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REVIEW

Potentials of the microalgae inoculant in restoration of biological soil crusts to combat desertification

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Abstract The world is presently faced to the many calamities, mainly the increased and rapidly developing environmental changes, soil degradation as an example of such environmental problems which is correlated with the destructive effects of the sandstorms. Biological soil crust (BSC), a main component of soil, has various environmental functions including reduction in the erosion by increasing soil stability and providing a sanctuary for the growth of the taxa and vascular plants communities. Destruction of BSC, which naturally can be recovered slowly in a long time processes, contributes to the desertification and other environmental catastrophes. Therefore, accelerating the BSC recovery both the quality and the quantity of the crust development, especially in the desert areas, is of the prime interest. Recent advances in the BSC restoration have provided an immense potential for emulating the natural restoration methods mainly through providing soils with inoculant. This paper reviews the present restoration-based procedures for the biological soil crust restoration practice. The main landmarks are presented and highlighted including strain(s) selection and development, mass biomass production, inoculum preparation, soil inoculation, soil augmentation, nurseries, and crust succession monitoring and control. The review also introduces several successful case studies in the USA and the Republic of China. Thereafter, the paper briefly documents the future directions of the research and technologies. Development of a restoration system through the application of the microalgae inoculant is an encouraging aspect for accelerating the BSC recovery of the arid and semi-arid areas. However, further researches will help to establish and consolidate the potential of the microalgae cells and their application in desertification programs in large scales and in accordance with principles and requirements mandated by economic standards.

Keywords Biotechnological productivity · Erosion control · Microalgal mat · Soil community restoration · Soil health

Introduction

Biological soil crust (BSC) has been the subject of interest of scientist from different science sectors, governments, communities, and international organizations such as United Nations (UNCCD 2015). The main reasons for such a high interest in BSC are the function, the vital role that it plays in the environment, along with the impacts that its disturbance would have on human life which threatens both the current, and the future lives on earth (UNCCD 2015). BSC is commonly defined as the outer cohesive thin horizontal ground cover, which is associated along with the living constituent that plays a vital ecological supporting roles such as protecting and stabilizing the soil against water and wind erosive forces, especially in the arid and semi-arid areas (Mor-Mussery et al. 2015).

Annually, a large scale and increasing amounts of environmental disturbances happen because of the direct or indirect disturbances in the global soil crust (Rosentreter et al. 2007). Several factors that cause BSC disturbances include climate change, soil degradation, desertification, vegetation depletion, drought, and low precipitation (i.e., rainfall) are among such factors. Loss of BSC and its

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destruction results in loss of its ecological functions leading to the environmental consequences such as sand storms, reduction in soil stability, reduction in nitrogen and carbon fixation, water-related activities and effects on other soil microorganisms, and vascular plants will occur. The ultimate consequences of these destructive events may affect health, economic and other aspects of human life, or in the worse scenario, there may not be any chance of adjustment left forever (Field et al. 2010). Both the natural causes and human activities are the principal drivers of the processes of BSC degradation and desertification. In this regard, artificial restoration of the BSC may help to put an end and help the management of the desertification.

The various ecological functions of the BSC have been evidenced (Abdel-Raouf et al. 2012) through many functions that have been attributed to the BSC in practice including soil erosion reduction and control (Belnap et al. 2003). BSC performs its influence by aggregating unconsolidated soil particle both by the physical net and/or by releasing chemical substances such as polysaccharides (Abdel-Raouf et al. 2012). This function is partly executed by fixing the atmospheric carbon and nitrogen (Bu et al. 2013) and stabilization of the chemical elements such as chromium in the soil (Belnap et al. 2003), thereby influencing soil organic and inorganic nutrient materials (Belnap and Harper 1995). Further, BSC has a role in retaining soil moisture, so improving soil hydraulic conductivity (Belnap et al. 2003) and soil infiltration. BSC improves vegetation by helping germination of the seeds and inhibition of the weed, as well as protection against UV (Belnap et al. 2003; Lan et al. 2014a). BSC also has been used as an indicator of ecological integrity (Bowker et al. 2006).

The objective of this review article is to present a comprehensive review of the role of BSC and to provide a summary of the present methods of the BSC engineering, BSC restoration, and the challenges that might be encountered in this respect. The review mainly focuses on the crust microalgae as effective pioneer microorganisms in the restoration of the BSC. In addition, the main crust microalgae succession steps are explained and a number of successful implementation is introduced, accordingly. The article discusses the artificial BSC restoration following to an introduction, BSC definition, ecology, functions, roles, and the natural succession. This paper provides a critical review on microalgal-based BSC restoration. The main stages of strain(s) selection and development, mass production of microalgae, inoculant preparation, soil inoculation, soil augmentation, nurseries, and restoration process monitoring and controlling are highlighted. Challenges and future directions on BSC restoration with microalgae species are also outlined.

Ecology of BSC

Often, the term BSC is referred to a consortium of autotrophic and heterotrophic living organisms in the outer layer of the soil surface. They may also be called cryptogamic, cryptobiotic (Clegg 2001), microbiotic, microphytic, and micropgytic soil crusts or soil- and rock-surface communities (SRSCs) (Pointing and Belnap 2012). Structurally, BSC consists of numerous kind of species including prokaryotic cyanobacteria (Brostoff et al. 2005), diatoms, eukaryotic microalgae (Cardon et al. 2008), lichen, mosses, fungi (Grishkan et al. 2015), liverworts, bacteria (Mengual et al. 2014a), and other taxa. BSC may be subdivided based on its biotic components such as cyanobacteria and microalgae crust (Karsten and Holzinger 2014a, b), lichen crust (Wu et al. 2011), mosses crusts, fungi crust, and bacterial crusts (Wang et al. 2007). Table 1 represents some of the genera and species of the BSC community. Geographically, BSC occurs in various areas and extreme habitats of the earth surface such as arid, hot, and cold desserts with a thickness ranging from few millimeters to several centimeters (Belnap et al. 2001). However, the community types and proportional amounts of the biological components of the crusts vary in different ecosystem and climates (Pietrasiak et al. 2013).

The natural sequences of BSC community succession generally include the development of cyanobacteria and microalgae, lichen and mosses, which is followed by other organisms and vegetation (Belnap et al. 2001). Figure 1 shows the stages of the BSC succession. Once a mat of these organisms has become established, the diversity of species increases through different succession stages and steps toward completion of the process (Bowker et al. 2006). Therefore, in developing engineered plans and methods for BSC restoration, all succession steps such as field practice should be considered to meet the desired crust formation.

Conventional systems of BSC restoration

Several options are available to protect degraded crusts or accelerate the natural BSC restoration. Selection of the methods is mainly dependent on the location and the conditions of damaged crust. For example, in deserts with high speed winds, a frequently used conventional approach is wind shelter or check boards to provide protective conditions in the early crust development stages. In addition, land chemical mulching such as petrochemical is also used as pretreatments. Mulching inhibits soil erosion by providing a cover layer on the soil surface. However, the efficiency of the mulching is dependent on the mulch layer

Table 1 Examples of the most common genera and species of the microorganisms in the natural BSC communities

Cyanobacteria and microalgae (Belnap 1995; Hu et al. 2002; Rahmonov and Piatek 2007; Karsten and Holzinger 2014b)	Lichen (Belnap 1995; Rosentreter et al. 2007; Wu et al. 2011)	Mosses (Rosentreter et al. 2007; Lan et al. 2012, 2014a; Xiao et al. 2015)
Microcoleus vaginatus	*Fulgensia fulgens*	*Bryum arcticum*
Chroococcus minor	*Psora decipiens*	*Didymodon vinealis*
Chroococcus minutus	*Squamarina* spp.	*Campylopus paradoxus*
Chroococcus varius	*Toninia sedifolia*	*Tortella tortuosa*
Synechococcus aeruginosus	*Catapyrenium* spp.	*Neckera crispa*
Gloeocapsa atrata	*Diploschistes* spp.	*Sphagnum*
Merismopedia glauca	*Endocarpon* spp.	*Tortula* spp.
Microcoleous vaginatus Gom	*Collema* spp.	*Bartramia pomiformis*
Scytonema javanicum		*Dicranum scoparium*
Phormidium tenue		*Bryum argenteum*
Cylindrocapsa sp.		
Klebsormidium crenulatum		
Pinnularia borealis		
Stichococcus chlorelloides		
Stichococcus cf. *fragilis*		

thickness and its resistance to erosion factors such as UV radiation, temperature, and characteristics of the soil particles (Chalker-Scott 2007). The combined systems of the mulching and windbreaks/shelterbelts have also been reported for reducing wind erosion in desert areas. Figure 2 shows an example of soil surface preparation before inoculation. However, these methods have temporary or insufficient effects and therefore should be renewed periodically. Vegetation is a useful environmental-friendly method and as a part of all features for combating desertification (Bainbridge and Darby 2014). However, in a study conducted by Lan et al., they compared the treatment of shifting sand dunes with *Salix* (*mongolica*) planting with and without inoculation of the cyanobacteria in an 8 years period and have found that only when *Salix* was planted to fix the sand dunes, the sand surface was relatively stabilized within a short time. When soil texture and nutrition had not been improved, only a number of vascular plants could survive at this time. However, after inoculation of sand dunes with the cyanobacteria, the BSCs restoration provided not only a more stable soil surface but also a favorable nutritional condition for the survival and succession of vascular vegetation communities. Therefore, compared to the shifting sand dunes and the dunes fixed with *Salix* planting, the higher vegetation coverage, biomass, and diversity could become attainable when dunes are covered with BSCs (Lan et al. 2014b).

The potential applications of the engineered systems for restoration of the existing BSC have a wide spectrum. Possibly the main advantage would be the acceleration in the succession procedure, a process that normally happens very slowly in case of natural systems (Mor-Mussery et al. 2015). In addition, new restoration systems make the ability to design a real BSC for any required special restoration conditions possible (Büdel et al. 2014).

Generally, the process of natural BSC formation takes the following steps in a very long time (Campbell et al. 1989). In the primary step which normally happens in the first year, the sandy soil surface may become fixed by the bacteria adhering to the sand particles with exopolysaccharides (Paulo et al. 2012). Up to 4 years, the exposed crusts to the sandy surface would mainly be composed of the filamentous cyanobacterial communities that are dominated by the *Microcoleus* spp., which occurs as a cluster of filaments surrounded by a gelatinous sheath. The next step is the restoration of lichen and moss components. Establishment of the moss-dominated crusts is crucial for the establishment of the vegetation and restoration of the ecology (Rosentreter et al. 2007). The time course of each step may vary depending on the local situation and the biotic community such as annual rainfall, temperature, soil composition, and availability of autotrophic organisms. (Campbell et al. 1989). In addition, the natural BSC succession depends on the climate conditions, available species, as well as other ecological parameters. These parameters are out of control and therefore achievement of the desired BSC is almost impossible; however, the engineered BSC restoration may provide BSC design and implementation based on the site situations. This feasibility provides other alternatives for the BSC restoration in the arid and semi-arid areas as well as the subsequent vegetation with an accelerated process (Bowker 2007).

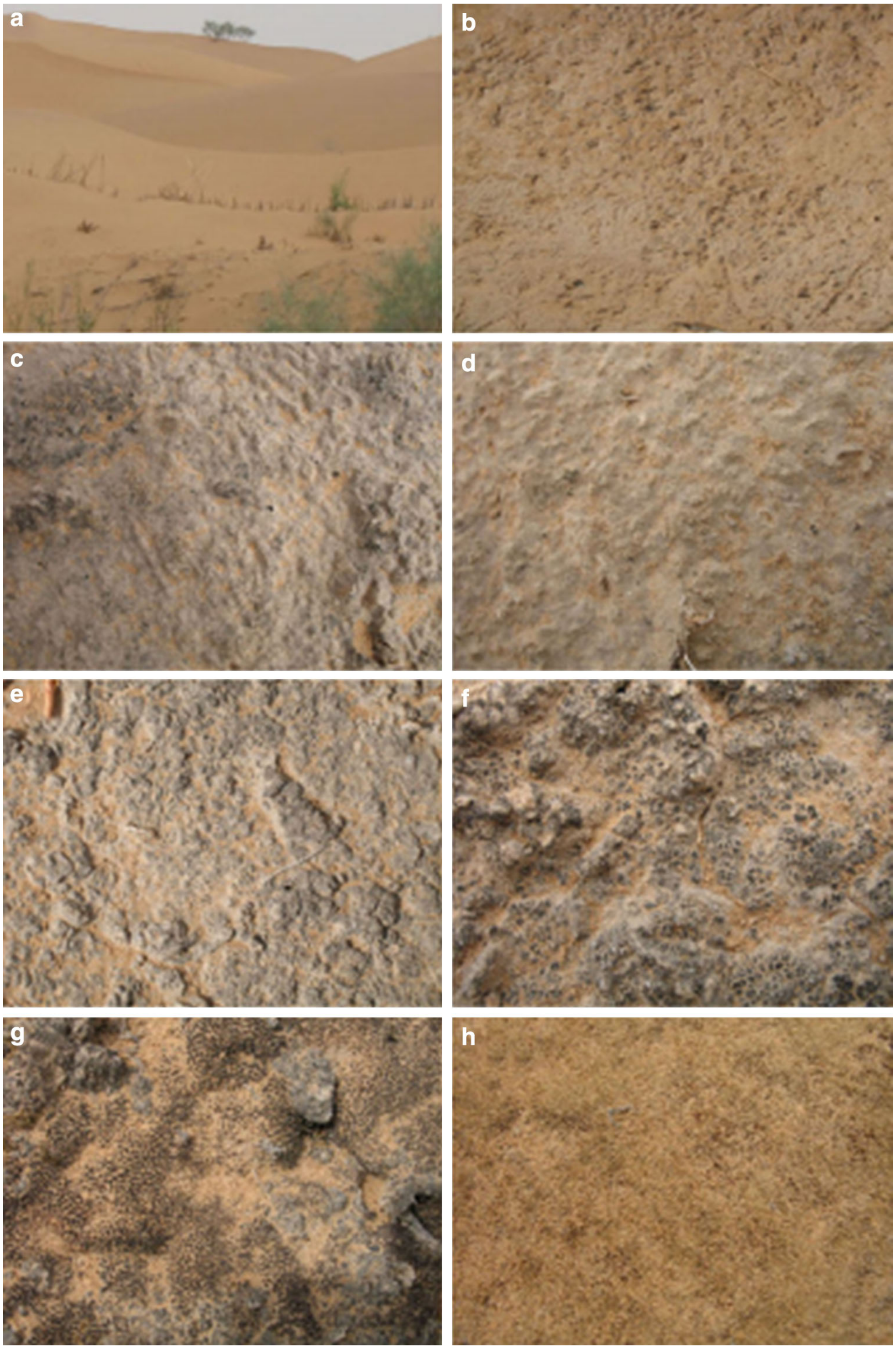

Fig. 1 Succession stages of the BSC: **a** moving sand dune, **b** algae crust, **c** algae-lichen crust, **d** algae-moss crusts, **f**, **g** lichen-moss crusts, **h** moss crust (Lan et al. 2012), respectively

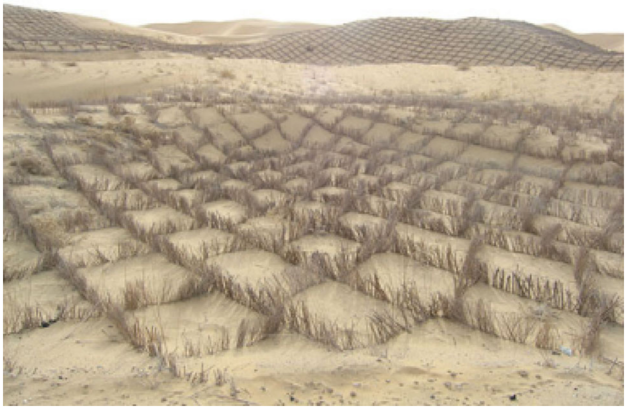

Fig. 2 Generally, land preparation is required before soil inoculation, to provide inoculant succession. *Picture* shows land preparation by shelter or check boards in China (Hu et al. 2012)

The general operation steps for the BSC restoration

The researches on the various BSC restoration concepts such as crust of microalgae, the crust of lichen, and the crust of mosses have been performed in the laboratory in addition to the field scale by various research groups (Xiao et al. 2015). These groups have often applied various techniques to their works in order to turn the unconsolidated sands into productive pasture or to accelerate the restoration of crust in the arid and semi-arid areas. The milestones in the restoration processes of the soil, as were identified and highlighted, might be divided and performed according to the following steps (Bu et al. 2013):

Criteria and restoration process design

Both biotic and abiotic criteria should be considered when an evaluation is taken under consideration for a BSC restoration plan. The main criteria in designing for a restoration plan includes definition of goals, determination of strategies, mode of operation (BSC restoration), thickness, crust development criteria, and distribution of BSC in the site (Liu et al. 2008). In addition, life cycle assessment and risk, possible combined options such as mulching, and implementation sequence stages are considered to be among these criteria. Other including factors are the required equipment and financial reserves, the ultimate site structure, capabilities and serviceability, and plans for monitoring and controlling including a list of present damaging factors, their influence and occurrence, and approaches for the modeling (Bowker et al. 2008). The main biotic parameters are present BSC community on the site, their pattern of distribution, required inoculant type and values, available options of inoculation, as well as feasible alternatives systems for massive production of the target biomass.

The main abiotic parameters are soil characteristics and topology, site climate condition including annual rainfall, temperature, humidity, and sunshine records as well as the possible available irrigation systems.

Preparation of the pure microalgae strain

The implementation process may start with strain preparation and development. Both pure microalgal culture and microalgae consortium of crust have been applied for BSC restoration in the laboratory and field studies (Lababpour et al. 2016). In some preliminary studies, the soil samples were harvested from a rich crust sites and inoculated into the new sites either directly or after dilution with water without further improving or cultivation in the open raceway or the closed photobioreactors (St. Clair and Johansen 1986). In the most published researches, mixed taxa were used for inoculation. For examples, moss components of the BSC have been used for BSC restoration by this method (Xiao et al. 2015). On the other hand, in other advanced technologies, the inoculant has been prepared by cultivation of the pure species in the open raceway systems and then was applied for inoculation (Liu et al. 2008). The strain preparation steps may include strain isolation and characterization by DNA extraction, amplification, and sequencing.

Figure 3 shows examples of the green algae isolated from desert habitats. In addition to taxonomic studies, diversity, physiology, and financial issues should also be subjected to the evaluations (Hu et al. 2012). Through, these evaluations and development of the methods were done along with other parameters including the effects of environmental parameters such as temperature, moisture, soil chemistry, and physical characteristics (Lin et al. 2013). In some studies, the applied microalgae strains were obtained from microalgae culture collections as a pure culture for BSC restoration studies (Rao et al. 2009).

Microalgae mass cultivation with high cell density

The selected species are mass cultivated in the open raceway or closed photobioreactors to obtain a large amount of the required biomass for inoculation. The open photobioreactors of up to 5 L bottles (Liu et al. 2008), 25L (Tan et al. 2012) and tank with the dimensions of $2 \times 2 \times 1.5\ m^3$ (Wang et al. 2009) and large raceway (Rao et al. 2009) were reported for microalgae biomass production. Two main mass cultivation systems for the photosynthetic microorganisms are the open and closed photobioreactors (Pulz 2001). The open raceway cultivation system was reported for the inoculation of the microalgae crust in the greenhouse (Rao et al. 2009). However, the growth rate of microalgae is heavily

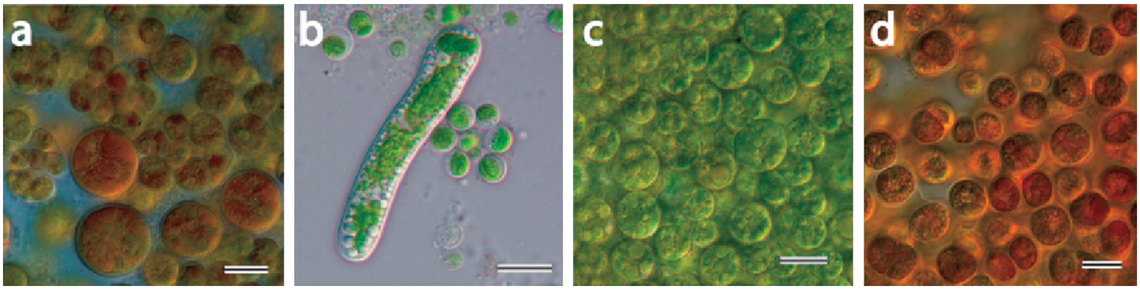

Fig. 3 Examples of the common green algae isolated from desert habitats: **a** *Scenedesmus rotundus* (*Chlorophyceae*); **b** *Cylindrocystis* sp. (*Zygnematophyceae*); **c** *Myrmecia* sp. (*Trebouxiophyceae*); and **d** *Chlorosarcinopsis* sp. (*Chlorophyceae*). *Scale bar* is equal to 10 μm (Cardon et al. 2008)

Table 2 Advantages and disadvantages of the liquid and solid inoculant preparation and field inoculation

	Advantages	disadvantages
Liquid inoculant	It is possible to include required micronutrients Preparation is easier compare to solid ones	Field inoculation timing is very important Storage is difficult Handling and transportation are difficult
Solid inoculant	Can be used in a loner time period compare to liquid ones Handling is easy	Field inoculation timing is not very important A carrier is required

dependent on the cultivation conditions. In addition, the mode of cultivation (autotrophic, heterotrophic, or mixotrophic) is options for cultivation which still remain to be developed for the crust restoration.

Inoculant formulation and dosage

The produced biomass might directly be used as an inoculant in suspension or it might be used for further processing before it could be used (Sears and Prithiviraj 2012). Both of these systems have advantages and disadvantages. Table 2 lists the main advantages as well as disadvantages of the raw inoculant systems. The processes of dry inoculant preparation may include biomass harvesting, drying, and the addition of some additives to serve as a protector (Hu et al. 2012). Preparation of a large amount of the required inoculum with the desired quality and purity is attainable through the cultivation of the species; an approach that eliminates the need for extraction of the inoculums from the limited natural sources. Table 3 represents a summary of the features of the source of inoculants for biomass production and application to the soil.

Soil inoculation

Both microalgal suspension and the dried microalgal biomass in the form of powder (normally a mixture of microalgae) have been applied as the soil inoculant (Hu et al. 2012). The microalgae inoculate contain viable cells and have the ability to germinate in the soil. The microalgae inoculant may be applied by tankers or agricultural aircraft (Hu et al. 2012; Sears and Prithiviraj 2012). In the case of direct application of the liquid inoculant, the inoculum concentration, timing, inoculum media, etc., should be considered before application in the field. The application of the liquid inoculant has been investigated in various concentrations and reported in the literature (Table 3). For example, a research group has used several concentrations of the microalgae inoculum and has found that 0.2 kg/ha of soil would be the best concentration of inoculation (Mengual et al. 2014b). Compare to dried inoculant, the direct application of the liquid inoculant does not need to a costly process of biomass harvesting, separation, and thickening, therefore, can be performed with less technological challenges and less expense.

On the other word, application of the dried biomass powder are easier in operation, simpler in transportations, and more stable for keeping for a long time. However, they are more expensive and their activity is always less effective compared to the liquid inoculants (Hu et al. 2012).

Soil augmentation

In the field practical operations, the soil may be supplemented with the chemical nutrients (Liu et al. 2015). Using such fertilizers which support growth of inoculated viable cells depends on the soil characteristics as well as environmental climate conditions (Bertrand et al. 2014). In addition, the feasibility and availability of the fertilizers, as well as their cost, are important parameters that should be

Table 3 Specifications of the applied liquid inoculant in the soil restoration programs so far

Inoculation method	Inoculated starter form	Value	References
Mosaic	Liquid as spray	0.3 mg Chl a/g dry soil	Liu et al. (2008)
Pure		1.6 g DCW/m2	Wang et al. (2009)
Mosaic	Spray	500 subsoil/500 mL H2O	St. Clair and Johansen (1986)
Microcoleous vaginatus	Sprinkling irrigation	1.0 mg in 2 × 15 m	Hu et al. (2002)

taken into the account when applications of the supplementary nutrients are desired (Khan et al. 2015). To improve the rate of BSC restoration in the field, recently biochar has been used in six concentration levels in a laboratory scale in order to investigate the effects of the supplementary biochar materials. Researchers have found that addition of 2 % biochar shows the highest influence on the microalgae concentration and the soil stabilization (Meng and Yuan 2014).

Nurseries

To achieve a successful BSC restoration technology, it is necessary to know how various environmental factors influence BSC community at a site. A study on the effects of environmental factors: shade, water, and concentrations of the minerals such as nitrogen, phosphorous, potassium, and calcium during a 4-month period in Sonoran desert, USA, has resulted in the following order of effects:

$$\begin{aligned}\mathrm{NH_4NO_3} &= \text{water frequency} > \text{shading} > \mathrm{CaCO_3}\\ &= \mathrm{KH_2PO_4}.\end{aligned}$$

Soil water content was the primary positive factor (Bu et al. 2014). In addition, it is necessary to know how the inoculated communities interact with the biotic and abiotic factors and the best-matched strain for the specific condition. The interaction between soil cyanobacteria and the environmental parameters have been studied and reviewed over a long time period (Gómez et al. 2012; Raanan et al. 2015). From these results, it could be concluded that water availability and the related factors, such as frequency of rainfall, soil moisture content, together with the clay, and the amount of available phosphate in the soil, have the greatest influence on the cyanobacterial biomass concentration. Several other nursery challenges are soil cracking, crust, soil layers, thickness, cellular infiltration into the soil, adherence of the cells to the soil particles, etc.

Monitoring and control of BSC dynamics

The monitoring of BSC development could be performed by a number of methods such as visual, light and electronic microscopic assays, molecular methods, or estimated by computer simulations (Pelizer and Moraes 2014). Visual evaluation generally considers the color and morphology of the soil surface and compares it with the standard indexes (Belnap et al. 2008). In the other words, the analytical and molecular monitoring of the crust succession may include direct measurement of the pigments such as chlorophyll and molecular structure of the organisms. Measurement of the soil physical and chemical parameters is also common in the evaluation of BSC dynamics (Hu et al. 2003). For example, wind tunnel test is a method for evaluation of the soil stability which could be performed in the laboratory wind tunnels or in the field with a portable wind tunnel test apparatus (Zhao et al. 2010). The advanced remote crust chlorophyll monitoring system is an option that was reported for application in large areas of evaluation (Bu et al. 2013). A rational BSC monitoring will ensure a successful succession and reduction in the soil erodibility in the real field (Raggio et al. 2014).

Successful case studies and challenges

Early BSC restoration practices in a laboratory scale were performed in the USA during the 1980s (St. Clair and Johansen 1986). Restoration was also practiced in the field in Colorado Plateau, Sonoran Desert, Mojave Desert, Chihuahuan Desert, Great Basin Desert, Florida shrubland, Massachusetts seashore, Oregon prairies, Wyoming steppe, Ohio, Michigan sand, and New Mexico (Bu et al. 2013). In the China, a widespread successful programs have been performed in the Kubuqi Desert, Hotq dessert, Loess plateau, Gurbantunggut Desert, Tengger Desert, Horqin Desert, Inner Mongolian steppe and Mu Us Desert during 2000s in the field area of up to 200 hectares supported by government and the United Nation (Bu et al. 2013). They have demonstrated a successful international cooperation to combat desertification. Results showed that cyanobacterial and algal soil coverage was increased up to 48.5 % and a total of 14 cyanobacterial and algal species were identified at the termination of inoculation experiment. The thickness, compressibility, and chlorophyll content of the biological crusts increased with inoculation time of 3–8 years; moss species appeared in

Table 4 Examples of the commonly studied BSC sites and restoration around the world

Vicente Blanes Ecological Park in Molina de Segura	southeast Spain	Mengual et al. (2014b)
Vicente Blanes Ecological Park in Molina de Segura	Southeast Spain	Mengual et al. (2014a)
Vicente Blanes Ecological Park in Molina de Segura	Southeast Spain	Mengual et al. (2014b)
Vicente Blanes Ecological Park in Molina de Segura	Southeast Spain	Schoebitz et al. (2014)
Arches National Park	Moab, Utah, USA	Belnap and Harper (1995)
McMurdo Dry Valleys	South pole	McKnight et al. (2007)
Colorado Plateau region	South-eastern Utah, USA	Harper and Belnap (2001)
GSENM	Southern Utah, USA	Bowker et al. (2008)
Page	Arizona, USA	Bowker et al. (2008)
Naiman County, eastern part of Inner Mongolia	Republic of China	Zhao et al. (2010)
Arches National Park	Moab, Utah, USA	Belnap (1995)
Zhongwei County in the Ningxia Hui Autonomous Region	Republic of China	Grishkan et al. (2015)
southern part of the Pustynia Błędowska desert	Poland	Cabala and Rahmonov (2004)
Sahel area	Western Niger	Bertrand et al. (2014)
Western Mojave Desert	Los Angeles, CA	Brostoff et al. (2005)
western Negev Desert	Israel	Kidron et al. (2008)
Dugway Proving Grounds	Salt Lake City, Utah, USA	Belnap et al. (1993)
Coachella Valley	California, USA	Bainbridge and Darby (2014)
	South-eastern Utah, USA	Bowker et al. (2006)
Bocabec Bay	Southern New Brunswick, Canada	Tracy and South (1989)
Dalateqi county, Inner Mongolia	Republic of China	Wang et al. (2009)
Sonoran Desert near Phoenix	Arizona, USA	Bu et al. (2014)
Tengger Desert	Ningxia Hui Autonomous Region of China	Hu et al. (2002), (Liu et al. (2008)
	Southern Australia	Briggs and Morgan (2012)
Sonoran Desert	Southwestern United States	Bu et al. (2014)
Gurbantunggut Desert	Republic of China	Zheng et al. (2011)

the second year and cyanobacterial inoculation has resulted in an increased organic carbon in addition to the total nitrogen of the soil. The total salt, calcium carbonate, and electrical conductivity of the soil were also increased after inoculation. Diverse vascular plants communities such as *Artemisia ordosica* Krasch species were established after cyanobacterial inoculation on the windward and leeward slope surface of the dunes, respectively (Wang et al. 2009).

The American company, Soil Technologies Corp. has patented its technology and released its product into the market with a brand name of MICROP$^{®}$ (Soil Technologies Corp. 2015). The company uses the dried powder inoculant instead of the liquid suspension for soil inoculation. According to the company's report, the usefulness of the product was approved by the farmers that have used the product. In addition, TerraDerm Foundation has developed biological soil crust starter culture formulation technology with the trade names of TerraDerm and Agri-Derm (Sears and Prithiviraj 2012). They have tested their products for soil stabilization and fertility in the USA and Africa. Figure 4 shows the BSC restoration technology procedure presented by TerraDerm Foundation. They used agricultural aircraft for inoculation of the soil surface. They claimed successful BSC restoration in the used areas (Sears and Prithiviraj 2012). Table 4 presents several examples of the BSC practice sites around the world.

BSC succession is a long time dependent dynamic process in the field practice (Kumar and Adhikary 2015). In addition, the scale of world arid and semi-arid areas is 33.6–52.3 % of the terrestrial land surface and is growing fast (Reynolds et al. 2007). Therefore, the potential method should promote large landscape-scale applications and in an economical fashion. Hopefully, with the current rapid advancement in the microalgae-related technologies, the economic feasibility of the artificial BSC restoration systems is very close to the reality and attainable. Furthermore, any BSC restoration program requires management of the socioeconomic-related affairs of nearby communities which affect any restoration programs and should be considered before and during restoration program (Reynolds et al. 2007).

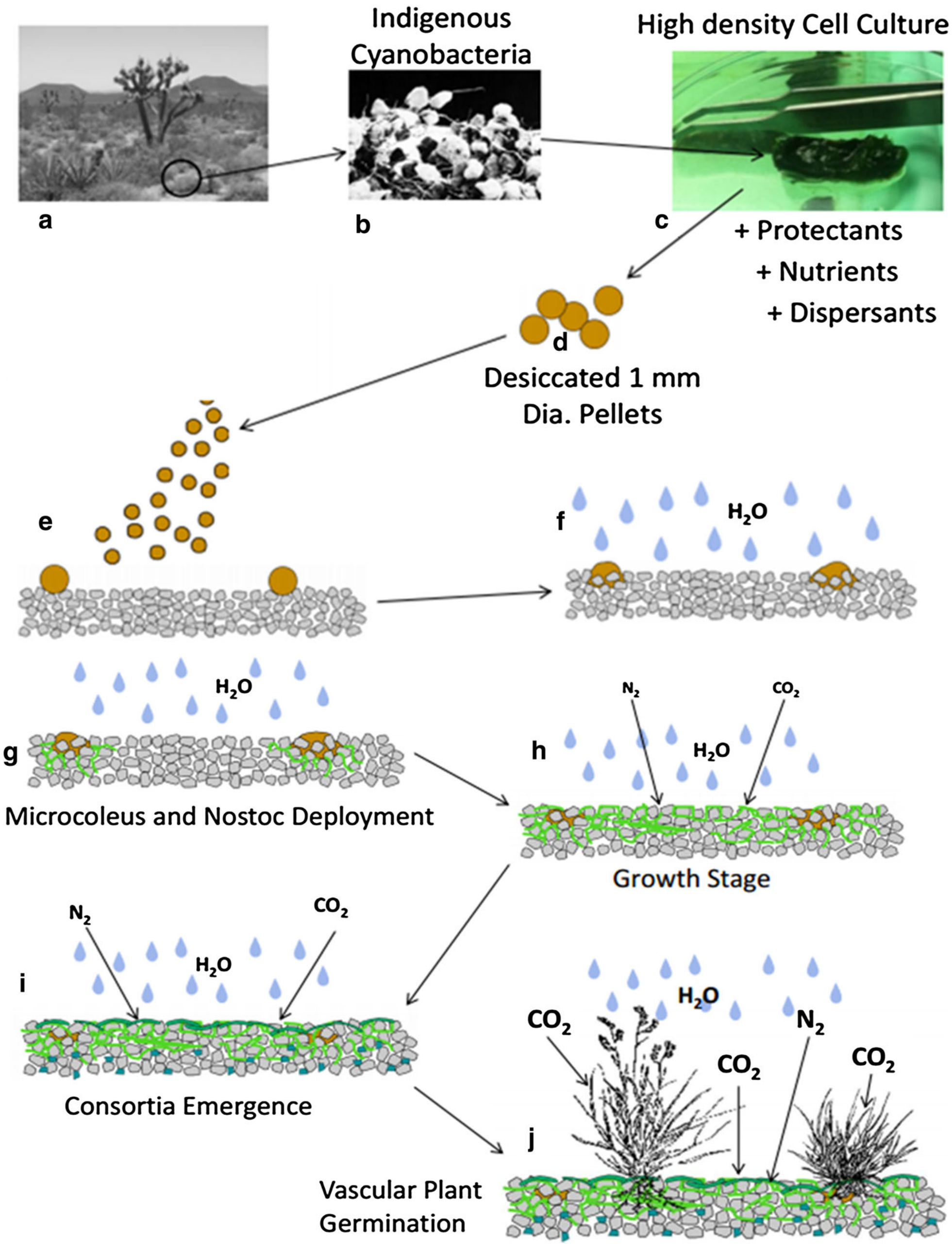

Fig. 4 BSC succession stages as presented by the TerraDerm Foundation; **a** strain isolation from the natural sources; **b** strains purification and characterization stages; **c** mass cultivation of selected microorganisms in the artificial systems; **d** solid inoculant preparation processes; **e** aerial soil inoculation; **f** irrigation; **g** deployment; **h** growth stage; **i** consortia emergence; and **j** vascular plant germination (Sears and Prithiviraj 2012)

Conclusion and future directions

The main objective of the present review was to discuss the potential of the engineered BSC restoration technologies especially crust microalgae for recovery of the arid and semi-arid areas. These systems lead to an accelerated BSC recovery compared to the natural BSC long-term restoration systems. For large-scale restoration of BSC, mass production of microalgae in the open raceway or closed photobioreactors systems could be a cost-effective option for providing large scale required inoculant. However, the efficiency of cultivation systems are still low and need further technological developments before they can be used in the large-scale field practices in the desertification programs.

Despite the technological challenges related to the cultivation, inoculation and nurseries, the potential benefits of the crust microalgae technologies are apparent.

Undoubtedly, implementation of the crust restoration in the arid and semi-arid areas presents major opportunities for the future research. Lastly, data on the effectiveness of the artificial BSC restoration in different soil types such as desserts, for instance, are needed to gain a realistic understanding of the impacts of microalgae strains on the BSC development and soil stabilization. In addition, the recent serious environmental and human health-related problems that are the consequence of the soil destruction are the leading causes and concerns for a drastic environmental change and its outcome such as sand-storm in dryland areas of the world, especially the Middle Eastern as well as African countries. This issue makes an urgent requirement for further researches and implementation of the BSC restoration projects, a subject which has been neglected so far.

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