Chapter 8
Biochar Coupled Rehabilitation of Cyanobacterial Soil Crusts: A Sustainable Approach in Stabilization of Arid and Semiarid Soils

Arun Kumar and Jay Shankar Singh

Abstract Cyanobacterial soil crusts (CSCs) are unique microhabitats in desert soil plays a significant role in stabilization of soil surface and provide favourable conditions for the establishment of vascular plants. The CSCs types and its distribution mainly depend up on the locality and climatic factors of the region. They help in retaining soil particles, nutrients, moisture and also add up carbon and nitrogen to the nutrient poor soils. The natural or anthropogenic intervention exerted immense pressure on the crusts community and diversity; leads to disturbed or distressed CSCs. Currently military use of the deserts have destroyed the fragile ecology of these CSCs and delay the time of recovery to reach functional state. To stabilize and rehabilitate the disturbed CSCs, a number of strategies successfully tested and implemented in small scale, some of them are artificial stabilization, resource augmentation and cyanobacterial inoculants. Biochar coupled rehabilitation of CSCs could be effective and sustainable approach for the stabilization of desert soils. Small scale biochar production would be helpful not only reducing the cost of rehabilitation but also help in providing livelihood to the local people.

Keywords Desert soils · Cyanobacterial soil crusts · Rehabilitation · Biochar

A. Kumar
Department of Environmental Science, Guru Nanak Khalsa College, Yamuna Nagar, Haryana, India

J. S. Singh (✉)
Department of Environmental Microbiology, Babasaheb Bhimrao Ambedkar University, Lucknow, Uttar Pradesh, India

J. S. Singh, C. Singh (eds.), *Biochar Applications in Agriculture and Environment Management*, https://doi.org/10.1007/978-3-030-40997-5_8

8.1 Introduction

The deserts are seems to lifeless and unproductive landscapes, as they have arid soils, harsh environment and very sparse vegetation. But they have unique soil surface structure known as cyanobacterial soil crusts (CSCs) that can occur on the surface or just below the surface of soils. Belnap and Gardner (1993) observed that CSCs includes primarily a number of communities such as cyanobacteria, green algae, lichens and mosses which exudates sticky extracellular polysaccharide, helps in binding of soil particles; leads to formation of intimate and living covering on the soil surface.

The CSCs often spread over as the living ground cover in hot, cool, and cold deserts. Further the CSCs can also found in temperate conditions like either in Pine Barrens or vacant area due to reduced plant cover (Belnap and Lange 2003). They play an important role in stabilizing the mobile sand dunes and helps in prevention of soil erosion by water and wind (Danin 1978). They further influence the capture, runoff, infiltration and percolation of rainfall water; improves the water-holding capacity and soil moisture content (Belnap 2003a, b, 2006).

There are various factors such as climate change and human intervention which adversely affected the composition and diversity of crust communities. Nowadays military use of deserts increased the further pressure on already distressed crusts, leads to complete destruction of CSCs. There is also risk of invasion of annual exotic grasses, which increased the chances of summer fires, leads to destruction of crusts. For the rehabilitation and fast recovery of CSCs, mainly three strategies i.e. artificial soil stabilizer, inoculation of cyanobacteria and addition of soil amendments, investigated in a number of studies.

Biochar coupled rehabilitation of CSCs could be a sustainable and feasible method for the stabilization of arid and semiarid soils. Biochar proved to be a very useful soil amendment in agriculture; it not only helps in improving the cation exchange capacity, pH, nutrient contents, plant growth, but also helps in reduction of greenhouse gas (GHG) emissions from the agricultural soils. Further small scale biochar production in regional level could help in better management of arid soils and also supports local livelihood.

This chapter gives a brief account on the structure and formation of CSCs in desert soil conditions and their role in maintaining and regulations of desert ecosystem functions. There are some factors that affecting the CSCs and the strategies for protection and rehabilitation of these CSCs. Further a biochar inoculation based method also discussed for the sustainable and effective approach for the rehabilitation of cyanobacterial soil crusts.

8.2 Cyanobacterial Soil Crusts (CSCs)

Cyanobacterial or biological desert crusts are quite unique and ecological significant microhabitats in the soil of arid areas (Belnap and Lange 2003). These cohesive surface formations on topsoil are mainly started with filamentous growth of cyanobacteria; and consequently expanded through periodic events of moisture availability and capturing mineral particles, either by cyanobacterial filaments or by extracellular slime secreted by cyanobacteria (Belnap and Gardner 1993; Cameron and Blank 1966; Johansen 1993). There would be further succession of other communities of bacteria, fungi, algae, lichens and mosses; made them a unique microhabitat in arid soils.

8.2.1 Formation and Structure

Cyanobacteria are naturally primary colonizers in bare soil of arid regions. Although cyanobacteria are almost present every types of CSCs, but rarely found in CSCs characterized by low pH conditions. Cyanobacteria considered to be one of the earliest inhabitants on planet earth and can thrive in a range of environments including desert soil and rock micro-habitats (Friedmann et al. 1967). Walter et al. (1976) suggested that cyanobacteria seem to be originated over 3 billion years ago, as evidenced in fossil record of marine stromatolites. These marine stromatolites containing large floating cyanobacterial mats considered to oxygenating the atmosphere and responsible for creating the basis of marine food web. Further Horodyski and Knauth (1994) suggested that 1.2 billion-year-old rocks evidenced the appearance of cyanobacteria in terrestrial habitats. Schwartzman and Volk (1989) stated that like the CSCs do currently, cyanobacteria might be hastened the weathering of barren bedrock and played an important role in soil formation which spread across the land. This newly formed soil supported the evolution and establishment of vascular plants and other terrestrial life forms.

Garcia-Pichel and Belnap (1996), Belnap (2003a, b) investigated that large, mobile filamentous cyanobacterial genus such as *Microcoleus vaginatus* (which that preferably live 1–4 mm below the soil surface) firstly inhabited the bare soils and further they can spread on the soil surface upon moisture availability during wet periods. After that, smaller and less mobile cyanobacterial genus such as *Nostoc*, *Scytonema* inhabited either on or just below the soil surface, facilitates the formation of layers of communities in the soils. These cyanobacterial communities constantly secreted out a sticky, polysaccharide outer sheath to the uppermost soil layers, leads to the formation of soil aggregates through binding the soil particles. Further these soil aggregates linked together by cyanobacterial filaments. When cyanobacteria stabilized the soil surface, lichens and mosses colonize according the suitable climate conditions.

The internal structure of CSCs differs due to composition and succession of different crust communities. Cyanobacteria and fungi are primary communities of all crust and provide them most of the cohesive property to CSCs. As cyanobacteria propagate inside the soil, lichens and bryophytes have blanket cover above the soil surface; which keeps underlying soils intact to resist from detachment of soil particles due to raindrops and overland water-flow. Lichens and bryophytes have rhizoptae, rhizinae, and rhizomorphs; act as anchoring structures that could enter in to the soil as deep as 14 mm (Belnap et al. 2003). Beside this, there is protonemata moss which is intermingled throughout the matrix; leads to form a dense, subterranean network that is connected with soil particles (Belnap and Gardner 1993; Belnap 2003a, b).

8.2.2 Distribution and Types of CSCs

The CSCs communities are widely distributed and occurred on every soil types and in almost all the ecosystems where sunlight able to reach the soil surface. Due to low moisture requirements and a high tolerance of extreme temperatures and light, they have ability to survive such conditions which limit the growth of vascular plants (Belnap et al. 2003). They are commonly thriving in low-productivity environments such as hyperarid, arid, semiarid, sub-humid, alpine and polar regions. Further CSCs found to be in limited to more mesic regions such as pine barrens, serpentine soils, temperate steppe. It is evident that tropical evergreen rain forests are the only ecosystems which appeared to lack CSCs (Büdel and Lange 2003).

Among climatic regimes, CSCs may differ in appearance, biomass, and species composition. Due to these differences, CSC's shows distinct external and internal structure; leads to different effect on ecological and hydrologic processes. Belnap et al. (2003) reviewed and proposed various classification schemes of CSCs. There is a classification mainly based on factors that influence runoff, infiltration, and sediment production. According to this, they are primarily categorized into four types:

1. Smooth CSCs-They are primarily found in hot hyper-arid deserts like in Atacama, Sahara deserts; which defined with high PET and absence of soil freezing. In smooth crusts, a thin layer of cyanobacteria and fungi dominated the crusts that can be survived on or just below the soil surface; lichens and mosses pockets rarely found specialized microhabitats. Smooth CSCs are often characterized by very low moisture availability which leads to low biomass and low absorptive of biota; ultimately result in the high porosity and low surface roughness of soil surface.
2. Rugose CSCs- They found in dryland areas like low-elevation Sonoran, Mojave, Australian deserts; which defined with lower PET than hyper-arid deserts and absence of soil freezing. In rugose crusts, a thin layer of cyanobacteria and fungi dominated the crusts but sparse patches of lichens and mosses commonly found

in drier regions of these CSCs. They have comparatively even soil surface. Although with increase in moisture availability in rugose CSCs, lichen and moss cover also increases as well but still have fairly flat soil surface. Overall rugose characterized by low moisture availability, leads to results in moderately low biomass and low absorptive; result in the moderately high soil surface porosity and low surface roughness.

3. Pinnacled crusts- They are found in occur in mid-latitude cool desert like low-elevation Colorado Plateau, mid-latitude China deserts, high-elevation Sonoran and Mojave deserts which defined with lower PET than in hot deserts but soils freezing occurred. In Pinnacled crusts, relatively thick layers of cyanobacteria dominated the crusts with up to 40% lichen and moss cover. Pinnacled crust characterized by remarkably pedicellate mounds, formed due to frost heaving; leads to uplifting. These uplifted mounds further differentially weathered by downward-cutting water. It can be high up to 15 cm with across 4–10 mm thin tip. Unlike smooth and rogose CSCs, they have high biomass & absorptive and high soil surface roughness with comparatively low soil surface porosity.
4. Rolling crusts-They are found in high altitude cold deserts like northern Great Basin, high-latitude deserts which defined with lower PET than pinnacled crusts regions. In rolling crusts, thick layer of lichens and mosses heavily dominated crusts. Unlike pinnacled crusts, soil uplifting due to frost heaving is counteracted by a cohesive and thick encrusted mat. This mat of lichens and mosses makes a roughened, slightly rolling surface that prevents differential downward cutting. Rolling CSCs characterized by high biomass & surface absorptive, with low soil surface porosity and moderate soil surface roughness.

8.2.3 Ecology and Physiology of CSCs

Cyanobacterial soil crusts play a significant role in the biogeochemistry and geomorphology of deserts (Eldridge and Greene 1994; Evans and Johansen 1999). Belnap and Eldridge (2001) investigated that communities of CSCs are almost alike around the world, despite the difference in climates and vegetation types in an area. Some genera such as *Microcoleus vaginatus*, *Psora decipiens*, *Collema tenax*, *Collema coccophorum*, and *Catapyrenium squamulosum* are occurred on almost all the continents. There are also some non-related communities which showed quite similar structures and functions, indicating that CSCs soil surface conditions have produced convergent evolutionary trends within these taxa. There are around hundreds of cyanobacterial and eukaryotic green algal species which found to be in cyanobacterial soil crusts (Evans and Johansen 1999). They mostly distributed in the upper soil layer, as they need sunlight for the photosynthesis. They are responsible for the change in the pH as well as oxygen, ammonium, and nitrate concentrations.

In the deserts, soil surface temperatures reached to very low as–20 °C to very high as over 70 °C. The precipitation is very low and quite sparse. They also face of high radiation as throughout the year. So for the survival of CSCs communities in deserts, they should have the ability to tolerate extreme dehydration. Sometimes the crust communities faced such conditions that dry-weight water content of biomass, might be reduced to extreme low as 5% or less, result in the terminating all metabolic processes (Bewley and Krochko 1982). These abilities can helps the crust communities to withstand extended periods of high heat, strong light, and no water.

Smaller cyanobacterial genera *Nostoc*, *Scytonema*, *Chroococcidiopsis* have large amounts of protective pigments for protection from excess radiation, while large filamentous cyanobacteria *Microcoleus* had no protective pigments, lives beneath the umbrella of smaller cyanobacteria and green algae (Bowker et al. 2002). Intracellular pigmented tissue like carotenoids and xanthophylls are able to reflect and or absorb incoming radiation up to 50–93% from reaching the interior of these communities (Castenholz and Garcia-Pichel 2000). Other taxa like lichens can “roll up” during drying, keeping to protect their photosynthetic pigments from radiation (Büdel and Wessels 1986; Frey and Kürschner 1991). Mosses also have some unique structures which can store and transport the water and also have the revolute (curled-under) leaf margins to reduce water loss through transpiration (Frey and Kürschner 1991).

8.3 Significance and Role of CSCs

The CSCs are unique micro-ecosystems that perform a variety of roles in the formation, stability, and fertility of semi-arid and arid soils. It is clearly evident that undisturbed CSCs shows greater biomass and better ability to perform the various functions than disturbed or damaged crusts at any stages of succession. Besides the discussed below roles of CSCs (Fig. 8.1), there may be another ecosystem services exists that couldn’t be investigated.

8.3.1 Dust Entrapment

CSCs have enhanced rough surface and adhesive sheath of polysaccharide, which increased the capability to capture of nutrient-rich dust from the nearby environment. Reynolds et al. (2001) observed that this dust can be able to increase the essential nutrients for the plants such as nitrogen, phosphorus, and potassium, up to fourfold. Due to this, there would be improvement in overall fertility and water holding capability of the soils (Verrecchia et al. 1995). Further undisturbed CSCs have greater capability to capture dust particles as their greater surface roughness as compared to disturbed (flattened) surfaces. Cyanobacteria fibres developed a web-like pattern which not only forms soil aggregates but also responsible for their holding in place.

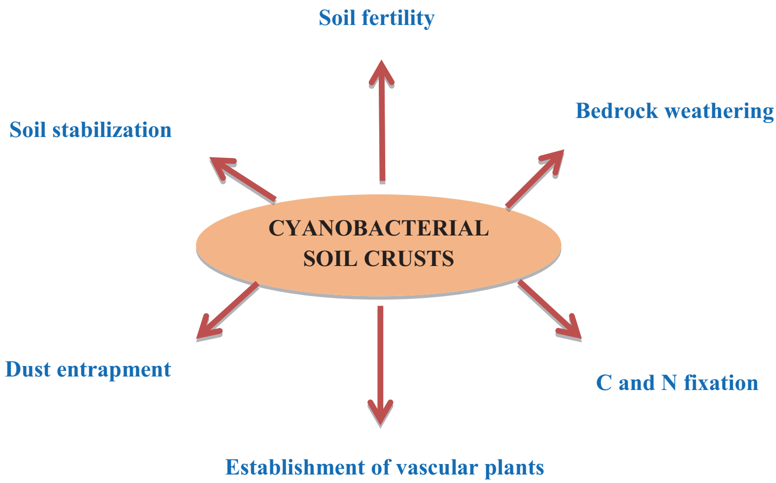

Fig. 8.1 Significance of cyanobacterial soil crusts (CSCs) in arid areas

8.3.2 Bedrock Weathering

Garcia-Pichel and Belnap (1996) observed that many organisms like lichens and cyanobacteria are considered to enhance substrate alkalinity from pH 8 to pH 10.5 in the CSCs of US, Venezuela, and South Africa. Schwartzman and Volk (1989) suggested that as CSCs have greater ability to hold water; lead to enhanced mineral dissolution and freeze–thaw action. Together these two factors can speed up the rate of weathering of bedrock up to 100 times.

8.3.3 Soil Physical Properties

Some crust organisms mainly cyanobacteria secretes extracellular substances (EPS) mainly polysaccharides (Mager and Thomas 2011), which organisms bind soil particles together to form into aggregates. Aggregation is an important aspect for proper functioning of soil and it is responsible to improve soil aeration and infiltration. Aggregate surfaces act as microsites for the most soil organisms and where maximum of the transformations of nutrient occurs (Herrick and Wander 1998). McKenna-Neuman et al. (1996) also suggested that aggregates showed greater resistance to soil erosion.

8.3.4 Soil Stabilization

In arid areas, soils are already nutrient deficient and further more susceptible to erosion (Dregne 1983). CSCs could cover the soil surfaces and provide resistance to wind and water erosion. As CSCs are also contains lichens and mosses which provide a protection cover to these soil surfaces from wind and water erosion; but Belnap and Eldridge (2001) found that as compared to healthy CSCs, disturbed crusts leads to 35 times more sediment loss in high winds or overland water flow.

8.3.5 Soil–Water Interaction

It is evident that water infiltration and soil moisture by CSCs affected by the climate, soil structure, soil texture; and also by the morphology and communities of the crusts. Smooth and rugose CSCs in high potential evapotranspiration areas have lower number of pores and little soil surface roughness that has lower water infiltration. It can be compensated by stored water by communities of CSCs which primarily depends upon rainfall amount. Eldridge et al. (2000) suggested that the phenomenon of better runoff in high PET areas is very important for the survival of heterogeneously distributed downslope plants. And if CSCs are experimentally disturbed in these areas, which accelerate the more localized infiltration; leads to death of downslope plants. While pinnacled and rolling CSCs in lower PET areas have greater soil surface roughness leads to slow movement of water that enhanced the infiltration, supports the better cover of the more homogeneously distributed vegetation found in cooler deserts.

8.3.6 Carbon and Nitrogen Fixation

Beymer and Klopatek (1991), Belnap (2001a) observed that CSCs are more significant in fixing carbon and nitrogen in deserts as there is limited cover of vascular plants and low atmospheric inputs (Peterjohn and Schlesinger 1990; Wullstein 1989). It is estimated that 0.4–2.3 g/m2/year (for cyanobacterial crusts) to 12–37 g/m2/year (for lichen crusts) carbon (Evans and Lange 2001) and 1 kg/ha/year (for cyanobacterial crusts) to 10 kg/ha/year (for lichen crusts) nitrogen (Belnap 2002) fixed by the CSCs. This is the main and significant source of carbon and nitrogen in desert soils (Evans and Ehleringer 1993).

Most of the fixation of carbon and nitrogen occurred during cool season comprises of fall, winter, and spring. Belnap (2001b) suggested that fixed carbon and nitrogen by CSCs generally released upon wetting, it means rainfall facilitates the nutrients and moisture to the desert soils. This released carbon and nitrogen assimilated by vascular plants, fungi, actinomycetes, and bacteria in nearby areas. Mostly cyanobacterial fixation of nitrogen provided by heterocystous cyanobacterial includes *Nostoc*, *Anabaena*, *Calothrix*, *Dicothrix Cylindrospermum*, *Schizothrix*, *Hapalosiphon*, *Nodularia*, *Plectonema*, and *Scytonema*; but some nitrogen fixation also observed in non-heterocystous genera such as *Oscillatoria*, *Lyngbya*, *Phoridium*, *Microcoleus* and *Tolypothrix* (Rogers and Gallon 1988; Harper and Marble 1988; Paerl 1990; Belnap 1996). Despite of free living form cyanobacteria symbiotically fixed nitrogen with lichens i.e. *Nostoc* in *Collema* sp. and *Peltula* sp. and *Scytonema* in *Heppia* sp.

8.3.7 Albedo (Reflective Power)

Belnap (1995) suggested that CSCs can absorbs much of the sunlight and reflect back only half the available sunlight as compared to in uncrusted or disturbed crusted surfaces; leads to reduce surface energy flux about 40 Joules/sec/m2, result in the increase in surface temperature by 10–14 °C. The surface temperature of the soil helps in maintaining many ecosystem functions such as rates of N and C fixation, seed germination, soil water evaporation, nutrient uptake by plants and their growth and microbial activity (Belnap 2003a, b). These ecosystem function and their timing plays an critical role for desert communities and a small change can affect community structure by reducing the species fitness and seedling establishment (Bush and Van Auken 1991). Crawford (1991) observed that many ants, insects and some small mammals segmented their surroundings according to foraging times and burrowing depths and they are regulated by surface temperature.

8.3.8 Establishment of Vascular Plants

CSCs cover and establishment of vascular plant quite interrelated especially in arid areas; at lower elevations vascular plant cover increases the cover of CSCs, because of the shade under the plant canopy. But at higher elevations, most of the soil surface occupied by vascular plants and plant litter, that reduce the opportunity for the CSCs to colonize the soil surface. Further CSCs morphology can influence establishing patterns of vascular plants. Belnap and Eldridge (2001) observed that smooth and rugose CSCs not able to retain the seeds and organic matter in space between the plants, whereas pinnacle and rolling CSCs enhance the retention of seeds and organic materials. In many field studies, germination and survival of native plants either increased or unaffected in CSCs as compared to uncrusted, areas. Once vascular plants established in crusted soils and start to growing, they have more biomass and better nutrient uptakes as compared to plants growing in uncrusted soils.

8.3.9 Soil Fertility

Combining all above said benefits, CSCs contributes great to enhance fertility of arid soils. There are numerous ways by which CSCs can improve the soil fertility and to enhance plant nutrient concentrations:

1. Adding C and N to the arid soils;
2. Secreting adhesive, negatively charged polysaccharides which keep retains the positively charged nutrients and stop further leaching loss of such nutrients essential to plants;
3. Producing chelators (ring shaped chemical compounds that bind the metal ions), which helps to keep minerals that available for plants;
4. Regulating soil temperatures and nutrient uptake rates;
5. Increasing dust capture and soil stabilization, which improves fertility and water-holding capacity of the soils; and
6. Facilitating the soil aggregation.

8.4 Factors Affecting CSCs

CSCs affected by many disturbances such as climate change, land use changes and invasion by exotic annual grasses and their associated risk of fire. All the disturbances responsible for the reduction in total crust cover; leads to decrease in soil surface temperature decreased. Lichens and mosses communities either distressed or substituted by more disturbance-tolerant cyanobacterial communities and soil surfaces are flattened. Further loss of lichens and mosses affected the soil fertility and stability, because of less extrusion of polysaccharide materials, less fixation of C & N, less entrapment of dust and other surface particles, less secretion of chelators and growth factors are, lesser nutrient uptake rates and there is a reduction in number and diversity of soil food web communities.

8.4.1 Land Use Changes

Compression and shear forces like animal hooves, human feet, tank treads, or off-road vehicle tires, thrashed soil crusts; it is more devastated when soil crusts are more dry as most the times crust are in dry state. Crusts are shattered in to pieces of crust, they can be either blow or wash away by the wind or water flow. If the pieces of crusts buried in the soil, they cannot survive as they need light to photosynthesize.

Direct human impact is the dominant force which is more responsible for the simplification and/or the destruction of CSCs. Nowadays deserts are used for the recreation, energy development, livestock grazing, habitation, and military exercises (Brooks and Pokshishevsky 1986), which undoubtedly led to a large scale devastation of lichen–moss cover and their associated ecosystem functions. Due to this slow recovery rate, CSCs cover and diversity decreases, leads to relatively permanent, less diverse and inefficient crusts. Pimm (2001) suggested that as human use of rangelands increased over the time, there are phenomenon of increasing the size and frequency of global dust storms also increased.

8.4.2 Invasion of Annual Exotic Grasses

Disturbances and devastation of CSCs leaves the vacant spaces, where exotic annual grasses easily expanded and their associated fire risk could be responsible for the crust cover and biodiversity loss. As annual exotic grasses starts to occupy the plant interspaces which once acquired by the CSCs and their diverse communities; gradually substituted by a bunch of cyanobacterial and annual moss species. Further absence of limited fires and growth of annual grasses supports the increase in rodent numbers and their burrows; probably responsible for this compositional shift. Unlike in the well-developed CSCs and less growth of annual grasses, limited fires generally expanded from shrub to shrub, leaves soil crusts unaffected between them. However excessive growth of annual grasses might be enhance size and frequency of wildfires, which now burned large areas, including the CSCs between plants; result in the death of soil crusts. This further prevents settlement of perennial lichens and mosses, leaving arid soils dominated by cyanobacteria and annual mosses.

8.4.3 Temperature and Precipitation

Cayan (1996) suggested that climatic alternations in deserts such as higher temperatures, greater summer precipitation, and drier-than-normal winters, responsible for affecting the structure and function of CSCs. It is very often for survival of mosses and lichens, water loss in respiration compensated by water gain in photosynthesis. But at higher temperature, soils of CSCs loose moisture faster (Jeffries et al. 1993); responsible for imbalance in respiratory loss and photosynthetic gain, leads to dryness of crust organisms. This stunted the further growth of crust communities, makes CSCs carbon deficits in the summer time.

Precipitation facilitates the soil wetting and temperature of soil surface also dropped, providing the conditions for CSCs to become metabolically active and perform better physiological functioning. As excess rain in summertime leads to flooding, wash away the soil crusts and less rain in wintertime leads to soil drying. This makes the CSCs carbon and nitrogen deficient. Due to inadequate carbon and nitrogen, CSCs will be less able to avoid or repair any disturbance; leads to increased mortality of more susceptible communities like lichens and mosses or even changing in distribution patterns. Belnap and Eldridge (2001) suggested that the current distribution pattern of lichen and moss in the deserts of US, Australia and central Asia, indicated towards this scenario; as diversity lichen and mosses reduces sharply with increase in temperature and summer rainfall.

8.4.4 UV Radiation

Most of the CSCs communities are quite susceptible to the UV radiation, which increases mortality through affecting the growth, motility, photosynthesis, nitrogen fixation and their uptake, photo-movements and cell differentiation (Castenholz and Garcia-Pichel 2000). UNEP/WMO (2002) predicted the risk of more UV radiation as ozone layer is thinning, which could be avoided through recovery of ozone layer due to decrease in chlorofluorocarbon (CFC) production and replacement with other alternatives. But this recovery might be slowed due to volcanic eruptions, airplane exhaust, and/or the renewed manufacture of ozone depleting substances. As CSCs in some deserts experienced so less days of rain, to rehydration and amplify their biomass; they are more vulnerable to UV radiation. Due to UV radiation, CSCs always faces severe damage, leaves limited time to acquire the carbon necessary to repair and produce new tissue. The condition of high UV radiation, less rain and higher temperature further worsen this situation.

8.4.5 Elevated CO_2 Concentration

Although increasing the atmospheric CO_2 levels might be help in increase the primary production of crust communities. But it would further limit the growth of crust communities. Lange et al. (1999) observed that CO_2 levels limit the photosynthesis in soil lichens as rates at ambient CO_2 levels are reaches to the maximum of 70–80%. Moore et al. (1999) stated that higher plants gradually slowed their processes or down-regulated, upon experiencing long-term exposure of elevated CO_2. In case of CSCs communities there is no substantial and comparable data regarding the response of crust communities to elevated CO_2. Unlike free-living and lichenized green algae in crusts, cyanobacteria have the intracellular CO_2 concentration mechanisms, which help to overcome the situation of, altered photosynthetic. Due to absence of intracellular CO_2 concentration mechanism, elevated CO_2 conditions might be favourable for green algae and lichenized green algae over cyanobacteria and cyano-lichens. So elevated CO_2 concentration induced the growth of some communities to increase in the more cover, leads to change in species composition of higher plant communities. Melillo et al. (1993) observed that enhanced water availability further increased the growth of such communities and result in the significant increase in net primary productivity in arid areas. Smith et al. (1987) further suggested that elevated CO_2 might be influence the competitive balance between higher plants and favoured the growth of invasive annual grasses, leads to reduction in crust cover and diversity.

8.4.6 Recovery Rates

Belnap and Eldridge (2001) underlined the factors responsible for recovery of soil crusts such as climate, nature of the soil & location, disturbances & their characteristics, inoculant availability and how recovery is addressed. It is observed that CSCs could be recover from disturbance in fairly quick (20 years) low PET arid areas, but it is tremendously slow (≥1000 years) in high PET arid areas. It is evident that CSCs are faster recovered in fine-textured soils as compared to coarse soils, as their low stability & fertility and poor water-holding capacity. Further stability of soils influence the recovery of crusts, as stable areas having low slopes, low wind deposition of sand, and/or embedded rocks showed better recovery than less stable areas having steep slopes, high sand deposition, and/or unstable rocks.

Due to severe or more frequent disturbance which are enough to disrupt already recovering CSCs, further recovery of crust communities slowed; if communities crumpled but stand still in their place. Although all the cyanobacterial communities vanished and blown by the disturbances. But large, highly mobile filamentous cyanobacteria such as *Microcoleus* survived even after burial and became the first colonizers of unstable soils. After larger cyanobacteria stabilized the crust soils; smaller and less mobile cyanobacteria starts to colonize. It is followed by lichens and mosses.

8.5 Rehabilitation of CSCs

There are many approaches which can be applied for the rehabilitation and stabilization of CSCs (Bowker 2007; Strong et al. 2013; Chock et al. 2019). These approaches are unique and diverse; and further adapted from various fields; related to restoration, ecology and agriculture. These approaches can classify into three major categories: (a) Artificial soil stabilization; (b) Resource augmentation; (c) Inoculation.

8.5.1 Artificial Soil Stabilization

In this method, soil surface is stabilized through the use of some artificial medium; which indirectly facilitates the successful rehabilitation of CSCs. There are some mediums such as polyacrilimide, coarse litter (such as straw), and vascular plants; that are successfully applied in the soil surface stabilization. Polyacrilimide (PAM) is a synthetic polymer, which effectively stabilize the soil surface and improves the soil moisture and nutrients availability. Further their application has no negative effect on chlorophyll fluorescence or nitrogenase activity of transplanted *Collema* (Collemataceae) lichens (Davidson et al. 2002).

Another medium straw has been effectively implied and examined in the dune stabilization and CSCs rehabilitation (Fearnehough et al. 1998; Hu et al. 2002; Li et al. 2004). In this approach, straw is vertically buried into soil spaced 1 m apart in lines and lines should make grid pattern. Sometimes, there are plantations of vascular plants along with these lines. Due to this, a succession of CSCs takes place; firstly cyanobacteria which are followed by chlorophytes, and in last mosses are colonized to form a cohesive and diverse CSCs. A number of researchers like van de Ancker et al. (1985), Maxwell and McKenna-Neuman (1994), Danin (1996, 1998) suggested that this approach would be helpful in that arid and semi-arid area where CSCs and vegetation have the capability to naturally stabilize the dunes. But the only problem with this approach is need of considerable economic incentive for the labour resources to execute and maintain it on large area.

Last one is introduction of vascular plants and grasses to stabilize the soil surface (Danin et al. 1998). Native and exotic plant species are more suitable for the stabilization and rehabilitation of CSCs (Aradottir et al. 2000). Danin (1978) suggested that due to plantation of trees in sandy area, wind velocity decreases; leads to succession of shrubs and CSCs and further development of more productive and diverse community. Aradottir et al. (2000) stated that fertilization coupled plantation of grasses could be very useful in highly eroded and unstable soils.

8.5.2 Resource Augmentation Approaches

In this approach, nutrients and moisture conditions are modified for the promotion of CSCs establishment in disturbed areas. However these approaches are not much explored. Singh (1950) investigated during India's monsoon season that earthen water catchments support the cyanobacterial growth and helpful in improving highly alkaline infertile soils in to suitable soils for agriculture. Belnap and Warren (1998), Maestre and Cortina (2002), Bowker et al. (2005) observed that the growth and stabilization of CSCs is favoured by somewhat cooler, shaded and wetter microsites. Although Davidson et al. (2002) reported that additional watering could have negative effect on transplanted lichens as it responsible for soil surface erosion. But in broad perspective, transplanted lichens showed more growth in mesic and cool microaspects of small, upraised elevations and mosses showed better growth in depressions in the CSCs surface (Maestre et al. 2001; Csotonyi and Addicott 2004). Tongway and Ludwig (1996), Maestre and Cortina (2004) suggested that brush piles could be useful to generate favourable microsites for the germination of vascular plants. Although brush piles likely favoured vascular plants more than CSCs. But applying that concept woody debris could be used to facilitate partial shade and mesic conditions for the stabilization CSCs.

Amendments such as minerals (Mn, Zn, and Mg), fertilizers (P, K and NPK) and biochar could be helpful in promoting the growth of cyanobacteria and chlorophytes in CSCs (Qiu and Gao 1999; Aradottir and Arnalds 2001; Elmarsdottir et al. 2003; Grettarsdottir et al. 2004; Bowker et al. 2006). Davidson et al. (2002) studied the effect of P and K fertilizers separately or combined and observed that addition of P and K had no effect on nitrogenase activity or condition of lichen transplants. There are variable effects of fertilization on chlorophyll fluorescence of the transplants. Qiu and Gao (1999) showed that K promote the photosynthetic recovery of *Nostoc flagelliforme* after desiccation in a laboratory study. Bowker et al. (2005, 2006) found that addition of Mn, Zn, K, and Mg have a positive effect on mosses and lichens in CSCs.

8.5.3 Inoculation-Based Approaches

Benefits of inoculation of cyanobacteria successfully investigated for soil reclamation, bioremediation and agricultural land improvement (Venkataraman 1972; Metting and Rayburn 1983; Ashley and Rushforth 1984; Rao and Burns 1990; Rogers and Burns 1994; Falchini et al. 1996; Singh 2014, 2015; Singh et al. 2016a, b, 2017a, b, c, 2018, 2019a, b; Kumar and Singh 2016, 2017; Tiwari et al. 2018; Kumar et al. 2017, 2018a, b;). Tiedemann et al. (1980) and Acea et al. (2001) investigated the benefits of cyanobacteria inoculation in forested ecosystems, either post-fire or as an N source in a tree plantation and observed that it has helpful in enhancing soil fertility and biological activity.

In relation to drylands, some studies carried out by St. Clair et al. (1986), Belnap (1993), Scarlett (1994), Davidson et al. (2002), Kubecková et al. (2003); which involves the application of crushed CSCs material, dry or in a slurry form, to the disturbed area. Although many studies relating inoculation based rehabilitation, significantly improved the enhanced recovery of CSCs; but full recovery time for the CSC development could be much longer in actual field conditions as compared to short duration and controlled field studies. It is found to be very successful to establish the founder communities of particular taxa through transplanting methods (Scarlett 1994; Bowler 1999). Davidson et al. (2002) observed that inoculation of cyanobacterial have apparently distinctive effects on transplanted *Collema* lichens, which primarily reliant on complex interactions with moisture and nutrient additions (Rossi et al. 2017; Wu et al. 2018).

8.6 Biochar Coupled Rehabilitation/Stabilization of CSCs

Biochar is a black and carbon rich solid material which could be obtained by heating the biomass at between 300 °C–700 °C under limited oxygen conditions; this process also known as pyrolysis (Singh et al. 2017a, b, c, 2018; Lehmann et al.

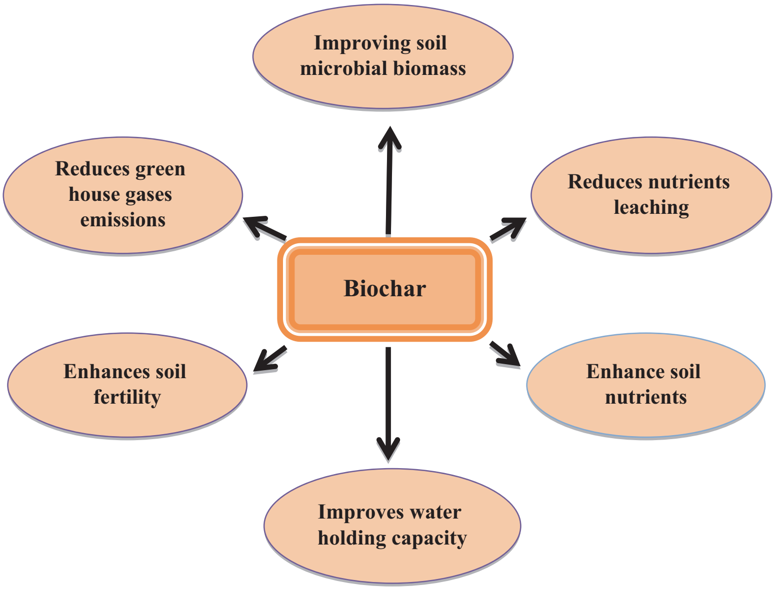

Fig. 8.2 Implications of biochar application in agriculture

2006; Nsamba et al. 2015). It is very helpful in improving soil physical characteristics like soil nutrient retention capacity, water holding capacity and reduced methane & N_20 emissions from soil (Fig. 8.2). Due to porous in structure it can also be helpful in maintaining microbial diversity in the soil (Lehmann et al. 2006; Verheijen et al. 2009; Lehmann 2007; Duku et al. 2011).

Lehmann (2007) investigated that biochar could be able to sink carbon up to 1 $Gtyr^{-1}$, which makes the biochar a attractive solution for the mitigation of climate change (Sohi et al. 2010; Yao et al. 2011). Lehmann et al. (2006), Laird et al. (2009), Lehmann (2007) suggested that it have a significant effect on cation exchange capacity (CEC; 40–80 meq per 100 g) and provide high surface area (51–900 m2•g − 1). Due to this, there is increase in soil pH and water holding capacity, and it also show greater ability to hold and capture micro- and macro- nutrients for the plants.

Considering benefits of biochar as soil amendments, it can be applied for the stabilization of CSCs. Although the previous studies mainly limited to effect of biochar in agricultural soils and emphasised that it improves such as the cation exchange capacity, pH, nutrient contents, plant growth; and also enhance carbon sequestration potential of the amended soils. Further it helps in reducing the greenhouse gas (GHG) emissions from the soils (van Straalen 1998; Gundale and DeLuca 2006; Sharkawi et al. 2006; Asai et al. 2009). Meng and Yuan (2014) investigated the use of biochar in improving the formation of cyanobacterial soil crust on sand under dry conditions and found that biochar have a significant effect on the cyanobacterial growth and sand fixation. Meng and Yuan (2014) conducted a study with application of 2% biochar (produced from the gasification of rice hull) on sandy soils, which undoubtedly enhanced the formation of cyanobacterial soil crust. So it can be concluded that biochar could be coupled with cyanobacteria or algae inoculation to improve or rehabilitation of the CSCs.

Although there are successful but few studies available related to beneficial effects of biochar on the fertility and communities of desert soils. And on quite pilot scale or theoretical way, it could be established that addition of biochar with other approaches recover or rehabilitate the CSCs. However there is need of further research in large scale to find that how biochar helps in rehabilitation of CSCs whether it improving soil physical properties and enhance CSCs formation in arid areas.

8.7 Small Scale Biochar Production

For the small scale biochar production a variety of raw materials such as rice hull, wheat straw, sugarcane bagasse, poultry litter, etc. are used. The pyrolysis reactors depending upon the heating, two methods can be used for the small scale biochar production:

1. Partial combustion- It is the most common pyrolysis method in which raw material combusted with a controlled air flow. But due to a portion of biomass be combusted in this process, it produces low yield of biochar, so they are applied in areas where raw materials are cheap;
2. Carbonization by contact with hot gases-In this method, hot gases from external source provided to the raw material which further converts the biomass into biochar and by-products. Although the costs are increased due to cost associated with heating the required inert gases. But biomass and by-products yield are high which makes the system suitable for medium to large scale production.

Biochar kilns may be simply earthen pits or made up of bricks, concrete or steel and cast iron. Earthen pits or pit kilns are very cost method and has been used from the centuries for the carbonizing woods. Biochar kilns are also made up of bricks or concrete to create a limited oxygen environment. Brick kilns are typically auto thermal and have a long lifespan and further portable as they easily dismantled and moved to be a new location. In last, steel or cast iron can used to make biochar kilns as they the heat easily transferred through walls made from these materials in Table 8.1.

Discarded oil drums also are used to make biochar kilns for the small scale production. Oil drums with both sides intact are most suitable; a big hole at the centre of top side provided for the loading of raw material and many small holes on the bottom side provided for the limited supply of oxygen (Venkatesh et al. 2010; Srinivasarao et al. 2013; Singh et al. 2017a, b, c).

Table 8.1 Biochar physicochemical properties from different raw materials

Raw material	Ash (%)	pH	EC (mS/cm)	C (%)	N (%)	Ca (ppm)	K (ppm)	Mg (ppm)	Si (mg/kg)	P (ppm)
Woodchip	25.4	7.88	0.14	51.9	0.4	0.56	0.21	0.04	–	0.06
Grass	14.7	6.1	–	42.5	1.9	4.3 4	64.8	2.3 4	7.44	2.31
Poultry litter	28.53	23.6	3	38.6	1.37	1.85	0.99	0.19	–	0.35
Rice husk	6.5	6.6	–	41	1.4	250	2604	827	5.8	–
Sugarcane bagasse	11.9–16.4	–	–	60.4–65.3	0.8–1.0	–	–	–	–	–
Wheat straw	5.9	6.76	2770	43.7	0.9	0.18	0.15	–	0.18	0.05

Modified from Mahinpey et al. (2009), Bruun et al. (2012). Jindo et al. (2012), Carrier et al. (2012), Shackley et al. (2012), Yargicoglu et al. (2015), Jouiada et al. (2015), Mohammed et al. (2015), and Singh et al. (2017a, b, c)

8.8 Conclusions

Cyanobacterial soil crusts are very essential in maintaining soil surface stability of desert soils and preventing them from erosion. The role of these crusts in carbon and nitrogen fixation, hydrological properties and surface stability of desert soil well understood. It is well established that extracellular polysaccharide secretion (EPS) from cyanobacteria play a major role in binding soil particles, nutrients and moisture. Further there is need of more *in-situ* studies related to the role of EPS in stabilization of crusts for the better understanding of CSCs.

In absence of CSCs, deserts could more prone to erosion, loss of organic matter, water availability, fine soil particles and nutrient content. Although there are many natural factors like high summer temperature, less rainfall and climate change, which are responsible for degradation of quality of cyanobacterial soil crusts. However there is no match of human intervention in terms of devastating effects that exert more pressure on already distressed crust; result in the complete destruction of crusts or increasing the recovery time for the CSCs. Due to disturbed crusts, exotic annual grasses occupied the vacant spaces and further increased the risk of surface fire; leads to simplifying species composition and flattening the crusts. So there is a need of comprehensive planning to maintain the CSCs in original and diverse condition that they further able to resist the changes caused by either natural or anthropogenic disturbances.

In all rehabilitation measures, cyanobacterial inoculants are seems to be very promising and successfully tested in many studies. But most of the studies carried out in lab conditions, and field applications are not so successful. Further the rehabilitation strategies such as biochar application could be used either separately or with the cyanobacteria inoculants. Biochar could be a game changing option in rehabilitation and stabilization of CSCs in deserts. It not only helps in capturing moisture but also provide microhabitat for microbial activities; helping in nutrient cycling. Small scale biochar production could be sustainable and viable option for the rehabilitation and stabilization of cyanobacterial soil crusts. It provides the livelihood to the locals of that region and also encourages the public participation.

In last, it is not necessary for a particular method to be effective for the rehabilitation and stabilization of all types of CSCs; so there is also need to consider conditions of the region where a particular type of CSCs existed. Further the information and strategies related to rehabilitation of CSCs are still in beginning stage, and the process of learning still going on. Currently the researchers are only focuses on the promoting faster recovery of CSCs in holistic way or of important community within the CSCs. In future, once these technological problems are solved, there would be focus on a particular aspect of CSCs and how this could be rehabilitated to the better recovery of ecosystem functions of interest.

References

Acea MJ, Diz N, Ferna'ndez AP (2001) Microbial populations in heated soils inoculated with cyanobacteria. Biol Fertil Soils 33:118–125

Aradottir AL, Arnalds O (2001) Ecosystem degradation and restoration of birch woodlands in Iceland. In: Wielgolaski FE (ed) Nordic mountain birch ecosystems. UNESCO, Paris and Parthenon Publishing, Carnforth, pp 295–308

Aradottir AL, Svavasdottir K, Jonsson XH, GuCbergsson G (2000) Carbon accumulation in vegetation and soils by reclamation of degraded areas. Icel Agric Sci 13:99–113

Asai H, Samson BK, Stephan HM, Songyikhangsuthor K, Homma K, Kiyono Y, Inoue Y, Shiraiwa T, Horie T (2009) Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, Leaf SPAD and grain yield. Field Crop Res 111:81–84

Ashley J, Rushforth SR (1984) Growth of soil algae on top soil and processed oil shale from the Uintah Basin, Utah, U.S.A. Reclam Reveg Res 3:49–63

Belnap J (1993) Recovery rates of cryptobiotic crusts: inoculant use and assessment methods. Great Basin Nat 53:89–95

Belnap J (1995) Surface disturbances: their role in accelerating desertification. Environ Monit Assess 37:39–57

Belnap J (1996) Soil surface disturbances in cold deserts: effects on nitrogenase activity in cyanobacterial-lichen soil crusts. Biol Fertil Soils 23:362–367

Belnap J (2001a) Factors influencing nitrogen fixation and nitrogen release in biological soil crusts. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 241–261

Belnap J (2001b) Microbes and microfauna associated with biological soil crusts. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 167–174

Belnap J (2002) Nitrogen fixation in biological soil crusts from southeast Utah, USA. Biol Fertil Soils 35:128–135

Belnap J (2003a) The world at your feet: desert biological soil crusts. Front Ecol Environ 1(5):181–189

Belnap J (2003b) Comparative structure of physical and biological soil crusts. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 177–191

Belnap J (2006) The potential roles of biological soil crusts in dryland hydrologic cycles. Hydrol Process 20:3159–3178

Belnap J, Eldridge D (2001) Disturbance and recovery of biological soil crusts. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 363–383
Belnap J, Gardner JS (1993) Soil microstructure in soils of the Colorado Plateau: the role of the cyanobacterium *Microcoleus vaginatus*. Great Basin Nat 53:40–47
Belnap J, Lange O (eds) (2003) Biological soil crusts: structure, function and management, in press. Springer, Berlin
Belnap J, Warren SD (1998) Measuring restoration success: a lesson from Patton's tank tracks. Ecol Bull 79:33
Belnap J, Büdel B, Lange OL (2003) Biological soil crusts: characteristics and distribution. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 3–30
Bewley JD, Krochko JE (1982) Desiccation-tolerance. In: Lange OL, Nobel PS, Osmund CB, Ziegler H (eds) Physiological plant ecology II. Springer, Berlin, pp 325–378
Beymer RJ, Klopatek JM (1991) Potential contribution of carbon by microphytic crusts in pinyon-juniper woodlands. Arid Soil Res Rehabil 5:187–198
Bowker MA (2007) Biological soil crust rehabilitation in theory and practice: an underexploited opportunity. Restor Ecol 15(1):13–23
Bowker M, Reed SC, Belnap J, Phillips S (2002) Temporal variation in community composition, pigmentation, and Fv/Fm of desert cyanobacterial soil crusts. Microb Ecol 43:13–25
Bowker MA, Belnap J, Davidson DW, Phillips SL (2005) Evidence for micronutrient limitation of biological soil crusts: importance to arid-lands restoration. Ecol Appl 15:1941–1951
Bowker MA, Belnap J, Davidson DW, Goldstein H (2006) Correlates of biological soil crust abundance: support for a hierarchical conceptual model. J Appl Ecol 43:152–163
Bowler PA (1999) Understory bulbs, grasses, bryophytes and liverworts transplant successfully in coastal sage scrub (California). Ecol Restor 17:82–83
Brooks SI, Pokshishevsky VV (1986) Population problems in the arid and semiarid regions of the world. In: Gerasimov IP (ed) Arid land development and the combat against desertification: an integrated approach. Commission for the United Nations Environment Program, Moscow
Bruun EW, Ambus P, Egsgaard H, Hauggaard-Nielsen H (2012) Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. Soil Biol Biochem 46:73–79
Büdel B, Lange OL (2003) Synopsis: comparative biogeography and ecology of soil-crust biota and communities. In: Belnap J, Lange O (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 141–152
Büdel B, Wessels DCJ (1986) Parmelia hueana Gyeln, a vagrant lichen from the Namib Desert, SWA/Namibia. I. Anatomical and reproductive adaptations. Dinteria 18:3–15
Bush JK, Van Auken OW (1991) Importance of time of germination and soil depth on growth of *Prosopis glandulosa* seedling in the presence of a C_4 grass. Am J Bot 78:1732–1739
Cameron RE, Blank GB (1966) Desert algae: soil crusts and diaphanous substrata as algal habitats. JPL Tech Rep 32:1–40
Carrier M, Hardieb AG, Urasa U, Gorgensa J, Knoetze J (2012) Production of char from vacuum pyrolysis of South-African sugar cane bagasse and its characterization as activated carbon and biochar. J Anal Appl Pyrolysis 96:24–32
Castenholz RW, Garcia-Pichel F (2000) Cyanobacterial responses to UV radiation. In: Whitton BA, Potts M (eds) The ecology of cyanobacteria. Kluwer Academic Publishers, Dordrecht, pp 591–611
Cayan DR (1996) Inter-annual climate variability and snowpack in the western United States. J Clim 9:928–948
Chock T, Antoninka AJ, Faist AM, Bowker MA, Belnap J, Barger NN (2019) Responses of biological soil crusts to rehabilitation strategies. J Arid Environ 163:77–85
Crawford CS (1991) The community ecology of macroarthropod detritivores. In: Polis G (ed) Ecology of desert communities. University of Arizona Press, Tucson, pp 89–112

Csotonyi JT, Addicott JF (2004) Influence of trampling-induced microtopography on growth of the soil crust bryophyte *Ceratodon purpureus* in Jasper National Park. Can J Bot 82:1382–1392

Danin A (1978) Plant species diversity and plant succession in a sandy region in the northern Negev. Flora 167:409–422

Danin A (1996) Plants of desert dunes. Springer, Berlin

Danin A, Dor I, Sandler A, Amit R (1998) Desert crust morphology and its relations to microbiotic succession at Mt. Sedom, Israel. J Arid Environ 38:161–174

Davidson DW, Bowker M, George D, Phillips SL, Belnap J (2002) Treatment effects on performance of N-fixing lichens in disturbed soil crusts on the Colorado Plateau. Ecol Appl 12:1391–1405

Dregne HE (1983) Desertification of arid lands. Harwood Academic Publishers, New York

Duku MH, Gu S, Hagan EB (2011) Biochar production potential in Ghana—a review. Renew Sust Energy Rev 15:3539–3551

Eldridge DJ, Greene RSB (1994) Assessment of sediment yield by splash erosion on a semi-arid soil with varying cryptogam cover. J Arid Environ 26:221–232

Eldridge DJ, Zaady E, Shachak M (2000) Infiltration through three contrasting biological soil crusts in patterned landscapes in the Negev, Israel. Catena 40:323–336

Elmarsdottir A, Aradottir AL, Trlica MJ (2003) Microsite availability and establishment of native species on degraded and reclaimed sites. J Appl Ecol 40:815–823

Evans RD, Ehleringer JR (1993) A break in the nitrogen cycle in aridlands? Evidence from 15N of soils. Oecologia 94:314–317

Evans RD, Johansen JR (1999) Microbiotic crusts and ecosystem processes. Crit Rev Plant Sci 18:183–225

Evans RD, Lange OL (2001) Biological soil crusts and ecosystems nitrogen and carbon dynamics. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 263–279

Falchini L, Sparvoli E, Tomaselli L (1996) Effect of *Nostoc* (cyanobacteria) inoculation on the structure and stability of clay soils. Biol Fertil Soils 23:346–352

Fearnehough W, Fullen MA, Mitchell DJ, Trueman IC, Zhang J (1998) Aeolian deposition and its effect on soil and vegetation changes on stabilized desert dunes in northern China. Geomorphology 23:171–182

Frey W, Kürschner H (1991) Morphological and anatomical adaptation of the species in terrestrial bryophyte communities along an ecological transect in the Judean Desert, Israel. Bot Jahrb Syst 112:529–552

Friedmann I, Lipkin Y, Ocampo-Paus R (1967) Desert algae of the Negev (Israel). Phycologia 6:185–195

Garcia-Pichel F, Belnap J (1996) Microenvironments and microscale productivity of cyanobacterial desert crusts. J Phycol 32:774–782

Grettarsdottir J, Aradottir AL, Vandvik V, Heegaard E, Birks HJB (2004) Long term effects of reclamation treatments on plant succession in Iceland. Restor Ecol 12:268–278

Gundale MJ, DeLuca TH (2006) Temperature and substrate influence the chemical properties of charcoal in the *Ponderosa* Pine/Douglas-Fire cosystem. Forest Eco Manag 231:86–93

Harper KT, Marble JR (1988) A role for nonvascular plants in management of arid and semiarid rangeland. In: Tueller PT (ed) Vegetation science applications for rangeland analysis and management. Kluwer Academic Publishers, Dordrecht, pp 135–169

Herrick JE, Wander MM (1998) Relationships between soil organic carbon and soil quality in cropped and rangeland soils: the importance of distribution, composition and soil biological activity. In: Lal R, Kimble J, Follett R, Stewart BA (eds) Advances in soil science: soil processes and the carbon cycle. CRC Press, Boca Raton, pp 405–425

Horodyski RJ, Knauth LP (1994) Life on land in the Precambrian. Science 263:494–498

Hu C, Liu Y, Song L, Zhang D (2002) Effect of desert soil algae on the stabilization of fine sands. J Appl Phycol 14(4):281–292

Jeffries DL, Link SO, Klopatek JM (1993) CO_2 fluxes of cryptogamic crusts. I. Response to resaturation. New Phytol 125:163–173
Jindo K, Suto K, Matsumoto K, García C, Sonoki T, Sanchez-Monedero MA (2012) Chemical and biochemical characterisation of biochar-blended composts prepared from poultry manure. Bioresour Technol 110:396–404
Johansen JR (1993) Cryptogamic crusts of semiarid and arid lands of North America. J Phycol 29:140–147
Jouiada M, Al-Nofeli N, Khalifa N, Benyettouc F, Yousef LF (2015) Characteristics of slow pyrolysis biochars produced from rhodes grass and fronds of edible date palm. J Anal Appl Pyrolysis 111:183–190
Kubeckova K, Johansen JR, Warren SD, Sparks RL (2003) Development of immobilized cyanobacterial amendments for reclamation of microbiotic soil crusts. Algol Stud 109:341–362
Kumar A, Singh JS (2016) Microalgae and cyanobacteria biofuels: a sustainable alternate to crop-based fuels. In: Singh JS, Singh DP (eds) Microbes and environmental management. Studium Press Pvt. Ltd, New Delhi, pp 1–20
Kumar A, Singh JS (2017) Cyanoremediation: a green-clean tool for decontamination of synthetic pesticides from agro- and aquatic ecosystems. In: Singh JS, Seneviratne G (eds) Agro-environmental sustainability: Vol-2: managing environmental pollution. Springer, Cham, pp 59–83
Kumar A, Kaushal S, Saraf SA, Singh JS (2017) Cyanobacterial biotechnology: an opportunity for sustainable industrial production. Clim Change Environ Sustain 5(1):97–110
Kumar A, Kaushal S, Saraf SA, Singh JS (2018a) Screening of chlorpyrifos (CPF) tolerant cyanobacteria from paddy field soil of Lucknow, India. Int J Appl Adv Sci Res 3(1):100–105
Kumar A, Kaushal S, Saraf SA, Singh JS (2018b) Microbial bio-fuels: a solution to carbon emissions and energy crisis. Front Biosci-Landmrk 23:1789–1802
Laird DA, Brown RC, Amonette JE, Lehmann J (2009) Review of the pyrolysis platform for coproducing bio-oil and biochar. Biofuels Bioprod Biorefin 3:547–562
Lange OL, Green TGA, Reichenberger H (1999) The response of lichen photosynthesis to external CO_2 concentration and its interaction with thallus water-status. J Plant Physiol 154:157–166
Lehmann J (2007) Bio-energy in the black. Front Ecol Environ 5:381–387
Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems—a review. Mitig Adapt Strategy Glob Change 11:403–427
Li X, Xiao H, Zhang J, Wang X (2004) Long-term ecosystem effects of sand-binding vegetation in the Tengger Desert, Northern China. Restor Ecol 12:376–390
Maestre FT, Cortina J (2002) Spatial patterns of surface soil properties and vegetation in a Mediterranean semi-arid steppe. Plant Soil 241:279–291
Maestre FT, Cortina J (2004) Insights into ecosystem composition and function in a sequence of degraded semiarid steppes. Restor Ecol 12:494–502
Maestre FT, Bautista S, Cortina J, Bellot J (2001) Potential for using facilitation by grasses to establish shrubs on a semiarid degraded steppe. Ecol Appl 11:1641–1655
Mager DM, Thomas AD (2011) Extracellular polysaccharides from cyanobacterial soil crusts: a review of their role in dryland soil processes. J Arid Environ 75:91–97
Mahinpey N, Murugan P, Mani T, Raina R (2009) Analysis of bio-oil, biogas, and biochar from pressurized pyrolysis of wheat straw using a tubular reactor. Energy Fuel 23:2736–2742
Maxwell CD, McKenna-Neuman C (1994) Photoautotrophs and the microaggregation of sand in a freshwater beach-dune complex: implications for sediment transport by wind. Soil Biol Biochem 26:221–233
McKenna-Neuman C, Maxwell CD, Boulton JW (1996) Wind transport of sand surfaces crusted with photoautotrophic microorganisms. Catena 27:229–247
Melillo JM, McGuire AD, Kicklighter DW, Moore B, Vorosmarty CJ, Schlos AL (1993) Global climate change and terrestrial net primary production. Nature 363:234–240
Meng X, Yuan W (2014) Can biochar couple with algae to deal with desertification? J Sustain Bioenergy Syst 4:194–198

Metting B, Rayburn WR (1983) The influence of a microalgal conditioner on selected Washington soils: an empirical study. Soil Sci Soc Am J 47:682–685
Mohammed IY, Abakr YA, Kazi FK, Yusuf S, Alshareef I, Chin SA (2015) Pyrolysis of napier grass in a fixed bed reactor: effect of operating conditions on product fields and characteristic. Bio Resources 10:6457–6478
Moore BD, Cheng S-H, Sims D, Seemann JR (1999) The biochemical and molecular basis for photosynthetic acclimation to elevated atmospheric CO_2. Plant Cell Environ 22:567–582
Nsamba HK, Hale S, Cornelissen G, Bachmann R (2015) Sustainable technologies for small-scale biochar production—a review. J Sustain Bioenergy Syst 5:10–31
Paerl HW (1990) Physiological ecology and regulation of N_2 fixation in natural waters. Adv Microb Ecol 11:305–343
Peterjohn WT, Schlesinger WH (1990) Nitrogen loss from deserts in the south western United States. Biogeochemistry 10:67–79
Pimm SL (2001) The world according to Pimm. McGraw-Hill, New York
Qiu B, Gao K (1999) Dried field populations of *Nostoc flagelliforme* (Cyanophyceae) require exogenous nutrients for their photosynthetic recovery. J Appl Phycol 11:535–541
Rao DLN, Burns RG (1990) The effect of surface growth of bluegreen algae and bryophytes on some microbiological, biochemical, and physical soil properties. Biol Fertil Soils 9:239–244
Reynolds R, Belnap J, Reheis M, Lamothe P, Luiszer F (2001) Aeolian dust in Colorado Plateau soils: nutrient inputs and recent change in source. Proc Natl Acad Sci 98:7123–7127
Rogers SL, Burns RG (1994) Changes in aggregate stability, nutrient status, indigenous microbial populations, and seedling emergence, following inoculation of soil with *Nostoc muscorum*. Biol Fertil Soils 18:209–215
Rogers L, Gallon J (1988) Biochemistry of the algae and cyanobacteria. Clarendon Press, Oxford
Rossi F, Li H, Liu Y, De Philippis R (2017) Cyanobacterial inoculation (cyanobacterisation): perspectives for the development of a standardized multifunctional technology for soil fertilization and desertification reversal. Earth-Sci Rev 171:28–43
Scarlett N (1994) Soil crusts, germination and weeds—issues to consider. Vic Nat 111:125–130
Schwartzman DW, Volk T (1989) Biotic enhancement of weathering and the habitability of earth. Nature 340:457–460
Shackley S, Carter S, Knowles T, Middelink E, Haefele S, Sohi S, Cross A, Haszeldine S (2012) Sustainable gasification–biochar systems? A case-study of rice-husk gasification in Cambodia, part I: context, chemical properties, environmental and health and safety issues. Energy Policy 42:49–58
Sharkawi H, Yamamoto S, Honna T (2006) Rice yield and nutrient uptake as affected by cyanobacteria and soil amendments—a pot experiment. J Soil Sci Plant Nutr 169:809–815
Singh RN (1950) Reclamation of 'Usar' lands in India through blue green algae. Nature 165:325–326
Singh JS (2014) Cyanobacteria: a vital bio-agent in eco-restoration of degraded lands and sustainable agriculture. Clim Change Environ Sustain 2:133–137
Singh JS (2015) Microbes: the chief ecological engineers in reinstating equilibrium in degraded ecosystems. Agric Ecosyst Environ 203:80–82
Singh JS, Kumar A, Rai AN, Singh DP (2016a) Cyanobacteria: a precious bio-resource in agriculture, ecosystem, and environmental sustainability. Front Microbiol 7:529
Singh JS, Koushal S, Kumar A, Vimal SR, Gupta VK (2016b) Book review: microbial inoculants in sustainable agricultural productivity- Vol. II: Functional Application. Front Microbiol 7:2105
Singh C, Tiwari S, Boudh S, Singh JS (2017a) Biochar application in management of paddy crop production and methane mitigation. In: Singh JS, Seneviratne G (eds) Agro-environmental sustainability: vol-2: managing environmental pollution. Springer, Cham, pp 123–146
Singh C, Tiwari S, Singh JS (2017b) Impact of rice husk biochar on nitrogen mineralization and methanotrophs community dynamics in paddy soil. Int J Pure Appl Biosci 5(5):428–435
Singh C, Tiwari S, Singh JS (2017c) Application of biochar in soil fertility and environmental management: a review. Bull Environ Pharmacol Life Sci 6(12):07–14

Singh C, Tiwari S, Gupta VK, Singh JS (2018) The effect of rice husk biochar on soil nutrient status, microbial biomass and paddy productivity of nutrient poor agriculture soils. Catena 171:485–493
Singh JS, Kumar A, Singh M (2019a) Cyanobacteria: a sustainable and commercial bio-resource in production of bio-fertilizer and bio-fuel from waste waters. Environ Sustain Indic 3–4:100008
Singh C, Tiwari S, Singh JS (2019b) Biochar: a sustainable tool in soil 2 pollutant bioremediation. In: Bharagava RN, Saxena G (eds) Bioremediation of industrial waste for environmental safety. Springer, Cham, pp 475–494
Smith SD, Strain BR, Sharkey TD (1987) Effects of CO_2 enrichment on four Great Basin grasses. Funct Ecol 1:139–143
Sohi S, Krull E, Lopez-Capel E, Bol R (2010) A review of biochar and its use and function in soil. Adv Agron 105:47–82
Srinivasarao C, Gopinath KA, Venkatesh G, Dubey AK, Wakudkar H, Purakayastha TJ, Pathak H, Jha P, Lakaria BL, Rajkhowa DJ, Mandal S, Jeyaraman S, Venkateswarlu B, Sikka AK (2013) Use of biochar for soil health enhancement and greenhouse gas mitigation in India. NICRA Bulletin, Hyderabad, pp 1–51
St. Clair LL, Johansen JR, Webb BL (1986) Rapid stabilization of fire-disturbed sites using a soil crust slurry: inoculation studies. Reclam Reveg Res 4:261–269
Strong CL, Bullard JE, Burford MA, McTainsh GH (2013) Response of cyanobacterial soil crusts to moisture and nutrient availability. Catena 109:195–202
Tiedemann AR, Lopushinsky W, Larsen HJ Jr (1980) Plant and soil responses to a commercial blue-green algae inoculant. Soil Biol Biochem 12:471–475
Tiwari S, Singh C, Singh JS (2018) Land use changes: a key ecological driver regulating methanotrophs abundance in upland soils. Energy Ecol Environ 3(6):355–371
Tongway DJ, Ludwig JA (1996) Rehabilitation of semiarid landscapes in Australia. I. Restoring productive soil patches. Restor Ecol 4:388–397
UNEP/WMO (2002) Executive summary (final): scientific assessment of ozone depletion: 2002. Scientific assessment panel of the montreal protocol on substances that deplete the ozone layer. United Nations, New York
Van den Ancker JAM, Jungerius PD, Mur LR (1985) The role of algae in the stabilization of coastal dune blowouts. Earth Surf Process Landf 10:189–192
van Straalen NM (1998) Evaluation of bio-indicator systems derived from soil arthropod communities. Appl Soil Ecol 9:429–437
Venkataraman GS (1972) Algal biofertilizers and rice cultivation. Today and Tommorrow's, New Delhi
Venkatesh G, Korwar GR, Venkateswarlu B, Gopinath KA, Mandal UK, Srinivasarao C, Grover MT (2010) Preliminary studies on conversion of maize stalks into biochar for terrestrial sequestration of carbon in rainfed agriculture. National Symposium on Climate Change and Rainfed Agriculture, CRIDA, Hyderabad, pp 388–391
Verheijen F, Jeffery S, Bastos AC, Velde MVD, Diafas I (2009) Biochar application to soils—a critical scientific review of effects on soil properties, processes and functions. EUR 24099 EN Office for the Official Publications of the European Communities, Luxemburg, p 149
Verrecchia E, Yair A, Kidron GJ, Verrecchia K (1995) Physical properties of the psammophile cryptogamic crust and their consequences to the water regime of sandy soils, north-western Negev Desert, Israel. J Arid Environ 29:427–437
Walter MR, Bauld J, Brock TD (1976) Microbiology and morphogenesis of columnar stromatolites (Conophyton, Vacerrilla) from hot springs in Yellowstone National Park. In: Walter MR (ed) Stromatolites. Elsevier, Amsterdam, pp 273–310
Wu L, Zhu Q, Yang L, Li B, Hu C, Lan S (2018) Nutrient transferring from wastewater to desert through artificial cultivation of desert cyanobacteria. Bioresour Technol 247:947–953
Wullstein LH (1989) Evaluation and significance of associative dinitrogen fixation for arid soil rehabilitation. Arid Soil Res Rehabil 3:259–265

Yao Y, Gao B, Inyang M, Zimmerman AR, Cao X, Pullammanappallil P, Yang L (2011) Biochar derived from anaerobically digested sugar beet tailings: characterization and phosphate removal potential. Bioresour Technol 102:6273–6278
Yargicoglu EN, Sadasivam BY, Reddy KR, Spokas K (2015) Physical and chemical characterization of waste wood derived biochars. Waste Manag 36:256–268