Brown biotechnology: a powerful toolbox for resolving current and future challenges in the development of arid lands

K. Rodríguez-Núñez¹ · F. Rodríguez-Ramos¹ · D. Leiva-Portilla¹ · C. Ibáñez²

Received: 29 October 2019 / Accepted: 29 May 2020 / Published online: 8 June 2020
© Springer Nature Switzerland AG 2020

Abstract

The aim of this study was to link the biotechnological advances made in arid lands, which are known as “brown biotechnology,” to the current environmental challenges facing these regions, their ecosystems and their inhabitants. We present a broad compilation of scientific evidence and technological advances developed over the past 15 years that have helped to address some of the classical constraints of arid environments, such as the development of sustainable agriculture in areas limited by water resources and low levels of organic matter in soils, including the relevant organisms and their interactions with biotic and abiotic stressors. New challenges and new opportunities related to the production of sustainable energy, versatile crops, phytoremediation, biofertilization, desalination, and the incorporation of genes into plants to improve their resistance to water scarcity and to obtain biomolecules from the organisms living in these hostile environments are also presented. To face the constant and recently extreme changes in the climate and the worrisome scarcity of natural resources successfully, issues that need to be resolved in the short and medium terms are described here.

Keywords Arid zones · Deserts · Brown biotechnology · Antarctica · Atacama Desert · Climate change

1 Introduction

The acceleration of climate change is a phenomenon that has driven research in all the regions of the world, particularly in the fragile arid and semiarid regions, which have delicate ecosystems and are sensitive to strong interactions between human activities and climate changes [1]. In this context, the use of biotechnology tools that allow the identification and preservation of the biota of these ecosystems, which are adapted to such extreme conditions, to safeguard their genetic inheritance is essential. This knowledge constitutes an opportunity to understand, develop and maintain the biodiversity in these ecosystems while making sustainable use of the benefits they can offer [2]. Rapid population growth has brought about the development of simultaneous economic activities, many of which

have been exclusively based on the exploitation of natural and energy resources, giving rise to environmental problems and changes in ecosystem equilibria. This population growth is of particular concern in arid areas, where the limited presence of natural resources, such as freshwater and arable land, generates pressure that could lead to the rapid collapse of these ecosystems [3].

Water constitutes a limiting factor for the development of life and any type of productive activity, especially agriculture [4]. The optimization of this valuable resource is imperative on a planet that has witnessed decreasing natural resources. In addition, a considerable proportion of the poorest population is concentrated around less productive agricultural land (poor soil quality, shortages of rainfall) [5]. Therefore, the sustainable management of these resources must be approached with urgency,

✉ C. Ibáñez, cibanez@userena.cl | ¹Departamento de Ingeniería de Alimentos, Universidad de La Serena, Av. Raúl Bitrán Nachary 1305, 1700000 La Serena, Chile. ²Departamento de Biología, Universidad de La Serena, Av. Raúl Bitrán Nachary 1305, 1700000 La Serena, Chile.

especially in communities that inhabit or develop productive activities in areas that suffer from sustained water shortages [6]. Recently, a group of researchers assessed the feasibility of using wastewater in oil and gas extraction processes and as a medium for microalgae cultivation [7]. Microalgae encountered no difficulties in absorbing part of the metals contained in water, and their growth and lipid production for later use as biofuels was as good as or better than those grown in conventional culture media. In other words, their freshwater and nutrient requirements, aside from nitrogen, were supplied almost completely by wastewater [7]. However, additional research is needed to standardize the conditions of growth in wastewaters, including a complete study of the chemical composition and the effect on media. Knowledge of these issues must be developed to scale up algal biotechnology to provide large quantities of biofuel, lipids, and coproducts.

In another study, the use of yeast wastewater (YW) in the arid environment of Al-Russeifa Park in Jordan was evaluated [8]. These researchers demonstrated how all the ecological parameters assessed in their work significantly increased in plants that were irrigated with wastewater. Although YW seems to be crop specific and care should be taken prior to using the effluent for pre-sowing irrigation purposes, the authors concluded that YW effluent can be beneficially used for irrigation purposes to support the growth of certain crops in arid areas, with the remaining challenge of better understanding the direct and indirect effects on soil, soil microbiota, and weed dynamics [8]. With a social focus, other authors proposed a technological development for wastewater management in a reservoir in an arid climate in Yeruham, Israel. The purpose was to evaluate the water quality (quantification of nutrients and organic micropollutants (OMPs)) and fish health (by histopathology) of this reservoir, which regularly receives wastewater and sporadic winter floods [9]. Facing the challenge of guaranteeing water quality and the necessary safety standards, this type of reservoir can be used for recreation, education, and the social and economic development of a rural environment in arid zones.

Although projects such as this one entail many challenges, their common ground is their use of biotechnological processes. Biotechnological research can solve the current challenges of the most vulnerable areas in the world. The modern and widely accepted definition of biotechnology describes it as “the application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or nonliving materials for the production of knowledge, goods and services” [10].

Given that biotechnology constitutes a broad field, a color classification has been used in recent years. All the study areas have been assigned a color to promote understanding of their applications [11, 12]. While some colors

describe wide ranges of activities, others refer to incipient branches, which may be inaccurate. However, this is a popular classification that has proven useful for biotechnology applications in science and development [11–13]. *Brown corresponds to arid zone and desert biotechnology* [11, 12]. This brown-coded area is the type of biotechnology that we will analyze in detail in this review. To learn more about the latest advances in other biotechnology areas, we recommend Barcelos et al. for the white, green and blue biotechnology areas [14]; Barrows et al. on green biotechnology [15]; Kiss et al. on gray biotechnology [16]; and Abiri et al. for red biotechnology [17].

In light of the above, the following objectives were established for this review: 1) report the status of brown biotechnology in arid regions, both globally and in Chile, and from recent years to present day; 2) analyze the contributions made by biotechnology tools on the basis of the generation of innovative solutions to socioenvironmental and economic problems typical of arid zones; and 3) develop an approach to tackling the current and future challenges of brown biotechnology. More specifically, a classification is made of the world's arid regions. Then, studies on the microbiota found in deserts, namely microalgae, bacteria and fungi, are presented. Furthermore, issues on environmental biotechnology in arid regions are discussed, with a focus on water shortages, nutrient availability and toxic minerals in soils, concluding with the challenges that still need to be resolved.

2 Arid regions around the world

Arid environments can be found at the poles, on mountains and plateaus and along coastlines and inland [18]. Given the diversity of broad terms within the concept of an “arid environment,” defining what these environments are is quite a complex task. Some scholars recognize arid zones as areas where the precipitation is less than the evapotranspiration of the permanent vegetation or traditional agricultural crops. When that ratio is lower than 0.65, then the zone is considered to have an arid or semi-arid climate [2, 19, 20]. Other researchers refer to an arid environment by using the term “aridity,” which also incorporates the temperature and level of precipitation. Of the total global area, hyperarid zones account for 4.2%, arid zones 14.6% and semiarid zones 12.2% [21]. Hence, almost a third of the world's area corresponds to arid regions. The Food and Agriculture Organization of the United Nations (FAO) has set forth the following classification of aridity based on the Aridity Index (AI):

1. The hyperarid zone (AI of 0.03). The rains are infrequent and irregular (with droughts that can span several con-

secutive years) and rarely exceed 100 mm per year. Most of these zones do not have vegetation, and they are recognized around the world as deserts. Among these areas, it is worth noting the Lut Salt Desert in Iran (the warmest), the Atacama Desert (the driest), the Sahara Desert in northern Africa (the largest), the Gobi Desert located in northern China and southern Mongolia (the most barren) and the Antarctic (the coldest) (Fig. 1).

2. The arid zone: (AI of 0.03–0.20). The annual rainfall ranges between 100 and 300 mm. The native vegetation is sparse, comprising annual and perennial grasses and other herbaceous vegetation, shrubs and small trees. Australia and Asia Minor constitute examples of arid zones (Fig. 1).
3. The semiarid zone: (AI of 0.20–0.50). The annual precipitation ranges from 300 to 600 mm in the summer and from 200–250 to 450–500 mm in the winter [22]. These zones are dominated by xerophytic vegetation and large trees, in particular, several leguminous tree species of the genera *Acacia* and *Prosopis*. Semiarid zones can be found in Kazakhstan, southeastern Spain and the Coquimbo region of Chile (Fig. 1).

Of all the arid zones in the world, the Antarctic is the largest. This cold desert covers 14,000,000 km² [23], with approximately half of this area corresponding to hyperarid areas. Other deserts are characterized by having hyperarid zones over their entire territorial extension, including

the Sahara Desert, the second-largest desert in the world (9,000,000 km²) [24], the Gobi Desert (1,040,000 km²) [25] and the Atacama Desert (180,000 km²) [26].

Due to its particular geography, Chile can be considered a natural laboratory within which to perform diverse types of research. Along its 4,270 km length, the country is characterized by a variety of climates that range from hyperarid to temperate, from Mediterranean to temperate dry and rainy, high-mountain and Andean areas. Chile also possesses many square kilometers of Antarctic territory and has jurisdiction over several islands, namely Sala y Gómez, Rapa Nui and the Juan Fernández archipelago [29]. Furthermore, Chile is a narrow country, spanning 445 km from sea to mountain range at its widest point (52°21' S) and 90 km at its narrowest point (31°37' S). However, it has a steep altitudinal cline from sea level to 6893 m at its highest point (Ojos del Salado Volcano) or, in the opposite direction, from sea level to 8081 m deep in the Atacama Trench (west of Antofagasta) in the Pacific Ocean.

In Chile, the arid zones primarily cover the far northern extreme of the territory, including the hyperarid zones ranging from 17° 29' 57" to 23° 38' 39" latitude south and from 67° 00' longitude east to the coast of the Pacific Ocean. The arid Mediterranean climate covers from 23° 38' 39" to 32° 02' latitude south and from 68° 17' longitude east to the Pacific Ocean. Finally, the semiarid climate ranges from 32° 02' to 33° 50' latitude south and from 70°39'2" longitude east to the Pacific Ocean [19]. Arid and semiarid soils account for more than 50%

Fig. 1 Global map of arid zones. The classification depends on the Aridity Index (AI) that relates the evapotranspiration and precipitation. Hyperarid (red), Arid (orange) and Semiarid (yellow) zones, with AIs of 0.03, 0.03–0.2 and 0.2–0.5, respectively. In the Antarctic

zone, this classification was performed according to the average precipitation (mm) for the 2007–2010 period [27]. Figure adapted from Smith et al. [28]

of the total Chilean landscape [30], which is distributed into arid (934,792 ha, 13%), semiarid (9,479,217 ha, 13%) and hyperarid zones (5,603,167 ha, 8%) [31].

The Atacama Desert is very impressive due to its extreme dryness and the great extent of its hyperarid lands. Ranging from 5° to 30° S latitude, the Atacama Desert could be considered a cold desert since the annual average temperature ranges from 14 to 16 °C, with an average annual precipitation of 2 mm. However, in some areas, no precipitation has been registered for long periods [32, 33]. In fact, at the heart of the Atacama Desert, the Yungay sector (37° 6' 16.02" latitude south, 71° 55' 50.92" longitude west) rainfall measurements indicate that only 1 mm of precipitation has been recorded in the last 100 years. It does not come as a surprise, then, that this desert is regarded as the most arid, driest and oldest in the world [34]. Its extreme dryness is the result of a constant climatic regime produced by the Pacific Anticyclone (which generates a dry air mass), with the cold water carried into the sea from the Humboldt Current and the effect of the rain shadow produced by the Andean mountain range [35].

In the midst of this diverse geography, great biodiversity can be found. In this regard, microorganisms have been described that are capable of reproducing under extreme environmental conditions with respect to their temperature, pH, salinity, solar radiation and atmospheric pressure. Chile has a high level of endemism, and it represents one of 25 biodiversity hotspots around the world [36]. The properties of this area can be considered a great opportunity for research and for the implementation of the beneficial scientific and technical developments needed for human–environment–ecosystem interactions in this diverse geography.

In this context, brown biotechnology emerges as an interesting alternative to address these challenges since it entails the study of organisms that naturally grow in arid zones and those that can adapt while also involving the production of bioproducts with potential food, medicinal or pharmaceutical uses. Through the application of biotechnological tools, the adaptability and productivity of these organisms under stress conditions can be improved, granting better economic opportunities to people inhabiting zones with limited production options [11, 12]. It is important to recognize that brown biotechnology is a science that goes beyond the cultivation of desert crops or the development of saline agriculture, saline aquaculture or rational use of water or wastewater in arid environments [37]. Brown biotechnology is a discipline with great potential in arid areas presented with challenges, combining traditional biotechnology with new approaches including new omics, data science, nanotechnology, and others.

3 Brown biotechnology in microorganisms, vegetable crops and animals

The climate characteristics, microorganisms, flora and fauna of arid environments vary considerably. Water shortages, clayey soils with low organic matter content, high levels of solar radiation, wind, low relative humidity and extreme temperatures during both day and night are major challenges encountered by living organisms [38]. In relation to these challenges, we believe that brown biotechnology can play a major role in the development of management strategies, studies and the technical and scientific uses of the organisms found in these zones and thus can aid us in facing the challenges of today's world, such as food security, the sustainable management of energy resources, climate change and biodiversity loss [39]. Below, some research studies on brown biotechnology in microorganisms, vegetable crops, animals and their interaction with the environment are noted.

3.1 The microbiota of arid regions

Studies have focused on the microorganisms of arid zones, from microalgae to fungi, and they have contributed a large amount of published information. Microalgae are present in arid zones worldwide [40, 41], and they are characterized as unicellular organisms that can be found both in marine and freshwater environments. In aquatic ecosystems, microbiota play a key role, constituting the base of the food chain [41]. These organisms are known for their ability to produce valuable metabolites, such as carotene, astaxanthin [41], lutein, polyunsaturated fatty acids, vitamins, antioxidants, antimicrobial agents and sterols [42]. Their applications range from food supplements (*Chlorella* sp., *Dunaliella* sp.), food colorants (*D. salina*) [42] and biofuels (*Chlorella* sp., *Nannochloris* sp., *Nitzschia* sp.) to products for the pharmaceutical and cosmetic industries [43], such as sunscreen and antiaging creams (*Chondrus crispus*, *Mastocarpus stellatus*, *Ascophyllum nodosum* and *Alaria esculenta*) [42].

The characterization of new microalgal species is especially interesting for their incorporation into the food and renewable energy industries [44]. To analyze the effect of the temperature on biomethane production in *Nannochloropsis gaditana*, two anaerobic sludges were used as raw materials, one at 35°C (mesophilic) and another at 55°C (thermophilic) [44]. A greater extent of hydrolysis was noted for the thermophilic temperature; for *N. gaditana*, more extreme temperature conditions

translated into better bioethanol production [45]. This discovery could have important biotechnological applications in regions where high temperatures limit the growth of mesophilic organisms and where there is a need for organisms that can adapt to higher temperatures. Compared to other feedstocks used in the production of bioenergy, microalgae offer several benefits, such as fixation of greenhouse gases, high areal productivity and a lack of competition with food crops. However, there are still challenges that must be faced, such as the low energy yields of the process and high-energy requirements of the harvesting and drying steps, which lead to a high cost per liter of fuel. Brown biotechnology could have a relevant role in the development of strategies to face these challenges.

In another study, the microalga *Chlorella pyrenoidosa* was cultivated in wastewater effluents in open-air tanks under sunlight in the arid region of Ouargla, in southern Algeria, to assess its ability to eliminate nutrients [46]. The average nutrient elimination was higher than 78%, showing the potential for nutrient removal by microalgae cultivated in wastewater in arid zones [46]. Similarly, *Chrootheca* (Rhodophyta) colonies were isolated from a small river in the semiarid zone of Murcia, Spain, where the annual solar radiation is $4349 \text{ Wh m}^{-2} \text{ day}^{-1}$ [47]. These microalgae had a high lipid composition (especially *w*-6 fatty acids (FAs)) in comparison with other commercial microalgae during most of their growth cycle as well as an unusual lipid physiology and contained FAs that were absent in other varieties [47].

This research not only made a valuable contribution in terms of microorganism adaptability in arid zones, but it also raises questions about the composition of microorganisms in areas with even higher solar radiation. For example, the average solar radiation found on a summer day in the Atacama Desert is above $7000 \text{ Wh m}^{-2} \text{ day}^{-1}$. This level shows the great potential to find and describe extremophiles in the area.

Deschampsia antarctica, a plant that inhabits the maritime territory of Antarctica, can survive at freezing temperatures and under high levels of UV-B radiation. Cuadra and collaborators suggest that this plant possesses genes associated with cold and UV tolerance such as the family of genes encoding chalcone synthase, a key enzyme of the flavonoid biosynthetic pathway [48]. New studies performed to characterize and examine the synthesis of flavonoids in these species can provide clues about how it survives in extreme environments and open the prospects for the development of photoprotective compounds and antifreeze molecules.

Cyanobacteria are another interesting source of bioactive compounds and constitute the largest, most diverse and most widely distributed group of photosynthetic

prokaryotic organisms [49]. Within their prokaryotic cells, cyanobacteria have a photosynthetic apparatus remarkably similar in functional, structural and molecular terms to the eukaryotic chloroplast content [49]. Cyanobacteria are distributed over diverse habitats, from the aquatic to the terrestrial, ultra-oligotrophic and hypereutrophic, in thermal waters and in hypersaline lakes. In arid soils, they are generally exposed to a regular cycle of hydration and dehydration due to low rainfall [50]. The study of isolated cyanobacteria in extreme environments is relevant due to their metabolic and ecophysiological versatility, allowing them to adapt to extreme conditions. Cyanobacteria are of great interest for biotechnological purposes since they are also known as active biomolecule producers endowed with peculiar biochemical pathways [51]. For instance, in the Wadi Muqshin Desert in Oman, studies were performed on the FA composition of five hypersaline cyanobacterial crusts to detect the presence of halotolerant, thermotolerant and UV-resistant cyanobacteria. *Microcoleus chthonoplastes*, *Johannesbaptistia pellucida* and the genera *Gloeocapsa*, *Chroococcus*, *Aphanocapsa* and *Synechococcus* were most abundant [52]. Depending on the saline concentration of each crust, major differences were found in the lipid composition. The primary FAs were 16:0 (most abundant) and 18:0, 16:1 and 18:1. These four FAs accounted for 70% of the total FAs. However, the high FA content should be of no surprise since certain microorganisms increase their FA desaturation under permanent environmental stress to increase the fluidity in the plasma membrane, and, with this action, they improve their tolerance to extreme salinity, temperature and dryness [52]. In unicellular organisms, the membrane lipids are generally maintained in a crystalline liquid state so that the temperature of the transition phase is lower than the environmental temperature; in this way, irreversible damage to the membrane can be avoided, such as the damage caused by free radicals. As many of the most degenerative diseases, such as diabetes, cancer, atherosclerosis, dementia and asthma, have their origin in deleterious free radical reactions, it is necessary to search for compounds with potential cytoprotective effects. Experimental and clinical assays could be useful to clarify the therapeutic potential of such compounds. This potential highlights the importance of studying the versatility of microorganisms and the products derived from their biological activity for human and veterinary medicine, nutrition and pharmaceuticals [53], with the aim of elucidating the structures of new biomolecules with relevant biological activity and aiding in efforts to replace currently non-sustainable processes.

In deserts, oleaginous microorganisms can also be found. Oleaginous microorganisms are species that accumulate lipids in more than 20% of their biomass, and they usually produce the ATP-citrate lyase enzyme [54]. This

group includes species of microalgae, yeasts, bacteria and fungi, which can show lipid composition yields ranging between 40 and 70% [55]. Under adequate growing conditions, this lipid production could have biotechnological uses, such as in biofuel production [56]. This possibility is strengthened in arid zones since it is believed that environments with limited water and nutrient availability promote lipid accumulation as an adaptive strategy. This is the case for *Rhodospiridium toruloides*, *R. gracilis*, *Mortierella* sp., *Cladosporium* sp., *Rhizopus* sp. and *Pytium* sp. [55]. A study performed in the arid soils of the Jeddah and Taif regions of Saudi Arabia isolated bacterial strains capable of synthesizing poly(hydroxybutyrate), triacylglycerols or wax esters [57]. Among them, a strain of *Streptomyces* (G25) showed an FA content of nearly 50% (p/p), which represents the highest lipid content described for a streptomycete to date [57]. Considering the common drawback of conventional biodiesel in terms of its poor low-temperature performance, which is greatly influenced by the chemical structures of common sources used as methyl or ethyl esters of straight-chain fatty acids, this result showed that oleaginous microorganisms could represent a promising novel feedstock for the biotechnological production of lipids or lipid-derived biofuels.

Microorganisms such as bacteria and mosses contribute to the biochemical composition of the arid soils they inhabit [58], and they improve infiltration and fix nitrogen. Additionally, due to their nitrogen decomposition and mineralization, these microorganisms are of great importance for organic compound transformation [59]. However, in arid environments, microorganisms do not always live under ideal conditions in terms of the temperature and humidity. Thus, mineralization in these ecosystems occurs heterogeneously in patches, where “islands of fertility” are formed, and they contain more nitrogen and nutrients in general [59]. Considering that the islands of fertility play supporting and structural roles in arid ecosystems, thus influencing the soil properties and ecological protection [60], their identification is key for discovering new biotic communities; thus, collecting soil samples after rainfall events, and obtaining detailed information on their population and reproduction, is essential. In this regard, special attention should be paid to the mycorrhiza-forming fungi found in deserts. The genera *Acaulospora*, *Archaeospora*, *Entrophospora*, *Glomus* and *Paraglomus* exert beneficial effects to improve plant establishment and development in soils with water deficiencies [61].

The same applies to antioxidant enzymes (superoxide dismutase, peroxidase and catalase) and phosphatase and nitrate reductase in crops growing under water deficits in the presence of mycorrhizal fungi [62]. Some examples are *Glomus intraradices* in lettuce crops under severe drought [62], in soy crops [63], in millet (*Setaria italica* L.) [64], in

alfalfa [65] and in acacia [66]. In addition, mycorrhizal plants under water deficit resist drought for longer periods and recover more quickly [67]. This adaptation is feasible because the fungal mycelium influences the edaphic environment, preventing gaps from developing between the roots and soil, thereby maintaining liquid continuity across the soil-root interface. Additionally, extraradical hyphae extend the area of water uptake [67]. Their influence is highly ecologically valuable since it favors plant establishment, vigor, productivity and survival under very water-limited conditions [67]. Through the in vitro cultivation of these fungal species, their controlled mass inoculation and the application of other biotechnological tools, the productive capacity could be increased, both for the soils and in the plants benefiting from these symbiotic relationships. Ultimately, this inoculation could also contribute to the resolution of the food challenges of today, producing more with fewer resources while protecting the environment.

In the Chilean territory, there are two arid zones of great interest: Antarctica and the Atacama Desert (Table 1). Both host a great diversity of microorganisms that have begun to be isolated and characterized for different purposes over the past two decades, namely biodiversity research studies, molecular analysis, development of technologies and applications and bioactive product development [26, 68–70]. However, few investigations have been reported on the bioprospection of microorganisms, despite the importance of understanding the diversity of microorganisms and their biotechnological potential.

Recent studies on the microbial life of the Atacama Desert report bacteria, cyanobacteria and fungi of particular concern in the fields of genomics, ecology, biogeochemistry and the Mars Analog Research Station Program [84, 85]. The biosynthesis of the ultraviolet sun-screen pigment known as cyanobacterial *scytonemin* has been studied as a survival strategy of cyanobacteria, with assessments of its quality as a biomarker [86]. Additionally, studies have been conducted on its biofilm formation capabilities and fixation to pyrite surfaces and the low-temperature survival of the bacterium *Acidithiobacillus ferriivorans*, an abundant strain in the desert [87]. For further information on the bacteria in this desert, the compilation prepared by Bull et al. is recommended [26].

By contrast, Antarctica is the coldest, windiest and driest continent in the world [74], making it a climatically extreme region [88]. Bacteria have been isolated as potential bioreactors for the clean synthesis of metal nanoparticles, which have medical, optical and electronic applications [89]. In addition, Antarctic psychrophilic bacteria have been described (*Psychrobacter* sp., *Aeromonas salmonicida*, *Pseudomonas veronii* and *Yersinia kristensenii*) as being capable of producing silver nanoparticles

Table 1 Comparison of environmental characteristics between Atacama and Antarctic deserts

Characteristics	Atacama Desert	Chilean Antarctic territory
Area	180,000 km ² [26]	1,250,000 km ² [71]
Average annual precipitation	10 mm [72]	Very little precipitation, often in the form of snow. The coast receives an average of 25–51 cm every year, whereas the interior receives less than 5 cm per year [73, 74]
Location	Runs north–south for 965 km, paralleling the Chilean coastline [72] between latitudes 19° S and 30° S, and from the coastal mountain range (west) to the Andean mountain range (east) [26]	Between 53° W and 90° W [75]
Altitude	Comprising a plateau ranging in elevation from near sea level to approximately 3500 masl. The southern extension of the highlands (northwest of the desert) is usually included, with an average elevation of 3750 masl [76]	Average 2300 masl [77]
Annual average temperature	10–30 °C [78]	–3 °C (2015) at Base Presidente Eduardo Frei Montalva (Chile's principal Antarctic base). From 2011 to 2014, the reported temperatures were between –3.2 and –2.5 °C [79]
UV radiation	Annual UV-B from 3.5 kWh.m ⁻² in coastal areas up to 5 kWh.m ⁻² on the Andean plateau. In this territory, the world's highest UV radiation levels have been measured [80]	UV-B 3–5 kWh.m ⁻² [81]
Microorganism diversity	For an overview of the fungal and microbial diversity of the Atacama Desert, please see Santiago et al. [70] and Schulze-Makuch et al. [82]	For an overview of the microbial communities in the Antarctic Territory, please see Lysak et al. [83]

extracellularly [90], and *Pseudomonas* sp. is capable of synthesizing tellurium nanoparticles intracellularly [91]. The supernatants of the psychrophilic bacteria *Phaeocystis antarctica*, *Pseudomonas proteolytica*, *P. meridiana*, *Arthrobacter kerguelensis* and *A. gangotriensis* have been used to biosynthesize silver particles [89]. Additionally, a high antioxidant capacity was found in the pigments of *Pedobacter* sp. [92]. These findings demonstrate the great potential of Antarctic microbiota in the generation of biotechnology products or services in both the health and cosmetic industries.

Fungi growing in the Antarctic Territory constitute one of the most tolerant eukaryotic life forms to abiotic stress, including extremely low temperatures, dryness and high solar radiation. Surprisingly, their ecological role is still little known. Among the most abundant genera are *Geomyces*, *Cadophora*, *Rhodotorula* and *Cryptococcus* [93], which likely remain dormant for most of the year and are activated during the short summer season. However, studies that compare the ecological differences and analogies between microcolonial fungi of the cold and hot deserts or their stress resistance in relation to their taxonomy at the molecular level are still scarce [94]. This constitutes a productive research field to study the isolation of extremophile desert fungi with resistance to extreme conditions, which could be a promising source for new biotechnological and medical adaptations such as protective agents against oxidative stress.

Microorganisms in the Antarctic region have been little explored. It is necessary to study their metabolic activity in light of their long period of winter dormancy and to obtain a detailed understanding of their growth phases in their natural environment, especially in relation to their ecological plasticity. Research conducted so far in the Atacama and Antarctic deserts suggests that the biotechnological use of these organisms in arid zones is in its infancy. However, a great future is envisaged to support the economic and conservation activities of arid ecosystems or other ecosystems that could benefit from these biotechnological applications. The authors of this review believe that in the coming years, efforts should be focused on the combination of basic research with the scientific application of the discoveries made to seek benefits, both for the environment and for human beings, and to increase the number of comparative studies in other deserts.

3.2 Vegetable crops in arid zones

Water is a limiting resource for the development of plant life. Therefore, improving water use efficiency would also improve plant productivity. Considering that agriculture uses approximately 80% of the global freshwater supply [95], developing new technologies capable of mitigating

water shortages has become a pressing matter. Through genetic engineering techniques, brown biotechnology offers interesting alternatives for increasing the resistance of agricultural crops to different biotic and abiotic stresses [96–99]. Plant drought resistance is a very complex response, generally entailing a combination of different mechanisms that involve morphological, physiological and molecular processes. The coordinated action of stomatal movements, photosynthesis, cellular osmoregulation and the synthesis of protective and antioxidant macromolecules, among other cellular processes, is vital, and these actions must be executed precisely in time and space to ensure synchronous development in a changing environment. Given that drought stress is dynamic and unpredictable, it is difficult to thoroughly and precisely assess the general drought resistance of a given plant species. However, in recent years, important advances have been made in this regard [100].

Drought-resistant plants have been developed by over-expressing the type 1 pyrabactin hormone of the abscisic acid receptors, having remarkable short-term (stomatal closure) and long-term (leaf senescence) impacts [101]. This overexpression diminishes the transpirational water loss, and, in the case of droughts, it inhibits growth in young tissues [101]. Tea plants (*Camellia sinensis* L.O. Kuntze) modified for the expression of osmotin, a protein associated with the abiotic stress response, showed a higher tolerance to water deficiency, a faster recovery from hydric stress and higher levels of flavonoids and caffeine with respect to nonmodified plants [102].

An interesting case of an agronomic crop that was developed on arid soils in Canada (Palliser's Triangle) with the native species *Brassica carinata*, commonly called "canola," the primary oleaginous crop in that country [103]. Canadian researchers have assessed the feasibility of establishing canola crops on arid lands, taking advantage of their adaptability, growth and high tolerability, to turn it into a raw material for bioindustrial oil production. After the development of a thorough genetic improvement program that identified the lines that were best adapted to arid conditions, and due to the combination of biotechnology applications and controlled breeding assessed in test fields for decades, highly productive lines of *B. carinata* were developed under water shortage conditions [103]. This effort not only enabled the use of a Canadian natural resource but also showed that the combination of traditional genetic improvement techniques with modern biotechnological techniques can result in important revenue production from impoverished lands, where traditional agricultural practices are difficult to perform.

At present, the global demand for vegetable oils is increasing, and the high quality of *B. carinata* oils has opened the market up to more demanding uses, such as

the manufacture of new biofuels intended for commercial aviation, surfactant production for enhanced oil recovery (bioplastics) and even as a raw material for products used in the symptomatic treatment of many neurodegenerative diseases, such as multiple sclerosis or Parkinson's disease, given their high nervonic acid content [104]. From these Canadian experiences, other biotechnological options could also be developed to improve agricultural crops that currently face problems arising from the acceleration of climate change. However, this acceleration is impossible to control, and producing appropriate crops for arid regions might involve a considerable amount of research, possibly requiring years to obtain suitable production. Nevertheless, brown biotechnology and related technological advances offer a plethora of new tools with which to address the current and future constraints encountered in arid lands.

In the same line of vegetable crops in arid zones, Jerusalem artichoke (*Helianthus tuberosus* L.) (a root vegetable) was used to study the economic feasibility and energy use efficiency for bioenergy production on arid and coastal saline lands [105]. This and other crops hold great promise as a source of biomass material. According to the results, the Jerusalem artichoke may make a large contribution to meeting the growing challenges for bioenergy; however, for a sustainable commercial-scale production of this crop, farmers should promote mechanization and reduce pesticide use. Another example is a study with a focus on sorghum (*Sorghum bicolor* (L.) Moench) for the production of bioethanol or forage and its relationship with soil nitrogen balance on semiarid marginal land in Ordos, Mongolia [106]. The authors concluded that future efforts are needed to improve the yield and quality of sorghum for forage and bioenergy production and to enhance sorghum hybrid breeding to increase N utilization efficiency and decrease water use on marginal lands. Biomass availability in arid regions is restricted by the scarcity of fresh water, which limits the extent of agricultural activities compared with those in non-arid regions. However, the use of biotechnology can contribute to solutions to these challenges and support bioenergy production, which could be the most important potential future energy source due to its low or absence of environmental pollution impact. We encourage readers to see the complete review by Bastides-Oyanedel et al. [107], who exposed possible alternatives focused on biomass residues available in arid/semiarid regions, palm tree residues, seawater biomass-based residues (coastal arid/semiarid regions), and the organic fraction of municipal solid waste.

In the Atacama Desert, a challenging region for the development of life, it is important to note the presence of queñoa (*Polylepis tarapacana*). This plant is considered to be best adapted to very restricted environmental

conditions [108]. *P. tarapacana* grows in Chile, Argentina, Peru and on the Bolivian Plateau, from 4000 to 5200 masl [109]. *P. tarapacana* is resistant to temperature variations, which range from 20 to -20°C in this habitat. This trait is attractive in terms of adaptation to extreme environments, and it is a relevant condition for studying the adaptation of other agriculturally important plants or crops [110]. Additionally, *P. tarapacana* could have potential use in dendroclimatology (the study of climates during past millennia) [109], with great possibilities for reconstructing past climatic variables and for understanding whether the current climate changes are cyclical and natural or are the product of human activity. Despite all these interesting properties, surprisingly, there are no studies available on the biotechnological potential of this extraordinary high Andean plant.

Antarctic organisms are exposed to extreme levels of UV radiation (A, B and C) during the summer season due to prolonged sun exposure and the thinning of the ozone layer [111]. UV rays generate reactive oxygen species (ROS) that irreversibly alter cellular processes [111]. This alteration gives rise to oxidative stress due to the direct influence of UV rays on the enzymes catalase and nitric oxide synthase [112]. Fortunately, plants have developed defense mechanisms to prevent oxidative damage, such as the activation of enzymes that deactivate ROS and antioxidant production [111]. Extracts of *Deschampsia antarctica*, one of Antarctica's two native plants, are used in cosmetic creams due to its antioxidant characteristics (patent US20130344528A1) [113].

The above findings show the potential uses of these resources and how the climate challenges ahead could be solved with biotechnological tools considering that the availability of productive agricultural lands and freshwater is gradually decreasing [114]. The application of biotechnological tools will allow the introduction of traits that improve crop yield. However, for this possibility to materialize, it is first necessary that the Chile examines its biotechnological policies, acknowledging the research studies and the time required to deliver effective solutions, to apply and assess measures that ensure the long-term safeguarding of native flora with a national vision regarding the intellectual property of scientific findings.

3.3 Animals and their products in arid zones

The fauna is an important and vital part of any ecosystem, and it has a key role in the maintenance of the natural ecological balance. Consequently, it is surprising that the literature available in this field is so limited. Using genetic tools, endemic desert animals can be characterized, with special interest in knowing the adaptation processes that these species have undergone throughout

their evolution and that could show interesting characteristics to apply to other animals via traditional genetic strategies.

The species *Empetrichthys latos* and *Crenichthys baileyi* are endemic fish of the arid regions of the Great Basin and Mojave Desert in western North America. These taxa survive as small, isolated populations in remote streams, and they have evolved to endure extremely high temperatures and low dissolved oxygen contents. Upon the sequencing of the mitochondrial genomes of the two species and the analysis of their phylogenetic relationships, a close relationship between the two genera and the Goodeidae fish from Mexico was confirmed [115]. This finding suggests that they share genes for resistance to adverse conditions. Thus, the eventual identification of these genes is of key importance for future applications in agriculture and agronomy.

The animals in arid ecosystems fill a role that goes beyond their participation in the ecological balance. Many have transcended merely being part of the ecological landscape due to their sociocultural relevance in different cultures. One example is the two-humped camel, *Camelus bactrianus*, which has been positioned not only as the primary means of transport in the desert regions of China, Kazakhstan, Mongolia and India but also as a source of milk, meat and wool [116]. However, the *Camelus bactrianus* population has decreased, and its risk of extinction is imminent [116]. Among conservation strategies, some are based on the cryopreservation of genetic material via the establishment and characterization of cell lines that will allow germplasm restoration in the future. If this goal is achieved, an important contribution could be made to future research studies on the cellular biology of these vulnerable or endangered species [117].

The fauna of arid ecosystems represents a challenge to biotechnology since survival patterns are unique. However, in arid environments in which desertification is advancing relentlessly, scientific developments are urgently needed to promote a positive flora-fauna balance given that animals that are directly dependent on the vegetation and are forced to move by desertification.

4 Environmental biotechnology in arid zones

The shortage of rain and freshwater sources is not the only challenge faced by the ecosystems that develop in arid environments. The contamination of water and soil is one of the issues to solve in the short term, and biotechnological tools could bring new approaches to these problems and provide sustainable and efficient solutions.

4.1 Biotechnology and water

The seawater surrounding global deserts offers an important advantage in natural ecological systems to restore wild biodiversity and to provide food sources for native flora and fauna. A sustainable and profitable approach that deserves mention is discussed by Moustafa [118], in which the greening of land is supported, along with the restoration of wildlife, in desert zones by using seawater desert-houses [118]. These constructions are mobile seawater ponds that are placed in the desert and are based on the principle of rain formation; these structures distill water in a natural and sustainable manner to provide small but reliable amounts of freshwater [118].

Using seawater desert-houses provides important environmental benefits since they can revive dry niches. An increase in the soil salinity would be a marginal effect if using these desert-houses increases the presence of living organisms. In addition, using halophytes constitutes a first key stage to generating a vegetation cover that can support other forms of life in these incipient “desert oases,” thereby reducing the frequency and intensity of dust storms in these regions [118]. However, certain operational challenges are encountered in terms of the continuing evaporation processes that cause the accumulation of salt in ponds, thus reducing the volume of evaporation. In this case, the seawater supply could be stopped for a period to recover the accumulated salt. Another risk would be the possible evaporation of freshwater before it is absorbed by the soil. To avoid this process, the collection pipes could be buried, and drops of freshwater would penetrate the soil once produced [118].

In northern Chile, the freshwater requirements are high, and efforts should be made to look for sustainable alternatives. The urgent need to leverage the abundant natural water resources in the region, such as freshwater, has motivated the building of numerous desalination plants. However, the high associated concentration of magnesium and calcium ions has generated problems with reverse osmosis. In this regard, biomineralization could be a solution. Research studies on the processes of urea hydrolysis using halotolerant ureolytic bacteria in the Salar de Atacama (*Pseudomonas* sp., *Bacillus subtilis* and primarily *Rhodococcus erythropolis*) showed the great capacity of these bacteria to precipitate calcium (Ca) and magnesium (Mg) crystals in seawater. These results indicate the great potential of these microorganisms as a pretreatment during water quality improvement processes [119]. These halotolerant bacteria have also been isolated in other deserts, such as in Dunhuang, the Gobi Desert in China [120] and Mongolia [121], the desert of Kuwait [122] and the Himalayas [123].

In arid lands surrounded by seas or close to salt lakes, desalination of water is a reasonable approach

to obtaining fresh water. Currently, the daily drinking-water requirement per person is 2–4 l; however, it takes 2000–5000 l of water to produce a person's daily food [124]. Although the desalination of salt water is decreasing in cost, the reverse osmosis (RO) processes is the most widely adopted commercial seawater desalination technology. The RO process presents several drawbacks, including the requirement of a relatively high amount of energy to achieve the pressures necessary to overcome the osmotic pressure of seawater [125]. Furthermore, RO requires extensive feedwater pretreatment to remove dissolved inorganic components, which foul the membranes [126]. In this sense, removal of boron (B) from saline water sources has presented a major challenge for commercially available RO desalination membranes [127]. This problem can be overcome with the use of microorganisms with biomineralization potential as described above. These microorganisms could eliminate boron from the membranes, reduce the pressure needed to push water through them and reduce the energy consumption of the RO process [128].

4.2 Soils: nutrient availability, toxicity and mining

It has been claimed that arid regions could have an early response to climate change since the ecosystem processes in these environments are closely linked to the rainfall [129]. Therefore, it is expected that changes in edaphic parameters will have an impact on soil activity and diversity. In arid soils, in addition to water scarcity, nutrient availability is a limiting factor. An increase in dryness produces an imbalance between nitrogen (N) and phosphorus (P) availability due to the decrease in organic matter and biological activity [130]. Given the poor vegetation cover, the organic matter is also insufficient. Thus, the microbial activity is low, and consequently, the soil activity is limited [59]. The little N present in the organic matter is transformed into inorganic compounds via mineralization processes [59].

In this context, biotechnology has allowed the recovery of bacterial and fungal strains capable of nitrogen fixation directly from the rhizosphere. At the end of the 1990s, *Paenibacillus polymyxa* improved the drought tolerance of *Arabidopsis thaliana*. The differential visualization of the RNA in plants that were treated and not treated with *P. polymyxa* revealed an increase in the mRNA transcription of a drought-responsive gene, *early responsive to dehydration 15* (ERD15) [131]. *Achromobacter piechaudii* ARV8 conferred tolerance to drought stress in pepper (*Capsicum annuum* L.) and tomato plants (*Solanum lycopersicum* L.). Under drought stress, the co-inoculation of beans (*Phaseolus vulgaris* L.) with *Rhizobium tropici* and two strains of *P. polymyxa* resulted in increased plant height and dry

weight in the shoots. During the co-inoculation of lettuce (*Lactuca sativa* L.) with *Pseudomonas mendocina* and arbuscular mycorrhizal fungi (*Glomus intraradices* or *G. mosseae*), the total catalase and peroxidase activities increased in response to drought. This result shows the potential use of these microorganisms as inoculants to reduce the oxidative damage caused by water stress because the antioxidant enzyme (peroxidase and catalase) activities increased, as did the proline accumulation in the leaves. In this sense, this amino acid could act as an organic nitrogen reserve [62, 132]. Nitrogen affects the modulation of plant growth and development, and more notably, it changes the root system architecture [133]. Therefore, lack of nitrogen is considered an important limiting factor in plant growth with a considerable impact on the socioeconomic development of agricultural areas. Biotechnology can be used to improve the bioavailability of nitrogen in plants, and smart nitrogen management can contribute positively to agricultural development. Another example is cyanophycin, a polymer present in most cyanobacteria (and a few bacteria) that has been reported to be extremely rich in nitrogen and an excellent nitrogen storage compound [134]. This polymer has great biotechnological potential and could be used in industrial applications such as agriculture to harness N, but certain drawbacks in the cyanophycin production have to be overcome to expand its application. These drawbacks are the slow growth of cyanobacteria and low abundance of products; new studies on genetic improvement and better production processes are necessary. While current practices for obtaining nitrogen in agriculture involve the addition of inorganic fertilizers, the use of bacteria and cyanobacteria for nitrogen synthesis and storage provides an environmentally friendly alternative to conventional approaches.

A similar situation occurs with P, a key element for the development of nucleic acids, proteins, cell membranes and cellular life in general [135]. In the soils in arid zones, P interacts strongly with clay and silt particles, which retain and immobilize it, thereby making P unavailable for plants [136]. The dynamics of P involve soil movement from the less available forms (FePO_4 , AlPO_4) to the most available forms (H_2PO_4 and HPO_4) and vice versa [136]. Given the edaphic conditions in arid and semiarid climates, this reaction tends to move toward the formation of non-available compounds, in which a great fraction of the soluble P is combined with Ca in the form of calcium phosphate, which is not taken up by plants [136]. Therefore, fertilizing with inorganic phosphates does not solve the P deficiency but, rather, generates more calcium phosphate. In some soils, more than 80% of the applied P becomes immobile. Achieving P bioavailability has become one of the major challenges faced by agricultural development in arid zones [136].

In this context, biofertilization plays a major role. This technique consists of the incorporation of living microorganisms with the capacity to regenerate and increase nutrient availability. Numerous fungal and bacterial species (*Laccaria bicolor*, *Scleroderma citrinum*, *Burkholderia glathei*, *Collimonas* sp., *Penicillium ostreatus* and *Bradyrhizobium elkanii*, among others) participate in the P cycle and promote its movement through the soil–plant system, thus acquiring great relevance for plant nutrition. A strain of *Bacillus subtilis* capable of solubilizing P was inoculated with the mycorrhizal fungus *G. intraradices*, resulting in a significant increase in the onion biomass and nitrogen and phosphorus accumulation [137]. An alternative to mobilizing the insoluble P in soils and increasing the efficiency of fertilization would be the participation of the microorganisms capable of solubilizing this element [136, 137].

Freshwater shortages in these areas and the presence of salt water have affected the availability of arable soil, as does the presence of chemical elements at toxic levels for the plants. An example of this effect can be found in the Lluta and Azapa valleys in northern Chile. There, the effluents that flow from the high Andes mountains toward the Pacific Ocean carry chemical elements in toxic amounts for most plants [138], including boron (B). B is a microelement that is essential for the growth of higher plants but toxic when present at high levels [139]. This situation presents a global problem in terms of crop yield and quality [140]. In the Lluta valley, research studies on a unique variety of sweet maize (*Zea mays* L. *amylacea*) have enabled a deeper analysis of the physiological mechanisms of plants that were naturally exposed to NaCl and B. In relation to this finding, Chilean researchers concluded that B availability partly mitigates the negative impact of salinity on this ecotype due to the osmotic balance that occurs at a cellular level, thus establishing that this species is an interesting germplasm source that could provide improved salt and/or B tolerance in other plants of agronomic interest through the application of biotechnology [141].

In studies on the B-hyperaccumulator perennial grass *Puccinellia frigida*, which is native to northern Chile, it was concluded that its high tolerance stemmed from internal mechanisms for reducing the net absorption of this mineral, which was consistent with the identification of the putative genes involved in the expression of a possible B efflux transporter [142, 143]. With genetic information and by using biotechnology tools, progress could be made toward the generation of agricultural crops that would be tolerant to B stress and would have potential use in phytoremediation.

Biotechnological innovation could contribute to the development of more sustainable mining activities. An example is the chalcopyrite bioleaching used in copper extraction, which is only possible in the presence of

thermophilic microorganisms [144] such as *Pyrolobus fumarii*, *Pyrococcus* ES4 and *Methanococcus kandleri* [145], *Sulfobacillus thermosulfidooxidans* and *Sulfolobus metallicus* [146]. Although suitable conditions can be created naturally via an exothermic reaction, the efficiency of the process could be further improved with an additional heat source [144]. To this end, a model was recently created for process optimization in Chilean copper mines located in the Atacama Desert. These mines take advantage of the high levels of solar radiation (the highest in the world) and apply thermal energy during the bioleaching process, thus increasing the copper extraction rates to between 76 and 85 [144]. For more information about the bioleaching processes used in mining, the microorganisms used, regions and industries, see Watling [147].

Biomineralization has also been studied in this ecosystem given the local environmental characteristics and salinity. The precipitation of carbonates was analyzed in 17 moderately halophilic strains of *Marinococcus halophilus* and *M. albus* that were isolated from the Salar de Atacama that were cultivated in a laboratory for 42 days at different salt concentrations (3 to 20%) [148]. The results suggest that the time required for mineral precipitation increased with the salt concentration, thus indicating the active role of the bacteria in carbonate production and their strong natural adaptation to hypersaline arid habitats [148].

In this same line, it is interesting to characterize and assess the resources that may improve soils in areas with heavy mining activity. A research study on the arsenic (As) concentration and the impact of mining activities on the water quality in the Loa River basin, the major water source of the Antofagasta region in Chile [149], revealed a total As concentration of $1400 \mu\text{g l}^{-1}$, a value that exceeds the maximum allowable level set by the World Health Organization for drinking water ($10 \mu\text{g l}^{-1}$) [150]. Arsenic is a toxic metalloid that is widely distributed in nature due to soil erosion but also due to anthropogenic activities. Its presence in water derives from solubilization processes [151]. The inorganic species of As—arsenite, As(III) and arsenate, As(V)—are the most toxic and carcinogenic to humans [152].

In the El Tatio geysers, As concentrations of up to $27,000 \mu\text{g l}^{-1}$ have been detected. These geysers are located at 4300 masl in the Altiplano-Puna volcanic complex [149]. The geothermal waters of El Tatio discharge arsenite, which oxidizes into arsenate. The microbial diversity of the geysers promoted the search for the 16S rRNA and Aio (arsenite oxidase) genes [84]. It was found that Chloroflexi was the most frequently noted phylum at this site, in which arsenite was transformed into arsenate. In a comparison of gene sequences similar to Aio, the majority showed homology with the genes of *Chloroflexus aurantiacus* [84]. The biotechnological application of this

microorganism could lower the toxicity of the water consumed in regions where the As level is above the allowed limit. Serious consequences have been reported in relation to water pollution with this metalloid in different countries such as India, Bangladesh, Taiwan, Hungary and China [153]. Levels between 10 and 1800 $\mu\text{g l}^{-1}$ in groundwater were reported in 2003 in black foot disease-hyperendemic areas in Taiwan [154]. During that same year, several endemic As-related poisoning events were also recorded in northern China, where the climate is arid and water resources are limited [155].

Thus, it is important to characterize the microorganisms associated with As metabolism and, in particular, those involved in arsenite oxidation. The study of endogenous microorganisms in these ecosystems would allow great advances and improvements in the quality of life of the inhabitants when considering the role of such microorganisms in the bioremediation of water bodies, which are the primary sources of this limited and valuable resource.

5 Contributions of brown biotechnology in technology improvement

The following table summarizes the contributions of brown biotechnology to technologies or methodologies with socioeconomic impact from the last 6 years (from 2016 to present) (Table 2). It is important to highlight the mainstreaming of brown biotechnology in different latitudes and through diverse technologies. The objectives are to address challenges and impact societies in a sustainable way.

6 Challenges to biotechnology development in arid zones

The world will face hydroclimatic events that could strongly impact fragile arid zones, in which droughts [161], which are classified as the greatest natural threats in the world [162], will reshape entire areas of the planet. Improving the efficiency of using the available water sources will not only increase food production but will also be key for the operation and maintenance of life on the planet. Given this scenario, a series of challenges arise to analyze and propose solutions from the tools offered by biotechnology. In the United Nations 2030 Agenda for Sustainable Development, science is recognized as an indispensable factor in addressing current sustainability challenges [163].

Some issues and challenges that should be addressed with regard to brown biotechnology are described below:

- *Conservation* Biotechnology has the challenge of working to conserve in a better way the biological resources of arid zones. Many of these resources are unique and are seriously threatened by lack of water, uncontrolled grazing, removal of land or pollution of their soil and groundwater, urbanization and inadequate conditions for agriculture and livestock. The challenge has always been to harmonize productivity with conservation; biotechnological processes oriented to productivity must integrate parameters that also consider the conservation of these resources.

On the one hand, tools of genetics and the cultivation of plant tissues can be used to increase productivity, using smaller amounts of inputs than through the propagation of traditional crops; this is especially important for organisms faced with some type of risk or shortage. On the other hand, it is important to identify the largest number of species that can develop in arid zones, organisms with adaptations critical to responding to drought stress to avoid desiccation, and to identify the genes governing adaptation or tolerance to drought and salinity. Through biotechnology, genetic improvement programs can be designed and executed.

- *Bioprospecting* Unusual environments, such as hyper-arid areas, are especially interesting for bioprospecting studies due to the high probability of finding new taxa and the prior adaptation of these organisms to extreme environments [164]. An interesting example is the use of *Bacillus amyloliquefaciens* in a process called biocementation. This process is based on the production of carbonates by heterotrophic bacteria as a method to suppress dust from erosion [157]. Biotechnology in arid areas is faced with the challenges of improving the analysis of bioprospecting and designing and implementing more efficient and sustainable assays. For this reason, active and strategic partnerships are needed among the academic, state and corporate sectors to support long-term research.
- *Bioremediation* Scientific and technological developments must be produced at industrial levels to produce tons of characterized bioremediators so that they are marketable, exportable, monitored, and sustainable products.
- *Mine tailings and bioextraction* Byproducts should be described to assess their environmental impacts and management criteria for later use. In addition, the efforts of local governments and universities must be linked. It is important to develop proposals that apply research already validated in the use of enzymes and microorganisms that improve the quality of water and soils.

Table 2 Recent contributions of brown biotechnology in technology improvement

Focus	Organism	Technological development	Application/solution	Location	References
Bioenergy	Jerusalem artichoke (<i>Helianthus tuberosus</i>)	Analysis of energy input and output of Jerusalem artichoke production	Bioenergy production	Gansu and Shandong Province, China	[105]
Bioenergy	<i>Hymenobacter</i> sp., <i>Chryseobacterium</i> sp.	Efficiency of solar cells	To use pigments produced by Antarctic bacteria resistant to UV rays as photosensitizers to improve solar cells	Samples collected from King George Island, Antarctica	[156]
Bioprospecting	Thermophilic microorganisms	Bleaching of chalcopyrite in Chilean copper mining in the presence of thermophilic microorganisms	Increase the copper extraction rates	Atacama Desert, Chile	[144]
Bioprospecting	<i>Bacillus amyloliquefaciens</i>	Biocomposite production, biocementation	Production of carbonates as a method to suppress dust from wind erosion	South of Iran	[157]
Bioprospecting	PID15: thermophilic microorganism	Use of thermophilic enzymes in the industry	Characterization of the thermostable enzyme glutamate dehydrogenase, which has potential biotechnological applications, for example, as a biosensor.	Deception Island, Antarctica	[158]
Bioprospecting	Sorghum (<i>Sorghum bicolor</i> (L.) Moench)	Study of biomass yield and quality response to N supply in cultivation of sorghum for the production of bioethanol or forage	Biomass sorghum for bioenergy feedstock prevents the soil degradation on semiarid marginal lands	Mongolia	[106]
Bioprospecting	<i>Deschampsia antarctica</i>	Identification and use of genes associated with UV-B radiation tolerance	Studies of characterization of a family of genes encoding chalcone synthase, a key enzyme of the flavonoid biosynthetic pathway. Flavonoids are associated with the high UV-B radiation tolerance of <i>D. antarctica</i>	Maritime territory of Antarctica and South Patagonia	[48]
Bioprospecting	<i>Humicola fuscoatra</i>	Isolation of endophytic fungi with several bioactivities from halophilic plants	Novel microbial source of metabolites with antifungal, antibacterial and antiproliferative/cytotoxic properties against plant pathogens	Iran	[159]
Biomineralization	<i>Pseudomonas</i> sp., <i>Bacillus subtilis</i> , <i>Rhodococcus erythropolis</i>	Urea hydrolysis by bacteria in the mineralization of Ca and Mg from seawater	Pretreatment strategy during water quality improvement processes	Antofagasta, Chile	[119]

Table 2 (continued)

Focus	Organism	Technological development	Application/solution	Location	References
Bioremediation	Biomass residues, palm trees residues	Biorefinery focus on organic residues and the reduction of water utilization for the production of diverse value (bio) chemicals	Use of seawater in the biorefinery processes (waste biorefinery treatment)	Global proposal	[107]
Greening drylands	Crops or plant species growing in the desert: xerophyte and halophyte species	Seawater desert-houses	Greening drylands and restoring wildlife and biodiversity in deserts	Global proposal	[118]
Drought-resistant plants	Transgenic plants	Use of extremely drought resistance genes	Drought-resistant pRD29A:PYL9 transgenic plants. The genes and mechanisms of ABA-induced foliar senescence under severe drought stress were identified.	–	[101]
Agricultural waste treatment	<i>Parageobacillus thermantarcticus</i> strain M1	Use of enzymes with high activity and thermostability in the bio-conversion of agro wastes	Conversion of waste lignocellulosic materials in high added value molecules using xylanolytic enzymes	Antarctic	[160]
Wastewater treatment	Microalgae	Use of microalgal cultivation in wastewater management in oil and gas extraction processes.	Microalgae as source of biofuel, lipids, and coproducts	Southwestern US, Australia, and Oman	[7]
Wastewater treatment	Yeast	Weed cultivation	Management of yeast wastewater; irrigation	Northeast of Amman, Jordan	[8]
Wastewater treatment	<i>Chlorella pyrenoidosa</i>	Microalgae cultivation	Cultivation of microalgae for nutrient removal as a wastewater treatment	Ouargla, Algeria	[46]
Wastewater treatment and fish health	Tilapia fish (<i>Oreochromis</i> sp.) Carp fish (<i>Cyprinus carpio</i>) Mosquitofish (<i>Gambusia affinis</i>)	Management of treated wastewater (TWW) reuse and floods: Temporal distribution of nutrients Measuring the occurrence of selected organic micropollutants in water, sediment and fish tissues Evaluating fish health using histopathology	TWW as water source for supporting a water reservoir for recreational activities	Negev Desert, Israel	[9]

- *Intensification* The geopolitical actors of the territories at risk should work together to promote the productive use of the land and its carrying capacities, taking into account that the agricultural activity could be limited by the accelerated population growth projected over the next 20 or 30 years.
- *Intellectual property*: Legislation should be developed that recognizes and protects potential biotechnological resources for their exploitation in these areas, thereby guaranteeing a respectful and ethical technology transfer beyond gaining an economic benefit.
- *Climate change* A global threat with repercussions on ecosystems and on the economic growth of societies is obvious consequences of rapid climate change. The dry areas of the planet, where almost 40% of the population is living, are the most sensitive areas on the planet due to climate change [165]. Biotechnology can offer sustainable solutions in fields such as water and soil optimization, CO₂ fixation, increasing the nutritive value of feedstock and increasing food supply. On this last point, climate change threatens three basic factors governing the production of food: temperature, availability of water and availability of nutrients. Facing this challenge, the future looks obscure because climate change is occurring so quickly that living organisms may not have enough time to establish a natural adaptation to address the new challenges. In the near future, genetic engineering appears to be a valid way to accelerate the adaptation of plants and crops to an unstable environment. Use of wild native flora that are naturally adapted to biotic and abiotic stress appears to be a promising way to speed up the response to the negative effects of climate change. An important part of this strategy is to discover and take advantage of natural genetic variation in germplasm collections to improve tolerances of more extreme drought in crops and heat stress as well as to find cultivars adapted to the warmest expected conditions, greater atmospheric CO₂ contents and more extreme cold or other climatic events [166]. However, domestication of wild flora requires time and economic resources that may not be available to all countries. The challenge here is to force biotechnology to play a more critical role in the optimization of process and chain of production, producing more environmentally friendly food and biofuels and increasing CO₂ mitigation with the improvement of microalgae systems. All these actions have the challenge of being incorporated efficiently into the local productive systems of arid environments.
- *Robotics applied to biotechnology studies* Sampling or monitoring in hard-to-reach locations or regions inaccessible to humans, especially in extreme environments, constitutes a challenge for biotechnology research. The need to intervene in hostile environments has led robotics to be adapted to research [167, 168]. In this line, a robot has also been used in the hyperarid core of the Atacama Desert (NASA's Subsurface Life in the Atacama Project) [168] for simulating excavations and sampling within the framework of the upcoming Mars2020 and ExoMars missions that will search for signs of biological activity on Mars. Antarctica could also be an important equivalent for the testing and validation of the technology and instruments of robotic space missions [169], as is the case for the research conducted in the subglacial Lake Vostok (similar to Jupiter's moons) [170]. Antarctic extremophiles could be considered as habitability indicators for the possible existence of past, present or future life on other planets. Therefore, the development of robotic technology could respond, albeit partially, to the question, "What is the limit of life as we know it on Earth?" As described throughout this review, these environments are rich in microorganisms that are capable of adapting to inhospitable conditions, and studying them provides a better understanding of life on Earth and outside of it. Therefore, the study of these extreme environments together with the use of robots will allow us to determine whether these environments are capable of hosting life.
- *The water challenge* Access to water is an issue incorporated into political agendas and academic research around the world [171–173]. The concepts of commitment, innovation and sustainable application take center stage. Improving the efficiency of the use of available water sources will not only increase food production but will also be key to the operation and maintenance of life on the planet. Surface and groundwater are the main sources of drinking water. Both forms of water are generally unsafe and require some form of treatment to become potable, where biological contaminants and organic and inorganic chemicals present are regulated, by means of microbiological filtration [174]. Another way to use water efficiently would be through the improvement of crops so that they require less water in their cultivation or are tolerant to irrigation with seawater.
- *The challenge of using clean energy* The integration of brown biotechnology in clean energy technologies can solve deficiencies of this system. Bacterial colonies have been used to improve the efficiency of solar cells so that they can operate in low light. For example, pigments produced by Antarctic bacteria (of the genus *Hymenobacter* and *Chryseobacterium*) to resist UV rays have been used as photosensitizers in solar cells [156]. Additionally, colonies of *E. coli* coated with a mineral have been incorporated into solar panels of [175]. In

this particular case, the challenge remains the effective integration into other clean energy systems.

7 Conclusions

This paper exposes the complex links between diverse topics related to biotechnology for arid zones. The review moves from a global perspective to a local one (Chile), in which different scientific and technological developments are discussed regarding the organisms and microorganisms living in such environments and how these developments have contributed to addressing difficult problems, such as the development of sustainable agriculture in areas limited by water resources and low levels of organic matter in soils. Recent studies on vegetative, animal and microbiological crops are reported, not only in terms of their interaction with the environment but also in terms of their potential use in processes such as bio- and phytoremediation and even in the adaptation of nonendemic species to arid environments. Dynamic adaptations to arid areas by each of these organisms, from micro- to macroorganisms, represent a valuable opportunity to solve problems and challenges of these areas and to obtain biotechnological benefits, products or services, and have potential applications in other types of non-extreme ecosystems due to their versatility and capacity to extrapolate the results.

Without a doubt, biotechnology has become a fundamental scientific tool to further the comprehensive development of arid zones. Research on the microorganisms, plants and animals present in arid zones have allowed strategies to be employed and unique survival models to be copied in these places under extreme conditions, often helping to establish alternative solutions to problems generally associated with the implementation of sustainable agricultural-farming systems and the use of water and energy resources.

With all of its unique diversity of climates and natural environments, Chile is positioned at the forefront of biotechnology development. Specifically, throughout all its arid areas, Chile hosts a range of ecosystems with interesting species due to their incredible survival patterns, thus providing the perfect object of study for brown biotechnology and its application. However, although extremophiles and their physiological characteristics have been studied in Chile, further research is needed, and there is still a long way to go.

In the near future, new findings and studies are key for understanding life and for improving living conditions in light of the current climate change and the high degree of global industrialization. Thus, it is important to understand the challenges to be confronted in relation to

science and technology, as well as countries need to adopt or adapt internal policies for a better implementation of practical solutions, which nowadays includes a plethora of biotechnological tools available for research in different fields such as bioremediation, genomics, bioprospecting, enzymology, microbiology, and data science. Together, these fields will contribute addressing the challenges that humanity will face in the near future for arid environments (and others). In a more local view, the substantial development of local biotechnology would position Chile as a research benchmark for global arid regions considering that it possesses all the necessary natural resources to achieve this goal due to its extreme and unique zones.

Finally, we would like to highlight that this research study was conducted only using documents available in the public domain. Therefore, we apologize for not referencing those research studies on brown biotechnology with restricted access here and for the editorial constraints encountered during the search, which are typical of these types of studies and did not allow us to include all the studies performed by our colleagues.

Compliance with ethical standards

Conflict of interest We do not have conflict of interest.

References

- Huang J, Ji M, Xie Y, Wang S, He Y, Ran J (2015) Global semi-arid climate change over last 60 years. *Clim Dyn* 46(3–4):1131–1150. <https://doi.org/10.1007/s00382-015-2636-8>
- Mazuela Águila PC (2013) Agricultura en zonas áridas y semi-áridas. *Idesia (Arica)* 31:3–4
- Dunbar WS (2017) Biotechnology and the mine of tomorrow. *Trends Biotechnol* 35(1):79–89. <https://doi.org/10.1016/j.tibtech.2016.07.004>
- Nations. FFAOotU (2017) Water for sustainable food and agriculture: a report produced for the G20 Presidency of Germany
- Barbier EB, Hochard JP (2017) Poverty, rural population distribution and climate change. *Environ Dev Econ* 23(3):234–256. <https://doi.org/10.1017/s1355770x17000353>
- Martínez Fernández J (2012) Agua y sostenibilidad: algunas claves desde los sistemas áridos
- Sullivan Graham EJ, Dean CA, Yoshida TM, Twary SN, Teshima M, Alvarez MA, Zidenga T, Heikoop JM, Perkins GB, Rahn TA, Wagner GL, Laur PM (2017) Oil and gas produced water as a growth medium for microalgae cultivation: a review and feasibility analysis. *Algal Res* 24:492–504. <https://doi.org/10.1016/j.algal.2017.01.009>
- Abu-Dieyeh MH, Diab M, Al-Ghouti MA (2017) Ecological and agriculture impacts of bakery yeast wastewater use on weed communities and crops in an arid environment. *Environ Sci Pollut Res Int* 24(17):14957–14969. <https://doi.org/10.1007/s11356-017-9115-1>
- Zaibel I, Zilberg D, Groisman L, Arnon S (2016) Impact of treated wastewater reuse and floods on water quality and

- fish health within a water reservoir in an arid climate. *Sci Total Environ* 559:268–281. <https://doi.org/10.1016/j.scitotenv.2016.03.099>
10. Development OTOFECa (2005) A framework for biotechnology statistics. OECD, Paris, p 2005
 11. DaSilva EJ (2004) The colours of biotechnology: science, development and humankind. *Electron J Biotechnol* 7:01–02
 12. De la Vega I, Requena J, Fernández-Gómez R (2015) The colors of biotechnology in Venezuela: a bibliometric analysis. *Technol Soc* 42:123–134. <https://doi.org/10.1016/j.techsoc.2015.03.007>
 13. Sharma B, Bharti SK, Anita M (2016) Green biotechnology and scope of genetically modified crops: facts and prejudices. *Indian J Agric Bus* 2(1):63–72
 14. Barcelos MCS, Lupki FB, Campolina GA, Nelson DL, Molina G (2018) The colors of biotechnology: general overview and developments of white, green and blue areas. *FEMS Microbiol Lett*. <https://doi.org/10.1093/femsle/fny239>
 15. Barrows G, Sexton S, Zilberman D (2014) Agricultural biotechnology: the promise and prospects of genetically modified crops. *J Econ Perspect* 28(1):99–120. <https://doi.org/10.1257/jep.28.1.99>
 16. Kiss AA, Grievink J, Rito-Palomares M (2015) A systems engineering perspective on process integration in industrial biotechnology. *J Chem Technol Biotechnol* 90(3):349–355. <https://doi.org/10.1002/jctb.4584>
 17. Abiri R, Valdiani A, Maziah M, Shaharuddin NA, Sahebi M, Yusof ZN, Atabaki N, Talei D (2016) A critical review of the concept of transgenic plants: insights into pharmaceutical biotechnology and molecular farming. *Curr Issues Mol Biol* 18:21–42
 18. Oliver J (2004) *Encyclopedia of world climatology*. Springer, Dordrecht
 19. Astaburuaga GR (2004) El agua en las zonas áridas de Chile. ARQ (Santiago) pp 68–73
 20. Shankarnarayan KA, Harsh LN, Kathju S (1987) Agroforestry in the arid zones of India. *Agrofor Syst* 5(1):69–88. <https://doi.org/10.1007/BF00046414>
 21. Zalibekov ZG (2011) The arid regions of the world and their dynamics in conditions of modern climatic warming. *Arid Ecosystems* 1(1):1. <https://doi.org/10.1134/S2079096111010094>
 22. Salem BB (1989) *Arid zone forestry: a guide for field technicians*. Food and Agriculture Organization (FAO), Rome. 143 pp. ISBN: 9251028095
 23. Fretwell P, Pritchard HD, Vaughan DG, Bamber JL, Barrand NE, Bell R, Bianchi C, Bingham RG, Blankenship DD, Casassa G, Catania G, Callens D, Conway H, Cook AJ, Corr HFJ, Damaske D, Damm V, Ferraccioli F, Forsberg R, Fujita S, Gim Y, Gogineni P, Griggs JA, Hindmarsh RCA, Holmlund P, Holt JW, Jacobel RW, Jenkins A, Jokat W, Jordan T, King EC, Kohler J, Krabill W, Riger-Kusk M, Langley KA, Leitchenkov G, Leuschen C, Luyendyk BP, Matsuoka K, Mouginot J, Nitsche FO, Nogi Y, Nost OA, Popov SV, Rignot E, Rippon DM, Rivera A, Roberts J, Ross N, Siegert MJ, Smith AM, Steinhage D, Studinger M, Sun B, Tinto BK, Welch BC, Wilson D, Young DA, Xiangbin C, Zirizzotti A (2013) Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *Cryosphere* 7(1):375–393. <https://doi.org/10.5194/tc-7-375-2013>
 24. Schuster M, Düringer P, Ghienne J-F, Vignaud P, Mackaye HT, Likius A, Brunet M (2006) The age of the Sahara desert. *Science* 311(5762):821. <https://doi.org/10.1126/science.1120161>
 25. Wang X, Lang L, Hua T, Wang H, Zhang C, Wang Z (2012) Characteristics of the Gobi desert and their significance for dust emissions in the Ala Shan Plateau (Central Asia): an experimental study. *J Arid Environ* 81:35–46. <https://doi.org/10.1016/j.jaridenv.2012.01.014>
 26. Bull AT, Asenjo JA, Goodfellow M, Gomez-Silva B (2016) The Atacama Desert: technical resources and the growing importance of novel microbial diversity. *Annu Rev Microbiol* 70:215–234. <https://doi.org/10.1146/annurev-micro-102215-095236>
 27. Palerme C, Claud C, Dufour A, Genthon C, Wood NB, L'Ecuyer T (2017) Evaluation of Antarctic snowfall in global meteorological reanalyses. *Atmos Res* 190:104–112. <https://doi.org/10.1016/j.atmosres.2017.02.015>
 28. Smith M, Veth P, Hiscock P, Wallis LA (2008) Global desert in perspective. In: Veth P, Hiscock P, Smith M (eds) *Desert peoples: archaeological perspectives*. Blackwell Publishing, Hoboken, pp 1–14
 29. Alonso JL (1990) Reforestation of arid and semi-arid zones in Chile. *Agr Ecosyst Environ* 33(2):111–127. [https://doi.org/10.1016/0167-8809\(90\)90237-8](https://doi.org/10.1016/0167-8809(90)90237-8)
 30. Díaz C, Wright C (1965) Soils of the arid zones of Chile. FAO (631.445.5)
 31. Casanova M, Salazar O, Seguel O, Luzio W (2013) The soils of Chile. *World Soils Book Ser*. <https://doi.org/10.1007/978-94-007-5949-7>
 32. Azúa-Bustos A, González-Silva C, Mancilla RA, Salas L, Gómez-Silva B, McKay CP, Vicuña R (2011) Hypolithic cyanobacteria supported mainly by fog in the coastal range of the Atacama Desert. *Microb Ecol* 61(3):568–581. <https://doi.org/10.1007/s00248-010-9784-5>
 33. Gómez-Silva B, Rainey FA, Warren-Rhodes KA, McKay CP, Navarro-González R (2008) Atacama Desert soil microbiology. In: Dion P (ed) *Microbiology of extreme soils*. Soil biology. Springer, Berlin
 34. Aleshire P (2008) *The extrem earth deserts*. Chelsea House Publisher, New York
 35. Marquet P, Bozinovic F, Bradshaw GA, Cornelius C, Gonzalez H, Gutierrez J, Hajek E, Lagos J, Lopez-Cortes F, Nuñez L, Rosell EF, Santor C, Samanieg H, Standen VG, Torres-Mura J, Jaksic F (1998) Los ecosistemas del desierto de Atacama y área andina adyacente en el norte de Chile. *Revista Chilena de Historia Nat* 71:593–617
 36. Arroyo M, Marquet P, Marticorena C, Simonetti J, Cavieres L, Squeo F (2008) Biodiversidad de Chile Patrimonio y Desafíos. In: Squeo F (ed) *LTDA OLE*, 2nd edn. pp 94–97
 37. Kafarski P (2012) Rainbow code of biotechnology. *Chemik* 66(8):811–816
 38. Hori Y, Stuhlberger C, Simonett O (eds) (2011) *Desertification: a visual synthesis*. In: *Desertification*. 52 pp. ISBN: 9789295943497
 39. Ziervogel G, Ericksen PJ (2010) Adapting to climate change to sustain food security. *Wiley Interdiscip Rev Clim Change* 1(4):525–540. <https://doi.org/10.1002/wcc.56>
 40. Isichei AO (1990) The role of algae and cyanobacteria in arid lands. A review. *Arid Soil Res Rehabil* 4(1):1–17. <https://doi.org/10.1080/15324989009381227>
 41. Usher PK, Ross AB, Camargo-Valero MA, Tomlin AS, Gale WF (2014) An overview of the potential environmental impacts of large-scale microalgae cultivation. *Biofuels* 5(3):331–349. <https://doi.org/10.1080/17597269.2014.913925>
 42. Priyadarshani I, Rath B (2012) Commercial and industrial applications of micro algae—a review. *J Algal Biomass Util* 3(4):89–100
 43. Mata TM, Martins AA, Caetano NS (2010) Microalgae for bio-diesel production and other applications: a review. *Renew Sustain Energy Rev* 14(1):217–232. <https://doi.org/10.1016/j.rser.2009.07.020>
 44. Acien FG, Molina E, Reis A, Torzillo G, Zittelli GC, Sepúlveda C, Masojidek J (2017) Photobioreactors for the production of microalgae. In: Gonzalez-Fernandez C, Muñoz R (eds) *Microalgae-based biofuels and bioproducts*. Woodhead Publishing, Cambridge, pp 1–44. <https://doi.org/10.1016/B978-0-08-101023-5.00001-7>

45. Capson-Tojo G, Torres A, Muñoz R, Bartacek J, Jeison D (2017) Mesophilic and thermophilic anaerobic digestion of lipid-extracted microalgae *N. gaditana* for methane production. *Renew Energy* 105:539–546. <https://doi.org/10.1016/j.renene.2016.12.052>
46. Dahmani S, Zerrouki D, Ramanna L, Rawat I, Bux F (2016) Cultivation of *Chlorella pyrenoidosa* in outdoor open raceway pond using domestic wastewater as medium in arid desert region. *Biores Technol* 219:749–752. <https://doi.org/10.1016/j.biortech.2016.08.019>
47. Aboal M, Gonzalez-Silvera D, Roldan M, Hernandez-Marine M, Lopez-Jimenez JA, Whitton BA (2014) The freshwater alga *Chroothoece richteriana* (Rhodophyta) as a potential source of lipids. *Food Chem* 162:143–148. <https://doi.org/10.1016/j.foodchem.2014.04.036>
48. Cuadra P, Guajardo J, Carrasco-Orellana C, Stappung Y, Fajardo V, Herrera R (2020) Differential expression after UV-B radiation and characterization of chalcone synthase from the Patagonian hairgrass *Deschampsia antarctica*. *Phytochemistry* 169:112179. <https://doi.org/10.1016/j.phytochem.2019.112179>
49. Stanier RY, Cohen-Bazire G (1977) Phototrophic prokaryotes: the cyanobacteria. *Annu Rev Microbiol* 31:225–274. <https://doi.org/10.1146/annurev.mi.31.100177.001301>
50. Kirkwood AE, Buchheim JA, Buchheim MA, Henley WJ (2008) Cyanobacterial diversity and halotolerance in a variable hypersaline environment. *Microb Ecol* 55(3):453–465. <https://doi.org/10.1007/s00248-007-9291-5>
51. Genuário DB, Vaz MGMV, Santos SN, Kavamura VN, Melo IS (2019) Cyanobacteria from Brazilian extreme environments. 66. In: Das S, Ranjan H (eds) *Microbial diversity in the genomic era*, pp 265–284. <https://doi.org/10.1016/b978-0-12-814849-5.00016-2>
52. Abed RMM, Klempová T, Gajdoš P, Čertík M (2015) Bacterial diversity and fatty acid composition of hypersaline cyanobacterial mats from an inland desert wadi. *J Arid Environ* 115:81–89. <https://doi.org/10.1016/j.jaridenv.2015.01.010>
53. García JJ, López-Pingarrón L, Almeida-Souza P, Tres A, Escudero P, García-Gil FA, Tan D-X, Reiter RJ, Ramírez JM, Bernal-Pérez M (2014) Protective effects of melatonin in reducing oxidative stress and in preserving the fluidity of biological membranes: a review. *J Pineal Res* 56(3):225–237. <https://doi.org/10.1111/jpi.12128>
54. Leman J (1997) Oleaginous microorganisms: an assessment of the potential. In: Neidleman SL, Laskin AI (eds) *Advances in applied microbiology*, vol 43. Academic Press, Cambridge, pp 195–243
55. Faife-Pérez E, Otero-Rambla M, Alvarez-Delgado A (2012) Producción de biodiesel a partir de microorganismos oleaginosos. Una fuente de energía renovable. Parte I. Levaduras y bacterias. *ICIDCA Sobre los Derivados de la Caña de Azúcar* 46(1):22–32
56. Santander C, Robles PA, Cisternas LA, Rivas M (2014) Technical–economic feasibility study of the installation of biodiesel from microalgae crops in the Atacama Desert of Chile. *Fuel Process Technol* 125:267–276. <https://doi.org/10.1016/j.fuproc.2014.03.038>
57. Rottig A, Hauschild P, Madkour MH, Al-Ansari AM, Almakishah NH, Steinbuechel A (2016) Analysis and optimization of triacylglycerol synthesis in novel oleaginous *Rhodococcus* and *Streptomyces* strains isolated from desert soil. *J Biotechnol* 225:48–56. <https://doi.org/10.1016/j.jbiotec.2016.03.040>
58. Nuñez Ravelo FA (2015) Efectos de la costra microbiótica en algunas propiedades del suelo en el sur de la quebrada Los Barrancos, Valle de Quibor, Venezuela. *Investigaciones Geográficas*. <https://doi.org/10.14350/rig.33959>
59. Celaya-Michel H, Castellanos-Villegas AE (2011) Mineralización de Nitrógeno en el suelo de zonas Áridas y Semiáridas. *Terra Latinoamericana* 29(3):343–356
60. Moncayo-Riascos MC, Gálvez-Cerón A (2018) Islas de fertilidad: una revisión sistemática de su estructura y operación. *Idesia (Arica)* 36:115–122
61. Shi ZY, Zhang LY, Li XL, Feng G, Tian CY, Christie P (2007) Diversity of arbuscular mycorrhizal fungi associated with desert ephemerals in plant communities of Junggar Basin, northwest China. *Appl Soil Ecol* 35(1):10–20. <https://doi.org/10.1016/j.apsoil.2006.06.002>
62. Kohler J, Hernández JA, Caravaca F, Roldán A (2008) Plant-growth-promoting rhizobacteria and arbuscular mycorrhizal fungi modify alleviation biochemical mechanisms in water-stressed plants. *Funct Plant Biol* 35(2):141–151. <https://doi.org/10.1071/FP07218>
63. Porcel R, Ruiz-Lozano JM (2004) Arbuscular mycorrhizal influence on leaf water potential, solute accumulation, and oxidative stress in soybean plants subjected to drought stress. *J Exp Bot* 55(403):1743–1750. <https://doi.org/10.1093/jxb/erh188>
64. Gong M, You X, Zhang Q (2015) Effects of *Glomus intraradices* on the growth and reactive oxygen metabolism of foxtail millet under drought. *Ann Microbiol* 65(1):595–602. <https://doi.org/10.1007/s13213-014-0895-y>
65. Jafari M, Yari M, Ghabooli M, Sepehri M, Ghasemi E, Jonker A (2018) Inoculation and co-inoculation of alfalfa seedlings with root growth promoting microorganisms (*Piriformospora indica*, *Glomus intraradices* and *Sinorhizobium meliloti*) affect molecular structures, nutrient profiles and availability of hay for ruminants. *Anim Nutr* 4(1):90–99. <https://doi.org/10.1016/j.aninu.2017.08.008>
66. Manga A, Dalpé Y, Soumaré A, Diop TA (2017) Diversity of Arbuscular mycorrhizal fungi associated to *Acacia seyal* (Delile) in semi-arid zone of Senegal. *World J Microbiol* 3(2):120–127
67. Guadarrama Chávez P, Sánchez-Gallen I, Álvarez Sánchez J, Ramos Zapata J (2004) Hongos y plantas, beneficios a diferentes escalas en micorrizas y arbusculares. *Ciencias* 73:38–45
68. Bull AT, Asenjo JA (2013) Microbiology of hyper-arid environments: recent insights from the Atacama Desert, Chile. *Antonie Van Leeuwenhoek* 103(6):1173–1179. <https://doi.org/10.1007/s10482-013-9911-7>
69. Okoro CK, Brown R, Jones AL, Andrews BA, Asenjo JA, Goodfellow M, Bull AT (2009) Diversity of culturable actinomycetes in hyper-arid soils of the Atacama Desert, Chile. *Antonie Van Leeuwenhoek* 95(2):121–133. <https://doi.org/10.1007/s10482-008-9295-2>
70. Santiago IF, Gonçalves VN, Gómez-Silva B, Galetovic A, Rosa LH (2018) Fungal diversity in the Atacama Desert. *Antonie Van Leeuwenhoek* 111(8):1345–1360. <https://doi.org/10.1007/s10482-018-1060-6>
71. Territorial. CNSIdI (2018) Indicadores socio-demográficos y económicos Región de Magallanes y Antártica Chilena. *Nuestro País*
72. Allaby M (2006) *Deserts (Bioes of Earth)*. Chelsea House Publishers, New York
73. Bohuslavová O, Macek P, Redčenko O, Láška K, Nedbalová L, Elster J (2018) Dispersal of lichens along a successional gradient after deglaciation of volcanic mesas on northern James Ross Island, Antarctic Peninsula. *Polar Biol* 41(11):2221–2232. <https://doi.org/10.1007/s00300-018-2357-7>
74. Kramme M (1997) *Exploring Antarctica: Continents of the world*. Mark Twain Media Inc, Geography Series
75. Dodds K, Hemmings A, Roberts P (2017) *Handbook on the politics of Antarctica*. Edward Elgar Publishing, Cheltenham

76. Bull AT, Andrews BA, Dorador C, Goodfellow M (2018) Introducing the Atacama Desert. *Antonie Van Leeuwenhoek* 111(8):1269–1272. <https://doi.org/10.1007/s10482-018-1100-2>
77. Vega E, Rojas L, Canales R, Fuentes A (2018) Enciclopedia visual de la Antártica. INACH, Santiago
78. Cáceres L, Davila AF, Soliz A, Saldívia J (2018) Corrosion of bare carbon steel as a passive sensor to assess moisture availability for biological activity in Atacama Desert soils. *Antonie Van Leeuwenhoek* 111(8):1293–1299. <https://doi.org/10.1007/s10482-018-1037-5>
79. INE Instituto Nacional de Estadísticas de Chile (2016) Informe anual 2016: Medio Ambiente. p 204. https://www.ine.cl/docs/default-source/variables-basicas-ambientales/publicaciones-y-anuarios/informe-anual-de-medio-ambiente/anuario-medio-ambiente-2016.pdf?sfvrsn=afd8c34_3
80. Cordero RR, Damiani A, Jorquera J, Sepúlveda E, Caballero M, Fernandez S, Feron S, Llanillo PJ, Carrasco J, Laroze D, Labbe F (2018) Ultraviolet radiation in the Atacama Desert. *Antonie Van Leeuwenhoek* 111(8):1301–1313. <https://doi.org/10.1007/s10482-018-1075-z>
81. Chile DnMd (2018) Índice UV-B observado y pronosticado—Antártica
82. Schulze-Makuch D, Wagner D, Kounaves SP, Mangelsdorf K, Devine KG, de Vera J-P, Schmitt-Kopplin P, Grossart H-P, Parro V, Kaupenjohann M, Galy A, Schneider B, Airo A, Frösler J, Davila AF, Arens FL, Cáceres L, Cornejo FS, Carrizo D, Dartnell L, DiRuggiero J, Flury M, Ganzert L, Gessner MO, Grathwohl P, Guan L, Heinz J, Hess M, Keppler F, Maus D, McKay CP, Meckenstock RU, Montgomery W, Oberlin EA, Probst AJ, Sáenz JS, Sattler T, Schirmack J, Sephton MA, Schlöter M, Uhl J, Valenzuela B, Vestergaard G, Wörmer L, Zamorano P (2018) Transitory microbial habitat in the hyperarid Atacama Desert. *Proc Natl Acad Sci* 115(11):2670–2675. <https://doi.org/10.1073/pnas.1714341115>
83. Lysak V, Maksimova IA, Nikitin DA, Ivanova AE, Kudina AG, Soina VS, Marfenina OE (2018) Soil microbial communities of Eastern Antarctica. *Moscow Univ Biol Sci Bull* 73(3):104–112. <https://doi.org/10.3103/S0096392518030124>
84. Engel AS, Johnson LR, Porter ML (2013) Arsenite oxidase gene diversity among Chloroflexi and Proteobacteria from El Tatio Geyser Field, Chile. *FEMS Microbiol Ecol* 83(3):745–756. <https://doi.org/10.1111/1574-6941.12030>
85. Gonçalves VN, Cantrell CL, Wedge DE, Ferreira MC, Soares MA, Jacob MR, Oliveira FS, Galante D, Rodrigues F, Alves TMA, Zani CL, Junior PAS, Murta S, Romanha AJ, Barbosa EC, Kroon EG, Oliveira JG, Gomez-Silva B, Galestovic A, Rosa CA, Rosa LH (2016) Fungi associated with rocks of the Atacama Desert: taxonomy, distribution, diversity, ecology and bioprospection for bioactive compounds. *Environ Microbiol* 18(1):232–245. <https://doi.org/10.1111/1462-2920.13005>
86. Vítek P, Jehlička J, Ascaso C, Mašek V, Gómez-Silva B, Olivares H, Wierzbosch J (2014) Distribution of scytonemin in endolithic microbial communities from halite crusts in the hyperarid zone of the Atacama Desert, Chile. *FEMS Microbiol Ecol* 90(2):351–366. <https://doi.org/10.1111/1574-6941.12387>
87. Barahona S, Dorador C, Zhang R, Aguilar P, Sand W, Vera M, Remonsellez F (2014) Isolation and characterization of a novel *Acidithiobacillus ferrivorans* strain from the Chilean Altiplano: attachment and biofilm formation on pyrite at low temperature. *Res Microbiol* 165(9):782–793. <https://doi.org/10.1016/j.resmic.2014.07.015>
88. Sanchez RA (2007) Antartida: Introduccion a un continente remoto. Editorial Albatros, Buenos Aires
89. Iravani S (2014) Bacteria in nanoparticle synthesis: current status and future prospects. *Int Sch Res Notices*. <https://doi.org/10.1155/2014/359316>
90. Javani S, Marín I, Amils R, Abad JP (2015) Four psychrophilic bacteria from Antarctica extracellularly biosynthesize at low temperature highly stable silver nanoparticles with outstanding antimicrobial activity. *Colloids Surf A* 483:60–69. <https://doi.org/10.1016/j.colsurfa.2015.07.028>
91. Pugin B, Cornejo FA, Muñoz-Díaz P, Muñoz-Villagrán CM, Vargas-Pérez JI, Arenas FA, Vásquez CC (2014) Glutathione reductase-mediated synthesis of tellurium-containing nanostructures exhibiting antibacterial properties. *Appl Environ Microbiol* 80(22):7061–7070. <https://doi.org/10.1128/aem.02207-14>
92. Correa-Llantén DN, Amenábar MJ, Blamey JM (2012) Antioxidant capacity of novel pigments from an Antarctic bacterium. *J Microbiol* 50(3):374–379. <https://doi.org/10.1007/s12275-012-2029-1>
93. Arenz BE, Blanchette RA (2011) Distribution and abundance of soil fungi in Antarctica at sites on the Peninsula, Ross Sea Region and McMurdo Dry Valleys. *Soil Biol Biochem* 43(2):308–315. <https://doi.org/10.1016/j.soilbio.2010.10.016>
94. Sterflinger K, Tesei D, Zakharova K (2012) Fungi in hot and cold deserts with particular reference to microcolonial fungi. *Fungal Ecol* 5(4):453–462. <https://doi.org/10.1016/j.funeco.2011.12.007>
95. Famiglietti JS (2014) The global groundwater crisis. *Nat Clim Chang* 4:945–948
96. Bechtold U (2018) Plant life in extreme environments: how do you improve drought tolerance? *Front Plant Sci*. <https://doi.org/10.3389/fpls.2018.00543>
97. Marco F, Bitrián M, Carrasco P, Rajam MV, Alcázar R (2015) Genetic engineering strategies for abiotic stress tolerance in plants. In: Bahadur B, Venkat Rajam M, Sahijram L, Krishnamurthy K (eds) *Plant biology and biotechnology*, pp 579–609. Springer, New Delhi
98. Singh NP, Bal SK, More NS, Singh Y, Gudge A (2019) Adaptation and intervention in crops for managing atmospheric stresses. In: Sheraz Mahdi S (ed) *Climate change and agriculture in India: impact and adaptation*. Springer International Publishing, Cham, pp 111–127. https://doi.org/10.1007/978-3-319-90086-5_10
99. Soussi A, Ferjani R, Marasco R, Guesmi A, Cherif H, Rolli E, Mapelli F, Ouzari HI, Daffonchio D, Cherif A (2016) Plant-associated microbiomes in arid lands: diversity, ecology and biotechnological potential. *Plant Soil* 405(1):357–370. <https://doi.org/10.1007/s11104-015-2650-y>
100. Fang Y, Xiong L (2015) General mechanisms of drought response and their application in drought resistance improvement in plants. *Cell Mol Life Sci* 72(4):673–689. <https://doi.org/10.1007/s00018-014-1767-0>
101. Zhao Y, Chan Z, Gao J, Xing L, Cao M, Yu C, Hu Y, You J, Shi H, Zhu Y, Gong Y, Mu Z, Wang H, Deng X, Wang P, Bressan RA, Zhu J-K (2016) ABA receptor PYL9 promotes drought resistance and leaf senescence. *Proc Natl Acad Sci* 113(7):1949–1954. <https://doi.org/10.1073/pnas.1522840113>
102. Bhattacharya A, Saini U, Joshi R, Kaur D, Pal AK, Kumar N, Gulati A, Mohanpuria P, Yadav SK, Kumar S, Ahuja PS (2014) Osmotin-expressing transgenic tea plants have improved stress tolerance and are of higher quality. *Transgenic Res* 23(2):211–223. <https://doi.org/10.1007/s11248-013-9740-5>
103. Navabi ZK, Stead KE, Pires JC, Xiong Z, Sharpe AG, Parkin IAP, Rahman MH, Good AG (2011) Analysis of B-genome chromosome introgression in interspecific hybrids of *Brassica napus* × *B. carinata*. *Genetics* 187(3):659–673. <https://doi.org/10.1534/genetics.110.124925>
104. Marillia E-F, Francis T, Falk KC, Smith M, Taylor DC (2014) Palliser's promise: *Brassica carinata*, an emerging western Canadian crop for delivery of new bio-industrial oil feedstocks.

- Biocatal Agric Biotechnol 3(1):65–74. <https://doi.org/10.1016/j.bcab.2013.09.012>
105. Fang YR, Liu JA, Steinberger Y, Xie GH (2018) Energy use efficiency and economic feasibility of Jerusalem artichoke production on arid and coastal saline lands. *Ind Crops Prod* 117:131–139. <https://doi.org/10.1016/j.indcrop.2018.02.085>
 106. Tang C, Yang X, Chen X, Ameen A, Xie G (2018) Sorghum biomass and quality and soil nitrogen balance response to nitrogen rate on semiarid marginal land. *Field Crops Res* 215:12–22. <https://doi.org/10.1016/j.fcr.2017.09.031>
 107. Bastidas-Oyanedel JR, Fang C, Almardeai S, Javid U, Yousuf A, Schmidt JE (2016) Waste biorefinery in arid/semi-arid regions. *Bioresour Technol* 215:21–28. <https://doi.org/10.1016/j.biortech.2016.04.010>
 108. Gajardo R (1994) La vegetación natural de Chile. Universitaria - CONAFE, Clasificación y distribución geográfica
 109. Argollo J, Soliz C, Villalba R (2004) Potencialidad dendrocronológica de *Polylepis tarapacana* en los Andes Centrales de Bolivia Dendrocronological potential of *Polylepis tarapacana* in the Central Andes of Bolivia. *Ecol en Boliv* 39(1):5–24
 110. Moya J, Lara A (2011) Tree rings chronologies of queñoa (*Polylepis tarapacana*) for the last 500 years in the Altiplano of Arica and Parinacota Region, Chile. *Bosque* 32(2):165–173. <https://doi.org/10.4067/S0717-92002011000200007>
 111. Chattopadhyay MK, Raghu G, Sharma YVRK, Biju AR, Rajasekharan MV, Shivaji S (2011) Increase in oxidative stress at low temperature in an Antarctic bacterium. *Curr Microbiol* 62(2):544–546. <https://doi.org/10.1007/s00284-010-9742-y>
 112. de Jager TL, Cockrell AE, Du Plessis SS (2017) Ultraviolet light induced generation of reactive oxygen species. *Adv Exp Med Biol* 996:15–23. https://doi.org/10.1007/978-3-319-56017-5_2
 113. Köhler H, Contreras RA, Pizarro M, Cortés-Antiquera R, Zúñiga GE (2017) Antioxidant responses induced by UVB radiation in *Deschampsia antarctica* Desv. *Front Plant Sci*. <https://doi.org/10.3389/fpls.2017.00921>
 114. Food and Agriculture Organization of the United Nations (2011) Escasez y degradación de las tierras y el agua: creciente amenaza para la seguridad alimentaria
 115. Jimenez M, Goodchild SC, Stockwell CA, Lema SC (2017) Characterization and phylogenetic analysis of complete mitochondrial genomes for two desert cyprinodontoid fishes, *Empetrichthys latos* and *Crenichthys baileyi*. *Gene* 626:163–172. <https://doi.org/10.1016/j.gene.2017.05.023>
 116. Potts DT (2004) Camel hybridization and the role of *Camelus bactrianus* in the ancient near East. *J Econ Soc Hist Orient* 47(2):143. <https://doi.org/10.1163/1568520041262314>
 117. Sharma R, Sharma H, Ahlawat S, Aggarwal RAK, Vij PK, Tania MS (2018) First attempt on somatic cell cryopreservation of critically endangered *Camelus bactrianus* of India. *Gene Rep* 10:109–115. <https://doi.org/10.1016/j.genrep.2017.11.007>
 118. Moustafa K (2017) Greening drylands with seawater easily and naturally. *Trends Biotechnol* 35(3):189–191. <https://doi.org/10.1016/j.tibtech.2016.09.005>
 119. Arias D, Cisternas LA, Rivas M (2017) Biomineralization of calcium and magnesium crystals from seawater by halotolerant bacteria isolated from Atacama Salar (Chile). *Desalination* 405:1–9. <https://doi.org/10.1016/j.desal.2016.11.027>
 120. Hua N-P, Kobayashi F, Iwasaka Y, Shi G-Y, Naganuma T (2007) Detailed identification of desert-originated bacteria carried by Asian dust storms to Japan. *Aerobiologia* 23(4):291–298. <https://doi.org/10.1007/s10453-007-9076-9>
 121. Kurapova AI, Zenova GM, Sudnitsyn II, Kizilova AK, Manucharova NA, Norovsuren Z, Zvyagintsev DG (2012) Thermotolerant and thermophilic actinomycetes from soils of Mongolia desert steppe zone. *Microbiology* 81(1):98–108. <https://doi.org/10.1134/S0026261712010092>
 122. Radwan SS, Al-Awadhi H, Sorkhoh NA, El-Nemr IM (1998) Rhizospheric hydrocarbon-utilizing microorganisms as potential contributors to phytoremediation for the oil Kuwaiti desert. *Microbiol Res* 153(3):247–251. [https://doi.org/10.1016/S0944-5013\(98\)80007-4](https://doi.org/10.1016/S0944-5013(98)80007-4)
 123. Trivedi P, Pandey A, Sa T (2007) Chromate reducing and plant growth promoting activities of psychrotrophic *Rhodococcus erythropolis* MtCC 7905. *J Basic Microbiol* 47(6):513–517. <https://doi.org/10.1002/jobm.200700224>
 124. FAO (2009) Water at a glance: the relationship between water, agriculture, food security and poverty. <http://www.fao.org/nr/water/docs/waterataglance.pdf>
 125. Lin S, Elimelech M (2015) Staged reverse osmosis operation: configurations, energy efficiency, and application potential. *Desalination* 366:9–14. <https://doi.org/10.1016/j.desal.2015.02.043>
 126. Wei X, Binger ZM, Achilli A, Sanders KT, Childress AE (2020) A modeling framework to evaluate blending of seawater and treated wastewater streams for synergistic desalination and potable reuse. *Water Res* 170:115282. <https://doi.org/10.1016/j.watres.2019.115282>
 127. Ali Z, Al Sunbul Y, Pacheco F, Ogieglo W, Wang Y, Genduso G, Pinnau I (2019) Defect-free highly selective polyamide thin-film composite membranes for desalination and boron removal. *J Membr Sci* 578:85–94. <https://doi.org/10.1016/j.memsci.2019.02.032>
 128. Raja CE, Omine K (2012) Characterization of boron resistant and accumulating bacteria *Lysinibacillus fusiformis* M1, *Bacillus cereus* M2, *Bacillus cereus* M3, *Bacillus pumilus* M4 isolated from former mining site, Hokkaido, Japan. *J Environ Sci Health A Toxic Hazard Subst Environ Eng* 47(10):1341–1349. <https://doi.org/10.1080/10934529.2012.672299>
 129. OIES (1991) Arid ecosystems interactions. Boulder, Colorado
 130. Delgado-Baquerizo M, Maestre FT, Gallardo A, Bowker MA, Wallenstein MD, Quero JL, Ochoa V, Gosaldo B, García-Gómez M, Soliveres S, García-Palacios P, Berdugo M, Valencia E, Escobar C, Arredondo T, Barraza-Zepeda C, Bran D, Carreira JA, Chaieb M, Conceição AA, Derak M, Eldridge DJ, Escudero A, Espinosa CI, Gaitán J, Gatica MG, Gómez-González S, Guzman E, Gutiérrez JR, Florentino A, Hepper E, Hernández RM, Huber-Sannwald E, Jankju M, Liu J, Mau RL, Miriti M, Moneris J, Naseri K, Noumi Z, Polo V, Prina A, Pucheta E, Ramírez E, Ramírez-Collantes DA, Romão R, Tighe M, Torres D, Torres-Díaz C, Ungar ED, Val J, Wamiti W, Wang D, Zaady E (2013) Decoupling of soil nutrient cycles as a function of aridity in global drylands. *Nature* 502(7473):672–676. <https://doi.org/10.1038/nature12670>
 131. Timmusk S, Grantcharova N, Wagner EGH (2005) *Paenibacillus polymyxa* invades plant roots and forms biofilms. *Appl Environ Microbiol* 71(11):7292–7300. <https://doi.org/10.1128/aem.71.11.7292-7300.2005>
 132. Yang J, Kloepper JW, Ryu C-M (2009) Rhizosphere bacteria help plants tolerate abiotic stress. *Trends Plant Sci* 14(1):1–4. <https://doi.org/10.1016/j.tplants.2008.10.004>
 133. Rütting T, Aronsson H, Delin S (2018) Efficient use of nitrogen in agriculture. *Nutr Cycl Agroecosyst* 110(1):1–5. <https://doi.org/10.1007/s10705-017-9900-8>
 134. Watzel B, Forchhammer K (2018) Cyanophycin: a nitrogen-rich reserve polymer. In: Tiwari A (ed) *Cyanobacteria*. <https://doi.org/10.5772/intechopen.77049>
 135. Alberts BBD, Lewis J, Raff M, Roberts K, Watson JD (2014) *Biología Molecular de la Célula*, 5th edn. Omega, Barcelona
 136. Lorenzo MG (2017) Suelos agrícolas: hacia un cambio de paradigma. *Rev Divulg Científica Fac Ciencias Agrar* 7
 137. Frey-Klett P, Burlinson P, Deveau A, Barret M, Tarkka M, Sarniguet A (2011) Bacterial-fungal interactions: hyphens between agricultural, clinical, environmental, and food

- microbiologists. *Microbiol Mol Biol Rev* 75(4):583–609. <https://doi.org/10.1128/MMBR.00020-11>
138. Torres HA, Acevedo HE (2008) El problema de salinidad en los recursos suelo y agua que afectan el riego y cultivos en los valles de Lluta y Azapa en el norte de Chile. *Idesia (Arica)* 26:31–44
 139. Princi MP, Lupini A, Araniti F, Longo C, Mauceri A, Sunseri F, Abenavoli MR (2016) Chapter 5—Boron toxicity and tolerance in plants: recent advances and future perspectives. In: Ahmad P (ed) *Plant metal interaction*. Elsevier, Amsterdam, pp 115–147. <https://doi.org/10.1016/B978-0-12-803158-2.00005-9>
 140. Martínez-Ballesta M, Bastías E, Carvajal M (2008) Combined effect of boron and salinity on water transport. *Plant Signal Behav* 3(10):844–845. <https://doi.org/10.4161/psb.3.10.5990>
 141. Bastías EI, González-Moro MB, González-Murua C (2004) Zea mays L. amylacea from the Lluta Valley (Arica-Chile) tolerates salinity stress when high levels of boron are available. *Plant Soil* 267(1):73–84. <https://doi.org/10.1007/s11104-005-4292-y>
 142. Rámila C, Contreras SA, Di Domenico C, Molina-Montenegro MA, Vega A, Handford M, Bonilla CA, Pizarro GE (2016) Boron stress response and accumulation potential of the extremely tolerant species *Puccinellia frigida*. *J Hazard Mater* 317:476–484. <https://doi.org/10.1016/j.jhazmat.2016.05.086>
 143. Rámila CDP, Leiva ED, Bonilla CA, Pastén PA, Pizarro GE (2015) Boron accumulation in *Puccinellia frigida*, an extremely tolerant and promising species for boron phytoremediation. *J Geochem Explor* 150:25–34. <https://doi.org/10.1016/j.jgexpl.2014.12.020>
 144. Murray C, Platzer W, Petersen J (2017) Potential for solar thermal energy in the heap bioleaching of chalcopyrite in Chilean copper mining. *Miner Eng* 100:75–82. <https://doi.org/10.1016/j.mineng.2016.09.022>
 145. Wiegel J, Canganella F (2011) Extremophiles: from abyssal to terrestrial ecosystems and possibly. *Naturwissenschaften* 98:253–279. <https://doi.org/10.1038/npg.els.0000392>
 146. Acosta M, Galleguillos P, Ghorbani Y, Tapia P, Contador Y, Velásquez A, Espoz C, Pinilla C, Demergasso C (2014) Variation in microbial community from predominantly mesophilic to thermotolerant and moderately thermophilic species in an industrial copper heap bioleaching operation. *Hydrometallurgy* 150:281–289. <https://doi.org/10.1016/j.hydro.2014.09.010>
 147. Watling HR (2006) The bioleaching of sulphide minerals with emphasis on copper sulphides—a review. *Hydrometallurgy* 84(1–2):81–108. <https://doi.org/10.1016/j.hydro.2006.05.001>
 148. Rivadeneyra M-A, Delgado G, Soriano M, Ramos-Cormenzana A, Delgado R (1999) Biomineralization of carbonates by *Marinococcus albus* and *Marinococcus halophilus* isolated from the Salar de Atacama (Chile). *Curr Microbiol* 39(1):53–57. <https://doi.org/10.1007/PL00006827>
 149. Romero L, Alonso H, Campano P, Fanfani L, Cidu R, Dadea C, Keegan T, Thornton I, Farago M (2003) Arsenic enrichment in waters and sediments of the Rio Loa (Second Region, Chile). *Appl Geochem* 18(9):1399–1416. [https://doi.org/10.1016/S0883-2927\(03\)00059-3](https://doi.org/10.1016/S0883-2927(03)00059-3)
 150. World Health Organization (2004) Guidelines for drinking-water Quality. Geneva. ISBN 92 4 154638 7. <https://apps.who.int/iris/bitstream/handle/10665/42852/9241546387.pdf;jsessionid=F54A7DDCBE17EFF327BF0F95EA21F610?sequence=1>
 151. Ulusoy Hİ, Akçay M, Ulusoy S, Gürkan R (2011) Determination of ultra trace arsenic species in water samples by hydride generation atomic absorption spectrometry after cloud point extraction. *Anal Chim Acta* 703(2):137–144. <https://doi.org/10.1016/j.aca.2011.07.026>
 152. Martínez VD, Vucic EA, Becker-Santos DD, Gil L, Lam WL (2011) Arsenic exposure and the induction of human cancers. *J Toxicol* 2011:431287. <https://doi.org/10.1155/2011/431287>
 153. Li R, Kuo Y-M, Liu W-w, Jang C-S, Zhao E, Yao L (2018) Potential health risk assessment through ingestion and dermal contact arsenic-contaminated groundwater in Jiangnan Plain, China. *Environ Geochem Health* 40(4):1585–1599. <https://doi.org/10.1007/s10653-018-0073-4>
 154. Liu C-W, Lin K-H, Kuo Y-M (2003) Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. *Sci Total Environ* 313(1):77–89. [https://doi.org/10.1016/S0048-9697\(02\)00683-6](https://doi.org/10.1016/S0048-9697(02)00683-6)
 155. Guo H, Wang Y, Li Y (2003) Analysis of factors resulting in anomalous arsenic concentration in groundwaters of Shanyin, Shanxi province. *Huan Jing Ke Xue* 24(4):60–67
 156. Ordenes-Aenishanslins N, Anziani-Ostuni G, Vargas-Reyes M, Alarcon J, Tello A, Perez-Donoso JM (2016) Pigments from UV-resistant Antarctic bacteria as photosensitizers in Dye Sensitized Solar Cells. *J Photochem Photobiol, B* 162:707–714. <https://doi.org/10.1016/j.jphotobiol.2016.08.004>
 157. Mohebbi MM, Habibagahi G, Niazi A, Ghahramani A (2019) A laboratory investigation of suppression of dust from wind erosion using biocementation with *Bacillus amyloliquefaciens*. *Scientia Iranica* 26(5):2665–2677. <https://doi.org/10.24200/sci.2018.20220>
 158. Flores PAM, Correa-Llanten DN, Blamey JM (2018) A thermophilic microorganism from Deception Island, Antarctica with a thermostable glutamate dehydrogenase activity. *Biol Res* 51(1):55. <https://doi.org/10.1186/s40659-018-0206-3>
 159. Hosseini Moghaddam MS, Safaie N, Soltani J, Pasdaran A (2020) Endophytic association of bioactive and halotolerant *Humicola fuscoatra* with halophytic plants, and its capability of producing anthraquinone and anthranol derivatives. *Antonie Van Leeuwenhoek* 113(2):279–291. <https://doi.org/10.1007/s10482-019-01336-x>
 160. Finore I, Lama L, Donato P, Romano I, Tramice A, Leone L, Nicolaus B, Poli A (2019) *Parageobacillus thermantarcticus*, an Antarctic cell factory: from crop residue valorization by green chemistry to astrobiology studies. *Diversity*. <https://doi.org/10.3390/d11080128>
 161. CIREN (2010) Determinación de erosión potencial V actual de Chile. Informe Técnico Final, Santiago
 162. Verbist K, Santibañez F, Gabriels D, Soto G (2010) ATLAS de Zonas Áridas de América Latina y el Caribe. Programa Hidrológico Internacional (PHI). UNESCO, Montevideo, Uruguay
 163. Montagu MV (2020) The future of plant biotechnology in a globalized and environmentally endangered world. *Genet Mol Biol* 43(1):e20190040. <https://doi.org/10.1590/1678-4685-GMB-2019-0040>
 164. Tanner K, Vilanova C, Porcar M (2017) Bioprospecting challenges in unusual environments. *Microb Biotechnol* 10(4):671–673. <https://doi.org/10.1111/1751-7915.12723>
 165. Huang J, Li Y, Fu C, Chen F, Fu Q, Dai A, Shinoda M, Ma Z, Guo W, Li Z, Zhang L, Liu Y, Yu H, He Y, Xie Y, Guan X, Ji M, Lin L, Wang S, Yan H, Wang G (2017) Dryland climate change: recent progress and challenges. *Rev Geophys* 55(3):719–778. <https://doi.org/10.1002/2016rg000550>
 166. Yadav SS, Redden RJ, Hatfield JL, Ebert AW, Hunter D (2019) Food security and climate change. Wiley, Hoboken
 167. Roldán JJ, del Cerro J, Garzón-Ramos D, García-Aunon P, Garzón M, de León J, Barrientos A (2017) Robots in agriculture: state of art and practical experiences. In: Neves A (ed) *Services robots*. National and University Library in Zagreb, Zagreb
 168. Warren-Rhodes KA, Lee KC, Archer SDJ, Lacap-Bugler DC, Boyle LN, Wettergreen D, Zacny K, Demergasso C, Moersch J, Chong G, Vijayarangan S, Tebes C, Wagner M, Tanaka K, Hare T, Gayle

- Tate C, Wang A, Wei J, Foil G, Cabrol N, Pointing SB (2018) Soil microbial habitats in an extreme desert Mars-analogue environment. *bioRxiv*. <https://doi.org/10.1101/269605>
169. Lveill R (2009) Validation of astrobiology technologies and instrument operations in terrestrial analogue environments. *CR Palevol* 8(7):637–648. <https://doi.org/10.1016/j.crv.2009.03.005>
170. Hartley K (2014) Extreme life and robots on ice: Antarctica as an astrobiology analogue. Supervised Project Report (ANTA604). <http://hdl.handle.net/10092/14127>
171. Garrick DE, Hanemann M, Hepburn C (2020) Rethinking the economics of water: an assessment. *Oxford Rev Econ Policy* 36(1):1–23. <https://doi.org/10.1093/oxrep/grz035>
172. Neto S, Camkin J (2020) What rights and whose responsibilities in water? Revisiting the purpose and reassessing the value of water services tariffs. *Util Policy* 63:101016. <https://doi.org/10.1016/j.jup.2020.101016>
173. Kirisits MJ, Emelko MB, Pinto AJ (2019) Applying biotechnology for drinking water biofiltration: advancing science and practice. *Curr Opin Biotechnol* 57:197–204. <https://doi.org/10.1016/j.copbio.2019.05.009>
174. Fowler SJ, Smets BF (2017) Microbial biotechnologies for potable water production. *Microb Biotechnol* 10(5):1094–1097. <https://doi.org/10.1111/1751-7915.12837>
175. Cross DT (2018) E. coli bacteria can help solar panels work on cloudy days. <https://www.sustainability-times.com/low-carbon-energy/e-coli-bacteria-can-help-solar-panels-work-on-cloudy-days/>. Accessed Feb 2020

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.