2** Algicolous *Penicillium* isolates and their algal hosts. (a) *Monostroma harti*, (b) *Palmaria decipiens*, (c) *Penicillium* sp. colonies, and (d, e) conidiophores of *Penicillium* sp. (optical and scanning electron microscopy, respectively)

produce bioactive natural products with selective antifungal activities against *Candida albicans*, *Candida krusei*, and *C. sphaerospermum*. Additionally, the authors demonstrated that *Penicillium steckii* isolated from *M. hariatii* was able to produce antiviral compounds that inhibited the yellow fever virus (Furbino et al. 2014).

Algaliculous fungi from Antarctica could also be of industrial interest because of their hydrolytic enzymes. Cold-adapted enzymes have considerable potential application in the food, fine chemical, and bioethanol industries because they have high specific activities at low and moderate temperatures and are inactivated by moderate temperature increases (Gerday et al. 2000). In this sense, Furbino et al. (2017) reported that *Beauveria bassiana*, *Penicillium chrysogenum*, *Penicillium* sp., *Pseudogymnoascus* sp., *Cladosporium* sp., and *Doratomyces* sp. displayed carrageenolytic and agarolytic activities. These results suggest that the Antarctic macroalgae shelter fungal saprobes are able to produce enzymes with potential to degrade the algal biomass and release essential minerals in the ocean surrounding. Finally, Gonçalves et al. (2013) recovered isolates of *Penicillium solitum* from Antarctic marine sediments with amylasic and esterase activities. All these studies highlight the need to discover and preserve this valuable fungal germplasm given that some cold-requiring species may not be able to persist in a warming environment.

## 11.5 Conclusion and Perspectives

Antarctica, especially the maritime region, has been considered to be influenced by strong and rapid climate change. Fungi and other microbes living in marine environments are likely to be perturbed by these changes. Given this situation, several efforts have been made to inventory and preserve *ex situ* the fungal components of different communities, particularly those associated with endemic seaweeds. The long-term monitoring of the balance and dynamics of richness, dominance, and distributional patterns among endemic, indigenous, and cosmopolitan fungal taxa might be used to understand and model the influence of climate change on the maritime Antarctic biota. In this regard, species like *M. australis*, *A. psychrotrophicus*, and species of *Pseudogymnoascus* that were isolated from different seaweeds are considered endemic to Antarctica. Instead, other algaliculous fungi as members of the genera *Penicillium*, *Cryptococcus*, and *Rhodotorula* are considered cold-adapted cosmopolitan species. A decrease in the above mentioned endemic species associated with an increase of cosmopolitan taxa within the fungal communities would reflect the influence of climate change in the Peninsula region of Antarctica. This is why it is of fundamental interest to continue monitoring these fungal communities.

In addition, several fungal isolates from marine Antarctic environments have shown great potential as producers of bioactive natural products and enzymes and may represent attractive sources of biotechnological products. However, the diversity, ecological role, and biotechnological application of Antarctic marine fungi are

still quite unexplored. Further research is necessary to unveil the fungal diversity associated with different substrates and environments from the Antarctic. The obtained fungal assemblages should be preserved in collections to serve as models in ecological, evolutionary, and biotechnological approaches.

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