Chapter 8
Mangrove Macroalgal Communities

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8.1 Introduction

Despite the high variation in abiotic parameters in estuaries, mangroves harbor a great diversity of organisms, from primary producers to consumers in high trophic levels. This ecosystem's macroalgal community shows a characteristic low species diversity (Oliveira 1984), growing on pneumatophores, seedlings, saplings, roots, and in the lower trunks of mangrove trees, including *Rhizophora mangle* L., *Avicennia schaueriana* Stapf & Leechmann, and *Laguncularia racemosa* (L.) Gaertner (Cordeiro-Marino et al. 1992).

Mangrove macroalgae are essential components of coastal ecosystems, providing several ecological services, such as nutrient retention, habitat provision, breeding and spawning grounds, and food source to diverse invertebrates and larvae of marine and terrestrial organisms. These will then serve as food for juvenile stages of fishes

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and invertebrates of commercial importance. Therefore, mangrove macroalgae have a primordial role in the maintenance of life and contribute significantly to the conservation of coastal and marine biodiversity.

8.2 Species Composition

The macroalgal community growing on the several microhabitats in the mangrove trees (Figs. 8.1–8.4) is dominated by a few genera, mainly *Bostrychia* Mont., *Caloglossa* (Harv.) G. Martens, and *Catenella* Grev. This assemblage is widely known as "Bostrychietum" (sensu Post 1968). Although composed of a few red algae, the delimitation of these species within each genus is quite complicated due to the wide morphological plasticity.

In Brazil, before Fontes (2012), Kano (2015), and Sena (2016), the identification of the mangrove macroalgae was primarily based on morphological features. The identification of specimens based solely on morphological characters may result in either underestimation or overestimation of diversity, since the phenotypic plasticity

Figs. 8.1–8.4 Mangrove macroalgal community. **8.1–8.2**: Macroalgal assemblage growing on the pneumatophores, rhizosphere, and on the trunks of mangrove trees at Rio Escuro, Ubatuba, São Paulo State (see Chap. 1 for location) (Bostrychietum *sensu* Post 1968). **8.3–8.4**: Details of the Bostrychietum (scale = 5 mm)

Table 8.1 Macroalgal species reported to the Brazilian mangroves

RHODOPHYTA
Ceramiales
Delesseriaceae
Caloglossa apomeiotica J.A. West and Zuccarello
C. confusa Krayesky, J.A. West and Kamiya
C. kamiyana Freshwater, Cath.E. Miller and Frankovich[a]
C. leprieurii (Mont.) G. Martens
C. rotundata Kamiya
Rhodomelaceae
Bostrychia binderi Harvey
B. calliptera (Mont.) Mont.
B. kelanensis Grunow ex E. Post
B. montagnei Harv.
B. moritziana (Sond. ex Kütz.) J. Agardh
B. pilulifera Mont.
B. radicans (Mont.) Mont.
B. tenella (J.V. Lamour.) J. Agardh
Dawsoniocolax bostrychiae (A.B.Joly & Yam.-Tomita) A.B.Joly & Yam.-Tomita
Gigartinales
Caulacanthaceae
Catenella caespitosa (Wither.) L.M. Irvine
CHLOROPHYTA
Ulotrichales
Gayraliaceae
Gayralia brasiliensis Pellizzari, M.C. Oliveira and N.S. Yokoya
G. oxysperma (Kütz.) K.L. Vinogr. ex Scagel et al.
Bryopsidales
Udoteaceae
Boodleopsis pusilla (Collins) W.R. Taylor, A.B. Joly and Bernat.
B. vaucherioidea Calderón-Saenz and Schnetter
Cladophorales
Boodleaceae
Cladophoropsis membranacea (C. Agardh) Børgesen
Cladophoraceae
Pseudorhizoclonium africanum (Kütz.) Boedeker
Rhizoclonium riparium (Roth) Kütz. ex Harv.

Sources: Paula et al. (1989), Fujii et al. (1990), Fontes (2012), Pellizzari et al. (2013), Sena (2016), Fontes et al. (2016), Kano et al. (2017), Wynne (2017), and Freshwater et al. (2021)

[a] *Caloglossa kamiyana* from Brazilian mangroves was previously identified as *C. ogasawaraensis* Okamura

of some taxa may lead to misidentifications (Krayesky et al. 2012). Sena (2016) and Kano et al. (2017) have used molecular approaches based on the 5’ region of the cox1 gene that encodes cytochrome c oxidase subunit 1 (COI-5P), as proposed by Saunders (2005); the universal plastid amplicon (UPA), as proposed for DNA barcoding in algae (Presting 2006; Sherwood and Presting 2007), and the gene encoding for the large subunit of RuBisCO (rbcL), which was tested as a DNA barcoding tool (Saunders and Kucera 2010).

The current estimation of the most common macroalgae in Brazilian mangroves points to 22 species (Table 8.1), with fifteen Rhodophyta and seven Chlorophyta

(Hadlich and Bouzon 1985; Paula et al. 1989; Fujii et al. 1990; Fontes 2012; Pellizzari et al. 2013; Fontes et al. 2016; Sena 2016; Kano et al. 2017; Wynne 2017; Freshwater et al. 2021). In some of these studies, the authors revealed that many taxa are genetically more diverse than what the morphology suggests. Species among the genus *Caloglossa* are specifically challenging to identify because of their widespread phenotypic plasticity (Kamiya et al. 1999, 2016; Krayesky et al. 2011, 2012; Kano et al. 2017; Wynne 2017; Freshwater et al. 2021). Some red algae have a more specific occurrence in Brazilian mangroves such as *Murrayella periclados* (C. Agardh) F. Schmitz, *Polyshiphonia subtilissima* Montagne*, P. tepida*, and *P. howei* (Cunha et al. 1999, Cutrim et al. 2004, Fontes et al. 2016, Farraboti 2018). In Brazil, the two last species are currently named *Vertebrata foetidissima* (Cocks ex Bornet) Díaz-Tapia and Maggs, and *Wilsonosiphonia fujiae* D. Bustamante, Won, and T.O. Cho, respectively. Few green algae had also occasional occurrences, as *Caulerpa fastigiata* Montagne (Fontes et al. 2007), *Cladophora vagabunda* (L.) Hoek, *Ulva flexuosa* Wulfen and *Chaetomorpha* sp. (Machado and Nassar 2007).

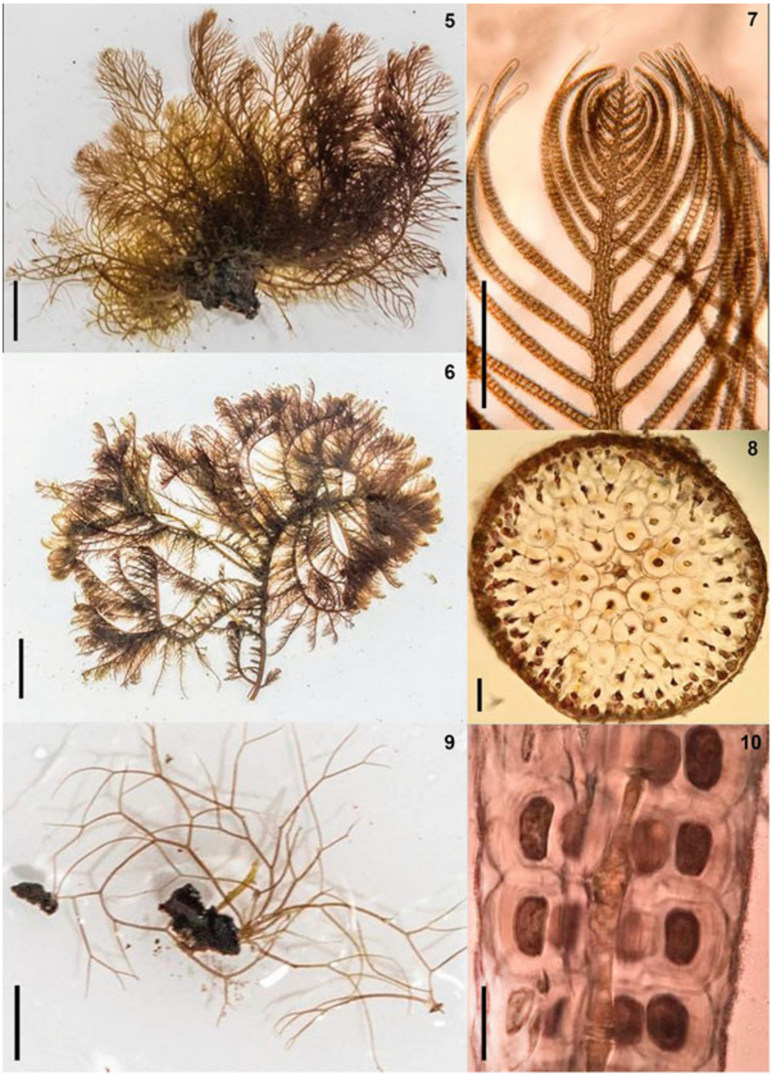
The most diverse genus is *Bostrychia*, comprising eight species widely distributed in mangroves (Menezes et al. 2015). The species of *Bostrychia* present morphological differences that allow their identification (Figs. 8.5–8.10). The thalli of *Bostrychia* are polysiphonous, typical of Rhodomelaceae, and the species distinction is based on the branching pattern, presence or absence of cortication, degree of polysiphonous branches, and the type of haptera (King and Puttock 1989).

Two types of haptera are described in *Bostrychia* species: Cladohapteron and peripherohapteron. The first is originated from pericentral and axial cells, like a first main branching with negative geotropism to attach to the substrate. Cladohapteron is found in *B. kelanensis*, *B. moritziana, B. pilulifera*, and *B. radicans*. On the other hand, peripherohapteron is originated from pericentral and cortical cells in the ventral side of the stoloniferous branches, and it can be found in *B. binderi*, *B. calliptera, B. montagnei,* and *B. tenella*.

Molecular and phylogenetic data have provided advances for the knowledge of the taxonomy of the genus *Bostrychia*. An important example is the *B. tenella* complex, in which *B. binderi* was synonymized to *B. tenella*, since the morphological characters to distinguish both species overlapped (King et al. 1988; King and Puttock 1989). However, *B. binderi* was resurrected from *B. tenella* species complex based on molecular and morphological data of specimens collected worldwide (Zuccarello et al. 2015).

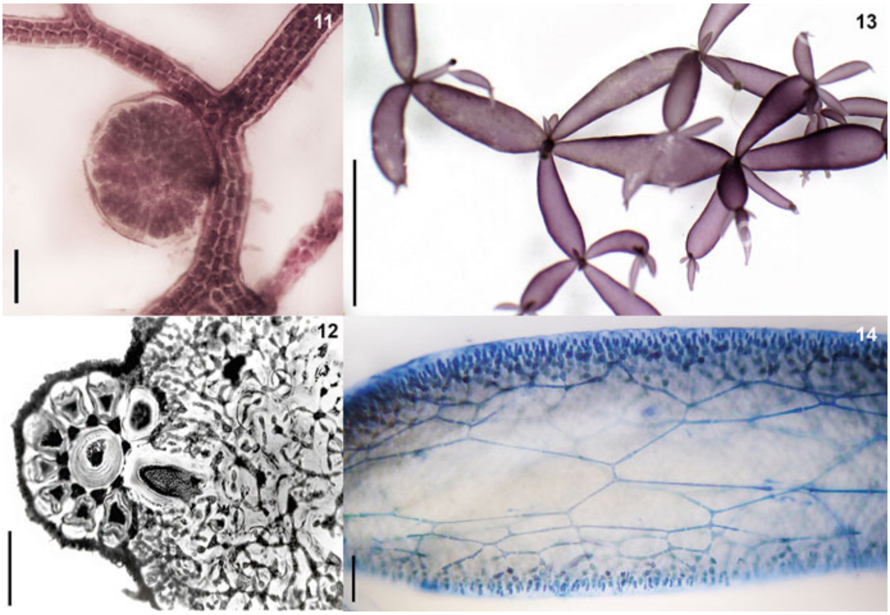
Dawsoniocolax bostrychiae is a Rhodomelacean adelphoparasite originally described growing on *Bostrychia radicans* (Figs. 8.11–8.12), and later also on *B. moritziana*. The thallus is small shaped with whitish warts. Guimarães (1993) described reproductive structures of female and male gametophytes as tetrasporophytes.

Among the red algal species growing on mangroves, the only one not belonging to Ceramiales is *Catenella caespitosa* (Caulacanthaceae, Gigartinales). This species is easily recognized by its cartilaginous, segmented sausage-shaped thallus (Figs. 8.13–8.14).



Figs. 8.5–8.10 Species of *Bostrychia* (Ceramiales, Rhodophyta) in Brazilian mangroves. **8.5**: *B. radicans* (scale = 5 mm). **8.6**: *B. montagnei*, gross morphology (scale = 5 mm). **8.7**. *B. calliptera*, detail of the thallus (scale = 100 μm). **8.8**: *B. montagnei*, cross section of the thallus showing dense cortication (scale = 25 μm). **8.9–8.10**: *B. kelanensis*, gross morphology (scale = 1 mm), and longitudinal section of the ecorticated thallus (scale = 50 μm)

In Brazil, the genus *Caloglossa* is represented by five species: *C. apomeiotica*, *C. confusa*, *C. leprieurii*, *C. kamiyana*, and *C. rotundata* (Figs. 8.15–8.20). Except for *C. kamiyana*, the other four species are morphologically similar, and the diagnostic characteristics are difficult to distinguish. Nevertheless, these taxa are genetically different (Kano et al. 2017). The main morphological characteristics used to

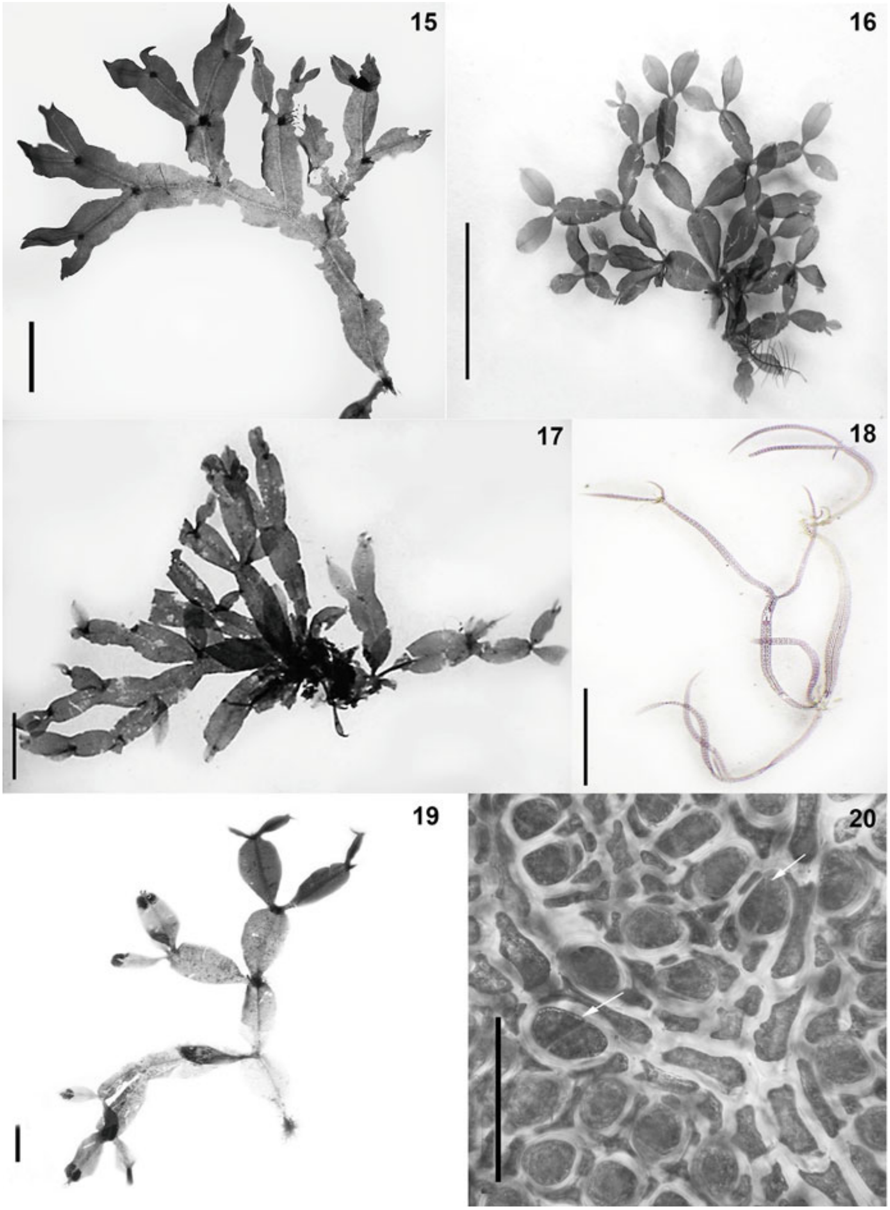


Figs. 8.11–8.14 Species of Rhodophyta in Brazilian mangroves. **8.11–8.12**: *Dawsoniocolax bostrychiae*, a Rhodomelacean adelphoparasite growing on *Bostrychia radicans* (scale = 300 μm); and cross section of *Bostrychia radicans* with *Dawsoniocolax bostrychiae* (scale = 100 μm). **8.13–8.14**: *Catenella caespitosa,* gross morphology (scale = 5 mm); and detail of the thallus in cross section (scale = 200 μm)

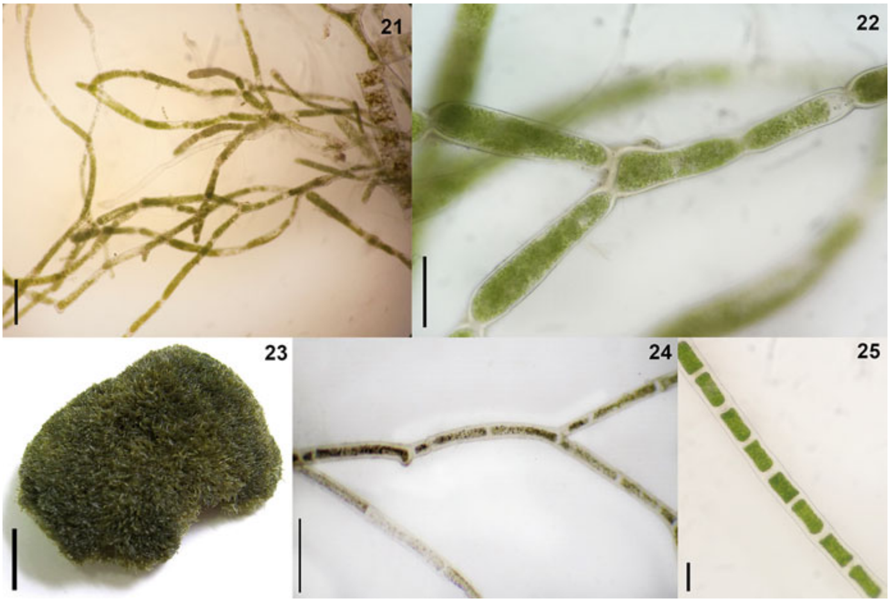
identify *Caloglossa* species are thallus size, blade shape, type and number of rhizoids per cell and their distribution along the thalli, and characteristic of vein on the blade.

Considering the Chlorophyta, mangrove green algae have filamentous thalli as found in Bryopsidales and Cladophorales, exemplified by *Boodleopsis pusilla*, *Cladophoropsis membranacea*, and *Rhizoclonium riparium* (Figs. 8.21–8.25). *Boodleopsis* is characterized by cenocytic, divaricately branched thalli (Figs. 8.21–8.22), and the distinction between *Boodleopsis pusilla* and *B. vaucherioidea* is based on the dichotomy degree. The first species presents regularly constricted thalli, and the angle of dichotomy is smaller than that presented by *B. vaucherioidea*, which has divaricated branching with an angle of 90–140°, without constrictions.

Among the monostromatic green algae described in Brazilian mangroves, two taxa were recognized based on the differences in life history, thallus ontogeny, and type of swarmer liberation: *Monostroma* sp. (zoospores germinate into a laminar blade) and *Ulvaria oxysperma* (Kützing) Bliding (zoospore germination gives rise to a saccate stage, and later forming laminar blade) (Cordeiro-Marino et al. 1993; Braga 1997). However, *U. oxysperma* is currently regarded as a synonym of *Gayralia oxysperma* (Kützing) K.L.Vinogradova ex Scagel et al. (Guiry and Guiry 2018).



Figs. 8.15–8.20 Species of *Caloglossa* in Brazilian mangroves: **8.15–8.16** *C. apomeiotica*, gross morphology (scale = 10 mm) and detail of the bisporangia in surface view (arrows, scale = 100 μm). **8.17** *C. confusa* (scale = 1 mm). **8.18** *C. leprieurii* (scale = 5 mm). **8.19** *C. kamiyana* (scale = 10 mm). **8.20** *C. rotundata* (scale = 10 mm). (Modified from Kano et al. 2017)



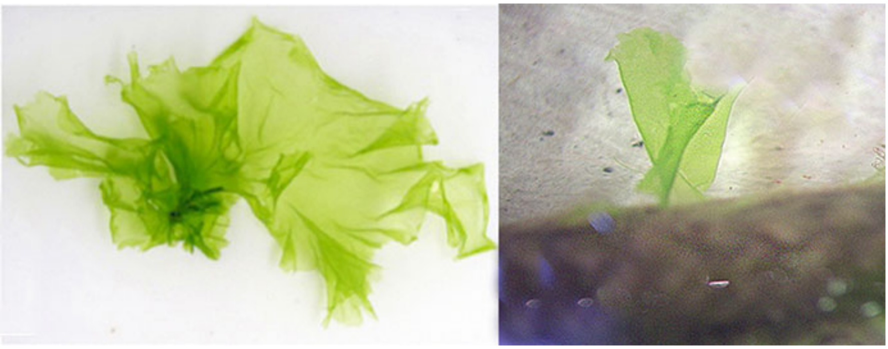
Figs. 8.21–8.25 Species of Chlorophyta in Brazilian mangroves. **8.21–8.22**: Cenocytic, divaricately branched and regularly constricted thalli in *Boodleopsis pusilla* (scales = 200 and 50 μm). **8.23**: *Cladophoropsis membranacea*, gross morphology (scale = 1 mm). **8.24–8.25**: *Rhizoclonium riparium*, gross morphology (scale = 500 μm), and detail of the unisseriate filament (scale = 100 μm)

Pellizzari et al. (2013) identified a new species of monostromatic green specimen based on molecular markers. In this new species, zoospores germinate directly into leafy monostromatic blades, and asexual reproduction occurs by biflagellate zoospores. Hence, the status of mangrove monostromatic chlorophytes indicates the occurrence of two species of *Gayralia*: *G. brasiliensis* and *G. oxysperma* (Pellizzari et al. 2013) (Figs. 8.26 and 8.27).

Therefore, taxonomical studies based on molecular markers in combination with morphological and developmental analyses have elucidated the occurrence of cryptic species in some genera of mangrove macroalgae, as reported to *Caloglossa* (Kano et al. 2017; Freshwater et al. 2021), and *Gayralia* (Pellizzari et al. 2013). However, further taxonomical studies are required to better knowledge of the small filamentous green algae belonging to the orders Bryopsidales and Cladophorales.

8.3 Diversity of Algal Propagules

Macroalgae are sessile organisms and can be dispersed by propagules (e.g., spores, gametes, and zygotes) or by free-floating seaweeds in different dispersal ranges. Algal propagules are spread in the marine environment and their richness in



Figs. 8.26 and 8.27 Monostromatic green algae in Brazilian mangroves. **8.26**: General aspect of *Gayralia brasiliensis*. **8.27**: Initial developmental stage of *G. brasiliensis* growing on net cultivation. Scales = 1 mm

comparison to the *in situ* populations can be distinct, and this phenomenon was studied mainly in the coastal habitats (Zechman and Mathieson 1985).

Temporal and spatial variations on the composition of macroalgal propagules in the water column are influenced by many factors, including, according to Hoffmann (1987): (a) Periodic variations in reproductive activity (related to reproductive seasonality and endogenous rhythms); (b) propagule production, which is associated with life strategies (e.g., opportunistic algae produce a larger number of propagules); and (c) environmental factors, which play an important role on algal reproduction, and spore release, settlement, and germination.

The only study on macroalgal propagules in mangroves was carried out by Cordeiro-Marino et al. (1990) who evaluated the composition of macroalgal propagules in Perequê River mangrove, Cardoso Island, Southeast Brazil (see Chap. 3, Map 14). Seawater samples (500 mL) were collected in three sites along a salinity gradient over 1 year, and aliquots of 100 mL were filtered in fiberglass membrane, and cultured under controlled conditions of temperature, photoperiod, and irradiance in the laboratory, with culture medium at a salinity of 25. After 2 weeks, plantlets growing on the membranes were isolated and cultured for several months until their taxonomic identification. The diversity of algal propagules was composed of 35 taxa, including 14 green algae, 16 red algae, and 5 brown algae (Table 8.2). However, within the total of 35 taxa, only eight species (26.7%) effectively colonized and grew successfully in the studied mangrove (Braga et al. 1990a, b; Yokoya et al. 1999). Propagule composition varied among the collecting sites and seasons (Table 8.2). The higher diversity of algal propagules was observed in the spring (southern hemisphere) with the presence of Ulvales (*Ulva* spp.), Ceramiales (*Callithamnion* and *Polysiphonia*), Gelidiales (*Gelidium*), and Ectocarpales (*Bachelotia* and *Feldmannia*). Except for *Gelidium* sp., these species are considered opportunistic, as they produce a large number of propagules of high dispersal capacity. These results evidenced that although the propagule flora is more diversified, only a few species can survive, attach, and grow as *in situ* populations in Brazilian mangroves.

Table 8.2 Composition of macroalgal propagules in seawater sampled in three different sites (S1, S2 and S3) in the mangrove of Cardoso Island, São Paulo State, Southeast Brazil. (After Cordeiro-Marino et al. 1990)

	February			June			October			February		
Taxon	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
CHLOROPHYTA												
1. ***Boodleopsis pusilla***	+	+	+	–	–	–	+	+	+	–	–	–
2. Chaetophoraceae	+	+	+	+	+	+	–	+	+	–	–	–
3. ***Cladophoropsis membranacea***	–	+	–	–	–	–	+	–	+	–	–	–
4. ***Gayralia brasiliensis***	–	–	–	–	–	–	+	–	–	–	–	–
5. ***Rhizoclonium tortuosum***	–	–	–	+	–	+	–	–	–	–	–	–
6. *Rhizoclonium* sp.	–	+	–	–	–	–	–	–	+	–	–	–
7. *Ulva clathrata*	+	+	–	+	–	–	–	+	+	+	–	–
8. *U. flexuosa*	–	–	–	–	+	–	+	+	+	–	+	–
9. *U. lactuca*	–	–	–	–	–	–	+	–	+	–	–	–
10. *U. linza*	–	–	–	–	–	–	–	–	+	–	–	–
11. *U. micrococca*	–	+	–	+	–	+	+	–	+	–	–	–
12. *Ulva* sp. 1	–	–	–	–	–	–	–	+	–	–	–	–
13. *Ulva* sp. 2	–	–	–	–	–	–	–	–	+	+	–	–
14. *Ulva* sp. 3	+	–	+	+	+	+	+	+	+	+	+	+
RHODOPHYTA												
15. *Acrochaetium* sp.	–	–	–	+	–	–	–	–	+	–	–	–
16. *Antithamnionella breviramosa*	–	–	–	–	–	–	–	+	–	–	–	–
17. ***Bostrychia calliptera***	–	–	–	–	–	+	–	–	–	–	–	–
18. ***B. moritziana***	+	–	–	–	+	–	–	–	–	–	+	–
19. ***B. radicans***	+	+	+	+	+	+	–	+	+	–	+	+
20. *Callithamnion* sp.	–	–	–	–	+	–	+	+	+	–	–	–
21. ***Caloglossa leprieurii***	–	–	+	–	–	–	–	–	+	–	–	–
22. ***C. kamiyana***	+	+	–	–	–	–	–	–	–	–	–	–
23. *Centroceras clavulatum*	–	–	–	–	–	–	+	–	–	–	–	–
24. *Ceramium codii*	–	+	–	–	–	–	+	–	–	–	–	–
25. *Erythrotrichia carnea*	–	–	–	+	–	–	–	–	–	–	–	–
26. *Herposiphonia secunda*	–	+	–	+	–	–	–	–	–	–	–	–
27. *Heterosiphonia crispella*	–	–	+	–	–	–	–	–	–	–	–	–
28. *Gelidium pusillum*	–	–	–	–	+	–	–	–	–	–	–	–
29. *Gelidium* sp.	–	–	–	+	+	–	+	+	+	–	–	–
30. *Polysiphonia subtilissima*	–	–	–	–	–	–	+	+	+	–	–	–
OCHOROPHYTA/PHAEOPHYCEAE												
31. *Bachelotia antillarum*	+	+	+	+	+	+	+	+	+	+	–	–
32. *Feldmannia irregularis*	–	–	–	+	–	–	+	–	+	–	–	–

(continued)

Table 8.2 (continued)

	February			June			October			February		
Taxon	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
33. *Feldmannia* sp.	–	–	–	+	–	–	+	–	–	–	–	–
34. *Sphacelaria rigidula*	–	–	–	–	–	–	+	–	–	–	–	–
35. *Sphacelaria* sp.	–	–	–	–	–	+	–	–	–	–	–	–
TOTAL	**8**	**12**	**7**	**13**	**9**	**7**	**16**	**12**	**19**	**4**	**4**	**2**

+ presence; − absence

S1: downstream site (salinity of 22–32); S2: intermediate site (salinity of 15–32); S3: upstream site (salinity of 15–32)

Species written in bold were recorded as *in situ* populations in the Cardoso Island mangroves (Braga et al. 1990a, b; Yokoya al. 1999)

Currently, the available molecular tools, such as DNA barcoding, have allowed a more accurate identification at the species level (e.g., Pellizzari et al. 2013; Kano et al. 2017), and consequently, the propagule-originating species, thus facilitating studies on species richness and dispersion of macroalgal propagules. Therefore, further research can contribute to understand the propagule dispersal in mangroves and the influence of seaweed communities from nearby rocky shores.

8.4 Ecology

Ecological studies on Brazilian mangroves were addressed mainly to evaluate the distribution, seasonality, biomass variation, zonation, colonization, and succession in macroalgal communities. However, these studies are restricted to certain regions, and there are gaps in the knowledge on macroalgal communities from mangroves along the Brazilian coast.

Bostrychia radicans and *B. calliptera* have been reported as the predominant species considering the percentage cover or biomass in the majority of Brazilian mangrove macroalgal communities (Eston et al. 1991; Cunha et al. 1999; Cutrim et al. 2004; Machado and Nassar 2007; Fontes et al. 2016), except for the green alga *Cladophoropsis membranacea*, which presented the highest biomass in Vila Velha and Suape mangroves, Pernambuco State (Fontes et al. 2007) (see Chap. 3, Map 8). *B. radicans* presented higher percentage cover and predominated in all sites and substrata (pneumatophores, plantlets, etc.) of mangroves of Cardoso Island, São Paulo State (Eston et al. 1991) (see Chap. 3, Map 14). Besides, macroalgal communities of Picinguaba and Fazenda rivers, in Ubatuba, São Paulo State, are predominated by *B. radicans* with the highest biomass values followed by *B. calliptera* and *B. moritziana*, and no clear spatial and temporal patterns in the distribution of the species were observed probably due to the similar environmental conditions of both rivers associated with the lack of a dry season throughout the year (Machado and Nassar 2007). Similarly, *B. radicans* also showed the highest biomass and frequency percentages in the mangrove of Boa Viagem Beach, Maranhão State (Fontes et al. 2016) (see Chap. 3, Map 3). However, *B. calliptera* predominated with higher biomass values in Parná-Açu and Tauá-Mirim mangroves, in Maranhão State (Cutrim et al. 2004), and Babitonga Bay mangrove, Santa Catarina State (Cunha et al. 1999) (see Chap. 3, Map 16).

There are no clear patterns in the recruitment and vertical distribution of macroalgae in the southeastern Brazilian mangroves, and this could be related to the absence of competition for bare space during colonization processes, as reported by Eston et al. (1992). Besides, the range of vertical distribution of macroalgae on trunks of *R. mangle, L. racemosa*, and *A. schaueriana* seems to be associated with tidal levels; however, zonation pattern was not observed, since *Rhizoclonium* spp., *Bostrychia calliptera*, and *B. radicans* occurred over the vertical range of distribution (Yokoya et al. 1999). Wilkinson (1980) suggested that a low number of species might reduce interspecific competition, resulting in a less well-defined zonation in the estuarine algal community. On the other hand, a clear zonation pattern in macroalgal communities was observed in mangroves of Puerto Rico (Almodovar and Pagan 1971) and Japan (Tanaka and Chihara 1987).

Temporal variations on species composition in mangroves of Cardoso Island are related to temperature, tidal levels, and tolerance of each species to withstand emersion, whereas spatial variations are related to salinity and light (Yokoya et al. 1999). Macroalgal distribution and biomass on trunks and roots of mangrove trees in Babitonga Bay were influenced by salinity gradients and flooding frequency (Cunha and Costa 2002). Salinity gradients also influenced species composition of macroalgal communities in Itapanhaú River mangroves, Bertioga, São Paulo State (Farraboti 2018).

Following Dawes (1998), the stages of the successional process consider pioneer species, intermediate, and stable forms (the final mature/climax stage). Pioneer species are usually annual, showing rapid growth and high reproduction rates, high productivity, short life histories, and simple morphology. All these characteristics allow them to colonize barren and disturbed areas, such as numerous species of Ulvales. In contrast, perennial species have long life histories, complex morphology, slow growth, and spend resources producing chemical and structural grazing defenses. However, the macroalgal colonization pattern on artificial substrates in the southeastern Brazilian mangroves showed that some perennial species may present early settlement, with *Bostrychia radicans* settling throughout the colonization process (Eston et al. 1992). Therefore, these authors suggested that mangrove macroalgal colonization patterns illustrate a successional series in which pioneer communities are also the final ones, and perennial species settled on available substrates as early colonists. Also, only species already observed on natural substrates settled on PVC tubes and wood canes placed as artificial substrates (Eston et al. 1992). Pellizzari et al. (2007) observed recruitment of *Gayralia brasiliensis* in artificial substrates (polypropylene nets) placed to evaluate the potential of its cultivation in estuaries (Fig. 8.28). Besides, no other propagules were attached in artificial or natural substrates during this experiment, suggesting an “exclusion hypothesis” of recruitment and successional patterns on mangroves, probably

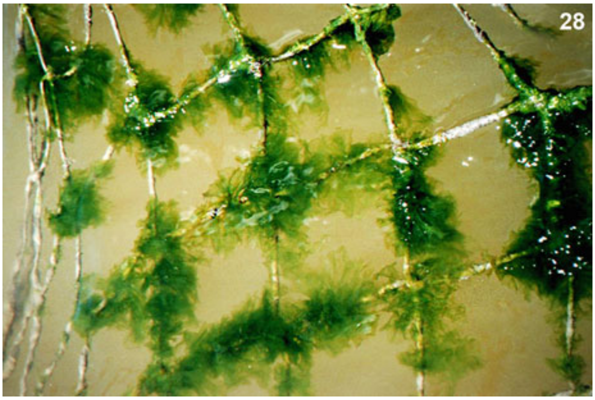


Fig. 8.28 Cultivation of *Gayralia brasiliensis* in polypropylene nets in the estuarine complex of Paranaguá Bay, Paraná State, South Brazil (Pellizzari et al. 2007)

associated with competition and the production of chemical compounds against biofouling and/or herbivory (Karsten et al. 2000; Cassolato et al. 2008).

Little information on the herbivory and fauna associated with mangrove macroalgae is available. Macrofauna diversity associated with the Bostrychietum community of pneumatophores in Araçá Bay, São Paulo State (see Chap. 3, Map 14), comprised mostly of omnivorous amphipods and desiccation-resistant detritivorous species, and emersion time of Bostrychietum and the period of the year affect the community structure, for both seaweeds and the associated fauna (García et al. 2016). Besides, epiphytic macroalgae were considered determinants for the fauna, since the volume of sediment retained among stems and algal biomass influenced their distribution (Lopes 2011).

8.5 Cultivation

The world market for seaweeds including species from mangrove-estuarine complexes is increasing due to a demand by cosmetic, pharmaceutical, and food industries. These sorts of experiments indicated that some mangrove algae species recruit and grow well even when seeded on artificial collectors, suggesting that some species are suitable for management and cultivation (Pellizzari et al. 2007). This may be relevant as an alternative livelihood of fishermen communities facing the present decline in fisheries. Asian countries, such as South Korea and Japan, already cultivate monostromatic green algae in the brackish water of inner bays and estuaries (Ohno and Largo 1998).

Among the species of Brazilian mangrove macroalgae, ecophysiological responses and life history of species belonging to Ulotrichales have been well investigated due to cultivation purposes. Cordeiro-Marino et al. (1993) and Braga (1997) described the reproduction and thallus ontogeny of mangrove monostromatic green algae, aiming to elucidate their taxonomy.

Pellizzari et al. (2006) described the *Gayralia* sp. phenology comprising recruitment and percentage cover in these populations, establishing databases for cultivation in Paranaguá Bay, while Pellizzari et al. (2007) reported details on cultivation strategies of the edible *Gayralia*. Pellizzari et al. (2008) studied in detail the life history, thallus ontogeny, and the effects of temperature, irradiance, and salinity on the growth of two species of *Gayralia*. Later these authors published the new species, *Gayralia brasiliensis*, based on morphology, ontogeny, and phylogenetic position (Pellizzari et al. 2013). The authors reported that *Gayralia* sp. grew better at 18–22 °C and that recruitment occurred year-round in Paranaguá Bay, with higher recruitment rates during autumn (see Chap. 3, Map 15).

Based on recruitment and succession studies, Pellizzari et al. (2007) underwent *Gayralia* pilot cultivation using floating polypropylene nets in shallow subtidal areas or set in fixed systems in the intertidal zone. The best locations for natural recruitment (by asexual zooids) and frond growth were in the outer estuary, surrounding the mangrove fringes, where mother-fronds usually grow attached to stems and roots. Net biomass production was 458 ± 157 g m^{-2} (wet weight) only 45 days after zooid settlement. Although higher growth rates have been observed in nets in floating rafts, the fixed systems showed more stable production with few disturbances from epiphytes, fouling, and grazing, mainly during the winter. Peña-Salamanca (2008) studied the spatial-temporal dynamics of algal biomass associated with mangrove roots in Buenaventura Bay, in the Pacific Coast of Colombia, observing that the average biomass per species at the mouth of the estuary was significantly higher than in the inner estuary (annual average of 30.7 ± 10.8 and 13.8 ± 4.1 g m^{-2}, respectively). These results could be related to the level of tidal flood and the vertical distribution on the root; both seem to be the most limiting factors for algal biomass.

8.6 Chemical Diversity and Biotechnological Application

Marine environments comprise a large variety of organisms with adaptations to extreme conditions or wide environmental variation, and the search for new medicinal or cosmetic active compounds has been proven promising. Marine Natural Products (MNPs) have taken a progressively important position as drugs or as lead structures for bioinspired chemicals (Maciel et al. 2018). The review of Blunt et al. (2016) reported the extraordinary number of 1378 new compounds in 456 papers for 2014, which were isolated from marine microorganisms, phytoplankton, seaweeds (including mangrove macroalgae), sponges, and cnidarians.

Most MNPs often demonstrate remarkable pharmacological potential such as anticancer, antiviral, anti-inflammatory, antimalarial, antioxidant, antifungal, and antibacterial properties. Besides, functional foods and nutraceuticals containing antioxidant peptides isolated from the marine environment have become a topic of attention for pharmaceutical products and the healthy food industry (Maciel et al. 2018).

8.6.1 Mangrove Macroalgae

In Brazil, studies on the chemical diversity of mangrove macroalgae are focused on a few genera, *Bostrychia* and *Gayralia*, mainly from São Paulo and Paraná states, and need to be extended to macroalgae from other regions of Brazil as well as to other taxonomic groups.

Earlier chemical studies on the genus *Bostrychia* were focused on the yield of primary metabolism compounds. Among these compounds, we could exemplify sulfated polysaccharides from *B. montagnei*, which showed antiviral effects against *Herpes simplex*, and demonstrated anticoagulant activity (Noseda et al. 1999; Duarte et al. 2002, 2010). However, the most extensively studied primary metabolites in *Bostrychia* spp. are the polyols (low molecular weight carbohydrates) with multiple functions for cell osmoregulation, and for protecting and stabilizing organelle systems, protein synthesis, and enzymatic functions (Zuccarello and West 2011). Studies on polyol in *Bostrychia* spp. collected in São Paulo mangroves showed that *B. binderi, B. tenella*, and *B. moritziana* produced sorbitol and dulcitol, *B. calliptera* and *B. montagne* produced sorbitol, dulcitol, and traces of digeneaside, and *B. radicans* showed only sorbitol (Karsten et al. 1992; Zuccarello and West 2011).

Further studies aiming to discover new metabolites with different structures led to the isolation of two aromatic compounds from *Bostrychia tenella*, the sulfate metabolite potassium 4-(hydroxymethyl)-benzenosulfonate and the compound 1-methoxyphenethyl alcohol, the latter described previously as a synthetic product (de Felício et al. 2008) (Fig. 8.29). De Oliveira et al. (2012) discovered two new amides (*N*,4-dihydroxy-*N*-(2′-hydroxyethyl)-benzamide and *N*,4-dihydroxy-*N*-(2′--hydroxyethyl)-benzeneacetamide) in *B. radicans* (Fig. 8.29).

Volatile compounds were identified from the nonpolar fractions of marine algae *Bostrychia radicans* and *B. tenella*, both growing on the rocky shore at Dura Beach, in Ubatuba, São Paulo State, and from *B. radicans* and *B. calliptera*, both collected in the mangrove at Escuro River, also in Ubatuba. A solid-phase microextraction (SPME) and GC-MS analyses showed the presence of aldehydes in all samples but in higher percentages in mangrove species as well as the alcohols class. Moreover, fatty acids and hydrocarbons could also be observed in the fractions (de Oliveira et al. 2009).

Mangrove macroalgae have been exposed to high solar radiation and produce mycosporine-like amino acids (MAAs), which have antioxidant and photoprotective properties. The MAA contents were quantified in several *Bostrychia* species, including *B. calliptera* and *B. radicans* from São Paulo mangroves, and the MAA profiles evidenced different chemotypes and can be used as taxonomic markers (Orfanoudaki et al. 2020a). Moreover, phytochemical profiles of several samples of *Bostrychia calliptera* from different countries, including samples collected in Cardoso Island mangroves, revealed that MAAs and brominated and sulfated phenols are suitable chemotaxonomic markers since the three different chemotypes were the same lineages evidenced by DNA sequence data (Orfanoudaki et al. 2020b).

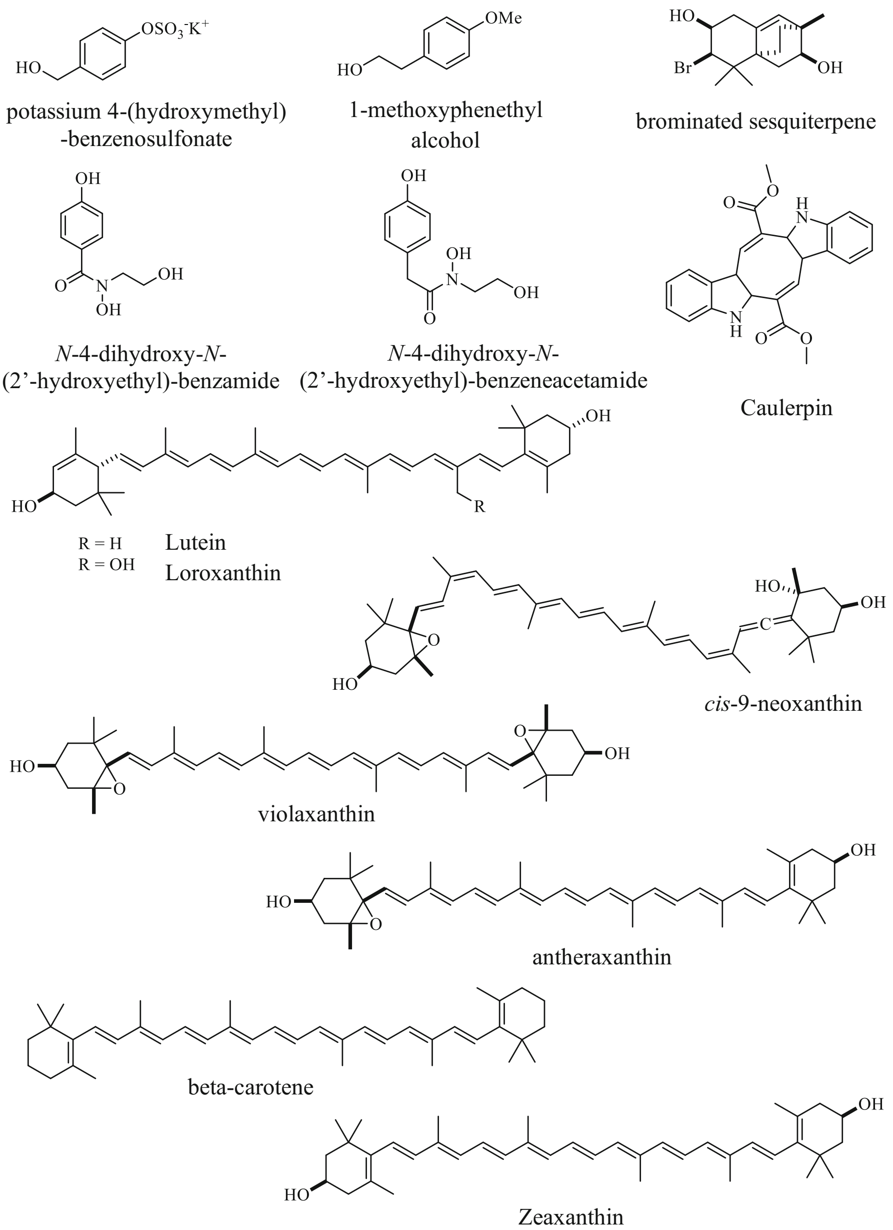


Fig. 8.29 Examples of metabolites found in macroalgae from Brazilian mangroves algae

A homogeneous sulfated heterorhamnan carbohydrate was obtained from the green seaweed *Gayralia brasiliensis* (previously identified as *G. oxysperma*) collected from mangroves in the Paraná State (Cassolato et al. 2008). The backbone is constituted by 3- and 2- linked rhamnosyl units, the latter being 50% substituted at C-3 by side chains containing 2-sulfated glucuronic and galacturonic acids and xylosyl units. The 3- and 2- linked rhamnosyl units are unsulfated (20%), disulfated (16%), and mostly monosulfated at C-2 (27%) and C-4 (37%). The branched and sulfated heterorhamnan of *G. brasiliensis* had high and specific activity against the *Herpes simplex* virus (Cassolato et al. 2008). Besides, antioxidant activities based on the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging method, by quantification of phenolic and carotenoid contents, were reported to *G. brasiliensis* from Paraná mangroves (Bernardi et al. 2016).

Although the chemical studies on Brazilian mangrove macroalgae are limited to *Bostrychia* and *Gayralia*, other classes of compounds were reported in other genera. As an example, a brominated sesquiterpene called (2S,3S,4aR,6R,7S)-6-bromo-2,5,5-trimethyl-3,4,5,6,7,8-hexahydro-2H- 2,4a-ethanonaphthalene-3,7-diol was isolated from the alga *Caloglossa leprieurii* from Xisha Island in the South China Sea (Fraga 2003).

Yoshii et al. (2004) investigated the carotenoid compositions of Cladophorales from Japan. The HPLC analysis showed that pigments of *Cladophoropsis membranacea* and *C. vaucheriiformis* (Areschoug) Papenfuss were classified as lutein type, while *C. fasciculatus* (Kjellman) Wille was included in loroxanthin type, which was considered as an inconsistency once it was expected for them to have the same precursor type. *Rhizoclonium grande* Børgesen was also included as loroxanthin type. Carotenoids 9-*cis*-neoxanthin, violaxanthin, antheraxanthin, lutein, and β-carotene were detected in all mentioned species and a small amount of zeaxanthin was detected only in *Cladophoropsis vaucheriiforms*. The authors concluded that the ancestral state for the Cladophorales was the loroxanthin type, based on the distribution pattern of the carotenoid types (Fig. 8.29).

Aqueous extract of *Rhizoclonium hieroglyphicum* (C.Agardh) Kützing from the Nan River in northern Thailand showed strong antioxidant properties with high free-radical scavenging capacity probably due to its large amount of sulfated polysaccharides and polyphenolic compounds. In addition, the authors of the study have evidenced a gelling ability of this extract that could be useful in nutritional, pharmaceutical, and cosmetic products (Mungmai et al. 2014).

Ethanolic extracts of *Cladophoropsis* sp. from the Persian Gulf showed cytotoxic effects on three tumor cell lines and, therefore, may be good candidates for further obtaining novel anticancer compounds. Moreover, stronger cytotoxic effects on estrogen-negative breast cancer cell line (MDA-MB-231(ER−)) in comparison to estrogen-positive cells (MCF-7 and T-47D) suggest that the extract of *Cladophoropsis* sp. may have an estrogen receptor/progesterone receptor-independent mechanism acting on cellular growth inhibition (Erfani et al. 2015).

Based on the information presently described, Brazilian mangrove species belonging to *Caloglossa* and Cladophorales have the potential to be a source of compounds with biological activities, and further studies are required to characterize their chemical profile.

8.6.2 Algicolous Fungi

Fungi colonize the internal tissues of different marine organisms, such as sponges, jellyfishes, and algae, being predominantly responsible to produce bioactive secondary metabolites that cannot be found in terrestrial organisms. Their relationship to the hosts is usually described as a symbiotic association of mutualism (Blunt et al. 2016; Maciel et al. 2018).

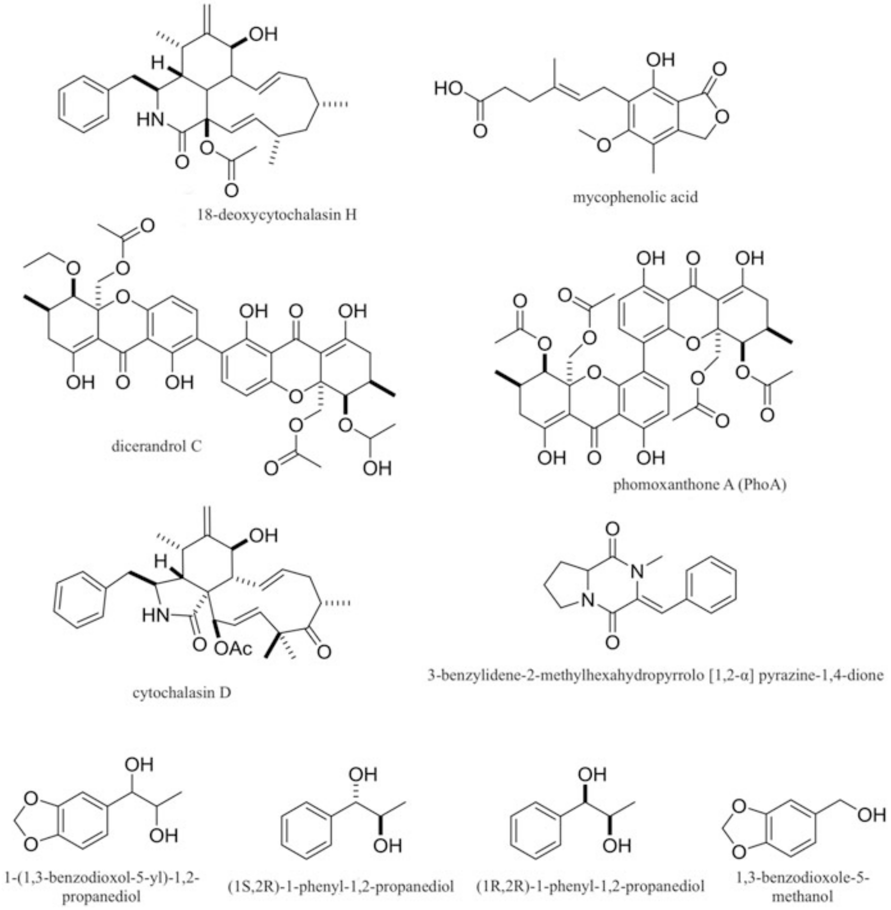
Many compounds biosynthesized by marine algae and associated endophytic fungi have been studied in the search of finding new natural alternatives to neutralizing the damage caused by solar radiation, for example, mycosporine produced by fungi and mycosporine-like amino acids found in algae, cyanobacteria, and invertebrates (Pallela et al. 2010).

It is important to mention that fungal chemical studies showed variations in the number of new compounds, with the figures of 318 in 2014 (Blunt et al. 2016), 371 in 2015 (Blunt et al. 2017), and 328 in 2016 (Blunt et al. 2018). Moreover, an increasing noteworthy number of compounds was observed in new substances isolated from endophytic fungi from mangroves, reaching 142 in 2016 (Blunt et al. 2018). These elevated numbers justify further studies employing endophytic fungi (Blunt et al. 2017, 2018).

In Brazil, information on fungi associated with mangrove macroalgae is limited to *Bostrychia* species. Endophytic fungi isolated from *Bostrychia radicans* and *B. tenella* were proven to be potential sources of bioactive secondary metabolites, acting as antimicrobial, cytotoxic, and exhibiting photoprotective properties (Erbert et al. 2012; de Felício et al. 2015; Pavão et al. 2016; Maciel et al. 2018).

The endophytic fungus *Phomopsis longicolla* isolated from *Bostrychia radicans* yielded three major compounds (Fig. 8.30): 18-deoxycytochalasin H, mycophenolic acid, and dicerandrol C; the latter showed antibacterial activity against *Staphylococcus aureus* (ATCC6538) and *S. saprophyticus* (ATCC 15305), with minimum inhibitory concentrations of 1 and 2 μg mL^{-1} (1.33 and 2.66 μm, respectively) (Erbert et al. 2012). Further studies on *P. longicolla* from *B. radicans* led to the isolation of another known structure called phomoxanthone A (PhoA), focusing on its cytotoxicity, genotoxicity, and mutagenicity in healthy lymphocytes and promyelocytic leukemia HL60 cells. Cells were treated with PhoA at concentrations from 0.01 to 100.0 μg mL^{-1}, not showing cytotoxicity, genotoxicity, or mutagenicity in lymphocytes at any tested concentration (Pavão et al. 2016). Otherwise, PhoA was highly cytotoxic, genotoxic, and mutagenic to HL60 cells. The obtained results highlight the selectivity of PhoA, which had a distinct performance on the cancer cell line, whereas no damage has been observed on healthy lymphocytes. The findings of this work suggest this compound has potential as a lead drug against cancer (Pavão et al. 2016).

Ten endophytic fungi strains were isolated from *Bostrychia tenella*, and they are identified as *Acremonium sp.*, *A. implicatum*, *Eurotium sp.*, *Nigrospora oryzae*, *Penicillium decaturense*, *P. waksmanii*, *Phomopsis sp.*, *Trichoderma atroviride*, *Xylaria sp.*, and Xylariaceae (de Felício et al. 2015). Furthermore, this is the first



18-deoxycytochalasin H

mycophenolic acid

dicerandrol C

phomoxanthone A (PhoA)

cytochalasin D

3-benzylidene-2-methylhexahydropyrrolo [1,2-α] pyrazine-1,4-dione

1-(1,3-benzodioxol-5-yl)-1,2-propanediol

(1S,2R)-1-phenyl-1,2-propanediol

(1R,2R)-1-phenyl-1,2-propanediol

1,3-benzodioxole-5-methanol

Fig. 8.30 Examples of metabolites isolated from algicolous fungi from Brazilian mangroves

description of *Acremonium implicatum* as a marine endophyte and *Xylaria* sp., *Trichoderma atroviride* and *Nigrospora oryzae* as marine seaweed endophytes. Their crude extracts and organic fractions obtained from mycelia after fungal cultivation were evaluated for diverse activities: Cytotoxic activity using SF-295 (glioblastoma), HL-60 (leukemia), and HCT-8 (human colon carcinoma) cell lines; antifungal activity against *Cladosporium cladosporioides* and *C. sphaerospermum* phytopathogenic fungi; and antibacterial potential against *Staphylococcus aureus* Rosenbach 1884 (ATCC 6538*)* and *Klebsiella pneumoniae* (Schroeter 1886) Trevisan 1887 (ATCC 13883) (de Felício et al. 2015). The strains of *Penicillium* are highlighted by their positive results in a diversity of assays, exhibiting efficient cell growth inhibition (80–100%) in all tumor cell lines, fungal growth inhibition of *Cladosporium*, and antibacterial activity against *S. aureus* and *K. pneumoniae*.

Besides, the other five strains were active in at least one test (de Felício et al. 2015). In addition, this work led to the isolation of a compound called cytochalasin D, which had its first report from a marine seaweed endophyte *Xylaria* sp. This compound was described at the first time as a metabolite from terrestrial fungi with antitumor and antibiotic properties (de Felício et al. 2015).

Maciel et al. (2018) evaluated the photoprotective activity of compounds isolated from the endophytic fungus *Annulohypoxylon stygium,* one of the strains isolated from the red alga *Bostrychia radicans.* This work yielded the isolation of five compounds: Two bioactive metabolites, the novel substance 3-benzylidene-2-methylhexahydropyrrolo [1,2-α] pyrazine-1,4-dione, which was previously described as a synthetic product in the literature, and the known compound 1-(1,3-benzodioxol-5-yl)-1,2-propanediol; two diastereomers (1*S*,2*R*)-1-phenyl-1,2-propanediol and (1*R*,2*R*)-1-phenyl-1,2-propanediol; and the 1,3-benzodioxole-5-methanol. The compounds were evaluated through the UVA/UVB absorption range, photostability, and phototoxicity using the 3T3 NRU phototoxicity test (OECD TG 432). Metabolites 3-benzylidene-2-methylhexahydropyrrolo [1,2-α] pyrazine-1,4-dione and 1-(1,3-benzodioxol-5-yl)-1,2-propanediol demonstrated expressive UVB absorption, photostability, and no phototoxicity (Fig. 8.30). This research allowed the discovery of a new photoprotective class of natural products.

8.7 Final Remarks

This chapter outlined the current state of knowledge on Brazilian mangrove macroalgae, and the later approaches in the elucidation of taxonomic problems in some genera, physiological and ecological processes, as well as chemical diversity. Taxonomical studies based on molecular markers in combination with morphological and developmental data have elucidated the occurrence of cryptic species in some genera, such as *Caloglossa* and *Gayralia*. The higher diversity of algal propagules is an interesting approach to understanding seaweed adaptation, distribution, and survival in mangrove ecosystems. Moreover, the strategies to survive in these conditions could explain the large number of compounds biosynthesized by mangrove algae and associated endophytic fungi, which are new natural products with potential to be considered as bioactive compounds for targeting pharmacological and cosmetic purposes. Studies on chemical diversity are focused on *Bostrychia* and *Gayralia* from the southern and southeastern regions, and need to be extended to mangroves from other regions of Brazil as well as to other taxonomic groups.

Finally, this chapter evidenced that the mangrove macroalgal commnities are well studied in certain regions, and there are gaps, which need to be filled in order to understand the macroalgal communities from mangroves distributed along the Brazilian coast.

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