Biotechnological Application of Extremophilic Fungi

15

Aneesa Fasim, H. K. Manjushree, A. Prakruti, S. Rashmi, V. Sindhuja, Veena S. More, K. S. Anantharaju, and Sunil S. More

Abstract

White biotechnology (BT), a sustainable and eco-friendly technology, has taken precedence over chemical industries in the last few decades. It has revolutionized the industrial BT sector by exploiting abundant natural resources for the production of important commodities benefiting mankind. Industries employ microorganisms or biomolecules extracted from them for production and processing in various industrial areas such as food and feed, beverages, agriculture, pharmaceutical, textile, leather, paper, detergent, polymers, cosmetics, waste management, etc. Despite the advantages, the use of biomolecules is not substantial because they cannot tolerate harsh industrial conditions, which in turn affects the production process. In the last decade, the industrial research focus has shifted toward extremophiles, organisms that can survive extreme conditions. These organisms have evolved defense mechanisms to survive severe conditions such as high or low temperature, salinity, pressure, pH, radiation, and desiccation. Biomolecules extracted from these organisms have robust characteristics to retain optimum activity even under unnatural conditions. A class of eukaryotes called extremophilic fungi are at the crux of this research focus as they are a reservoir of sturdy biomolecules with many industrial applications. Fungal extremozymes can be easily cultured on agro-industrial waste and also easily purified. All these factors make fungal extremozymes an attractive resource for large-scale, cost-effective, and eco-friendly industrial processes. In addition to extremozymes, extremophilic fungi are an abundant resource of potent cytotoxic, antimicrobial

---

A. Fasim · H. K. Manjushree · A. Prakruti · S. Rashmi · V. Sindhuja · S. S. More (✉)
School of Basic and Applied Sciences, Dayananda Sagar University, Bengaluru, Karnataka, India

V. S. More
Department of Biotechnology, Sapthagiri College of Engineering, Bangalore, Karnataka, India

K. S. Anantharaju
Department of Chemistry, Dayananda Sagar College of Engineering, Bangalore, Karnataka, India

S. Sahay (ed.), *Extremophilic Fungi*, https://doi.org/10.1007/978-981-16-4907-3_15

drugs. This chapter focuses on various extremophilic fungi used in the BT industry. It also covers the different extremozymes, biomolecules, and secondary metabolites secreted by them and their potential biotechnological applications.

Keywords

Extremophilic fungi · Extremozymes · Natural products · Bioactive compounds · Biotechnological applications

15.1 Introduction

A sustainable bio-based economy is a ray of hope in response to the present environmental crisis such as population expansion, climatic changes, exhaustion of nonrenewable resources, global warming, pollution, etc. The advent of bioprocess technology, also known as white biotechnology, has revolutionized the industrial sector by exploiting natural resources for the production and processing of value-added products that positively impact the global economy and environment. This contemporary technology employs enzymes or microorganisms such as yeast, bacteria, fungi, and plant extracts in numerous industrial applications. Fungal sources have been the major contributors in this field as many enzymes, organic acids, antibiotics, etc., are produced on a commercial scale (Meyer et al. 2016). The discovery of penicillin, fungal antibiotics along with the commercial production of citric acid by *Aspergillus niger,* marked a milestone in the era of fungal biotechnology, and since then many more discoveries have steadily transformed it into a powerful and proficient technology. Fungi play a vital and irreplaceable role in energy recycling of the ecosystem by helping in the decomposition and recycling of organic matter. This versatile class of eukaryotes are omnipresent and can be found in soil, desserts, glaciers, sea, freshwater bodies, and various other environments including the stratosphere (van der Giezen 2011). Fungi have proven to be a valuable resource to humanity from being consumed as food to combating infectious diseases and many biomolecules with important industrial applications. Besides, helping in the fermentation processes of baking, brewing, etc., they aid in the production of enzymes, antibiotics, organic acids, pigments, vitamins, lipids, and numerous other products that are economically important (Adrio and Demain 2003). Their fast growth rate, short life cycles, ease of culture, and purification are highly favorable attributes that benefit the industrial production processes (Hooker et al. 2019).

Fungi are highly resilient organisms that can adapt to diverse habitats and due to their ecological plasticity, they can survive harsh environments precluded to most life forms. They dwell in virtually all types of extreme habitats ranging from extremely dry and cold deserts in the Antarctic and other very cold areas worldwide to highest mountain peaks (Selbmann et al. 2008) to deep permafrost soils (Ozerskaya et al. 2009; Selbmann et al. 2015), geothermal and fumarole soils in volcanic areas, acid mine drainages with sulfuric acid (Selbmann et al. 2008), or in highly alkaline sites (Gunde-Cimerman et al. 2009; Selbmann et al. 2013). Under

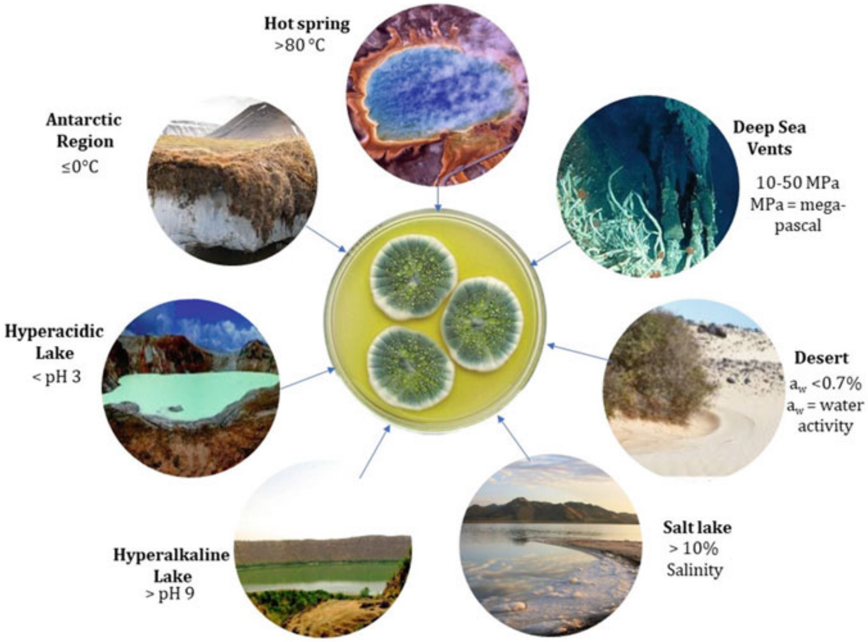

Fig. 15.1 Extreme environments of the earth

severe conditions and high competition, fungi acquire peculiar skills to exploit natural or xenobiotic resources and such fungi are termed as extremophilic fungi (Zhang et al. 2018).

These fungi have evolved defense mechanisms in the form of regulation and expression of specific genes or production of robust enzymes that help them to survive conditions such as high or low temperature, salinity, pressure, pH, radiation, and desiccation. Biomolecules extracted from these organisms have robust characteristics and retain optimum activity even under harsh industrial conditions. All these factors make fungal extremozymes an attractive resource for large-scale, cost-effective, and eco-friendly industrial processes, and the scope to use extremophilic fungi for biotechnological applications is increasing with time (Sarmiento et al. 2015).

The term "extremophile" was first proposed by MacElroy in 1974 to describe a broad group of organisms that can live optimally under extreme conditions. They belong to all three domains of life —Eucarya, Bacteria, and Archaea. Extremophiles are classified into seven categories based on the extreme habitats they inhabit (Fig. 15.1). Piezophiles can survive high hydrostatic pressure and have been isolated from deep sea sediments (>3000 m deep). Thermophiles or hyperthermophiles are organisms that inhabit hot springs, deep sea hydrothermal vents, and can tolerate very high temperatures varying from 50 to 80 °C or over 80 °C (Raddadi 2015). Some halotolerant fungi can tolerate high salt concentration and abiotic stress

(Gunde-Cimerman et al. 2003). This is why many fungi inhabit marine environments. Alkalophiles can tolerate a pH range between 9 and 12, whereas acidophiles can survive extremely low pH of 1–2 (Jin and Kirk 2018). Psychrophiles are the next class that can tolerate extreme cold conditions of the Antarctic zone (Selbmann et al. 2008) and some yeasts can survive ultraviolet rays (UV-B) exposure even at lethal doses (Selbmann et al. 2011). Due to their uncommon adaptability, fungi may also easily colonize stressful and extreme environments created by anthropogenic activities, such as those polluted with heavy metals, toxic chemicals, sewage, etc. (Ceci et al. 2019). Therefore, polluted sites are a rich source to screen for extremophilic fungi. Fungal strains isolated from these environments are strongly adapted to high toxicity and extreme physical parameters (i.e., high salt concentration and high pH). These strains are potentially useful in biotechnological applications such as the biodegradation of the pollutants (Gomes and Steiner 2004; Selbmann et al. 2013) or they can be considered as sources of important bioactive compounds, specific enzymes, biosurfactants, and antioxidants, useful for applications in medicine or food, cosmetics, and chemical industry (Adrio and Demain 2003). They are also employed in biofuel and bioenergy industries since solar cells of specialized pigments work only under extreme conditions like polar caps.

15.2 Biotechnological Applications

Biotechnological industries are exploiting a variety of enzymes as solutions to numerous industrial processes. Fungi from the extreme environment are considered a vital source of commercial hydrolytic enzymes due to their exceptional properties of high catalytic activity, stability, high enzyme yield, ease of culture, and retention of activity even under high-stress conditions. Lipases, amylases, proteases, cellulases, xylanases, etc., are highly used in industries that require efficient breakdown of lignocellulosic biomass in the processing and production of good quality biobased products. Hence, fungal extremozymes help in large-scale, cost-effective, and eco-friendly industrial processes that could significantly affect the growth of the biotechnology sector (Shukla and Singh 2020). Some of the important fungal extremozymes are listed in Table 15.1. The important fields that use these enzymes include decolorization of dyes in the textile industry, detoxify pesticides, degrade agricultural waste to valuable by-products, delignify biomass for biofuel production, bleach the kraft pulp in the paper industry, processing and stabilization of juice, wine, bakery products in the food industry, bioremediation, and many other processes (Baldrian 2006; Brijwani et al. 2010). Along with extremozymes, secondary metabolites and bioactive peptides are also products of extremophilic fungi. Their potential role in preventive medicine as antimicrobials, antivirals, cytotoxic agents, antitumorigenic, antidiabetic, anti-inflammatory, lipid-lowering activities is also illustrated in this chapter (Fig. 15.2).

Table 15.1 Extremophilic enzymes sources and uses in industries

Enzymes	Organisms	Applications in industries	References
Proteases	*Penicillium buponti, Malbranchea pulchella var. sulfurea, Humicola lanuginose* *Rhodotorula mucilaginosa L7* *Leucosporidium antarcticum* *Acremonium sp. L1–4B* *Pseudogymnoascus pannorum* *Candida humicola*	Food, detergents, leather, pharmaceutical, agricultural industries	(Maheshwari et al. 2000) (Lario et al. 2015) (Turkiewicz et al. 2003) (Evaristo da Silva Nascimento et al. 2015) (Krishnan et al. 2011) (Ray et al. 1992)
Laccases	*Chaetomium thermophilium* *Corynascus thermophiles* *aspergillus oryzae* *Aigialus grandis, Cirrenalia pygmea, Gliocladium sp., Hypoxylon oceanicum, Halosarpheia ratnagiriensis, Gongronella sp., Sordaria flmicola, Verruculina enalia and Zalerion varium.* *Cladosporium halotolerans, Cladosporium sphaerospermum, Penicillium canescens.* *Cerrena unicolor (MTCC 5159)* and *Penicillium pinophilum (MCC 1049)*	Paper and pulp, Textile industry, agriculture, Food and beverages	(Chefetz et al. 1998) (Babot et al. 2011; Berka et al. 1997; Bulter et al. 2003; Xu et al. 1996) (Raghukumar et al. 1994) (Jaouani et al. 2014) (D'Souza-Ticlo et al. 2009)
Cellulases	*Trichoderma resei* *Chaetomiumthermophile, Sporotrichum thermophile, Humicola grisea var thermoidea, Humicola insolens, Myceliopthera thermophila, Thermoascus aurantiacus and Talaromyces emrsonii* *Cadophora, Pseudeurotium, Geomyces, Wardomyces, Pseudogymnoascus,*	Biofuel production, paper and pulp, Textile	(Mandels and Weber 1969) (Maheshwari et al. 2000) (Krishnan et al. 2011; Tsuji et al. 2014; Vaz et al. 2011; Wang et al. 2013)

(continued)

Table 15.1 (continued)

Enzymes	Organisms	Applications in industries	References
	Verticillium, Cryptococcus and Mrakia		
Xylanases	*Aureobasidium pullulans varmelangium,* *Pencillium occitanis PO16,* *Aureobasidium pullulans* *Pencillium oxalicum* *Pencillium citrinum,* *Aspergillus fumigatus* *Humicola insolensY1,* *Sporotrichum thermophile* *Rhizomucor pusillus,* *Aspergillus gracilis,* *Aspergillus penicillioides* *Naganishia adeliensis.*	Paper and pulp, Animal feed, Textile, Food and brewery	(Ohta et al. 2001) (Driss et al. 2011) (Yegin 2017) (Muthezhilan et al. 2007) (Dutta et al. 2007) (Deshmukh et al. 2016) (Du et al. 2013) (Sadaf and Khare 2014) (Robledo et al. 2016) (Ali et al. 2012) (Gomes et al. 2003)
Lipases	*Rhizomucor miehei* *Kurtzmanomyces sp. I-11* *Moesziomyces antarcticus* *Leucosporidium scottii L117* *Mrakia blollopis SK-4* *Geomyces sp. P7*	Biofuel, detergent, food, and beverages	(Maheshwari et al. 2000) (Kakugawa et al. 2002; Goto et al. 1969) (Goto et al. 1969) (Duarte et al. 2015) (Tsuji et al. 2013) (Tsuji et al. 2013)
Amylases	*Rhizomucor pusillus,* *Humicola lanuginose,* *Myriococcum thermophilum,* *Thermomyces ibadanensis,* *Thermomyces lanuginosus* *Candida antarctica* *Geomyces pannorum*	Starch processing, food and beverage, paper and pulp, Textile, and pharmaceutical	(Adams 1994; Arnesen et al. 1998; Barnett and Fergus 1971; Bunni et al. 1989; Fergus 1969; Jayachandran and Ramabadran 1970; Sadhukhan et al. 1992) (Mot and Verachtert 1987) (Gao et al. 2016)
Pectinases	*Aspergillus Niger* *Cryptococcus albidus var. albidus,* *Aspergillus Niger MTCC478,* *Saccharomyces cerevisiae,* *Penicillium sp. CGMCC 1669* *Rhizomucor pusilis* *Thermomucor indicae-seudaticae* *Arthrobotrys,* *Aureobasidium,* *Cladosporium,* *Leucosporidium* *Tetracladium*	Biofuel production, oil extraction, paper and pulp, food, and beverage	(Lara-Márquez et al. 2011) (Federici 1985) (Anand et al. 2017) (Gainvors et al. 2000) (Yuan et al. 2011) (Siddiqui et al. 2012) (Martin et al. 2010) (Fenice et al. 1997) (Carrasco et al. 2016)

(continued)

Table 15.1 (continued)

Enzymes	Organisms	Applications in industries	References
Chitinases	*Trichoderma, Oenicillium, Penicillium, Lecanicillium, Neurospora, Mucor, Beauveria, Lycoperdon, aspergillus, Myrothecium, Conidiobolus, Metharhizium, Stachybotrys, Agaricus* *Talaromyces emersonii, Thermomyces lanuginosus* *Dioszegia, Glaciozyma, Lecanicillium, Leuconeurospora, Mrakia, Metschnikowia Phoma, Sporidiobolus, Verticillium lecanii* *Glaciozyma antarctica* PI12	Pharmaceutical and agricultural industry	(Hamid et al. 2013; Karthik et al. 2014) (McCormack et al. 1991) (Zhang et al. 2012) (Barghini et al. 2013; Carrasco et al. 2012; Fenice et al. 2012, 1998, 1997; Onofri et al. 2000) (Ramli et al. 2011)
Phytases	*Aspergillus Niger* *Myceliophthora thermophila, Talaromyces* *Papiliotrema laurentii AL27* R*hodotorula mucilaginosa strain JMUY1*	Bread making and animal feed	(Haros et al. 2001) (Maheshwari et al. 2000) (Pavlova et al. 2008) (Yu et al. 2015)

15.2.1 Food and Beverage Industry

Use of enzymes instead of chemicals improves the quality of the processed food and creates superior products with improved yields. In addition, enzymes also play key role in enhancing the nutrition and appeal of the products. Enzymes are used in baking, making sugar syrups, cheese and dairy making, extraction and clarification of juices, oil, as sweeteners, for flavor development, meat tenderizing, etc., and in many other processes. From making food products to storage of food and beverage all require extreme conditions making extremozymes an essential ingredient to achieve food quality at low costs in this industry.

Cold-active enzymes produced by psychrophiles are flexible, resulting in higher catalytic activity at low temperatures (Arora and Panosyan 2019). These enzymes can be used to soften frozen meat products, preserve the heat-sensitive nutrients, accelerate cheese ripening, and they are also effective against wine and juice clarification. *Rhodotorula mucilaginosa L7* is a yeast strain from the Antarctic region that produces acid protease with an activity range between 15 °C and 60 °C and pH 5 (Lario et al. 2015). A similar discovery of a psychrophilic and halotolerant serine protease from Antarctic region resulted in isolation of *Leucosporidium antarcticum* fungal strain where the enzyme was found most active at 10–25 °C

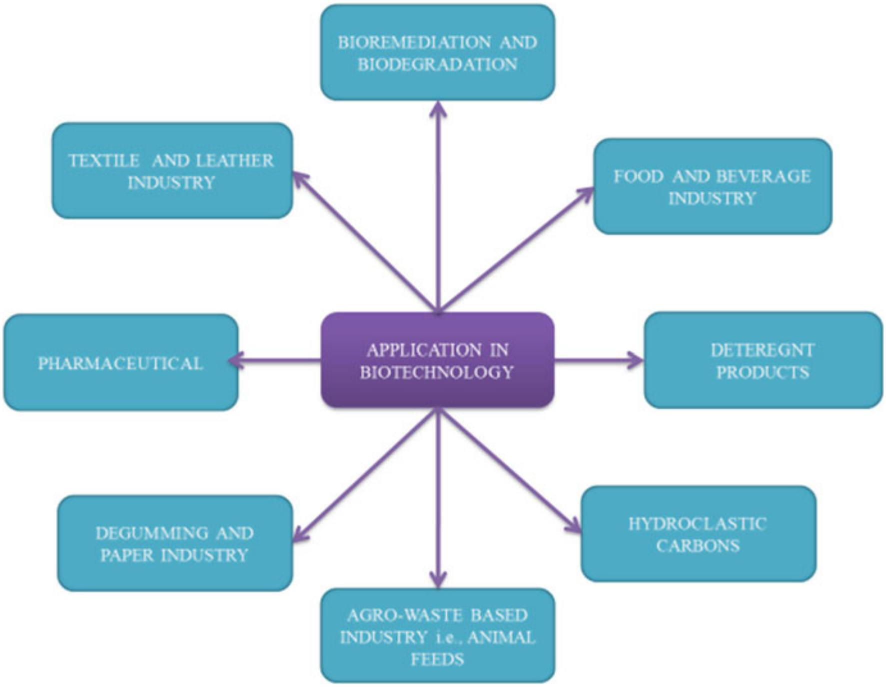

Fig. 15.2 Representation of extremophilic fungi biotechnological applications

and 3.5% marine salt (Turkiewicz et al. 2003). Additionally, Laccases have many applications like processing and stabilization of juice, wine, bakery products in the food industry, and many other processes (Baldrian 2006; Brijwani et al. 2010).

Amylases are another class of enzymes highly used in food industry; they are also used in various other industries such as starch processing, textile, food and beverage, paper, pharmaceutical, and many other industries (Pandey et al. 2000). Extremophilic fungal α-amylases have achieved an important place in industrial enzymes. Many thermophilic fungal species studied so far are capable of secreting amylases. *Rhizomucor pusillus,* and *Humicola lanuginose*, *Myriococcum thermophilum, Thermomyces ibadanensis,* and *Thermomyces lanuginosus* are a few of the thermophilic fungi found to produce amylase enzyme (Sadhukhan et al.1992; Jayachandran and Ramabadran 1970; Fergus 1969; Bunni et al. 1989; Barnett and Fergus 1971; Arnesen et al. 1998; Adams 1981; Adams 1994). Psychotolerant fungi are also a good source of amylases. *Candida antarctica* from Antarctic region was observed to produce both α and γ amylases. Both enzymes were active on high molecular weight polysaccharides with α-amylase showing activity even on cyclodextrins (Mot and Verachtert 1987). Extremophilic fungal xylanases and pectinases also have many benefits such as pulping, juice and wine clarification, oil extraction etc. (Soni et al. 2017). *Trichoderma sp, Aspergillus sp, Penicillium sp,* and *Acido bacterium spp.* are the major extremophilic fungal genera that contribute to the production of xylanases. Similarly, many acidic fungal pectinases like *Aspergillus niger* between pH 3 and 5.5 (Lara-Márquez et al. 2011). *Cryptococcus albidus* var. *albidus,* pH 3.75 (Federici 1985), *Aspergillus niger* MTCC478, pH 4 (Anand et al. 2016), *Penicillium* sp. CGMCC 1669, pH 3.5 (Yuan et al. 2011), and *Saccharomyces cerevisiae* pH 3–5.5 (Gainvors et al. 2000) have been screened. Novoshape (novozymes), pectinase 62 L (biocatalysts), and lallzyme (lallemand) are few commercially available food-based companies that use pectinase enzyme (Dumorné et al. 2017; Sarmiento et al. 2015). Acidic pectinases are one such enzyme used in the clarification of fruit juices, beer, and wine as well (Kashyap et al. 2001). Recent research has indicatedS screening of bacterial strains known to produce alkaline and thermophilic pectinases. Anand et al. 2016 purified and characterized an alkaline pectinase from *Aspergillus fumigatus MTCC 2584* having a pH optima of 10. In another study, thermophilic pectinase was purified from *Rhizomucor pusilis* having temperature optima of 55 °C was isolated (Siddiqui et al. 2012). Martin et al. 2010 also isolated a thermophilic pectinase producing fungal strain *Thermomucor indicae-seudaticae* that could grow at 45 °C. Recently, psychrophilic and pectinolytic fungi were isolated from Antarctic region. The representative genera are *Arthrobotrys, Aureobasidium, Cladosporium,* and *Leucosporidium* showed the pectinase activities even at 5 °C (Fenice et al. 1997). A cold-adapted pectinase-producing fungi was also isolated from *Tetracladium* sp. with highest activity at 15 °C (Carrasco et al. 2019).

15.2.2 Detergents

Extermophilic fungal lipases are sought-after enzymes in detergent industries as they possess robust properties. Particularly esterases (EC 3.1.1.1) and lipases (EC 3.1.1.3) are important as they catalyze the cleavage of esterbonds and also help in reverse reactions in organic solvents (Fuciños et al. 2012). Lipases help in acidolysis, alcoholysis, aminolysis, esterification hydrolysis, interesterification, etc. (Daiha et al. 2015), making them versatile and having many applications in organic and fine chemical synthesis, and cleaning products. A thermostable lipase from *Humicola lanuginosa* strain Y-38 was isolated from compost in Japan. The enzyme was thermophilic having temperature optima of 60 °C and alkalophilic with pH optima of 8.0. *Rhizomucor miehei*, formerly called *Mucor miehei*, also produced active lipase (Maheshwari et al. 2000). Kakugawa et al. (2002) reported a thermostable and acidophilic lipase-producing yeast strain *Kurtzmanomyces sp. I-11* with optimum activity at 75 °C and pH 2–4. Another noteworthy example of thermostable and alkalophilic lipase is produced by *Thermomyces lanuginosus*, known as TLL showing maximum lipase activity between 60 and 85 °C and pH 10 (Avila-Cisneros et al. 2014). Lipolase, Lipoclean, and Lipex are few of the genetically improved lipases from the fungus *Thermomyces lanuginosus* included in detergent formulations by Novozymes (Jurado-Alameda et al. 2012). Cellulases are the next class of enzymes that have found applications in the detergent industry to increase brightness and dirt removal from cotton mixed garments (Kuhad et al. 2011). Many commercially available detergents have been reported where enzyme such as lipase, protease, amylases, cellulases, and mannanases are included in the formulations (Sarmiento et al. 2015).

15.2.3 Paper and Pulp Industry

In the paper and pulp industry, the significant application of enzymes is in the prebleaching of kraft pulp. Xylanases, hemicellulases, and cellulases are the commonly used enzymes for this purpose due to its displayed efficiency. Enzymes have also been used to raise water retention, pulp fibrillation, and decrease the beating time in virgin pulps. Enzymes are also involved in increasing the freeness and in the deinking process (Dumorné et al. 2017; Bajpai 1999). Fungal laccases are involved in lignin degradation due to displayed efficiency (Alcalde 2007; Thurston 1994). Due to high enzyme yield and higher redox potential, fungal laccases are preferred over the plant or bacterial enzymes in the biotechnology sector (Thurston 1994). *Corynascus thermophilus* is a fungal strain secreting highly active thermostable laccase that was used to delignify eucalypt pulp. This laccase was heterologously expressed in *Aspergillus oryzae*, characterized, and commercialized (Xu et al. 1996; Berka et al. 1997; Bulter et al. 2003; Babot et al. 2011). Cellulases are also heavily used in this industry. *Penicillium roqueforti, Cadophora malorum, Geomyces sp.,* and *Mrakia blollopis* are few of the cold-adapted cellulase-producing fungal strains (Carrasco et al. 2016; Duncan et al. 2006; Duncan et al. 2008). *Trichoderma sp, Aspergillus sp, Penicillium sp,* and *Acidobacterium spp* are the major extremophilic fungal genera that contribute to the production of xylanases.

15.2.4 Agricultural Applications

Many cellulolytic and xylanolytic fungi are acknowledged to have applications in the field of agriculture by boosting the seed germination, improved root system and flowering, increased crop yields, and rapid plant growth (Ahmed and Bibi 2018). Fungal xylanases such as *Pencillium oxalicum* (Muthezhilan et al. 2007)*, Pencillium citrinum* (Dutta et al. 2007)*, Aspergillus fumigatus* (Deshmukh et al. 2016)*,* and *Humicola insolensY1*(Du et al. 2013) are isolated showing optimum activity between pH 8–9 and 45–55 °C with *H.insolensY1* also being highly thermophilic with a temperature optima of 70–80 °C. Other thermophilic xylanase-producing fungi include *Chaetomium sp. CQ31, Sporotrichum thermophile* isolated from composting soil having activity at neutral pH and 60–70 °C temperature (Jiang et al. 2010; Sadaf and Khare 2014). *Rhizomucor pusillus* and *Aspergillus fumigatus* screened from the maize silage showed optimum xylanase activity at 75 °C and pH 6 (Robledo et al. 2016). Many thermophilic xylanase-producing fungi such as *Chaetomium thermophilum, Humicola insolens, Melanocarpus sp., Malbranchea sp.,* and *Thermoascus aurantiacus* were reported by Ghatora et al. 2006. Halotolerant fungal xylanase *Phoma sp* isolated from mangrove sediments having enzyme activity at pH 5, 45 °C, and a high salt concentration of 4 M NaCl (Wu et al. 2018). *Aspergillus gracilis* and *Aspergillus penicillioides* were screened from man-made solar saltern (Ali et al. 2012) and psychrophilic fungal xylanases were isolated from Antarctic soils, marine sponges, etc. *Cladosporium sp.* from marine sponge showed high xylanase activity at low temperatures (Del Cid et al. 2014). *Naganishia adeliensis* are isolated from Antarctica (Gomes et al. 2003). Phytases are another class of enzymes involved in seed germination, but they are also considered antinutrients because they act as strong chelators of divalent mineral ions such as calcium, magnesium, iron, and zinc. Chitinases have many applications, especially as antiphytopathogenic and antifungal agents. They are used to protect crops to control pathogens. Cola-active extremozymes are used in agriculture to enhance the water management by plants, which are under deficiency stress (Dumorné et al. 2017).

15.2.5 Animal Feed Industry

Cellulases and xylanases have advantage in the animal feed industry in the treatment of agricultural silage, grains, and seeds to enhance nutritional value. Cold-adapted phytases have advantages as they can be directly included in the feed of monogastric animals and also in aquaculture.

15.2.6 Bioremediation and Biodegradation: Major Application of Extremozymes

Bioremediation and biodegradation employ microbes in the elimination of pollutants, contaminants, and toxins from water, soil, and other environments. Waste from any kind of industry is hazardous. It is highly acidic or alkaline, and contains all kinds of biomass and proteinaceous waste. It also has a high content of metal ions and many other toxins, dyes, chemicals, radioactive material, etc., making it very harmful to the flora and fauna around it.

Certain microbes can be used to recycle and degrade pollutants as they produce hydrolytic enzymes that can degrade and help clean up the contaminated sites. Fungal extremozymes are extremely useful in these processes as they can sustain harsh conditions and still work on organic toxins. Thermophiles convert recalcitrant materials in bioprocessing and favor the in situ bioremediation process (Castro et al. 2019). As the solubility of the pollutants increases, the metabolic activity of thermophiles also increases (Zeldes et al. 2015). Thermophilic fungi such as *Pyrodictium, Clostridium,* and *Methanopyrus* can metabolize naphthalene, anthracene, and phenanthrene (Ghosal et al. 2016). White rot fungi are the chief representatives of the biodegradation of lignin substances (Deshmukh et al. 2016). 21 PAH degrading fungi were isolated from PAH-contaminated soils that could efficiently degrade PAH. A*spergillus niger*, *Diaporthe sp., Coriolopsis byrsina, Pestalotiopsis sp.,* and *Cerrena* are known to treat and bioremediate textile mill effluents (Rani et al. 2014). *Stenotrophomonas maltophilia* strain AJH1 has been isolated from Arabia, which was able to degrade low and high molecular weight PAHs such as anthracene, naphthalene, phenanthrene, pyrene, and benzo(k)-f^{2}uoranthene (Rajkumari et al. 2019). *D. radiouridans* is another important fungus used in bioremediation of radioactively contaminated sites (Brim et al. 2006). *Sulfolobus sulfataricus* secrete lactonase enzyme that acts against organophosphates (Hawwa et al. 2009). *Thermoascus aurantiacus,* another fungal strain, can secrete phenol oxidase and target phenolic hydrocarbons (Machuca et al. 1998).

Rajkumari et al. (2019) studied different approaches of degradation of hydrocarbon waste. *Candida, Aspergillus, Chlorella*, and *Penicillium* were found to be most suitable in the elimination of these wastes. A marine fungal laccase-mediated detoxification and bioremediation of anthraquinone dye called reactive blue was reported (Verma et al. 2012). These laccases could work under very high salinity. Similarly, laccase from *Fusarium incarnatum* was able to degrade bisphenol A, which is a endocrine-disrupting chemical (Chhaya and Gupte 2013). Other studies indicated heavy metal and chloropyriphos bioremediation can be achieved by using *Aspergillus sp, Curvularia,* and *Acrimonium sp*. (Akhtar et al. 2013; Silambarasan and Abraham 2013); likewise, polychlorinated biphenyl degradation can be degraded by *Phoma eupyrena, Doratomyces nanus, Myceliophthora thermophila,* and *D. verrucisporus* (Barghini et al. 2013). Lugowski et al. 1998 has reported that *Pseudomonas sp* is used for degradation of aromatic hydrocarbons. *Halomonas* sp. and *Pseudomonas aeruginosa* strain is used for cleaving of aliphatic hydrocarbons.

15.2.7 Bioactive Peptides from Marine Fungi

Oceans are the biggest resource for novel therapeutic compounds. Thousands of secondary metabolites such as polyketides, lactones, alkaloids, steroids, and peptides having pharmacological significance are discovered from marine fungal strains (Jin et al. 2016). Sessile marine microorganisms usually harbor the fungal strains in a symbiotic relationship where the marine fungi protect the host against predators and disease by releasing bioactive compounds (Schueffler and Anke 2014). The unique structural and functional diversity of the marine bioactive compounds is attributed to the extreme conditions of salinity, pressure, and temperature that also give immense stability from all kinds of degradation to these peptides, making them promising candidates for drug discovery. Thus, isolating and characterizing novel bioactive peptides and metabolites from marine fungi with therapeutic properties is a promising avenue to explore in the prevention of human diseases. To date, thousands of compounds have been isolated from many marine fungi, but curating them all is not feasible. So, the data from two latest reviews covering last 15 years of research (Ibrar et al. 2020; Youssef et al. 2019) on the fungal bioactive peptides and compounds is adapted and a comprehensive summary is presented in Table 15.1 with additions and modifications made according to the relevance and scope of this chapter.

15.2.7.1 Peptides

In the last five decades, a significant number of marine bioactive peptides are discovered that either fall in the class of synthetic, non-ribosomally produced peptides such as bacitracins, polymixins, glycopeptides, or gramicidins, etc., or natural, ribosomal peptide class. The synthetic peptides are mostly produced by bacteria, but natural peptides are produced by many species including marine fungi with potent activities (Saleem et al. 2007). Many fungi belonging to various genus produce potent peptides showing antimicrobial, antiviral, cytotoxic, antitumorigenic, antidiabetic, anti-inflammatory, lipid-lowering activities. These peptides are structurally diverse from being cyclic to N-methylated. Some are dipeptides, nonapeptides, depsipeptides, or pentadecapeptides having complex backbones and many side chains. Genus *Aspergillus* is found to be a rich source of bioactive peptides with Aspergellicins A–E, Cyclodipeptide, Sclerotide A–B, Terrelumamide A–B, Psychriphillin E–G, Aspersymmatide A, Cotteslosin A, Diketopiperazine dimer, cyclic tetrapeptide, Aspergellipeptide D–E, and 14-hydroxycyclopeptine being produced by them showing cytotoxic, anticancer, and anti-inflammatory properties (Table 15.1). Cordyhehptapeptides and efrapeptins are certain other bioactive peptides isolated from *Acremonium sp* with cytotoxic and antibacterial activities. Lajollamide A from *Asteromyces*, Dictyonamide A from *Certodictyon*, Clonostachysins from *Clonostachys,* and Ungusin A, Emercellamide from *Emericella sp,* and Rostratins from *Exserohilium* are cytotoxic, antidinoflagellate, and antimicrobial in nature. Similarly, peptides from *Microsporum, Penicillium, Scytalidium, Simplicillium, Stachylidium, Talaromyces,* and *Zygosporium* fungi also show various toxic effects on cancers and microbes.

The general procedure for isolating fungal peptides involves culturing of fungi under appropriate conditions and extraction of peptides using solvents such as ethyl acetate. The extracted sample is lyophilized and further purified using chromatographic techniques until pure forms of peptides are obtained. 1D and 2D NMR techniques in combination with mass spectrometry are used to determine the structure of the peptides and Marfey's and Mosher's reactions are used to elucidate the absolute configuration, amino acid composition, and structural modifications (Wang et al. 2017) Biological activity of the purified peptide is measured using IC_{50} or MIC (minimum inhibitory concentrations) values against cancer cell lines, pathogenic bacteria, and many other microbes.

15.2.7.2 Bioactive Compounds

Marine secondary metabolites have gained a lot of attention in the recent past due to their potent pharmacological properties. The accidental discovery of cephalosporin C antibiotic from the marine *Cephalosporium sp.* fungus in 1949 started a trend to explore marine habitats for bioactive compounds. Many other marine fungi-derived products are currently available in the market such as antibacterial terpenoid fusidic acid, polyketide griseofulvin antibiotic, penicillins, cephalosporins, macrolides, statins, many alkaloids, glycosides, isoprenoids, lipids, etc. (Chandra and Arora 2009; Hamilton-Miller 2008), that exhibit potent toxicity towards tumors, cell proliferation, microtubule formation, pathogenic bacteria, viruses, nematodes, foul smells, and also exhibit photo-protective activities (Rateb and Ebel 2011). Bioactive compounds are produced by all kinds of extremophilic fungi from psychotolerant, to thermophiles, piezophiles, acidophiles, halotolerant, and xerophiles. Table 15.2 recapitulates different secondary metabolites and their biological activities. Many bioactive compound-secreting fungal strains are discovered by exploring extremely toxic environments such as Berkeley acid lake, hot springs, salt salterns, fumaroles, deep sea sediments and vents, mangroves, Antarctic permafrost, etc. These places have become rich biodiversity for the exploration of such value-added compounds (Ibrar et al. 2020).

Bioactive compounds are also extracted and purified in the same way as peptides, although the characterization techniques will differ. A bioassay-guided fractionation procedure is employed to obtain pure compound fractions, where the potential activity of the fractions is assessed. Most marine compounds have different chemical composition so different polar compounds have to be used for the fractionation method so that the active compound can be separated from the inactive fractions depending on the partition coefficients of the analytes. Polyketides alkaloids, sugars, steroids, and saponins are generally found in aqueous fractions, whereas peptides need mildly polar solvents, and terpenes, hydrocarbons, and fatty acids are found in low-polar fractions. The bioactive fractions are next subjected to gel permeation chromatography to further purify the molecules. The purified compounds are then structurally and chemically characterized by sophisticated techniques such as mass spectrometry (MS) and nuclear magnetic resonance (NMR) spectroscopy. High-resolution 1D and 2D NMR spectroscopy are routinely used for the structural characterization of the bioactive compounds.

15.3 Conclusion

Biotechnological industries are using a variety of extremophilic fungi as solutions to diverse industrial processes. The survival strategies of extremophilic fungi are unique and associated with the production of extremozymes and various secondary metabolites with robust qualities, making them a rich and abundant resource. Despite their potential, a very small percent of extremophilic fungi are discovered. Exploration of extremophilic organisms will make a huge impact and open new avenues in biotechnology research. With the advancement in various technologies like metagenomics, genetic engineering, in silico analysis, and technology that can access uninhabitable and inaccessible places on earth, it is now possible to identify, isolate, and extract potent compounds that can cater to the needs of almost every sector of the biotech industry to help form a sustainable and efficient biobased economy.

Table 15.2 Bioactive peptides and secondary metabolites isolated from marine fungi, their structure, sources, and biological activities

Bioactive peptides	Marine fungi	Features	Source	Biological activity	References
Peptides					
Cordyheptapeptide C Cordyheptapeptide C	*Acremonium persicinum SCSIO 115*	Cyclic heptapeptides	Marine fungus	Cytotoxic and antitumor activity	(Chen et al. 2012)
Efrapeptin Eα	*Acremonium*	Pentadecapeptides	Marine fungus	Cytotoxic activity	(Gupta et al. 1992)
Efrapeptin F Efrapeptin G RHMI	*Tolypocladium niueum* *Acremonium sp* *Acremonium sp.*	Polypeptides Polypeptide N-methylated linear octapeptides	Fractionated extract of *T. niueum* Cultured from a marine sponge	Cytotoxic activity Cytotoxic and antibacterial activity Antibacterial activity	(Boot et al. 2006) (Boot et al. 2007)
Aspergillicins A-E	*Aspergillus carneus*	Depsipeptides	Estuarine sediment in Tasmania	Cytotoxic activity	(Capon et al. 2003)
Cyclo-(L-Trp-L-Tyr)	*Aspergillus Niger EN-13*	Cyclic dipeptide	Isolated from the marine brown alga *Colpomenia sinuosa*	Cytotoxic activity	(Zhang et al. 2010)
Sclerotide A Sclerotide B	*Aspergillus sclerotiorum PT06–1*	Cyclic hexapeptide	Putian Sea salt field, China	Antifungal activity Antifungal, antibacterial, and cytotoxic activity	(Zheng et al. 2009)
Similanamide	*Aspergillus similanensis KUFA 0013*	Cyclohexapeptide	Ethyl acetate extracts of marine unknown sponge	Cytotoxic and antitumor activity	(Prompanya et al. 2015)
Terrelumamide A Terrelumamide B	*Aspergillus terreus*	Linear lumazine peptides	Marine sediments	Improved insulin sensitivity	(You et al. 2015)
Psychrophilin E	*Aspergillus sp*	Cyclic tropeptide	Isolated from marine brown algae *Sargassum*	Cytotoxic activity	(Ebada et al. 2014)
Psychrophilin G	*Aspergillus* Versicolor ZLN-60	Cyclic peptides with anthranilic acid	Marine-derived fungi	Lipid-lowering activity	(Peng et al. 2014)
Aspersymmetide A	*Aspergillus* Versicolor	Cyclic hexapeptide	Isolated from a gorgonian coral *Carijoa* sp.	Cytotoxic activity	(Hou et al. 2017)

(continued)

Table 15.2 (continued)

Bioactive peptides	Marine fungi	Features	Source	Biological activity	References
Cotteslosin A	*Aspergillus* versicolor (MST-MF495)	Cyclic pentapeptides	Isolated from Australian beach sand	Cytotoxic and antitumor activity	(Fremlin et al. 2009)
Diketopiperazine dimer Cyclic tetrapeptide	*Aspergillus Violaceofuscus*	Diketopiperazine dimer Cyclic tetrapeptide	Isolated from marine sponge *Reniochalina* sp.	Anti-inflammatory activity	(Liu et al. 2018)
Aspergillipeptid D Aspergillipeptid E	*Aspergillus*sp. SCSIO 41501	Cyclic pentapeptide Tripeptide	Isolated from marine gorgonians	Antiviral activity	(Ma et al. 2017)
14-Hydroxy-cyclopeptine	*Aspergillus sp. SCSIOW2*	Cyclic dipeptide	Isolated from deep sea (1000 m depth) fugus	NO inhibition activity	(Zhou et al. 2016)
Clavatustides A Clavatustides B	*Aspergillus clavatus* C2WU	Cyclodepsipeptides	*Xenograpsus testudinatus* Sulphur-rich hydrothermal vents in Taiwan	Cytotoxic and Antitumor activity	(Jiang et al. 2010)
Lajollamide A	*Asteromyces Cruciatus*	Pentapeptide	Isolated from the Coast of La Jolla, USA	Antibacterial	(Gulder et al. 2012)
Dictyonamide A	*Fungus KO63*	Linear dodecapeptides	Isolated from marine red alga *Ceratodictyon spongiosum*	CDK-4 inhibition	(Komatsu et al. 2001)
Clonostachysin A Clonostachysin B	*Clonostachys rogersoniana* strain HJK9	N-methylated cyclic nona peptides	Isolated from a sponge, *Halicondria japonica*	Antidinoflagellate activity	(Adachi et al. 2005)
Unguisin A Emericellamide B	*Emericella* CNL-878	Cyclic depsipeptides	Isolated from co-culture with marine *Salinispora arenicola*	Antibacterial activity	(Oh et al. 2007)
Microsporin A Microsporin B	*Microsporum* cf. *gypseum*	Cyclic tetrapeptides	Isolated bryozoan *Bugula* sp., Virgin Islands USA	Inhibition of histone deacetylases, cytotoxic and antitumor activity	(Gu et al. 2007)

Penicimutide	*Penicillium purpurogenum G59*	Cyclic dipeptide	Isolated from a neomycin-resistant mutant marine *Penicillium purpurogenum G59*	Cytotoxic activity	(Wang et al. 2016)
Psychrophilin D	*Penicillium algidum*	Cyclic nitropeptide	Soil under a Ribes sp. east of Oksestien, Greenland	Antimicrobial, antiviral, anticancer, and antiplasmodial	(Dalsgaard et al. 2005)
Cis-Cyclo (Leucyl-Tyrosyl)	*Penicillium F37*	Dipeptide	Isolated from marine sponge *Axinella corrugate*	Antibiofilim activity	(Scopel et al. 2013)
Halovir A Halovirs B–E	*Scytalidium CNL240* *Scytalidium*	Linear, lipophilic Peptides,	Deep sea-derived fungi	Antiviral activity	(Rowley et al. 2003, 2004)
Simplicilliumtide A Simplicilliumtide D Simplicilliumtide E, G and H Simplicilliumtide J	*Simplicillin obclavatum EIODSF 020*	Linear peptides	Deep sea-derived fungi	Cytotoxic activity Antifouling activity Cytotoxic and antitumor activity Antifungal and antiviral activity	(Liang et al. 2017, 2016)
Endolide A Endolide B	*Stachylidium sps.*	N-methylated peptides	Isolated from a Marine sponge	Binding to vasopressin receptor Binding to seratonin receptor	(Almeida et al. 2016)
Talaropeptide A Talaropeptide B	*Talaromyces sps,*	N-methylated linear peptides	Isolated from a marine Tunicate.	Antibacterial activity	(Dewapriya et al. 2018)
Zygosporamide	*Zygosporium masonii*	Cyclic depsipeptide	Marine-derived fungus	Cytotoxic and antitumor activity	(Oh et al. 2007; Torres-García et al. 2014)

(continued)

Table 15.2 (continued)

Bioactive peptides	Marine fungi	Features	Source	Biological activity	References
Secondary metabolites					
Fuscin, dihydrofuscin, dihydrosecofuscin, and secofuscin	*Oidiodendron griseum* UBOCC-A-114129	Polyketide	765 m below the seafloor	Antibacterial, inhibited CLK1 kinase	(Navarri et al. 2017)
Cytochalasin D	Endophytic fungi *Xylaria* sp	Polyketide amino acid hybrid	From marine seaweed *Bostrychia tenella*	Antitumor and antibiotic	(de Felício et al. 2015)
Pentacyclic cytochalasin	*Diaporthaceae sp PSU-SP2/4*	Polyketide amino acid hybrid	Isolated from the marine sponge	Antibacterial	(Khamthong et al. 2014)
Sterigmantocystin	*Aspergillus sp*	Polyketide derivative	Marine algae derived, Germany	Cytotoxic	(Ebada et al. 2014)
Rugulosin and skyrin	*Pencillium Chrysogenum*	Polyketides	Marine benthic-derived Antarctic lake	Antimicrobial	(Brunati et al. 2009)
Malbranpyrroles A–F	*Malbranchea sulfurea*	Polyketides	Fumerole soil	Cytotoxic	(Yang et al. 2009)
Myceliothermophins A–E	*Myceliophthora thermophila*	Polyketides containing tetramic acid	Fumarole soil	Cytotoxic	(Yang et al. 2007)
Xanthone and chromone	*Penicillium sp. SCSIO Ind16F01*	Xanthones and quinolones	Deep sea sediments	Cytotoxic and antimicrobial	(Liu and Kokare 2017)
Anthraquinone	*Penicillium sp. OUCMDZ 4736*	Polyketide	Sediment roots of mangrove	Antiviral	(Jin and Kirk 2018)
Anthraquinone	*Aspergillus Versricolor*	Polyketide	Deep sea	Antimicrobial	(Wang et al. 2017)
Azophilones	*Pleurostomophora sp*	Polyketides	Acidic Berkeley lake	Antimicrobial	(Stierle et al. 2015)

Berkeley lactones	*Penicillium fuscum and P. camembertii / clavigerum*	Cyclic macrolides	Acidic Berkeley lake	Antimicrobial	(Stierle et al. 2017)
Purpurquinones A-C	*Penicillium purpurogenum JS03–21*	Polyketides	Red soil from Yunnan, China	Antiviral	(Wang et al. 2017)
Pennicitrinone C	*Penicillium citrinumB-57*	Citrinin dimers	Jilantai salt field	Antioxidant	(Lu et al. 2008)
Terraquinone	*Aspergillus sp*	Curvularian derivative	Sonoran Desert	Cytotoxic	(He et al. 2004)
Paecilin E	*Neosartorya fennelliae KUFA 0811*	Dihydrochromone dimer	Marine sponge-associated fungus	Antimicrobial	(Kumla et al. 2017)
Curvularin derivatives	*Penicillium sp. Sf-5859*	Lactone polyketide	Marine sponge-associated fungus	Anti-inflammatory	(Ha et al. 2017)
Graphostrin A	*Graphostroma sp. MCCC 3A00421*	Chlorinated polyketide	Deep sea hydrothermal sulfide deposits	Anti-allergic	(Niu et al. 2018)
Berkeleydioneand berkeleytrione	*Penicillium sp*	Polyketide-terpenoid hybrid	Acidic Berkeley lake	Cytotoxic	(Stierle et al. 2004)
Berkazaphilones A-C and many other polyketides	*Penicillium rubrum*	Polyketide metabolites	Acidic Berkeley lake	Cytotoxic	(Stierle et al. 2012)
Phomopsolides	*Penicillium clavigerum*	Polyketides	Alga associated from acidic Berkeley lake	Cytotoxic	(Stierle et al. 2014)
Eremophilanetype sesquiterpenes	*Penicillium sp. PR19N-1*	Sesquiterpenes	Prydz Bay, Antarctica	Cytotoxic	(Lin et al. 2014) (Wu et al. 2013)
Purpurides B and C	*Penicillium purpurogenum JS03–21*	Sesquiterpene esters	Red soil from Yunnan, China	Antiviral	(Wang et al. 2017)

(continued)

Table 15.2 (continued)

Bioactive peptides	Marine fungi	Features	Source	Biological activity	References
Indole-diterpinoids	*Penicillium camemberti OUCMDZ-1492*	Terpenes	Rhizospora apiculata roots from acid niche, China	Antiviral	(Fan et al. 2013)
Penicilliumin B	*Penicillium sp. F00120*	Methylcyclopent-enedione sesquiterpene	Deep sea sediment	Antioxidant and antiallergic	(Lin et al. 2014)
Spirograterpene A	*Penicillium granulatum MCCC3A00475*	Spiro tetracyclic diterpene	Deep sea sediment	Antiallergic	(Niu et al. 2017)
Bisabalone sesquiterpenes, and coumarin	*Penicillium sp.*	Terpenes	Acidic Berkeley lake	Cytotoxic	(Stierle et al. 2004)
Berkeley acetals A–C	*Penicillium sp.*	Meroterpenes	Acidic Berkeley lake	Cytotoxic	(Stierle et al. 2007)
Berkidrimanes A and B	*Penicillium solitum*	Drimane sesquiterpenes	Acidic Berkeley lake	Cytotoxic	(Stierle et al. 2012)
Gliotoxin	*Aspergillus* SCSIO Ind09F01	Diketopiperazine alkaloids	Deep sea	Cytotoxic and antibacterial	(Luo et al. 2017)
Aspochalasins I, J, and K	*Aspergillus flavipes*	Cytochalasans alkaloids	Rihizospere of plant Sonoran Desert	Cytotoxic	(Zhou et al. 2004)
Globosumones A − C	*Chaetomium.Globosum*	Orsellinic acid esters alkaloids	Endophytic fungi from Sonoran Desert	Cytotoxic	(Bashyal et al. 2005)
Terremides A–B	*A terreus PTO6–2*	Terremides	Putian salt field	Antimicrobial/antiviral	(Wang et al. 2011)
Indole 3 ethanamide	*Aspergillus.Sclerotiorum sp. PT06–1*	Alkaloid	Putian salt field	Cytotoxic	(Wang et al. 2011)
Variecolorquinones A–B	*Aspergillus.variecolorB-17*	Quinone alkaloid	Jilantai salt field	Cytotoxic	(Wang et al. 2007)
Asperentin B	*Aspergillus sydowii*	Alkaloid	Deep sea	Tuyosine phosphatase inhibitor	(Wiese et al. 2017)

Tyrosine derivatives	*Pithomyces sp*	Aromatic alkaloids	Acidic Berkeley lake	Antihypertensive and antimigraine	(Stierle et al. 2007)
Berkeley amides A–D	*Penicillium sp.*	Amide	Acidic Berkeley lake	Cytotoxic	(Stierle et al. 2008)
Glionitrin A	*Aspergillus fumigatus KMC-901and* *A. sphinogomonas KMK 001*	Diketopiperazine disulfide	Acid mine drainage	Cytotoxic and antimicrobial	(Park et al. 2009)
Talathermophilins A and B	*Talaromyces. Thermophilus YM1–3*	Prenylated Indol alkaloids	Hot spring	Nematocidal	(Chu et al. 2010)
Thermolides	*Talaromyces. Thermophilus YM3–4*	Macrocyclic PKS-NRPS hybrids	Hot spring	Nematocidal	(Guo et al. 2012)
Dichotomocejs A–D	*Dichotomomyces.Cejpii F31–1*	NRPS hybrid dichotomocej A	Marine-lobophytum crissum derived	Cytotoxic	(Chen et al. 2017)
Brevianamides/ Mycochromenic acid	*B.brevicompactum DFFSCS025*	Alkaloids	Deep sea sediment	Cytotoxic/antifouling	(Xu et al. 2017)

References

Adachi K, Kanoh K, Wisespongp P, Nishijima M, Shizuri Y (2005) Clonostachysins a and B, new anti-dinoflagellate cyclic peptides from a marine-derived fungus. J Antibiot (Tokyo) 58:145–150

Adams PR (1981) Amylase production by Mucor pusillus and Humicola lanuginosa as related to mycelial growth. Mycopathologia 76:97–101

Adams PR (1994) Extracellular amylase activities of Rhizomucor pusillus and Humicola lanuginosa at initial stages of growth. Mycopathologia 128:139–141

Adrio JL, Demain AL (2003) Fungal biotechnology. Int Microbiol 6:191–199

Ahmed A, Bibi A (2018) Fungal Cellulase; production and applications: Minireview. Life Int J Health Life-Sci 4:19–36

Akhtar S, Mahmood-ul-Hassan M, Ahmad R, Suthar V, Yasin M (2013) Metal tolerance potential of filamentous fungi isolated from soils irrigated with untreated municipal effluent. Soil Environ 32:55–62

Alcalde M (2007) Laccases: biological functions, molecular structure and industrial applications. In: Polaina J, MacCabe AP (eds) Industrial enzymes: structure, function and applications. Springer, Dordrecht, pp 461–476

Ali I, Kanhayuwa L, Rachdawong S, Rakshit S (2012) Identification, phylogenetic analysis and characterization of obligate halophilic fungi isolated from a man-made solar saltern in Phetchaburi province, Thailand. Ann Microbiol 63:887–895

Almeida C, El Maddah F, Kehraus S, Schnakenburg G, König GM (2016) Endolides a and B, vasopressin and serotonin-receptor interacting N-methylated peptides from the sponge-derived fungus Stachylidium sp. Org Lett 18:528–531

Anand G, Yadav S, Yadav D (2017) Production, purification and biochemical characterization of an exo-polygalacturonase from aspergillus Niger MTCC 478 suitable for clarification of orange juice. 3 Biotech 7:122

Arnesen S, Havn Eriksen S, Olsen Ørgen J, Jensen B (1998) Increased production of α-amylase from Thermomyces lanuginosus by the addition of tween 80. Enzym Microb Technol 23:249–252

Arora NK, Panosyan H (2019) Extremophiles: applications and roles in environmental sustainability. Environ Sustain 2:217–218

Avila-Cisneros N, Velasco-Lozano S, Huerta-Ochoa S, Córdova-López J, Gimeno M, Favela-Torres E (2014) Production of thermostable lipase by Thermomyces lanuginosus on solid-state fermentation: selective hydrolysis of sardine oil. Appl Biochem Biotechnol 174:1859–1872

Babot ED, Rico A, Rencoret J, Kalum L, Lund H, Romero J, del Río JC, Martínez ÁT, Gutiérrez A (2011) Towards industrially-feasible delignification and pitch removal by treating paper pulp with Myceliophthora thermophila laccase and a phenolic mediator. Bioresour Technol 102: 6717–6722

Bajpai P (1999) Application of enzymes in the pulp and paper industry. Biotechnol Prog 15:147–157

Baldrian P (2006) Fungal laccases – occurrence and properties. FEMS Microbiol Rev 30:215–242

Barghini P, Moscatelli D, Garzillo AMV, Crognale S, Fenice M (2013) High production of cold-tolerant chitinases on shrimp wastes in bench-top bioreactor by the Antarctic fungus Lecanicillium muscarium CCFEE 5003: bioprocess optimization and characterization of two main enzymes. Enzym Microb Technol 53:331–338

Barnett EA, Fergus CL (1971) The relation of extracellular amylase, mycelium, and time, in some thermophilic and mesophilic Humicola species. Mycopathol Mycol Appl 44:131–141

Bashyal BP, Wijeratne EMK, Faeth SH, Gunatilaka AAL (2005) Globosumones a−C, cytotoxic Orsellinic acid esters from the Sonoran Desert endophytic fungus Chaetomium globosum. J Nat Prod 68:724–728

Berka RM, Schneider P, Golightly EJ, Brown SH, Madden M, Brown KM, Halkier T, Mondorf K, Xu F (1997) Characterization of the gene encoding an extracellular laccase of Myceliophthora thermophila and analysis of the recombinant enzyme expressed in aspergillus oryzae. Appl Environ Microbiol 63:3151–3157

Boot CM, Amagata T, Tenney K, Compton JE, Pietraszkiewicz H, Valeriote FA, Crews P (2007) Four classes of structurally unusual peptides from two marine-derived fungi: structures and bioactivities. Tetrahedron 63:9903–9914

Boot CM, Tenney K, Valeriote FA, Crews P (2006) Highly N-methylated linear peptides produced by an atypical sponge-derived Acremonium sp. J Nat Prod 69:83–92

Brijwani K, Rigdon A, Vadlani PV (2010) Fungal laccases: production, function, and applications in food processing. Enzyme Res 2010:149748

Brim H, Osborne JP, Kostandarithes HM, Fredrickson JK, Wackett LP, Daly MJ (2006) Deinococcus radiodurans engineered for complete toluene degradation facilitates Cr (VI) reduction. Microbiology (Reading) 152:2469–2477

Brunati M, Rojas JL, Sponga F, Ciciliato I, Losi D, Göttlich E, de Hoog S, Genilloud O, Marinelli F (2009) Diversity and pharmaceutical screening of fungi from benthic mats of Antarctic lakes. Mar Gen 1(2):43–50

Bulter T, Alcalde M, Sieber V, Meinhold P, Schlachtbauer C, Arnold FH (2003) Functional expression of a fungal laccase in Saccharomyces cerevisiae by directed evolution. Appl Environ Microbiol 69:987–995

Bunni L, McHale L, McHale AP (1989) Production, isolation and partial characterization of an amylase system produced by Talaromyces emersonii CBS 814.70. Enzym Microb Technol 11: 370–375

Capon RJ, Skene C, Stewart M, Ford J, O'Hair RAJ, Williams L, Lacey E, Gill JH, Heiland K, Friedel T (2003) Aspergillicins A–E: five novel depsipeptides from the marine-derived fungus Aspergillus carneus. Org Biomol Chem 1:1856–1862

Carrasco M, Rozas JM, Barahona S, Alcaíno J, Cifuentes V, Baeza M (2012) Diversity and extracellular enzymatic activities of yeasts isolated from King George Island, the sub-Antarctic region. BMC Microbiol 12:251

Carrasco M, Villarreal P, Barahona S, Alcaíno J, Cifuentes V, Baeza M (2016) Screening and characterization of amylase and cellulase activities in psychrotolerant yeasts. BMC Microbiol 16:21

Carrasco M, Rozas JM, Alcaíno J, Cifuentes V, Baeza M (2019) Pectinase secreted by psychrotolerant fungi: identification, molecular characterization and heterologous expression of a cold-active polygalacturonase from Tetracladium sp. Microb Cell Fact 18:1–11

Castro C, Urbieta MS, Plaza Cazón J, Donati ER (2019) Metal biorecovery and bioremediation: whether or not thermophilic are better than mesophilic microorganisms. Bioresour Technol 279: 317–326

Ceci A, Pinzari F, Russo F, Persiani AM, Gadd GM (2019) Roles of saprotrophic fungi in biodegradation or transformation of organic and inorganic pollutants in co-contaminated sites. Appl Microbiol Biotechnol 103:53–68

Chandra P, Arora DS (2009) Antioxidant activity of fungi isolated from soil of different areas of Punjab, India. Journal of Applied and Natural Science 1(2):123–128

Chefetz B, Chen Y, Hadar Y (1998) Purification and characterization of laccase from Chaetomium thermophilium and its role in humification. Appl Environ Microbiol 64:3175–3179

Chen Z, Song Y, Chen Y, Huang H, Zhang W, Ju J (2012) Cyclic heptapeptides, cordyheptapeptides C-E, from the marine-derived fungus Acremonium persicinum SCSIO 115 and their cytotoxic activities. J Nat Prod 75:1215–1219

Chen YX, Xu MY, Li HJ, Zeng KJ, Ma WZ, Tian GB, Xu J, Yang DP, Lan WJ (2017) Diverse secondary metabolites from the marine-derived fungus Dichotomomyces cejpii F31–1. Mar Drugs 15:339

Chhaya U, Gupte A (2013) Possible role of laccase from fusarium incarnatum UC-14 in bioremediation of bisphenol a using reverse micelles system. J Hazard Mater 254–255:149–156

Chu YS, Niu XM, Wang YL, Guo JP, Pan WZ, Huang XW, Zhang KQ (2010) Isolation of putative biosynthetic intermediates of prenylated indole alkaloids from a thermophilic fungus Talaromyces thermophilus. Org Lett 12(19):4356–4359

D'Souza-Ticlo D, Sharma D, Raghukumar C (2009) A thermostable metal-tolerant laccase with bioremediation potential from a marine-derived fungus. Mar Biotechnol (NY) 11:725–737

Daiha KDG, Angeli R, de Oliveira SD, Almeida RV (2015) Are lipases still important biocatalysts? A study of scientific publications and patents for technological forecasting. PLoS One 10: e0131624

Dalsgaard PW, Larsen TO, Christophersen C (2005) Bioactive cyclic peptides from the Psychrotolerant fungus Penicillium algidum. J Antibiot 58:141–144

Del Cid A, Ubilla P, Ravanal MC, Medina E, Vaca I, Levicán G, Eyzaguirre J, Chávez R (2014) Cold-active xylanase produced by fungi associated with Antarctic marine sponges. Appl Biochem Biotechnol 172:524–532

Deshmukh RA, Jagtap S, Mandal MK, Mandal SK (2016) Purification, biochemical characterization and structural modelling of alkali-stable β-1,4-xylan xylanohydrolase from aspergillus fumigatus R1 isolated from soil. BMC Biotechnol 16:11

Dewapriya P, Khalil ZG, Prasad P, Salim AA, Cruz-Morales P, Marcellin E, Capon RJ (2018) Talaropeptides A-D: structure and biosynthesis of extensively N-methylated linear peptides from an Australian marine tunicate-derived Talaromyces sp. Front Chem 6:394

Driss D, Bhiri F, Elleuch L, Bouly N, Stals I, Miled N, Blibech M, Ghorbel R, Chaabouni SE (2011) Purification and properties of an extracellular acidophilic endo-1,4-β-xylanase, naturally deleted in the "thumb", from Penicillium occitanis Pol6. Process Biochem 46:1299–1306

Du Y, Shi P, Huang H, Zhang X, Luo H, Wang Y, Yao B (2013) Characterization of three novel thermophilic xylanases from Humicola insolens Y1 with application potentials in the brewing industry. Bioresour Technol 130:161–167

Duarte AWF, Lopes AM, Molino JVD, Pessoa A, Sette LD (2015) Liquid–liquid extraction of lipase produced by psychrotrophic yeast Leucosporidium scottii L117 using aqueous two-phase systems. Sep Purif Technol 156:215–225

Dumorné K, Córdova DC, Astorga-Eló M, Renganathan P (2017) Extremozymes: a potential source for industrial applications. J Microbiol Biotechnol 27(4):649–659

Duncan SM, Farrell RL, Thwaites JM, Held BW, Arenz BE, Jurgens JA, Blanchette RA (2006) Endoglucanase-producing fungi isolated from Cape Evans historic expedition hut on Ross Island, Antarctica. Environ Microbiol 8:1212–1219

Duncan SM, Minasaki R, Farrell RL, Thwaites JM, Held BW, Arenz BE, Jurgens JA, Blanchette RA (2008) Screening fungi isolated from historic discovery hut on Ross Island, Antarctica for cellulose degradation. Antarctic Sci 20:463–470

Dutta T, Sengupta R, SahooR RS, Bhattacharjee A, Ghosh S (2007) A novel cellulase free alkaliphilic xylanase from alkali tolerant Penicillium citrinum: production, purification and characterization. Lett Appl Microbiol 44:206–211

Ebada SS, Fischer T, Hamacher A, Du FY, Roth YO, Kassack MU, Wang BG, Roth EH (2014) Psychrophilin E, a new cyclotripeptide, from co-fermentation of two marine alga-derived fungi of the genus aspergillus. Nat Prod Res 28:776–781

Evaristo da Silva Nascimento TC, de Sena AR, Gomes JEG, dos Santos WL, Agamez Montalvo GS, Tambourgi EB, de Medeiros EV, Sette LD, Pessoa Junior A, Moreira KA (2015) Extracellular serine proteases by Acremonium sp. L1-4B isolated from Antarctica: overproduction using cactus pear extract with response surface methodology. Biocatal Agric Biotechnol 4:737–744

Fan Y, Wang Y, Liu P, Fu P, Zhu T, Wang W, Zhu W (2013) Indole-diterpenoids with anti-H1N1 activity from the aciduric fungus Penicillium camemberti OUCMDZ-1492. J Nat Prod 76:1328–1336

Federici F (1985) Production, purification and partial characterization of an endopolygalacturonase fromCryptococcus albidus var.albidus. Antonie Van Leeuwenhoek 51:139–150

de Felício R, Pavão GB, de Oliveira ALL, Erbert C, Conti R, Pupo MT, Furtado NAJC, Ferreira EG, Costa-Lotufo LV, Young MCM, Yokoya NS, Debonsi HM (2015) Antibacterial, antifungal and cytotoxic activities exhibited by endophytic fungi from the Brazilian marine red alga Bostrychia tenella (Ceramiales). Rev Bras 25:641–650

Fenice M, Barghini P, Selbmann L, Federici F (2012) Combined effects of agitation and aeration on the chitinolytic enzymes production by the Antarctic fungus Lecanicillium muscarium CCFEE 5003. Microb Cell Factories 11:12

Fenice M, Selbmann L, Di Giambattista R, Federici F (1998) Chitinolytic activity at low temperature of an Antarctic strain (A3) of Verticillium lecanii. Res Microbiol 149:289–300

Fenice M, Selbmann L, Zucconi L, Onofri S (1997) Production of extracellular enzymes by Antarctic fungal strains. Polar Biol 17:275–280

Fergus CL (1969) The production of amylase by some thermophilic fungi. Mycologia 61:1171–1175

Fremlin LJ, Piggott AM, Lacey E, Capon RJ (2009) Cottoquinazoline a and cotteslosins a and B, metabolites from an Australian marine-derived strain of aspergillus versicolor. J Nat Prod 72: 666–670

Fuciños P, González R, Atanes E, Sestelo ABF, Pérez-Guerra N, Pastrana L, Rúa ML (2012) Lipases and esterases from extremophiles: overview and case example of the production and purification of an esterase from Thermus thermophilus HB27. Methods Mol Biol 861:239–266

Gainvors A, Nedjaoum N, Gognies S, Muzart M, Nedjma M, Belarbi A (2000) Purification and characterization of acidic endo-polygalacturonase encoded by the *PGL1-1* gene from *Saccharomyces cerevisiae*. FEMS Microbiol Lett 183:131–135

Gao B, Mao Y, Zhang L, He L, Wei D (2016) A novel saccharifying α-amylase of Antarctic psychrotolerant fungi Geomyces pannorum: gene cloning, functional expression, and characterization. Starch - Stärke 68:20–28

Ghatora SK, Chadha BS, Badhan AK, Saini HS, Bhat MK (2006) Identification and characterization of diverse xylanases from thermophilic and thermotolrant fungi. BioResources 1:18–33

Ghosal D, Ghosh S, Dutta TK, Ahn Y (2016) Current state of knowledge in microbial degradation of polycyclic aromatic hydrocarbons (PAHs): a review. Front Microbiol 7:1369

Gomes J, Steiner W (2004) The biocatalytic potential of extremophiles and Extremozymes. Food Technol Biotechnol 42:223–225

Gomes I, Gomes J, Steiner W (2003) Highly thermostable amylase and pullulanase of the extreme thermophilic eubacterium Rhodothermus marinus: production and partial characterization. Bioresour Technol 90:207–214

Goto S, Sugiyama J, Iizuka H (1969) A taxonomic study of Antarctic yeasts. Mycologia 61:748–774

Gupta S, Krasnoff SB, Roberts DW, Renwick JAA, Brinen LS, Clardy J (1992) Structure of efrapeptins from the fungus Tolypocladium niveum: peptide inhibitors of mitochondrial ATPase. J Org Chem 57:2306–2313

Gu W, Cueto M, Jensen PR, Fenical W, Silverman RB (2007) Microsporins A and B: new histone deacetylase inhibitors from the marine-derived fungus Microsporum cf. gypseum and the solid-phase synthesis of microsporin A. Tetrahedron 63:6535–6541

Gulder TAM, Hong H, Correa J, Egereva E, Wiese J, Imhoff JF, Gross H (2012) Isolation, structure elucidation and Total synthesis of Lajollamide a from the marine fungus Asteromyces cruciatus. Mar Drugs 10:2912–2935

Gunde-Cimerman N, Ramos J, Plemenitaš A (2009) Halotolerant and halophilic fungi. Mycol Res 113:1231–1241

Gunde-Cimerman N, Sonjak S, Zalar P, Frisvad JC, Diderichsen B, Plemenitaš A (2003) Extremophilic fungi in arctic ice: a relationship between adaptation to low temperature and water activity. Phys Chem Earth Parts A/B/C 28:1273–1278

Guo JP, Zhu CY, Zhang CP, Chu YS, Wang YL, Zhang JX, Wu DK, Zhang KQ, Niu XM (2012) Thermolides, potent Nematocidal PKS-NRPS hybrid metabolites from thermophilic fungus Talaromyces thermophilus. J Am Chem Soc 134:20306–20309

Ha TM, Ko W, Lee SJ, Kim YC, Son JY, Sohn JH, Yim JH, Oh H (2017) Anti-inflammatory effects of Curvularin-type metabolites from a marine-derived fungal strain Penicillium sp. SF-5859 in lipopolysaccharide-induced RAW264.7 macrophages. Mar Drugs 15:282

Hamid R, Khan MA, Ahmad M, Ahmad MM, Abdin MZ, Musarrat J, Javed S (2013) Chitinases: an update. J Pharm Bioallied Sci 5:21

Hamilton-Miller JMT (2008) Development of the semi-synthetic penicillins and cephalosporins. Int J Antimicrob Agents 31:189–192

Haros M, Rosell CM, Benedito C (2001) Use of fungal phytase to improve breadmaking performance of whole wheat bread. J Agric Food Chem 49:5450–5454

Hawwa R, Aikens J, Turner R, Santarsiero B, Mesecar A (2009) Structural basis for thermostability revealed through the identification and characterization of a highly thermostable phosphotriesterase-like lactonase from Geobacillus stearothermophilus. Arch Biochem Biophys 488:109–120

He J, Wijeratne EMK, Bashyal BP, Zhan J, Seliga CJ, Liu MX, Pierson EE, Pierson LS, VanEtten HD, Gunatilaka AAL (2004) Cytotoxic and other metabolites of aspergillus inhabiting the rhizosphere of Sonoran desert plants. J Nat Prod 67:1985–1991

Hooker C, Lee KZ, Solomon K (2019) Leveraging anaerobic fungi for biotechnology. Curr Opin Biotechnol 59:103–110

Hou XM, Zhang YH, Hai Y, Zheng JY, Gu YC, Wang CY, Shao CL (2017) Aspersymmetide A, a new centrosymmetric cyclohexapeptide from the marine-derived fungus Aspergillus versicolor. Mar Drugs 15:363

Ibrar M, Ullah MW, Manan S, Farooq U, Rafiq M, Hasan F (2020) Fungi from the extremes of life: an untapped treasure for bioactive compounds. Appl Microbiol Biotechnol 104:2777–2801

Jaouani A, Neifar M, Prigione V, Ayari A, Sbissi I, Ben Amor S, Ben Tekaya S, Varese GC, Cherif A, Gtari M (2014) Diversity and enzymatic profiling of halotolerant Micromycetes from Sebkha El Melah, a Saharan salt flat in southern Tunisia [WWW document]. Biomed Res Int 2014:439197

Jayachandran S, Ramabadran R (1970) Production of amylase by Thermoascus aurantiacus Miehe. Indian J Exp Biol 8:344

Jiang W, Ye P, Chen CTA, Wang K, Liu P, He S, Wu X, Gan L, Ye Y, Wu B (2010) Two novel hepatocellular carcinoma cycle inhibitory cyclodepsipeptides from a hydrothermal vent crab-associated fungus Aspergillus clavatus C2WU. Mar Drugs 11:4761–4772

Jin L, Quan C, Hou X, Fan S (2016) Potential pharmacological resources: natural bioactive compounds from marine-derived fungi. Mar Drugs 14:76

Jin Q, Kirk F (2018) pH as a primary control in environmental microbiology: 1. Thermodynamic perspective. Front Environ Sci 6:21

Jin Y, Qin S, Gao H, Zhu G, Wang W, Zhu W, Wang Y (2018) An anti-HBV anthraquinone from aciduric fungus Penicillium sp. OUCMDZ-4736 under low pH stress. Extremophiles 22:39–45

Jurado-Alameda E, Román MG, Vaz DA, Jiménez Pérez JL (2012) Fatty soil cleaning with ozone and lipases—a way to develop more environmentally friendly washing processes. Househ Pers Care Today 7:49–52

Kakugawa K, Shobayashi M, Suzuki O, Miyakawa T (2002) Purification and characterization of a lipase from the glycolipid-producing yeast *Kurtzmanomyces* sp. I-11. Biosci Biotechnol Biochem 66:978–985

Karthik N, Akanksha K, Pandey A (2014) Production, purification and properties of fungal chitinases--a review. Indian J Exp Biol 52(11):1025–1035

Kashyap D, Vohra P, Chopra S, Tewari R (2001) Applications of pectinases in the commercial sector: a review. Bioresour Technol 77:215–227

Khamthong N, Rukachaisirikul V, Phongpaichit S, Preedanon S, Sakayaroj J (2014) An antibacterial cytochalasin derivative from the marine-derived fungus Diaporthaceae sp. PSU-SP2/4. Phytochem Lett 10:5–9

Komatsu K, Shigemori H, Kobayashi J (2001) Dictyonamides A and B, new peptides from marine-derived fungus. J Org Chem 66(18):6189–6192

Krishnan A, Alias SA, Wong CMVL, Pang KL, Convey P (2011) Extracellular hydrolase enzyme production by soil fungi from King George Island, Antarctica. Polar Biol 34:1535–1542

Kuhad RC, Gupta R, Singh A (2011) Microbial Cellulases and their industrial applications. Enzyme Res 2011:280696

Kumla D, Shine Aung T, Buttachon S, DethoupT GL, Pereira JA, Inácio Â, Costa PM, Lee M, Sekeroglu N, Silva AMS, Pinto MMM, Kijjoa A (2017) A new Dihydrochromone dimer and other secondary metabolites from cultures of the marine sponge-associated fungi Neosartorya fennelliae KUFA 0811 and Neosartorya tsunodae KUFC 9213. Mar Drugs 15:375

Lara-Márquez A, Zavala-Páramo MG, López-Romero E, Camacho HC (2011) Biotechnological potential of pectinolytic complexes of fungi. Biotechnol Lett 33:859–868

Lario LD, Chaud L, das Graças Almeida M, Converti A, Durães Sette L, Pessoa A (2015) Production, purification, and characterization of an extracellular acid protease from the marine Antarctic yeast Rhodotorula mucilaginosa L7. Fungal Biol 119:1129–1136

Liang X, Nong XH, Huang ZH, Qi SH (2017) Antifungal and antiviral cyclic peptides from the Deep-Sea-derived fungus Simplicillium obclavatum EIODSF 020. J Agric Food Chem 65: 5114–5121

Liang X, Zhang XY, Nong XH, Wang J, Huang ZH, Qi SH (2016) Eight linear peptides from the deep-sea-derived fungus Simplicillium obclavatum EIODSF 020. Tetrahedron 72:3092–3097

Lin A, Wu G, Gu Q, Zhu T, Li D (2014) New eremophilane-type sesquiterpenes from an Antarctic deepsea derived fungus, Penicillium sp. PR19 N-1. Arch Pharm Res 37:839–844

Liu X, Kokare C (2017) Chapter 11 - microbial enzymes of use in industry. In: Brahmachari G (ed) Biotechnology of microbial enzymes. Academic Press, Boston, pp 267–298

Liu J, Gu B, Yang L, Yang F, Lin H (2018) New anti-inflammatory cyclopeptides from a sponge-derived fungus Aspergillus violaceofuscus. Front Chem 6:226

Lu ZY, Lin ZJ, Wang WL, Du L, ZhuTJ FYC, Gu QQ, Zhu WM (2008) Citrinin dimers from the halotolerant fungus Penicillium citrinum B-57. J Nat Prod 71:543–546

Lugowski AJ, Palmateer GA, Boose TR, Merriman JE (1998) Biodegradation process for de-toxifying liquid streams. WO1998005597A1

Luo X, Zhou X, Lin X, Qin X, Zhang T, Wang J, Tu Z, Yang B, Liao S, Tian Y, Pang X, Kaliyaperumal K, Li JL, Tao H, Liu Y (2017) Antituberculosis compounds from a deep-sea-derived fungus aspergillus sp. SCSIO Ind09F01. Nat Prod Res 31:1958–1962

Ma X, Nong XH, Ren Z, Wang J, Liang X, Wang L, Qi SH (2017) Antiviral peptides from marine gorgonianderived fungus Aspergillus sp. SCSIO 41501. Tetrahedron Lett 58:1151–1155

Machuca A, Aoyama H, Durán N (1998) Production and characterization of thermostable phenol oxidases of the ascomycete Thermoascus aurantiacus. Biotechnol Appl Biochem 27:217–223

Maheshwari R, Bharadwaj G, Bhat MK (2000) Thermophilic fungi: their physiology and enzymes. Microbiol Mol Biol Rev 64:461–488

Mandels M, Weber J (1969) The production of Cellulases. In: Cellulases and their applications, advances in chemistry. American Chemical Society, Washington, pp 391–414

Martin N, Guez MAU, Sette LD, Da Silva R, Gomes E (2010) Pectinase production by a Brazilian thermophilic fungus Thermomucor indicae-seudaticae N31 in solid-state and submerged fermentation. Microbiology 79:306–313

McCormack J, Hackett TJ, Tuohy MG, Coughlan MP (1991) Chitinase production byTalaromyces emersonii. Biotechnol Lett 13:677–682

Meyer V, Andersen MR, Brakhage AA, Braus GH, Caddick MX, Cairns TC, de Vries RP, Haarmann T, Hansen K, Hertz-Fowler C, Krappmann S, Mortensen UH, Peñalva MA, Ram AFJ, Head RM (2016) Current challenges of research on filamentous fungi in relation to human welfare and a sustainable bio-economy: a white paper. Fungal Biol Biotechnol 3:6

Mot RD, Verachtert H (1987) Purification and characterization of extracellular α-amylase and glucoamylase from the yeast Candida antarctica CBS 6678. Eur J Biochem 164:643–654

Muthezhilan R, Ashok R, Jayalakshmi S (2007) Production and optimization of thermostable alkaline xylanase by Penicillium oxalicum in solid state fermentation. Afr J Microbiol Res 9: 20–28

Navarri M, Jégou C, Bondon A, Pottier S, Bach S, Baratte B, Ruchaud S, Barbier G, Burgaud G, Fleury Y (2017) Bioactive metabolites from the deep subseafloor fungus Oidiodendron griseum UBOCC-A-114129. Mar Drugs 15:111

Niu S, Fan ZW, Xie CL, Liu Q, Luo ZH, Liu G, Yang XW (2017) Spirograterpene a, a tetracyclic Spiro-Diterpene with a fused 5/5/5/5 ring system from the Deep-Sea-derived fungus Penicillium granulatum MCCC 3A00475. J Nat Prod 80:2174–2177

Niu S, Liu Q, Xia JM, Xie CL, Luo ZH, Shao Z, Liu G, Yang XW (2018) Polyketides from the Deep-Sea-derived fungus Graphostroma sp. MCCC 3A00421 showed potent Antifood allergic activities. J Agric Food Chem 66:1369–1376

Oh DC, Kauffman CA, Jensen PR, Fenical W (2007) Induced production of emericellamides a and B from the marine-derived fungus Emericella sp. in competing co-culture. J Nat Prod 70:515–520

Ohta K, Moriyama S, Tanaka H, Shige T, Akimoto H (2001) Purification and characterization of an acidophilic xylanase from Aureobasidium pullulans var. melanigenum and sequence analysis of the encoding gene. J Biosci Bioeng 92:262–270

Onofri S, Fenice M, Cicalini AR, Tosi S, Magrino A, Pagano S, Selbmann L, Zucconi L, Ocampo-Friedmann R, Friedmann E (2000) Ecology and biology of microfungi from Antarctic rocks and soils. Italian J Zoology 67:163–167

Ozerskaya S, Kochkina G, Ivanushkina N, Gilichinsky DA (2009) Fungi in permafrost. In: Permafrost soils. Springer, Cham, pp 85–95

Pandey A, Soccol CR, Nigam P, Soccol VT (2000) Biotechnological potential of agro-industrial residues. I: sugarcane bagasse. Bioresour Technol 74:69–80

Park HB, Kwon HC, Lee CH, Yang HO (2009) Glionitrin a, an antibiotic−antitumor metabolite derived from competitive interaction between abandoned mine microbes. J Nat Prod 72:248–252

Pavlova K, Gargova S, Hristozova T, Tankova Z (2008) Phytase from antarctic yeast strain Cryptococcus laurentii AL27. Folia Microbiol 53:29–34

Peng J, Gao H, Zhang X, Wang S, Wu C, Gu Q, Guo P, Zhu T, Li D (2014) Psychrophilins E-H and Versicotide C, Cyclic Peptides from the Marine-Derived Fungus Aspergillus versicolor ZLN-60. J Nat Prod 77, 2218–2223

Prompanya C, Fernandes C, Cravo S, Pinto MMM, Dethoup T, Silva AMS, Kijjoa A (2015) A new cyclic Hexapeptide and a new Isocoumarin derivative from the marine sponge-associated fungus aspergillus similanensis KUFA 0013. Mar Drugs 13:1432–1450

Raghukumar C, Raghukumar S, Chinnaraj A, Chandramohan D, D'Souza T, Reddy C (1994) Laccase and other lignocellulose modifying enzymes of marine fungi isolated from the coast of India. Botanica Marina - BOT MAR 37:515–524

Rajkumari J, Bhuyan B, Das N, Pandey P (2019) Environmental applications of microbial extremophiles in the degradation of petroleum hydrocarbons in extreme environments. Environ Sustain 2:311–328

Ramli AN, Mahadi NM, Rabu A, Murad AM, Bakar FD, Illias RM (2011) Molecular cloning, expression and biochemical characterisation of a cold-adapted novel recombinant chitinase from Glaciozyma antarctica PI12. Microb Cell Factories 10:94

Rani B, Kumar V, Singh J, Bisht S, Teotia P, Sharma S, Kela R (2014) Bioremediation of dyes by fungi isolated from contaminated dye effluent sites for bio-usability. Braz J Microbiol 45:1055–1063

Rateb ME, Ebel R (2011) Secondary metabolites of fungi from marine habitats. Nat Prod Rep 28: 290–344

Ray MK, Devi KU, Kumar GS, Shivaji S (1992) Extracellular protease from the antarctic yeast Candida humicola. Appl Environ Microbiol 58:1918–1923

Robledo A, Aguilar CN, Belmares-Cerda RE, Flores-Gallegos AC, Contreras-Esquivel JC, Montañez JC, Mussatto SI (2016) Production of thermostable xylanase by thermophilic fungal strains isolated from maize silage. CyTA J Food 14:302–308

Rowley DC, Kelly S, Kauffman CA, Jensen PR, Fenical W, Halovirs A-E (2003) New antiviral agents from a marine-derived fungus of the genus Scytalidium. Bioorg Med Chem 11 (19):4263–4274

Rowley DC, Kelly S, Jensen P, Fenical W (2004) Synthesis and structure-activity relationships of the halovirs, antiviral natural products from a marine derived fungus. Bioorg Med Chem 12 (18):4929–4936

Sadaf A, Khare SK (2014) Production of Sporotrichum thermophile xylanase by solid state fermentation utilizing deoiled Jatropha curcas seed cake and its application in xylooligosachharide synthesis. Bioresour Technol 153:126–130

Sadhukhan R, Roy SK, Raha SK, Manna S, Chakrabarty SL (1992) Induction and regulation of alpha-amylase synthesis in a cellulolytic thermophilic fungus Myceliophthora thermophila D14 (ATCC 48104). Indian J Exp Biol 30:482–486

Saleem M, Ali MS, Hussain S, Jabbar A, Ashraf M, Lee YS (2007) Marine natural products of fungal origin. Nat Prod Rep 24:1142

Sarmiento F, Peralta R, Blamey J (2015) Cold and hot Extremozymes: industrial relevance and current trends. Front Bioeng Biotechnol 3:148

Schueffler A, Anke T (2014) Fungal natural products in research and development. Nat Prod Rep 31:1425–1448

Scopel M, Abraham WR, Henriques AT, Macedo AJ (2013) Dipeptide cis-cyclo(Leucyl-Tyrosyl) produced by sponge associated Penicillium sp. F37 inhibits biofilm formation of the pathogenic Staphylococcus epidermidis. Bioorg Med Chem Lett 23:624–626

Selbmann L, de Hoog GS, Zucconi L, Isola D, Ruisi S, van den Ende AHGG, Ruibal C, De Leo F, Urzì C, Onofri S (2008) Drought meets acid: three new genera in a dothidealean clade of extremotolerant fungi. Stud Mycol 61:1–20

Selbmann L, Egidi E, Isola D, Onofri S, Zucconi L, de Hoog GS, Chinaglia S, Testa L, Tosi S, Balestrazzi A (2013) Biodiversity, evolution and adaptation of fungi in extreme environments. Plant Biosyst 147:237–246

Selbmann L, Isola D, Zucconi L, Onofri S (2011) Resistance to UV-B induced DNA damage in extreme-tolerant cryptoendolithic Antarctic fungi: detection by PCR assays. Fungal Biol 115: 937–944

Selbmann L, Zucconi L, Isola D, Onofri S (2015) Rock black fungi: excellence in the extremes, from the Antarctic to space. Curr Genet 61:335–345

Shukla AK, Singh AK (2020) Exploitation of potential extremophiles for bioremediation of xenobiotics compounds: a biotechnological approach. Curr Genom 21:161–167

Siddiqui D, Pande V, Arif M (2012) Production, purification, and characterization of Polygalacturonase from Rhizomucor pusillus isolated from Decomposting Orange peels. Enzyme Res 2012:138634

Silambarasan S, Abraham J (2013) Ecofriendly method for bioremediation of Chlorpyrifos from agricultural soil by novel fungus aspergillus Terreus JAS1. Water Air and Soil Pollution 224:1–11

Soni H, Rawat H, Kango N (2017) Extremophilic xylanases. In: Extremophilic enzymatic processing of lignocellulosic feedstocks to bioenergy. Springer, Cham, pp 73–88

Stierle A, StierleD MG, Snyder S, Antczak C, Djaballah H (2014) Phomopsolides and related compounds from the alga-associated fungus, Penicillium clavigerum. Nat Prod Commun 9:87–90

Stierle AA, Stierle DB, Decato D, Priestley ND, Alverson JB, Hoody J, McGrath K, Klepacki D (2017) The Berkeleylactones, antibiotic macrolides from fungal Coculture. J Nat Prod 80:1150–1160

Stierle AA, Stierle DB, Girtsman T (2012) Caspase-1 inhibitors from an Extremophilic fungus that target specific leukemia cell lines. J Nat Prod 75:344–350

Stierle AA, Stierle DB, Girtsman T, Mou TC, Antczak C, Djaballah H (2015) Azaphilones from an acid mine extremophile strain of a Pleurostomophora sp. J Nat Prod 78:2917–2923

Stierle AA, Stierle DB, Patacini B (2008) The Berkeleyamides, amides from the acid Lake fungus Penicillum rubrum. J Nat Prod 71:856–860

Stierle DB, Stierle AA, Hobbs JD, Stokken J, Clardy J (2004) Berkeleydione and Berkeleytrione, new bioactive metabolites from an acid mine organism. Org Lett 6:1049–1052

Stierle DB, Stierle AA, Patacini B (2007) The Berkeleyacetals, three Meroterpenes from a deep water acid mine waste Penicillium. J Nat Prod 70:1820–1823

Thurston CF (1994) The structure and function of fungal laccases. Microbiology 140:19–26

Torres-García C, Pulido D, Albericio F, Royo M, Nicolás E (2014) Triazene as a powerful tool for solid-phase derivatization of phenylalanine containing peptides: Zygosporamide analogues as a proof of concept. J Org Chem 79:11409–11415

Tsuji M, Yokota Y, Kudoh S, Hoshino T (2014) Improvement of direct ethanol fermentation from woody biomasses by the Antarctic basidiomycetous yeast, Mrakia blollopis, under a low temperature condition. Cryobiology 68:303–305

Tsuji M, Yokota Y, Shimohara K, Kudoh S, Hoshino T (2013) An application of wastewater treatment in a cold environment and stable lipase production of Antarctic Basidiomycetous yeast Mrakia blollopis. PLoS One 8:e59376

Turkiewicz M, Pazgier M, Kalinowska H, Bielecki S (2003) A cold-adapted extracellular serine proteinase of the yeast Leucosporidium antarcticum. Extremophiles 7:435–442

Van der Giezen M (2011) Mitochondria and the rise of eukaryotes. Bioscience 61:594–601

Vaz ABM, Rosa LH, Vieira MLA, de Garcia V, Brandão LR, Teixeira LCRS, Moliné M, Libkind D, Van Broock M, Rosa CA (2011) The diversity, extracellular enzymatic activities and photoprotective compounds of yeasts isolated in Antarctica. Braz J Microbiol 42:937–947

Verma AK, Raghukumar C, Parvatkar RR, Naik CG (2012) A rapid two-step bioremediation of the Anthraquinone dye, reactive blue 4 by a marine-derived fungus. Water Air Soil Pollut 223: 3499–3509

Wang W, Tianjiao Z, Hongwen T, Lu Z, Fang Y, Gu Q, Zhu W (2007) Two new cytotoxic quinone type compounds from the halotolerant fungus Aspergillus variecolor. J Antibiot 60(10): 603–607

Wang H, Zheng JK, Qu HJ, Liu PP, Wang Y, Zhu WM (2011) A new cytotoxic indole-3-ethenamide from the halotolerant fungus aspergillus sclerotiorum PT06-1. J Antibiot 64:679–681

Wang N, Zang J, Ming K, Liu Y, Wu Z, Ding H (2013) Production of cold-adapted cellulase by Verticillium sp. isolated from Antarctic soils. Electron J Biotechnol 16:10–10

Wang N, Cui CB, Li CW (2016) A new cyclic dipeptide penicimutide: the activated production of cyclic dipeptides by introduction of neomycin-resistance in the marine-derived fungus Penicillium purpurogenum G59. Arch Pharm Res 39:762–770

Wang X, Yu H, Xing R, Li P (2017) Characterization, preparation, and purification of marine bioactive peptides. Biomed Res Int 2017:9746720

Wiese J, Aldemir H, Schmaljohann R, Gulder TA, Imhoff JF (2017) Asperentin B, a new inhibitor of the protein tyrosine phosphatase 1B. Mar Drugs 15:191

Wu G, Lin A, Gu Q, Zhu T, Li D (2013) Four new Chloro-Eremophilane Sesquiterpenes from an Antarctic Deep-Sea derived fungus, Penicillium sp. PR19N-1. Mar Drugs 11:1399–1408

Wu HY, Yang FL, Li LH, Rao YK, Ju TC, Wong WT, Hsieh CY, Pivkin MV, Hua KF, Wu SH (2018) Ergosterol peroxide from marine fungus Phoma sp. induces ROS-dependent apoptosis and autophagy in human lung adenocarcinoma cells. Sci Rep 8:1–14

Xu F, Shin W, Brown SH, Wahleithner JA, Sundaram UM, Solomon EI (1996) A Study of a series of recombinant fungal laccases and bilirubin oxidase that exhibit significant differences in redox potential, substrate specificity, and stability. Biochim Biophys Acta 1292:303–311

Xu X, Zhang X, Nong X, Wang J, Qi S (2017) Brevianamides and mycophenolic acid derivatives from the Deep-Sea-derived fungus Penicillium brevicompactum DFFSCS025. Mar Drugs 15:43

Yang YL, Liao WY, Liu WY, Liaw CC, Shen CN, Huang ZY, Wu SH (2009) Discovery of new natural products by intact-cell mass spectrometry and LC-SPE-NMR: malbranpyrroles, novel polyketides from thermophilic fungus Malbranchea sulfurea. Chemistry 15:11573–11580

Yang YL, Lu CP, Chen MY, Chen KY, Wu YC, Wu SH (2007) Cytotoxic polyketides containing tetramic acid moieties isolated from the fungus Myceliophthora Thermophila: elucidation of the relationship between cytotoxicity and stereoconfiguration. Chemistry 13:6985–6991

Yegin S (2017) Single-step purification and characterization of an extreme halophilic, ethanol tolerant and acidophilic xylanase from Aureobasidium pullulans NRRL Y-2311-1 with application potential in the food industry. Food Chem 221:67–75

You M, Liao L, Hong SH, Park W, Kwon DI, Lee J, Noh M, Oh DC, Oh K, Shin J (2015) Lumazine peptides from the marine-derived fungus aspergillus terreus. Mar Drugs 13:1290–1303

Youssef FS, Ashour ML, Singab ANB, Wink M (2019) A comprehensive review of bioactive peptides from marine fungi and their biological significance. Mar Drugs 17:559

Yu P, Wang XT, Liu JW (2015) Purification and characterization of a novel cold-adapted phytase from Rhodotorula mucilaginosa strain JMUY14 isolated from Antarctic. J Basic Microbiol 55: 1029–1039

Yuan P, Meng K, Huang H, Shi P, Luo H, Yang P, Yao B (2011) A novel acidic and low-temperature-active endo-polygalacturonase from Penicillium sp. CGMCC 1669 with potential for application in apple juice clarification. Food Chem 129:1369–1375

Zeldes BM, Keller MW, Loder AJ, Straub CT, Adams MWW, Kelly RM (2015) Extremely thermophilic microorganisms as metabolic engineering platforms for production of fuels and industrial chemicals. Front Microbiol 6:1209

Zhang X, Li SJ, Li JJ, Liang ZZ, Zhao CQ (2018) Novel natural products from Extremophilic fungi. Mar Drugs 16:194

Zhang Y, Li XM, Feng Y, Wang BG (2010) Phenethyl-α-pyrone derivatives and cyclodipeptides from a marine algous endophytic fungus aspergillus Niger EN–13. Nat Prod Res 24:1036–1043

Zheng J, Zhu H, Hong K, Wang Y, Liu P, Wang X, Peng X, Zhu W (2009) Novel cyclic Hexapeptides from marine-derived fungus, aspergillus sclerotiorum PT06-1. Org Lett 11: 5262–5265

Zhou GX, Wijeratne EM, Bigelow D, Pierson LS, VanEtten HD, Gunatilaka AA (2004) Aspochalasins I, J, and K: three new cytotoxic cytochalasans of Aspergillus flavipes from the rhizosphere of Ericameria laricifolia of the Sonoran Desert. J Nat Prod 67(3):328–332

Zhou X, Fang P, Tang J, Wu Z, Li X, Li S, Wang Y, Liu G, He Z, Gou D (2016) A novel cyclic dipeptide from deep marine-derived fungus Aspergillus sp. SCSIOW2. Nat Prod Res 30:52–57