Indian Forester, **149** (2) : 131-139, 2023
DOI: 10.36808/if/2023/v149i2/169800
ISSN: 0019-4816
eISSN: 2321-094X

Desertification control Using microbes:
A mini-review

Desertification is a global issue impacting millions of hectares of land worldwide. A large portion of the earth's surface comprising arid, semi-arid and hyper-arid lands has been subjected to harsh environmental conditions, such as salinity, heavy metal toxicity, soil erosion, drought and others. The survival of various life forms in these conditions has been largely affected. Therefore, timely effective interventions are necessary to tackle these global challenges. Various microbial communities have been reported to play an important role in desertification reversal. Well adapted to harsh environments, these act against a broad range of abiotic and biotic stresses. Their potential can be utilized to improve soil structure/fertility and to increase plant tolerance to several stresses. The present article discusses the research efforts made for the restoration of degraded lands using various microbial communities.

Key words: Microbes, Desertification, Land degradation, Mycorrhiza, Cyanobacteria, Fungi, Drought

Research efforts made for the restoration of degraded lands using microbial communities are discussed.

RAMKRISHNA, NITIKA NEGI, AMIT PANDEY, MANEESH S. BHANDARI AND SHAILESH PANDEY
Forest Pathology Discipline,
Forest Protection Division,
Forest Research Institute,
Dehradun, India
Email : shailesh31712@yahoo.co.in,
pandeysh@icfre.org

Received January, 2023
Accepted February, 2023

Introduction

Land is an essential resource for sustaining forests and wildlife, growing food, facilitating the natural management of water systems, and storing carbon. Biodiversity and the maintenance of the hydrological, nutrient, and carbon cycles are ecosystem services (Nachtergaele and Petri, 2013). The resulting loss of these services due to land degradation can unleash a vicious circle of environmental degradation, poverty, migration, and conflicts, in the affected countries and regions at risk. Desertification degrades the land quality and is identified as one of the greatest challenges to the environment. The United Nations Convention to Combat Desertification defines desertification as the degradation of land in arid, semi-arid, and dry sub-humid areas as a result of several factors, such as climate change and human activities (Ambalam, 2014). In the mid-nineties, scientific studies revealed that each year about 12 million hectares of land are transformed into man-made deserts (Secretary-General, U.N., 1995). Later, Adger (2000) reported that over 250 million people are directly affected due to desertification and billions of people in over 100 nations are at risk. The livelihood of more than 25% of the world's population has been affected by desertification resulting in continuing and apparent loss of vegetation coverage and bareness of soil surface (Kefi *et al.,* 2007). The current global assessment suggests that 9% of the total land is under extreme desertification risk, which is expected to rise by over 23% by the end of this century (Huang *et al.,* 2020). Desertification affected 51.7% of the South-East region in Italy (Ladisa *et al.,* 2012), 77% of the north-western region in Bangladesh (Hoque *et al.,* 2020), and about 46% of Africa (Reich *et al.,* 2019). The European Environment Agency indicated that 14 Mha, that is 8% of the territory of the European Union (mostly in Bulgaria, Cyprus, Greece, Italy, Romania, Spain, and Portugal), had a 'very high' and 'high sensitivity' to desertification (European Court of Auditors, 2018).

India is the seventh largest country in the world with 328.72 Mha area and the second-highest populated country with 1.21 billion population (Census, 2011). India is a signatory to the United Nations Convention on Combating Desertification (UNCCD) and is committed to achieving a land degradation neutral status by 2030. The Convention addresses specifically the issue of Desertification, Land Degradation, and Drought. Accordingly, Desertification and Land Degradation has been identified as one of the thrust areas by the Standing Committee on Bio-resources and Environment under the National Natural Resources Management System, (NNRMS SC-B), (SAC, 2016). The Desertification and Land Degradation Atlas of India has been developed by the Indian Space Research Organisation (ISRO), along with 19 concerned Central/State government departments and academic institutes under NNRMS SC-B. This Atlas presents Desertification /Land Degradation Status Maps depicting Land Use, Process of Degradation and Severity Level along with area statistics consolidated for the entire country as well state-wise for 2011–13 and 2003–05-time frame and reports the changes. Approximately 96.40 Mha area of the country is undergoing the process of land degradation *i.e.*, 29.32% of the Total Geographic Area (TGA) of the country during 2011–13, while during 2003–05 the area undergoing process of land degradation is 94.53 Mha (28.76% of the TGA). Analysis shows that around 23.95% (2011–13) and 23.64% (2003–05) of desertification/land degradation with respect to total TGA is contributed by Rajasthan, Maharashtra, Gujarat, Jammu and Kashmir, Karnataka, Jharkhand, Odisha, Madhya Pradesh, and Telangana in descending order (SAC, 2016). Among various factors, the salinity of the soils is one of the problems that most contribute to the degradation of the soils of the regions susceptible to desertification (Castro and Santos, 2020). Salinity-related land degradation has become a serious challenge to food and nutritional security in the developing world. High concentration of salts in the root zone soil limits the productivity of nearly 953 million ha of productive land in the world. Most of the salt-affected soils and brackish groundwater resources are confined to arid and semi-arid regions and are the causative factors for triggering the process of desertification. The problem of salinity and sodicity has degraded about 6.73 Mha area in India (Singh, 2009).

Desertification negatively affects a wide range of products and services that land provides and results in decreasing economic returns. The loss consequence of these declining returns imposes a cost on both land owners/users and society as a whole. The effects of desertification on the economy can be classified into three main categories: direct effects, which have an impact on land users; indirect effects, which may have an impact on people who live far from the site of the degradation; and economy-wide effects, which result from complex links between different economic sectors and the resulting "multiplier effect" (Low, 2013). Some of these effects are invisible or challenging to measure and may occur on or off-site. All these effects can have a significant impact on poverty and national income (Low, 2013). Given these facts, in the past few decades, researchers have devised a series of ecological restoration technologies (ERTs) and models to manage desertification, in which microbial remediation are one of the important biological ERTs. However, there is a need for newer ERTs, such as the identification and cultivation of new stress-resistant species, the generation of artificial biological crusts, and microbial soil amendments (Yunjie, 2022).

Stress Tolerance in Plants

Natural stressors (irradiance, salinity, heavy metal, temperature, frost, drought, pathogens) or anthropogenic stressors may act simultaneously leading to land degradation or desertification. Given this, finding viable approaches to reverse desertification has become such an urgent issue globally. A simple and widely accepted method of stabilizing decertified soil is planting native plants (Park, 2017a) as they have the potential to protect themselves to some measure by altering their physiological, anatomical, genetical and molecular level attributes. For instance, the harmful effects of salt stress can be shown to alleviate in plants by responding towards toxic ion uptake, ion exclusion, osmotic regulation, CO_2 assimilation, increased photosynthetic pathway, chlorophyll content and fluorescence, reactive oxygen species (ROS) generation, and antioxidant defences (Acosta-Motos, 2017). Similarly, the over-expression of stress responsive genes and proteins, such as protein kinases, transcription factors, heat shock protein (HSPs) and catalases (CAT) have been reported to help plants in reducing heat stress (Qu, 2013). Before being exposed to stresses, the plants are in a standard physiological state. The stressors start a cascade of reactions and lowers plants vitality and death may occur if the intensity of stress is too high (Lichtenthaler, 1998). However, plants develop tolerance to stress with the activation of repair system. The response of plant to various stresses and their positive or negative impacts has been comprehensively studied (Abuqamar *et al*., 2009). It is interesting to note that some plants may escape stress altogether, for instance, ephemerals (drought), psychrophiles (cold) and halophytes (salinity). The signalling pathways serve as a conduit between sensing the stress environment and producing the appropriate response (Lichtenthaler, 1998). Stress avoidance strategies include changing leaf orientation, rolling leaf blades, transpiration cooling, or modification of membrane lipid compositions (Hasanuzzaman, 2013). However, with respect to long-term defence mechanisms, studies have revealed that higher accumulation of osmotically active compounds or osmo-protectants during extreme stress led to osmotic regulation in plants, stabilizing cell membranes and proteins, thus preventing cell dehydration (Lang, 2007; Shahbaz, 2013; Filippou, 2014). Furthermore, some researchers have discussed about stress imprints in plants which enables them to retain a memory of the initial stress and responds to the future attacks accordingly. The potential mechanism proposed for the memory is accumulation of signalling proteins, transcription factors and epigenetic changes (Bruce, 2007). However, production of superoxide dismutase (SOD), peroxidase, ascorbate peroxidase, guaiacol peroxidase, glutathione-s-transferase, ascorbate, glutathione, a-tocopherol, carotenoids, catalase (CAT) and flavonoids has been reported to detoxify ROS-mediated stress (Kadioglu, 2011; Kubiś, 2014). *Populus tremula*, for instance, has been shown to reduce salt stress by accumulating various osmo-protectants (proline, spermine, sucrose, mannitol, and raffinose) as well as antioxidants (lipid peroxidases) (Jouve, 2004). Over-expression of genes responsible for production of secondary metabolites aiding in stress response is the major attribute of stress tolerance. Similar research in *P. euphratica* revealed higher SOD activity and noticeably lower malondialdehyde levels when stress responsive genes were overexpressed (Tian, 2017). Several inducible genes, which are essential for plant survival, are known to be up-regulated by a small number of specialised cell proteins, such as heat-shock proteins (HSPs). Only certain plant developmental stages, such as seed germination, embryogenesis, microsporogenesis, and fruit maturation, allow for the expression of HSPs (Hasanuzzaman, 2013). However, monotonous cultivation of the same plant species is prone to attack by diseases or pests (Park, 2017a). Further, the evaporation of trees is over 3000 mm while the annual precipitation of arid regions is generally less than 300 mm, (Jia *et al*., 2012). Hence, plants may not survive without proper management of water supply and may even drain ground water from nearby grasslands (Park, 2017a). Further, desertification reduces the inoculum potential of microbes that are one of the major factors sustaining the natural vegetation (Jeffries and Barea, 2000). Microbial communities are known to play an important role in plant ecosystems, and influence tolerance to biotic and abiotic stresses through various mechanisms, such as the induction of osmo-protectants and HSPs (Grover *et al*., 2011). Therefore, isolation and characterization of microbial communities from harsh environments and their field testing remains a possibility for controlling desertification. In the following sections, we review the research focused on inoculating native plants with beneficial bacteria and fungi that has shown promise as the best environmental practice for degraded land reclamation.

Biological Soil Crust

Among the important issues in desertification control, topsoil stability and vegetation regeneration are severely impacted by the extreme desert environmental stresses. In addition, the soil surface has never been fully covered and stabilizes due to the meagre surviving populations, and the spaces among the patchy vegetation remain a source of dust and sand (Lan, 2013). In contrast, biological soil crusts (BSCs) survive and reach maximum coverage in deserted areas due to their exceptional physiological and ecological characteristics (Belnap and Lange, 2001). In arid or semi-arid conditions, BSCs are home to a community of interacting organisms (Rossi, 2015; Antoninka, 2020). The formation of BSCs includes a multifaceted alliance among fungi (free-living, lichenized, and mycorrhizal); bacteria (cyanobacteria, chemoheterotrophic and diazotrophic (nitrogen-fixing); terrestrial algae (including diatoms); bryophytes (mosses, liverworts, and hornworts) and soil particles within the uppermost millimeters of topsoil, where the filamentous cyanobacteria first inhabit and grow, and then other organisms emerge after the stabilization of topsoil (Warren *et al*., 2021). Thus, the development of BSCs is considered to have an important role in desertification control (Lan *et al*., 2012a; Lan *et al.,* 2013a). The BSCs are crucial for ecosystems with significant levels of abiotic stresses, such as severe resource limitations (water or nutrients), geographical constraints (inadequate rooting depth), or temporal constraints (short growing seasons), high solar radiation and salinity levels (Bowker, 2007). It supports food webs by providing nutrition to micro-, meso-, and macro-organisms (Antoninka, 2020). The restoration of ecosystem function and resilience depends on the development of efficient techniques for restoring damaged drylands. Strategies to successfully grow BSCs by inoculation-based technique enable enhanced recovery rates (Bowker, 2007). For instance, an artificial cyanobacterial crust was constructed over 30 km^2 in 2010 via inoculating two mixed filamentous cyanobacteria in Dalate Banner of Inner Mongolia in 2002, which is perhaps the first and only attempt to develop an artificial cyanobacterial crust on such a large-scale worldwide (Chen *et al*., 2006; Lan *et al*., 2012b and Lan and Rossi, 2021). It is interesting to note that diverse vegetation communities were established after three years of cyanobacterial inoculation (Wang *et al*., 2009). Biotechnological approaches by applying microorganisms as soil inoculants has been regarded as a promising alternative to improve soil quality and offset soil degradation in affected areas (Bowker, 2007; Maestre *et al*., 2017; Rossi *et al*., 2017). Successful restoration of terrestrial ecosystems may be achieved by microbial inoculations (Wubs *et al*., 2016). Furnished below is a brief review on microbial inoculation based-techniques to reduce desertification.

Cyanobacterial Inoculation

Utilization of certain photoautotrophic and dinitrogen fixing organisms, such as cyanobacteria and microbial-plant symbionts, is one the promising approaches for restoring degraded arid soils and enhancing their productivity (El-Tayeb, 1989). Cyanobacteria are the oldest, gram-negative prokaryotic oxygenic phototrophs that are usually the early immigrants inhabiting almost every habitat and produces a significant level of extracellular polysaccharides, forming a biotic layer on which eventually other organisms, such as bacteria and fungi are recruited (Rossi, 2015). They can with stand extreme environmental conditions like high or low temperature, acidic or alkaline condition, salinity, low precipitation, strong irradiation, and desiccation that ultimately leads to desertification (Park, 2017a).They play a significant role due to their ability to improve surface micro-environments and increase the likelihood of colonisation and survival of later successional species by enhancing mineral chelation, dust entrapment, and nutrient fixation (Lan, 2014; Park, 2017b; Afkairin, 2021). The direct effect of application of cyanobacteria as soil conditioners includes soil stabilization and improvement, enrichment in nutrients and increase in moisture content. The first cynobacteria inoculation technology were mostly aimed to improve agricultural conditions, however more recent approaches have been found promising for land rehabilitation in arid and semiarid environments (Rossi, 2017). Development of BSCs by the application of cyanobacteria has been regarded as a novel biotechnological tool for the restoration of barren degraded areas and combating desertification in arid lands (Chamizo *et al*., 2018). Under natural conditions, the recovery times for cyanobacterial crusts are predicted to take several decades. Therefore, several researchers have proposed to artificially induce the development of cyanobacterial crusts in order to restore the function of the soil ecosystem (Acea, 2001; Hu, 2003; Bowker, 2007; Park, 2017b). In Qubqi Desert (Inner Mangolia), where desertification was quite severe, artificial cyanobacterial crusts were successfully constructed with two filamentous cyanobacteria (*Microcoleus vaginatus* and *Scytonema javanicum*) combined with Salix planting (Lan *et al*., 2013b). A few studies have commended to use a stabilizer along with the cyanobacteria for greater stability in BSCs (Zhao, 2019a; Zhao, 2019b; Lan, 2014). For instance, Zaady (2017) reported better soil stability due to cumulative effect of the filamentous cyanobacteria and fly ash. Recently, chemical methods, such as the addition of modified water-borne polyurethane and cationic poly copolymer emulsion to cyanobacteria, have been used conveniently to enhance the effectiveness of BSCs formation (Fick, 2019; Meng, 2017; Park, 2017b). In a novel approach to combat desertification in arid regions, combined application of *Nostoc* sp. *Phormidium* sp. and *Scytonema arcangeli* with Tacki-SprayTM (soil fixing agent) and superabsorbent polymer (water-holding material and nutrient supplement) remarkably improved macro-aggregate stability against water and erodibility against wind after 12 months of inoculation when compared to the control soil (Park, 2017a). A more promising approach based on nanocomposites has recently emerged as a research frontier in ecological restoration techniques (Li, 2021). Chi (2020) introduced aquatic cyanobacteria (AC) to encourage the growth of BSCs in Tengger Desert (Inner Magnolia). A network-structured nanocomposite (SXA), which showed high water-retention ability, viscosity, and biosafety, also provided a suitable microenvironment for AC and desert cyanobacteria (DC) growth. Importantly, the combination of AC and SXA effectively increased sand nutrient levels, facilitating the growth of DC and BSCs which maintained stability for at least 210 days and played a key role in stabilizing the sand surface. Importantly, large-scale cyanobacterial inoculation (*Microcoleus vaginatus* and *Scytonema javanicum*) was carried out in more than 40 km^2 in Inner Mongolia to induce BSCs development for combating desertification (Hu *et al*., 2012). Zhu *et al*., (2021) proposed a technology of cultivating sand-consolidating cyanobacterium (*S. javanicum*) in wastewater having significant potential in human settlements and desert areas. These finding suggest that cyanobacterial inoculation technology has the potential to create artificially induced BSCs to combat desertification.

Plant Growth Promoting Rhizobacterial Inoculation

Soil bacteria are extremely crucial for nutrient cycling (Uroz *et al*., 2011; Qi, 2018). For instance, ammonia and nitrate oxidising bacteria play a significant role in nitrogen cycle (De Boer and Kowalchuk, 2001; Kowalchuk and Stephen, 2001; Mursyida *et al*., 2015). Further, to withstand harsh environmental conditions, plant growth promoting rhizobacteria (PGPR) aid in the dissolution of insoluble phosphates, and other essential minerals responsible for plant growth (Bashan, 2010). As evident from previous studies, many bacterial communities remain attached to the vegetation present in harsh environment, helping them adapt to the condition by promoting growth and imparting resistance (Liu *et al*., 2014; Opelt and Berg, 2004; Spiess *et al*., 1986; Tang *et al*., 2016). The mechanism of action can be demonstrated to be the best environmental practise for recovering degraded land (He, 2020). Bacterial communities including Actinobacteria, Acidobacteria and Firmicutes are usually known to predominate in barren deserted lands as they can adapt to dry environments by going dormant, however, these genera can also produce antimicrobial substances that affect a broad range of microorganisms (Shah, 2011; Li, 2015; Sathya, 2017; Hazarika, 2020; Yan, 2021; Hayat, 2021). In Ningxia, China, members of the genera *Nitrosomonas*, *Pirellula*, and *Methylobacterium* were selected as potential indicator species to predict very severe desertification, thus providing new insights for the restoration of degraded habitats (Fan, 2020). A similar study showed predominance of Proterobacteria, Actinobacteria and Acidobacteria and a calcium-driven bacterial response mechanism that contributed to desertification process in Karst areas in China (Tang, 2019). Thus, a most common approach is the isolation of bacteria from arid or deserted areas and then inoculation to plants under harsh conditions for stress control (Cipriano, 2016; Saikia, 2018; Quoreshi, 2019; Xie, 2019; He, 2020; Astorga-Eló, 2021). For instance, among the three bacterial strains (*Acinetobacter*, *Paraburkholderia* and *Pseudomonas*) isolated from fruit tree rhizosphere soils in Karst rocky desertification region in China, *Acinetobacter* sp. Ac-14 had a sustained and stable phosphate-solubilizing ability. This strain increased the number of lateral roots, fresh weight, and chlorophyll content of *Arabidopsis thaliana*. Metabolomics analysis revealed the production of 23 types of organic acids, majorly including gluconic acid and D-(-)-quinic acid by Ac-14 (Xie *et al*., 2021). Likewise, a novel strain of *Bacillus tequilensis* CGMCC 17603 has been found to be a promising soil fixing agent to combat desertification in arid and semi-arid areas (Zhao, 2019c). Similarly, *B. amyloliquefaciens* strain GB03 and water retaining agents (super absorbent hydrogels) significantly enhanced ryegrass survival rate, biomass and chlorophyll content under deserted conditions (Su, 2017). These studies hold promise for the reversal of desertification and therefore must be replicated in other regions at risk.

Mycorrhizal Inoculation

Fungi have been regarded to play a critical role in modulating physiological processes by tolerating several stressors (Mona, 2017; Chepsergon, 2014). They can significantly affect hormone balance by altering their levels as well as through stress tolerance and resistance pathways and defend the plant from biotic and abiotic factors (Dreischhoff, 2020). Stressed plants colonized by the fungal endophytes release phytohormones (gibberellic acid, abscisic acid) and over-express genes, thereby, helping them cope harsh environment (Khan, 2013). Mycorrhizal inoculation is considered as one of the most promising methods for improving plant growth and nutrient absorption under various biotic and abiotic stresses by altering signalling pathways, plant physiology, osmotic adjustment stimulants, and antioxidant enzyme activity (Porcel and Ruiz-Lozano, 2004; Marulanda *et al*., 2006; Yooyongwech *et al*., 2013; Chen, 2014; Millar and Bennett, 2016; Zhang, 2019; Silva, 2022). Mycorrhizal fungi via stabilizing and equalizing mechanisms (soil nutrient partitioning, feedback to soil antagonists, differential mycorrhizal benefits, and nutrient trade) regulate plant establishment and species coexistence, and hence plant diversity (Tederso *et al*., 2020). Some of the most important genera of desert mycorrhizal fungi include *Acaulospora*, *Archaeospora*, *Glomus*, and *Paraglomus* (Shi *et al*., 2006). The AMF, namely *G. mosseae*, *G. etunicatum*, and *G. intradices*, which are dominant species in the desert (Shi *et al*., 2007), can be used in desertification reversal. In Gurbantunggut Desert (China), 89% of the desert ephemerals can form mutualisms with arbuscular mycorrhizal fungi (AMF) (Shi *et al*., 2006), and a sharp decline in the biomass and number of seeds produced by desert plants was observed without AMF (Sun *et al*., 2008). In a follow up study, field inoculation experiments with (AMF) conducted for three years in a central Asian desert indicated significant improvement in the biomass, density, and cover of ephemerals. Importantly, a significant increase in the community productivity revealed that AMF inoculations can be used as an effective biological approach to restore degraded desert ephemeral plant communities (Zhang *et al*., 2012). Importantly, AMF infection significantly increased ephemeral plant growth and biomass, and significantly influenced ecosystem respiration and methane flux in a field control experiment conducted in the Gurbantunggut Desert (Yue *et al*., 2020). In Karst rocky desertification area in China, inoculation of mulberry saplings with *Gigaspora rosea* showed an increase in height, stem diameter, leaf area, leaf number, fibrous roots and shoots and roots biomass, chlorophyll content, net photosynthetic rate, transpiration rate, and stomatal conductance (Chen *et al*., 2014). In the Karst regions of China, before afforestation under drought stress, the growth of AMF has been observed in inoculated plants (Wang *et al*., 2012)

Importantly, significant growth promotion of *C. migao* seedlings was observed after inoculation with *G. lamellosum* and *G. etunicatum*. Further, root colonization with *G. lamellosum* or *G. etunicatum* had lowered the of malondialdehyde accumulation and increased the accumulation of enzymes, osmotic substances and water content in drought-stressed seedlings in Karst soil (Liao *et al*., 2021). More recently, in Karst regions, inoculation with AMF (*G. etunicatum* and *F. mosseae*) positively affected the growth and root vigor of *Cinnamomum migao* under drought stress by upregulating antioxidant enzyme activities and osmotic adjustment substances. The stimulatory effect of *G. etunicatum* was found to be more efficient as compared to *F. mosseae* and provides a strategy to prevent rocky desertification in Karst ecosystems (Xiao *et al*., 2022). Moreover, an interaction of AMF *Claroideoglomu setunicatum* with Earthworm (*Amynthas divergens yunnanensis*) had a greater potential in increasing plant growth via the complementary and dynamic mechanisms of on amending nutrient supply in nutrient-poor Karst stony desertification land (Li, 2019). Interestingly, soil treatment with biopolymers obtained from a fungus (*Aureobasidium pullulans*) offers a unique possibility of desertification control (Chang, 2015).

Conclusion

This paper summarizes the research conducted on desertification control by the application of microbes, including cyanobacteria, PGPR and mycorrhiza. However, it is necessary to first understand the diversity of microbes in unexplored deserted areas, their testing for stress tolerance and devising suitable inoculation strategies for the effective desertification management. Development of a consortium of fungal and bacterial strains seems to be more promising against salinity, drought, and other factors contributing to land degradation. Application of biocontrol agents that also act as a plant growth promoter (especially *Trichoderma* species) has also been reported to alleviate abiotic stress (salinity and drought) in agricultural crops. Therefore, identification of these fascination fungi from harsh environment, their testing and further application in degraded lands may contribute to better vegetation growth and development.

सूक्ष्मजीवों का उपयोग कर मरुस्थलीकरण नियंत्रण : एक छोटी समीक्षा

रामकृष्ण, नीतिका नेगी, अमित पांडेय, मनीष एस. भंडारी और शैलेश पांडेय

सारांश

मरुस्थलीकरण एक वैश्विक मुद्दा है, जो दुनिया भर में लाखों हेक्टेयर भूमि को प्रभावित करता है। पृथ्वी की सतह का एक बड़ा हिस्सा जिसमें शुष्क, अर्ध-शुष्क और अति शुष्क भूमि शामिल है, कठोर पर्यावरणीय परिस्थितियों, जैसे पानी की कमी, लवणता, भारी धातु विषाक्तता, मिट्टी के कटाव जैसी समस्यायों के अधीन है। इन स्थितियों में विभिन्न जीवन रूपों का अस्तित्व काफी हद तक प्रभावित हुआ है। इसलिए, इन वैश्विक चुनौतियों से निपटने के लिए समय पर प्रभावी हस्तक्षेप आवश्यक है। मरुस्थलीकरण उत्क्रमण में विभिन्न सूक्ष्मजीवी समुदायों की महत्वपूर्ण भूमिका है। कठोर वातावरण के लिए अच्छी तरह से अनुकूलित, ये अजैविक और जैविक तनावों की एक विस्तृत श्रृंखला के खिलाफ कार्य करते हैं। इनकी क्षमता का उपयोग मिट्टी की संरचना/उर्वरता में सुधार करने और कई तनावों के लिए पौधों की सहनशीलता बढ़ाने के लिए किया जा सकता है। वर्तमान लेख में विभिन्न सूक्ष्मजीवी समुदायों का उपयोग करके मरुस्थलीय क्षेत्रों की बहाली के लिए किए गए शोध प्रयासों पर चर्चा की गई है।

References

AbuQamar S., Luo H., Laluk K., Mickelbart M.V. and Mengiste T. (2009). Crosstalk between biotic and abiotic stress responses in tomato is mediated by the AIM1 transcription factor. *The Plant Journal*, **58**(2): 347–360.

Acea M.J., Diz N. and Prieto-Fernandez A. (2001). Microbial populations in heated soils inoculated with cyanobacteria. *Biology and Fertility of Soils*, **33**(2): 118–125.

Acosta-Motos J.R., Ortuño M.F., Bernal-Vicente A., Diaz-Vivancos P., Sanchez-Blanco M. J. and Hernandez J.A. (2017). Plant responses to salt stress: adaptive mechanisms. *Agronomy*, **7**(1): 18.

Adger W.N., Benjaminsen T.A., Brown K., and Svarstad H. (2000). Advancing a political ecology of global environmental discourses. *Development and change*, **32**(4): 681–715.

Afkairin A., Ippolito J.A., Stromberger M. and Davis J.G. (2021). Solubilization of organic phosphorus sources by cyanobacteria and a commercially available bacterial consortium. *Applied Soil Ecology*, https://doi.org/10.1016/j.apsoil.2021.103900.

Ambalam K. (2014). United Nations Convention to Combat Desertification: Issues and Challenges. *E-Int. Rel*, **1**–15.

Antoninka A., Faist A., Rodriguez-Caballero E., Young K.E., Chaudhary V.B., Condon L.A. and Pyke D.A. (2020). Biological soil crusts in ecological restoration: emerging research and perspectives. *Restoration Ecology*, **28**: S3-S8.

Astorga-Eló M., Gonzalez S., Acuña J.J., Sadowsky M.J. and Jorquera M.A. (2021) Rhizobacteria from 'flowering desert' events contribute to the mitigation of water scarcity stress during tomato seedling germination and growth. *Scientific Reports*, https://doi.org/10.1038/s41598-021-93303-8

Bashan Y. and de-Bashan L.E. (2010). Microbial populations of arid lands and their potential for restoration of deserts. In: *Soil biology and agriculture in the tropics* (pp. 109–137). Springer, Berlin, Heidelberg.

Belnap J. (2001). Biological soil crusts: structure, function, and management (pp. 241–261). O. L. Lange (Ed.). Berlin: Springer.

Bowker M.A. (2007). Biological soil crust rehabilitation in theory and practice: an underexploited opportunity. *Restoration Ecology*, **15**(1): 13–23.

Bruce T.J., Matthes M.C., Napier J.A. and Pickett J.A. (2007). Stressful "memories" of plants: evidence and possible mechanisms. *Plant science*, **173**(6): 603–608.

Castro F.C. and Santos A.M.D. (2020). Salinity of the soil and the risk of desertification in the Semiarid region. Mercator (Fortaleza), **19**(1): 1–14.

Census of India and DoCOi Orissa. (2011). Census of India 2011, Odisha, District Census Handbook, Kendujhar, Village and Town Wise Primary Census Abstract (PCA).

Chamizo S., Mugnai G., Rossi F., Certini G. and De Philippis R. (2018). Cyanobacteria inoculation improves soil stability and fertility on different textured soils: gaining insights for applicability in soil restoration. *Frontiers in Environmental Science*, **6**: 1–14.

Chang I., Prasidhi A.K., Im J., Shin H-D. and Cho G-C (2015). Soil treatment using microbial biopolymers for anti-desertification purposes. *Geoderma*, **253**: 39-47.

Chen K., Shi S.M., Yang X.H. and Huang X.Z. (2014). Contribution of arbuscular mycorrhizal inoculation to the growth and photosynthesis of mulberry in karst rocky desertification area. In Applied Mechanics and Materials (Vol. 488, pp. 769–773). Trans Tech Publications Ltd.

Chen L., Xie Z., Hu C., Li D., Wang G. and Liu Y. (2006). Man-made desert algal crusts as affected by environmental factors in Inner Mongolia, China. *Journal of Arid Environments*, **67**(3): 521–527.

Chepsergon J., Mwamburi L. and Kassim M.K. (2014). Mechanism of drought tolerance in plants using *Trichoderma* spp. *International Journal of Science and Research*, **3**(11): 1592–1595.

Chi Y., Li Z., Zhang G., Zhao L., Gao Y., Wang D. and Wu Z. (2020). Inhibiting desertification using aquatic cyanobacteria assisted by a nanocomposite. *ACS Sustainable Chemistry and Engineering*, **8**(8): 3477–3486.

Cipriano M.A.P., Lupatini M., Lopes-Santos L., da Silva M.J., Roesch L.F.W., Destéfano S.A.L., Freitas S.S. and Kuramae E.E. (2016). Lettuce and rhizosphere microbiome responses to growth promoting *Pseudomonas* species under field conditions. FEMS *Microbiology Ecology*, **92**, https://doi.org/10.1093/femsec/fiw197.

De Boer W. and Kowalchuk G. (2001). Nitrification in acid soils: micro-organisms and mechanisms. *Soil Biology and Biochemistry,* **33**: 853–866.

Dreischhoff S., Das I.S., Jakobi M., Kasper K. and Polle A. (2020). Local responses and systemic induced resistance mediated by ectomycorrhizal fungi. *Frontiers in Plant Science, 11*, https://doi.org/10.3389/fpls.2020.590063.

El-Tayeb O.M. and Skujinš J. (1989). Introduction: Potential of biological processes in desertification control. *Arid Land Research and Management*, **3**(2): 91–98.

European Court of Auditors (ECA) (2018). Desertfication in Europe. Backgroundpaper, European Court of Auditors, Luxembourg, 15 pp.

Fan M., Li J., Tang Z. and Shangguan Z. (2020). Soil bacterial community succession during desertification in a desert steppe ecosystem. *Land Degradation and Development,* **31**(13): 1662–1674.

Fick S.E., Barger N.N. and Duniway M.C. (2019). Hydrological function of rapidly induced biocrusts. *Ecohydrology*, **12**(4), https://doi.org/10.1002/eco.2089

Filippou P., Bouchagier P., Skotti E. and Fotopoulos V. (2014). Proline and reactive oxygen/nitrogen species metabolism is involved in the tolerant response of the invasive plant species *Ailanthus altissima* to drought and salinity. *Environmental and Experimental Botany*, **97**: 1–10.

Grover M., Ali S.Z., Sandhya V., Rasul A. and Venkateswarlu B. (2011). Role of microorganisms in adaptation of agriculture crops to abiotic stresses. *World Journal of Microbiology and Biotechnology,* **27**(5): 1231–1240.

Hasanuzzaman M., Nahar K., Alam M.M., Roychowdhury R. and Fujita M. (2013). Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. *International Journal of Molecular Sciences*, **14**(5): 9643–9684.

Hayat S., Ashraf A., Aslam B., Asif R., Muzammil S., Zahoor M.A. and Sabir S. (2021). Actinobacteria: potential candidate as plant growth promoters. *Plant Stress Physiology,* https://doi.org/10.5772/intechopen.93272.

Hazarika S.N. and Thakur D. (2020). Actinobacteria. In Beneficial Microbes in Agro-Ecology (pp. 443–476). Academic Press.

He M. (2020). Evaluation of potential contribution of plant growth-promoting bacteria to land desertification. In *E3S Web Conference*, https://doi.org/10.1051/e3sconf/20201652013.

Hoque S.N.M., Ahmed M.M.M. and Bhuiyan M.I. (2019). Investigating rapid deforestation and carbon dioxide release in Bangladesh using geospatial information from remote sensing data. *Ecocycles*, **5**(2): 97–105.

Hu C.X. and Liu Y.D. (2003). Primary succession of algal community structure in desert soil. *Acta Botanica Sinica*, https://hdl.handle.net/1807/1945.

Hu C., Gao K. and Whitton B.A. (2012). Semi-arid regions and deserts. *Ecology of Cyanobacteria II: their diversity in space and time*, **345**–369.

Huang J., Zhang G., Zhang Y., Guan X., Wei Y. and Guo R. (2020). Global desertification vulnerability to climate change and human activities. *Land Degradation and Development,* **31**(11): 1380–1391.

Hussain Wani S., Brajendra Singh N., Haribhushan A. and Iqbal Mir J. (2013). Compatible solute engineering in plants for abiotic stress tolerance-role of glycine betaine. *Current genomics*, **14**(3): 157–165.

Jeffries P. and Barea J.M. (2000). Arbuscular mycorrhiza:A key component of sustainable plant-soil ecosystems. In: B. Hock (Ed.), The Mycota. IX Fungal Associations (pp. 95–113). Berlin: SpringerVerlag. http://dx.doi.org/10.1007/978-3-662-07334-6_6.

Jia R.L., Li X.R., Liu L.C., Gao Y.H. and Zhang X.T. (2012). Differential wind tolerance of soil crust mosses explains their micro-distribution in nature. *Soil Biology and Biochemistry*, **45**: 31–39.

Jouve L., Hoffmann L. and Hausman J.F. (2004). Polyamine, carbohydrate, and proline content changes during salt stress exposure of aspen (*Populus tremula* L.): involvement of oxidation and osmoregulation metabolism. *Plant Biology*, **7**(01): 74–80.

Kadioglu A., Saruhan N., Sağlam A., Terzi R. and Acet T. (2011). Exogenous salicylic acid alleviates effects of long-term drought stress and delays leaf rolling by inducing antioxidant system. *Plant Growth Regulation*, **64**(1): 27–37.

Kéfi S., Rietkerk M., Alados C.L., Pueyo Y., Papanastasis V.P., ElAich A. and De Ruiter P.C. (2007). Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature*, **449**(7159): 213–217.

Khan A.L., Waqas M., Khan A.R., Hussain J., Kang S.M., Gilani S.A. and Lee I.J. (2013). Fungal endophyte *Penicillium janthinellum* LK5 improves growth of ABA-deficient tomato under salinity. *World Journal of Microbiology and Biotechnology,* **29**(11): 2133–2144.

Kowalchuk G.A. and Stephen J.R. (2001). Ammonia-oxidizing bacteria: a model for molecular microbial ecology. *Annual Review of Microbiology,* **55**: 485–529.

Kubiś J., Floryszak-Wieczorek J. and Arasimowicz-Jelonek M. (2014). Polyamines induce adaptive responses in water deficit stressed cucumber roots. *Journal of Plant Research*, **127**(1): 151–158.

Ladisa G., Todorovic M. and Liuzzi G.T. (2012). A GIS-based approach for desertification risk assessment in Apulia region, SE Italy. *Physics and Chemistry of the Earth, Parts a/B/C*, **49,** 103–113.

Lan S. and Rossi F. (2021). Combination of Chemical and Cyanobacterial Inoculation Promotes Biocrust Development: A Novel Perspective for Combating Desertification. *ACS Sustainable Chemistry and Engineering*, **9**(29): 9506–9507.

Lan S., Wu L., Zhang D. and Hu C. (2012a). Composition of photosynthetic organisms and diurnal changes of photosynthetic efficiency in algae and moss crusts. *Plant and Soil*, **351**: 325–336.

Lan S., Wu L., Zhang D. and Hu C. (2012b). Successional stages of biological soil crusts and their microstructure variability in Shapotou region (China). *Environmental Earth Sciences*, **65**: 77–88.

Lan S., Wu L., Zhang D. and Hu C. (2013a). Assessing level of development and successional stages in biological soil crusts with biological indicators. *Microbial Ecology*, **66**: 394–403.

Lan S., Zhang Q., Wu L., Liu Y., Zhang D. and Hu C. (2013b). Artificially accelerating the reversal of desertification: cyanobacterial inoculation facilitates the succession of vegetation communities. *Environmental Science and Technology*, **48**(1): 307–315.

Lan S., Zhang Q., Wu L., Liu Y., Zhang D. and Hu C. (2014). Artificially accelerating the reversal of desertification: cyanobacterial inoculation facilitates the succession of vegetation communities. *Environmental Science & Technology*, **48**(1): 307–315.

Lang F. (2007). Mechanisms and significance of cell volume regulation. *Journal of the American college of nutrition*, http://dx.doi.org/10.1080/07315724.2007.10719667.

Li Y., Chen L. and Wen H. (2015). Changes in the composition and diversity of bacterial communities 13 years after soil reclamation of abandoned mine land in eastern China. *Ecological Research*, **30**: 357–366.

Li Y., Wang S., Lu M., Zhang Z., Chen M., Li S. and Cao R. (2019). Rhizosphere interactions between earthworms and arbuscular mycorrhizal fungi increase nutrient availability and plant growth in the desertification soils. *Soil and Tillage Research,* **186**: 146–151.

Li Z., Chen C., Gao Y., Wang B., Wang D., Du Y. and Cai D. (2021). Synergistic effect of cyanobacteria and nano-sand-stabilizer on biocrust formation and sand fixation. *Journal of Environmental Chemical Engineering*, https://doi.org/10.1016/j.jece.2020.104887.

Liao X., Chen J., Guan R., Liu J. and Sun Q. (2021). Two arbuscular mycorrhizal fungi alleviates drought stress and improves plant growth in *Cinnamomum migao* seedlings. *Mycobiology*, **49**(4): 396–405.

Lichtenthaler H.K. (1998). The stress concept in plants: an introduction. *Annals of the New York Academy of sciences*, **851**: 187–198.

Liu X.L., Liu S.L., Liu M., Kong B.H., Liu L. and Li Y.H. (2014). A primary assessment of the endophytic bacterial community in a xerophilous moss (*Grimmiamontana*) using molecular method and cultivated isolates. *Brazilian Journal of Microbiology,* **45**(1): 165–173.

Low P.S. (2013). Economic and social impacts of desertification, land degradation and drought. White paper I. UNCCD 2nd scientific conference, prepared with the contributions of an international group of scientists.

Maestre F.T., Sole R. and Singh B.K. (2017). Microbial biotechnology as a tool to restore degraded drylands. *Microbial biotechnology*, **10**(5): 1250–1253.

Marulanda A., Barea J.M. and Azcón R. (2006). An indigenous drought-tolerant strain of glomus intraradices associated with a native bacterium improves water transport and root development in *Retama sphaerocarpa*. *Microbial Ecology,* **52**: 670–678.

Meng X., Liang L. and Liu B. (2017). Synthesis and sand-fixing properties of cationic poly (vinyl acetate-butyl acrylate-2-hydroxyethyl acrylate-DMC) copolymer emulsions. *Journal of Polymers and the Environment*, **25**(2): 487–498.

Millar N.S. and Bennett A.E. (2016). Stressed out symbiotes: hypotheses for the infuence of abiotic stress on arbuscular mycorrhizal fungi. *Oecologia,* **182**: 625–641.

Mona S.A., Hashem A., Abd Allah E.F., Alqarawi A.A., Soliman D.W.K., Wirth S., and Egamberdieva D. (2017). Increased resistance of drought by Trichoderma harzianum fungal treatment correlates with increased secondary metabolites and proline content. *Journal of integrative agriculture*, **16**(8): 1751–1757.

Mursyida E., Mubarik N.R. and Tjahjoleksono A. (2015). Selection and identification of phosphate-potassium solubilizing bacteria from the area around the limestone mining in Cirebon quarry. *Research Journal of Microbiology,* **10**: 270–279.

Nachtergaele F and Petri M. (2013). Mapping Land Use Systems at global and regional scales for Land Degradation Assessment Analysis. Land degradation assessment in drylands. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/i3242e/i3242e.pdf

Opelt K. and Berg G. (2004). Diversity and antagonistic potential of bacteria associated with bryophytes from nutrient-poor habitats of the Baltic Sea coast. *Applied and environmental microbiology,* **70**(11): 6569–6579.

Park C.H., Li X.R., Jia R.L. and Hur J.S. (2017b). Combined application of cyanobacteria with soil fixing chemicals for rapid induction of biological soil crust formation. *Arid Land Research and Management*, **31**(1): 81–93.

Park C.H., Li X.R., Zhao Y., Jia R.L. and Hur J.S. (2017a). Rapid development of cyanobacterial crust in the field for combating desertification. *PLoS One*, https://doi.org/10.1371/journal.pone.0179903.

Porcel R. and Ruiz-Lozano J.M. (2004). Arbuscular mycorrhizal influence on leaf water potential, solute accumulation, and oxidative stress in soybean plants subjected to drought stress. *Journal of experimental botany,* **55**(403): 1743–1750.

Qi D., Wieneke X., Tao J., Zhou X. and Desilva U. (2018). Soil pH is the primary factor correlating with soil microbiome in karst rocky desertification regions in the Wushan County, Chongqing, China. *Frontiers in microbiology,* https://doi.org/10.3389/fmicb.2018.01027.

Qu A.L., Ding Y.F., Jiang Q. and Zhu C. (2013). Molecular mechanisms of the plant heat stress response. *Biochemical and biophysical research communications*, **432**(2): 203–207.

Quoreshi A.M., Suleiman M.K., Manuvel A.J., Sivadasan M.T., Jacob S. and Thomas R. (2019). Biofertilizers for Agriculture and Reclamation of Disturbed Lands: An Eco-friendly Resource for Plant Nutrition. *Journal of Mechanics of Continua and Mathematical Sciences*, https://doi.org/10.26782/jmcms.spl.4/2019.11.00023

Reich P.F., Numbem S.T., Almaraz R.A. and Eswaran H. (2019). Land resource stresses and desertification in Africa. In: *Response to Land Degradation* (pp. 101–116). CRC Press.

Rossi F., Li H., Liu Y. and De Philippis R. (2017). Cyanobacterial inoculation (cyanobacterisation): perspectives for the development of a standardized multifunctional technology for soil fertilization and desertification reversal. *Earth-Science Reviews*, **171**: 28–43.

Rossi F., Olguín E.J., Diels L. and De Philippis R. (2015). Microbial fixation of CO2 in water bodies and in drylands to combat climate change, soil loss and desertification. *New biotechnology*, **32**(1): 109–120.

SAC I. (2016). Desertification and land degradation atlas of India (Based on IRS AWiFS data of 2011-13 and 2003-05). *Ahmedabad: Space Applications Centre, ISRO, Ahmedabad, India*, *219*.

Saikia J., Sarma R.K., Dhandia R., Yadav A., Bharali R., Gupta V.K. and Saikia R. (2018). Alleviation of drought stress in pulse crops with ACC deaminase producing rhizobacteria isolated from acidic soil of Northeast India. *Scientific reports*, **8**(1): 1–16.

Sathya A., Vijayabharathi R. and Gopalakrishnan S. (2017). Plant growth-promoting actinobacteria: a new strategy for enhancing sustainable production and protection of grain legumes. *3 Biotech,* **7**(2): 1–10.

Secretary-General U.N. (1995). Elaboration of an international convention to combat desertification in those countries experiencing serious drought and/or desertification, particularly in Africa: note/by the Secretary-General.

Shah V., Shah S., Kambhampati M.S., Ambrose J., Smith N. and Dowd S.E. (2011). Bacterial and archaea community present in the Pine Barrens Forest of Long Island, NY: unusually high percentage of ammonia oxidizing bacteria. *PLoS One,* https://doi.org/*10.1371/journal.pone.0026263*.

Shahbaz M., Mushtaq Z., Andaz F. and Masood A. (2013). Does proline application ameliorate adverse effects of salt stress on growth, ions and photosynthetic ability of eggplant (*Solanum melongena* L.)? *Scientia Horticulturae*, **164**: 507–511.

Shi Z.Y., Feng G., Christie P. and Li X. L. (2006). Arbuscular mycorrhizal status of spring ephemerals in the desert ecosystem of Junggar Basin, China. *Mycorrhiza*, **16**: 269–275.

Shi Z.Y., Zhang L.Y., Li X.L., Feng G., Tian C.Y. and Christie P. (2007). Diversity of arbuscular mycorrhizal fungi associated with desert ephemerals in plant communities of Junggar Basin, northwest China. *Applied Soil Ecology*, **35**(1): 10–20.

Silva D.F., Moreira J.V., de Sousa L.I.S., Santana M.C., Mota J.C.A., dos Santos Queiroz A. and de Araujo Pereira A.P. (2022). Arbuscular mycorrhizal fungi community in soils under desertification and restoration in the Brazilian semiarid. *Microbiological Research,* https://doi.org/10.1016/j.micres.2022.127161.

Singh G. (2009). Salinity-related desertification and management strategies: Indian experience. *Land Degradation and Development*, **20**(4): 367–385.

Spiess L.D., Lippincott B.B. and Lippincott J.A. (1986). Specificity of moss response to moss-associated bacteria—some influences of moss species, habitat, and locale. *Botanical Gazzette,* **147**(4): 418–424.

Su A.Y., Niu S.Q., Liu Y.Z., He A.L., Zhao Q., Paré P.W. and Zhang J.L. (2017). Synergistic effects of *Bacillus amyloliquefaciens* (GB03) and water retaining agent on drought tolerance of perennial ryegrass. *International journal of molecular sciences*, https://doi.org/10.3390/ijms18122651.

Sun Y., Li X.L. and Feng G. (2008). Effect of arbuscular mycorrhizal colonization on ecological functional traits of ephemerals in the Gurbantonggut desert. *Symbiosis*, **46**: 121–127.

Tang J.Y., Ma J., Li X.D. and Li Y.H. (2016). Illumina sequencing-based community analysis of bacteria associated with different bryophytes collected from Tibet, China. *BMC microbiology*, **16**(1): 1–15.

Tang J., Tang X., Qin Y., He Q., Yi Y. and Ji Z. (2019). Karst rocky desertification progress: Soil calcium as a possible driving force. *Science of The Total Environment*, **649**: 1250–1259.

Tedersoo L., Bahram M. and Zobel M. (2020). Plant-soil feedbacks and mycorrhizal type influence temperate forest population dynamics. *Science*, https://doi.org/10.1126/science.aai8212.

Tian Q., Chen J., Wang D., Wang H.L., Liu C., Wang S. and Yin W. (2017). Overexpression of a Populus euphratica CBF4 gene in poplar confers tolerance to multiple stresses. *Plant Cell, Tissue and Organ Culture,* **128**: 391–407.

Uroz S., Oger P., Lepleux C., Collignon C., Frey-Klett P. and Turpault M.P. (2011). Bacterial weathering and its contribution to nutrient cycling in temperate forest ecosystems. *Research in microbiology*, **162**(9): 820–831.

Wang W., Liu Y., Li D., Hu C. and Rao B. (2009). Feasibility of cyanobacterial inoculation for biological soil crusts formation in desert area. *Soil Biology and Biochemistry*, **41**(5): 926–929.

Wang J.H., Zhang W.X., Lai G.L., Zhao Y.B., Li B., Zhang L.P. and Xiong Z. (2012). Effect of *Rhizobium* inoculation on growth of stony desertification-grown white clover (*Trifolium*) by *Rhizobium* sp. SWFU27, SWFU29. *Advanced Materials Research*, 2416–2421.

Warren S.D., Rosentreter R. and Pietrasiak N. (2021). Biological soil crusts of the Great Plains: A review. *Rangeland Ecology and Management*, **78**: 213–219.

Wubs E.R., Van Der Putten W.H., Bosch M. and Bezemer T.M. (2016). Soil inoculation steers restoration of terrestrial ecosystems. *Nature plants*, **2**(8) : 1–5.

Xiao X., Chen J., Liao X., Yan Q., Liang G., Liu J., Gelin L., Liu Jiming, Deng W., and Guan R. (2022). Different arbuscular mycorrhizal fungi established by two inoculation methods improve growth and drought resistance of *Cinnamomum migao* seedlings differently. *Biology*, **11**(2):1–19.

Xie J., Xue W., Li C., Yan Z., Li D., Li G. and Chen D. (2019). Water-soluble phosphorus contributes significantly to shaping the community structure of rhizospheric bacteria in rocky desertification areas. *Scientific reports*, **9**(1): 1–11.

Xie J., Yan Z., Wang G., Xue W., Li C., Chen X. and Chen D. (2021). A bacterium isolated from soil in a Karst rocky desertification region has efficient phosphate-solubilizing and plant growth promoting ability. *Frontiers in microbiology*, https://doi.org/10.3389/fmicb.2020.625450.

Yan B., Liu N., Liu M., Du X., Shang F. and Huang Y. (2021). Soil actinobacteria tend to have neutral interactions with other co-occurring microorganisms, especially under oligotrophic conditions. *Environmental Microbiology,* **23**(8): 4126–4140.

Yooyongwech S., Phaukinsang N., Cha-um S. and Supaibulwatana K. (2013) Arbuscular mycorrhiza improved growth performance in *Macadamia tetraphylla* L. grown under water deficit stress involves soluble sugar and proline accumulation. Journal of *Plant Growth Regulation,* **69**: 285–293

Yue P., Cui X., Zuo X., Li K., Wang S., Jia Y. and Liu X. (2020). The contribution of arbuscular mycorrhizal fungi to ecosystem respiration and methane flux in an ephemeral plants-dominated desert. *Land Degradation and Development*, **32**(4): 1844–1853.

Yunjie W., Lin Z. and Bingzhen D. (2022). The Evolution of Desertification Control and Restoration Technology in Typical Ecologically Vulnerable Regions. Journal of Resources and Ecology, **13**(5): 775–785.

Zaady E., Katra I., Barkai D., Knoll Y. and Sarig S. (2017). The coupling effects of using coal fly-ash and bio-inoculant for rehabilitation of disturbed biocrusts in active sand dunes. *Land Degradation and Development*, **28**(4): 1228–1236.

Zhang T., Sun Y., Shi Z. and Feng G. (2012). Arbuscular mycorrhizal fungi can accelerate the restoration of degraded spring grassland in Central Asia. *Rangeland ecology and management*, **65**(4): 426–432.

Zhang Z., Zhang J., Xu G., Zhou L. and Li Y. (2019). Arbuscular mycorrhizal fungi improve the growth and drought tolerance of *Zenia insignis* seedlings under drought stress. *New Forests,* **50**(4): 593–604.

Zhao L., Li X., Wang Z., Qi J., Zhang W., Wang Y. and Liu Y. (2019c). A new strain of *Bacillus tequilensis* CGMCC 17603 isolated from biological soil crusts: A promising sand-fixation agent for desertification control. *Sustainability*, https://doi.org/10.3390/su11226501.

Zhao Y. and Wang J. (2019a). Mechanical sand fixing is more beneficial than chemical sand fixing for artificial cyanobacteria crust colonization and development in a sand desert. *Applied Soil Ecology*, **140**: 115–120.

Zhao Y., Jia R.L. and Wang J. (2019b). Towards stopping land degradation in drylands: Water-saving techniques for cultivating biocrusts in situ. *Land Degradation and Development*, **30**(18): 2336–2346.

Zhu Q., Wu L., Li G., Li X., Zhao C., Du C. and Zhang L. (2021). A novel of transforming wastewater pollution into resources for desertification control by sand-consolidating cyanobacteria, *Scytonema javanicum*. *Environmental Science and Pollution Research*, **28**: 13861–13872.

Acknowledgement

The authors are thankful to the Indian Council of Forestry Research and Education, Dehradun for support. The fourth author acknowledge the financial support by the Compensatory Afforestation Fund Management and Planning Authority CAMPA, Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India, New Delhi 75/2019/ICFRE (R)/RP/SFRESPE (CAMPA)/AICRP-24/Main File/43, dated 10th January 2020.