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# Brown Biotechnology – A Science for Sustainable Landmass Utilization and Conservation

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***Abstract***

Terrestrial ecosystems are essential for sustaining life on Earth, making our planet unique in the cosmos. However, these brown bodies have been significantly undervalued and represent one of the most neglected biomes. This neglect underscores the urgent need for their protection and sustainable management. Biotechnology offers promising tools to address this challenge, with brown biotechnology emerging as a specialized domain dedicated to the conservation and sustainable use of arid environments. Despite its potential, current definitions of brown biotechnology remain narrow, limiting its scope to arid ecosystems. Thus, this article aims to redefine the current understanding of brown biotechnology, expanding its scope beyond its traditional applications to encompass the protection and sustainable use of all terrestrial ecosystems. This redefinition will align the field with global sustainability objectives, allowing for the integration of innovative biotechnological solutions to combat desertification, rehabilitate degraded soils, and optimize the use of land-based resources. Furthermore, it provides a comprehensive overview of the diverse applications of brown biotechnology, including soil conservation, water management, and improving soil health.

**Keywords:** Brown Biotechnology, Arid Zones, Brown Bodies, Soil Health, Arid Microbes

## The Cosmic Value of Brown Bodies

Soil (Brown Bodies) is one of the most widespread, yet often overlooked, biome on Earth, and in many remarkable ways, it holds the key to sustaining life. Often dismissed as mere “dirt” or “mud,” soil is viewed by scientists as Earth’s living skin: a thin, delicate layer essential to human health and the global biosphere. Professor Bridget Emmett of the UK Centre for Ecology and Hydrology describes soil as “one of the most underrated and little understood wonders on our fragile planet” [1]. Primordial Earth was barren and rocky, much like Mars, until around 500 million years ago when land plants began to evolve from freshwater algae, gradually transforming the rocky surface. Over millions of years, these plants gave rise to vast forests. This surge in plant diversity was driven by a major underground change: the development of roots and soils. These 'brown bodies,' or the soil as we know them, have existed for less than 10% of Earth's history [2]. The earliest evidence of soil evolution comes from 400-million-year-old plant fossils in the Rhynie Chert of northeastern Scotland. These fossils show plants with simple root systems, made of hair- like structures called rhizoids, which anchored them to the rocky surface and helped absorb water and nutrients. New stems grew and intertwined with decaying ones, forming a thin, peaty soil just a few centimetres thick. Despite its thinness, this soil was stable enough to support more plant growth [3]. The early soils also supported a variety of fungi, some in symbiotic relationships with plants to exchange nutrients, while others decomposed plant matter. Additionally, these soils became a habitat for mites, nematodes, and early arachnids, creating a complex food web teeming with life [2]. Thus, these brown bodies have changed more than what's we think of them - they have reshaped our planet, influencing landscapes, waterways, nutrient cycles, and atmospheric composition in transformative ways. As deep soils formed, they altered the water cycle, turning small streams into large river channels and storing water to support more plant life and return it to the atmosphere. This period of soil evolution coincided with a significant drop in atmospheric carbon dioxide and cooling temperatures. Plant roots accelerated rock weathering, drawing down carbon dioxide, while organic-rich soils stored carbon. Decaying plants released carbon dioxide, but in many soils, this carbon was partially buried, ultimately forming carbon reservoirs like peat and coal. The emergence of deep soils and forests thus dramatically boosted Earth's carbon storage [4,5]. A single gram of soil may contain up to 50,000 species of microorganisms, and a teaspoon holds more individual microorganisms than Earth's entire human population. The intricate "soil web" of underground life creates a porous structure that absorbs rainwater, storing moisture for crops and preventing flooding, which is increasingly vital as global warming intensifies rainfall patterns worldwide. Thus, soil is undeniably essential to our survival, supporting 98% of biodiversity, directly sustains 95% of our food sources, from crops to grasses that feed livestock, producing 99% of our food, filtering all rainfall into drinkable water, and storing more active carbon than forests, oceans, or the atmosphere combined [6]. But as the global population grows, soil pollution has become a critical issue; deteriorating soil quality contaminates our food, water, and air. Human activities like deforestation, industrial farming, climate change, and urbanization are rapidly degrading soil health, threatening its ability to support life [7]. Given soil's fundamental role in supporting life and its contribution to making Earth unique in the cosmos, it is essential that we protect this vital biome. Thus, safeguarding soil health is crucial not only for sustaining human life but for preserving the intricate web of life that depends on it.



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**Understanding the Importance of Arid Zones**

Arid lands evoke images of barren, sandy dunes and rocky terrain, but their diversity extends far beyond this stereotype. These regions can be found not only in traditional desert settings but also at the poles, on mountains and plateaus, and along coastlines and inland areas [8]. Arid zones are quantitatively defined using the Aridity Index (AI), which considers temperature and precipitation levels, or the ratio of precipitation to evapotranspiration (the combined rate of water loss through plant transpiration, soil evaporation, and surface evaporation) [9, 10]. This nuanced definition highlights the complexity and variability of arid landscapes. The Food and Agriculture Organization (FAO) of the United Nations categorizes arid environments into three distinct zones based on the Aridity Index (AI). These zones comprise: *Hyper-arid zones* (4.2% of global area): Characterized by extreme aridity, these regions include the vast Sahara Desert in North Africa and the frozen landscape of Antarctica. *Arid zones* (14.6% of global area): This category encompasses iconic deserts such as Australia's central deserts, Taklimakan, and Gobi in Central East Asia. *Semi-arid zones* (12.2% of global area): Found in regions like Kazakhstan and southeastern Spain, these areas experience relatively milder arid conditions [9, 11]. Contrary to their reputation as desolate wastelands, arid zones are surprisingly vibrant ecosystems, supporting one-sixth of the world's population and covering over one-fifth of the Earth's landmass. Present on every continent, these regions play a crucial role in sustaining animals, humans, and the environment, despite their water scarcity [12]. Defying their inhospitable conditions, arid zones harbour an impressive array of plant and animal life. For instance, the Sahara Desert alone is home to an astonishing diversity of species, including over 500 plant species, 70 mammal species, 300 bird species, 100 reptile species, and numerous spider and scorpion species. This remarkable adaptability underscores the importance and resilience of arid ecosystems [13]. In addition to enriching the Earth's biodiversity, many of these plants and animals offer significant benefits to humans. For thousands of years, domesticated camels have served as reliable pack animals in the deserts of Asia and North Africa. Desert plants, such as dates, play a crucial role as a food source in North Africa and the Middle East; in fact, dates are among the oldest cultivated foods in the world, with origins dating back to biblical times. Alongside animals like camels and goats, a diverse array of desert vegetation can be found in oases and along the shores of rivers and lakes. Figs, olives, and oranges thrive in these desert oases, where they have been harvested for centuries, contributing to the sustenance and livelihoods of local populations [12,14].

Many ancient civilizations flourished in arid regions, which also became integral to their cultural heritage. Ancient Egypt, for example, renowned for its architectural wonders and cultural advancements, was strategically located amidst vast desert expanses. These barren landscapes, often perceived as inhospitable, played a pivotal role in shaping the civilization’s history. The desert environment not only provided crucial resources but also offered protection and served as a wellspring of inspiration for the Egyptians. The vast Sahara Desert, covering much of North Africa, acted as a formidable natural barrier for Egypt. Its extreme conditions like intense heat, scarce rainfall, and challenging terrain served as a natural defence, protecting the Nile Valley from external threats. The harsh desert environment discouraged foreign armies from crossing its vast emptiness, effectively creating a protective buffer around Egypt. This isolation allowed the civilization to develop with minimal outside interference, fostering a sense of autonomy and cultural uniqueness that allowed Egypt to thrive in peace, preserving its customs, traditions, and distinctive identity [15]. Thus, today, Egypt is primarily dominated by vast deserts surrounding the lush, fertile Nile Valley and its vibrant cities. To the west lies the arid Libyan Desert, while the Arabian and Sinai deserts stretch to the east of the Nile Valley [16]. In contrast, some of the planet's coldest and most extreme arid regions, such as the Arctic and Antarctic, are frozen zones known as the cryosphere. These regions are critical in regulating the Earth's climate and ocean systems. They reflect sunlight, helping to stabilize the planet's temperature, and store the majority of the Earth's freshwater. Additionally, they play a key role in the global water cycle, circulating ocean currents that transfer heat from the tropics to the poles and enhance the ocean's ability to absorb carbon dioxide, making them essential carbon sinks [17]. In the Kalahari Desert of Africa, fascinating discoveries have been made about bacteria living in its sands. These bacteria are capable of capturing and storing carbon dioxide, a major contributor to global warming. This suggests that desert sands might play an important role in mitigating the increase of carbon dioxide in the atmosphere [12]. Moreover, scientific research in Antarctica has provided valuable insights into the effects of human activity on the environment. The 1985 discovery of the ozone hole by scientists from the British Antarctic Survey (BAS) highlighted the destructive impact of human- made chemicals on the Earth's atmosphere (British Antarctic Survey). Deserts are also rich in economically significant resources that have been crucial for the development of civilizations and economies. One of the most prominent resources found in deserts is the vast oil reserves beneath the Arabian Desert in the Middle East. The region, particularly Saudi Arabia, holds more than half of the world’s proven oil reserves. This has attracted companies, migrant workers, engineers, geologists, and biologists to the Middle East to explore and exploit these resources [14]. Furthermore, the arid conditions of deserts are conducive to the formation and concentration of valuable minerals. As water evaporates, minerals such as gypsum, borates, nitrates, potassium, and various salts accumulate in desert regions. The sparse vegetation in these areas has also made it easier to mine and extract these essential minerals, further increasing the economic importance of deserts. According to United

Nations data, over half of the world's copper is sourced from deserts in Mexico, Australia, and Chile. Other valuable minerals and metals, such as bauxite, gold, and diamonds, are also found in abundance across desert regions in China, the United States, and Namibia [12]. Remarkably, studies indicate that the survival of the Amazon rainforest depends in part on the Sahara Desert. Each year, vast clouds of Saharan dust travel across the Atlantic Ocean, supplying around 22,000 tons of phosphorus to the Amazon, which is almost exactly the amount the rainforest loses annually through river systems. This vital nutrient transfer, tracked by NASA satellite data, suggests that African dust plays a crucial role in sustaining Amazonian soil fertility. Without this influx of phosphorus, the rainforest's soils would face significant nutrient depletion over time, impacting the health and productivity of the ecosystem [18,19]. Thus, despite appearing barren, deserts hold immense ecological and civilizational importance. Recognizing this, numerous policies have been developed to protect and sustainably manage desert resources. As technology advances, biotechnology has emerged as a powerful tool for conserving and sustainably utilizing arid landscapes, offering new ways to harness their resources responsibly.

**Brown Biotechnology**

The term biotechnology has gained tremendous popularity and significance over the past few decades due to its vast potential to benefit and advance human society. The wide range of applications and focus areas within biotechnology has led to a classification system based on colour in the beginning of 21st century [20,21]. Initially, only a few colours were defined, but over ime, the classification has expanded (today, biotechnology encompasses 11 recognized colours), enabling clearer differentiation between overlapping fields, fostering cross-sector collaboration, and driving technological innovation [22]. Although these classifications have highlighted the growing significance of colour coding in biotechnology, many of these definitions were established long ago, making some notions outdated. Thus, there is a need to re-define these colours/domains of biotechnology for expanding their potential application in the evolving circumstances [23,24]. Brown biotechnology, also known as desert biotechnology, currently focuses on leveraging biotechnology for the conservation and sustainable utilization of arid environments [9] (**Fig. 1**). While its current definition centers on arid regions, this field has the potential to address challenges and promote sustainable use across all terrestrial ecosystems or brown bodies. Therefore, ***brown biotechnology can be redefined as the field/colour of biotechnology for the sustainable management, restoration, and use of terrestrial environments, including arid lands, grasslands, forests, and other non-aquatic biomes, to support biodiversity, soil health, and resource conservation for a balanced ecosystem.***

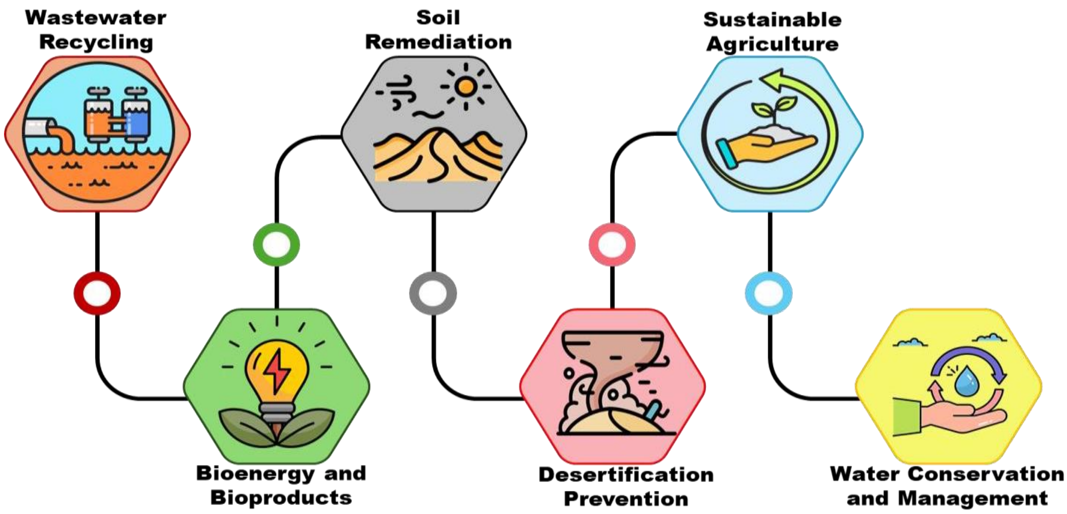


**Figure 1. Various Applications of Brown Biotechnology.** The figure was created using free icons available from Flaticon at: www.flaticon.com

**Water Scarcity Solutions**

Water is a critical limiting factor in many places, and biotechnology offers promising solutions to help address this challenge. Through innovative methods, biotechnology can play a significant role in alleviating water scarcity. One impactful approach involves advanced desalination technologies, which transform seawater into drinkable water. Desalination, a well- established method, is particularly valuable in water-scarce regions, such as the Near East, where it provides a vital source of freshwater. In Persian Gulf countries and on many islands worldwide, desalination is the primary source of potable water, and in certain regions, it is even used to irrigate high-value crops [25]. Globally, there are around 16,000 desalination plants operating across 177 countries, collectively producing approximately 95 million cubic meters of freshwater per day. Saudi Arabia leads in desalination volume, closely followed by the United Arab Emirates; both desert nations are heavily reliant on this technology. Other Middle Eastern countries, such as Kuwait and Qatar, have also adopted desalination to meet their water needs [26]. A promising sustainable alternative, biodesalination, leverages biotechnology by using microorganisms like algae and cyanobacteria to remove salt from seawater. Advances in this field have focused on optimizing nutrient media to promote faster growth rates for algae and cyanobacteria, enhancing desalination efficiencies up to 40%. Additionally, research has introduced microbial strains with greater tolerance to salinity. This sustainable, energy-efficient method offers significant potential in addressing the growing water crisis, especially in arid regions with limited freshwater access [27]. Biotechnology also plays a crucial role in wastewater treatment, providing various effective methods widely used around the world. Techniques like biofilters, activated sludge, oxidation ponds etc. are all biotechnological approaches commonly applied to manage and treat wastewater [28]. Additionally, biotechnology presents promising solutions for delivering clean water in remote or resource-limited areas. For instance, portable water purification devices that utilize biotechnological processes can supply safe drinking water during emergencies or in locations lacking clean water infrastructure. These devices present a scalable, cost-effective approach to tackling global water scarcity and contamination, significantly improving the health and well- being of vulnerable communities [29]. Biotechnology has driven advancements in water purification technologies, including the creation of biosensors that monitor water quality in real time. These state-of-the-art tools deliver quick and precise assessments of contamination levels, enabling prompt actions to safeguard public health. Furthermore, progress in biotechnological nanotechnology has resulted in nanomaterials capable of efficiently removing pollutants from water sources, providing a sustainable and environmentally friendly solution for water purification [30]. Biotechnology has also facilitated sustainable approaches to revitalizing drylands by utilizing seawater as an alternative water source, addressing both water scarcity and land degradation in arid regions. Research indicates that land greening and wildlife restoration in desert areas can be supported through seawater desert-houses. These mobile seawater ponds, positioned in desert landscapes, operate on the principle of natural rain formation, distilling water sustainably to produce small but dependable quantities of freshwater [31].

**Improving Soil Health and Agriculture**

The growing global population, combined with the finite availability of natural resources, land loss due to climate change and extensive environmental degradation, poses a formidable challenge for agriculture. Biotechnology-based agricultural systems offer innovative alternatives to traditional practices, providing new strategies to enhance environmental sustainability and resilience. Thus, Brown biotechnology, through genetic engineering methods, presents promising alternatives for boosting crop resistance to various biotic and abiotic stresses [32]. For instance, desert plant biotechnology has emerged as an exciting field for research and innovation, with a growing focus on stress tolerance traits, particularly those related to drought and salinity [33]. The growing interest in vegetative desiccation tolerance is reflected in the substantial number of publications on its ecology, physiology, and molecular mechanisms over the past two decades, with nearly 900 publications highlighting the significance of this field. Biotechnology has facilitated the creation of drought-resistant plants, including those that overexpress type 1 pyrabactin, an abscisic acid receptor hormone. This genetic modification helps minimize water loss by promoting stomatal closure and induces leaf senescence during drought conditions, effectively limiting growth in young tissues [34]. In tea plants,



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the introduction of osmotin, a protein associated with the response to abiotic stress, improves tolerance to water deficiency, accelerates recovery from drought, and boosts flavonoid and caffeine content compared to non- modified plants [35]. Moreover, genetic diversity in water-use efficiency (WUE) has been identified across crops, with breeding programs improving WUE through the identification and mapping of key genes. Physiological WUE is critical for successful bio-watering, requiring careful management. Researchers have cloned important WUE genes, such as Erecta and alx8, in *Arabidopsis thaliana* and transferred drought-resistant genes into crops, enhancing WUE and drought tolerance. Despite limited adoption of transgenic plants due to a lack of molecular understanding, advancements in breeding and biotechnology present opportunities to significantly improve crop WUE in varying water conditions [36]. In arid soils, phosphorus binds strongly with clay and silt, forming insoluble compounds like calcium phosphate that plants cannot absorb. As a result, the application of inorganic phosphates often leads to more than 80% immobilization, worsening phosphorus deficiency [9]. Biofertilization provides a solution by introducing microorganisms that enhance the bioavailability of phosphorus. For instance, *B. subtilis* and *G. intraradices* have been shown to increase onion biomass and nutrient uptake. Therefore, phosphorus-solubilizing microbes play a crucial role in enhancing fertilization efficiency in arid regions [37]. Moreover, in Canada's Palliser's Triangle, *Brassica carinata* (canola) was developed as a crop suited for arid soils, valued for its adaptability, resilience, and potential for bioindustrial oil production. Through decades of genetic enhancement and biotechnology, researchers developed high-yielding, drought-resistant varieties of *B. carinata*, demonstrating how combining traditional breeding with biotechnology can transform marginal lands into productive areas. With the growing global demand for vegetable oils, *B. carinata* oils now support industries such as biofuels, bioplastics, and treatments for neurodegenerative diseases, due to their high nervonic acid content [38,39].

Beyond boosting crop production, biotechnology offers transformative solutions for enhancing soil quality through phytoremediation. It plays a crucial role in conserving natural resources, improving plant nutrient uptake, minimizing nutrient runoff, and increasing carbon storage capacity of soil [40]. Phytoremediation is a sustainable and eco-friendly biotechnology tool which utilizes plants to reduce the environmental impact of pollutants, particularly metals and metalloids, in contaminated soils [41]. Certain hyperaccumulator plants, such as *Thlaspi caerulescens* and *Arabidopsis halleri*, can absorb high metal concentrations without toxicity, offering a cost-effective, minimally invasive alternative to conventional remediation methods [42]. Phytoremediation involves complex biochemical and physiological processes in plants. One key mechanism is chelation, where plants release organic compounds like acids or amino acids into the rhizosphere, forming soluble complexes with metal ions for easier uptake. Additionally, enzymatic activities in plants can reduce metal ions to less toxic forms, facilitating their sequestration in plant tissues [40]. Techniques such as phytoextraction (a type of phytoremediation) involves plants absorbing metals in their aerial parts for later harvesting, effective for metals like cadmium, lead, and zinc. Rhizofiltration uses plants' roots to extract metals from contaminated water, whereas phytostabilization immobilizes metals in the soil, reducing their mobility and bioavailability, with certain plants secreting compounds that bind metals in the root zone, preventing uptake by other plants and minimizing leaching into groundwater. Moreover, research on molecular mechanisms has identified key transporters and genes involved in metal uptake and accumulation, paving the way for enhancing phytoremediation efficiency and broadening its applications [42]. These studies highlight the potential of brown biotechnology in offering innovative solutions to enhance land quality, thereby promoting sustainable agricultural practices worldwide.

**Biotechnological Applications of Arid Microbes**

Life in arid zones has long been a key research focus due to the survival of organisms under extreme conditions, with microorganisms attracting significant attention for their diverse applications and crucial role in these harsh environments. Desert soils, or aridisols, are characterized by extreme dryness, low nitrogen and organic matter, and high salt and mineral content, influenced by factors such as wind erosion, temperature variations, and water scarcity. Biological soil crusts (BSCs) are a characteristic of aridisols, which consist of soil particles bound together by cyanobacteria, lichens, mosses, and fungi, cover the soil surface, enhancing stability and fertility. These crusts help prevent erosion, capture nutrient-rich dust, and improve water retention. The polysaccharide sheaths produced by BSC microbes contribute to soil cohesion. Furthermore, BSC communities enrich the soil by fixing atmospheric carbon and nitrogen, fostering microbial biomass, and promoting plant growth [43]. Cyanobacteria, the largest group of photosynthetic prokaryotes, are important sources of bioactive compounds due to their metabolic flexibility, particularly in extreme environments. Their ability to thrive in harsh conditions enables them to produce distinctive biomolecules with valuable biotechnological applications [44]. Research in Oman’s Wadi Muqshin Desert has uncovered a variety of cyanobacterial species in hypersaline crusts, which adapt to high salinity and temperatures by enhancing the desaturation of fatty acids, thereby improving membrane fluidity and stability [45]. Given that free radical damage plays a key role in many degenerative diseases, exploring the cytoprotective properties of cyanobacterial compounds could lead to the discovery of potential therapeutic agents, benefiting medicine, nutrition, and the development of sustainable pharmaceuticals [9]. Microalgae found in arid regions are also being increasingly studied for their



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potential applications in biotechnology. For instance, research has shown that *Nannochloropsis gaditana* demonstrates a higher degree of hydrolysis at thermophilic temperatures, enhancing the efficiency of organic matter degradation and subsequently increasing biogas production. This discovery could have significant biotechnological implications, particularly in areas where high temperatures inhibit the growth of mesophilic organisms, creating a need for organisms that can thrive in such conditions [46]. In Ouargla, Algeria, a study involving the cultivation of *Chlorella pyrenoidosa* in wastewater at high temperature achieved over 78% nutrient removal, showcasing its potential for wastewater treatment in arid environments [47]. Similarly, a rhodophyte species like *Chroothece*, found in Murcia, Spain, exhibited a high lipid content, particularly of omega-6 fatty acids, under intense solar radiation, demonstrating a unique lipid metabolism that highlights the adaptability of microorganisms to extreme conditions. This suggests the potential for discovering similar extremophiles in regions like the Atacama Desert, where solar radiation is even more intense [48].

Additionally, *Deschampsia antarctica*, native to Antarctica, is known for its tolerance to UV radiation and cold, with genes encoding chalcone synthase involved in the flavonoid biosynthesis pathway. Further research into these mechanisms could lead to the development of photoprotective and antifreeze compounds [49]. Research on desert plants and their resilient microbial communities, which thrive under extreme conditions of drought, heat, and salinity, has become a key focus for promoting sustainable agriculture. Advances in sequencing technologies have allowed for in-depth analysis of microbial communities across various plant compartments. For example, Na et al. [50] investigated the rhizosphere bacteria of *Caragana* shrubs in North China, uncovering dominant bacterial groups influenced by soil factors like pH and humidity. Their study found that geographic location and soil type have a stronger impact on these microbial communities than the plant genotype itself [50]. Similarly, Marasco et al. [51] discovered that desert soil conditions govern the microbial composition in *Heteropogon contortus* (dune grass), independent of the host plant's genotype [51]. These findings demonstrate that desert plants host diverse bacterial communities uniquely adapted to their specific environmental challenges. Many of these beneficial microbes have been isolated and studied for their potential to enhance plant growth and health.

**Concluding Remarks**

Brown biotechnology, traditionally defined as the use of biological resources from arid ecosystems to promote sustainable resource management, must be redefined to address challenges and promote sustainability across all terrestrial ecosystems (i.e brown bodies). This broader perspective will position brown biotechnology as a powerful tool for enhancing resource management and



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promoting environmental resilience worldwide. Arid ecosystems, which face

extreme conditions such as water scarcity, limited soil fertility, and temperature fluctuations, have long been the primary focus of brown biotechnology. However, its potential extends far beyond these regions, offering innovative solutions for improving land quality and sustainability across diverse landscapes. By utilizing natural biological processes, brown biotechnology can enhance land productivity, mitigate the effects of environmental stressors, and boost the resilience of ecosystems, all while conserving biodiversity. However, the application of brown biotechnology also comes with challenges. Balancing productivity with ecosystem conservation, addressing issues of intellectual property rights, and ensuring that biotechnological innovations are affordable and accessible to resource-limited areas are key considerations. To overcome these challenges, collaboration across sectors is essential. Interdisciplinary partnerships between academia, government, and industry will be crucial in driving innovation, scaling successful applications, and ensuring that these technologies reach the communities that need them most. Technological advancements, such as remote sensing, robotics, and data analytics, will also play a pivotal role in enhancing the effectiveness of brown biotechnology. These technologies can improve ecosystem monitoring, track the success of biotechnological interventions, and identify areas where further research is needed. By integrating these tools, we can better manage the health of terrestrial ecosystems and ensure that biotechnological solutions are implemented efficiently. Thus, brown biotechnology offers a comprehensive and innovative approach to addressing the challenges of food security, water scarcity, and climate change across all terrestrial ecosystems. By redefining brown biotechnology to encompass all "brown bodies" or terrestrial ecosystems, we unlock its full potential to promote sustainability and resilience in the face of global environmental challenges. Through continued research, interdisciplinary collaboration, and technological integration, brown biotechnology can significantly contribute to the sustainable use and management of Earth's terrestrial ecosystems.

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