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Soil treatment using microbial biopolymers for anti-desertification purposes

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ABSTRACT

Desertification and soil degradation are becoming more serious due to global warming and concurrent extreme climate events. Although anti-desertification efforts have been mounted worldwide, most undertakings have shown poor performance because of failure to consider soil and geotechnical aspects. Soil erosion is accelerated by reductions in soil cohesion and water retention due to the transfer of fine particles from the original ground. Thus, soil internal cohesion must be recovered to ensure effective and reliable anti-desertification attempts. In this study, soil treatment using biopolymers is suggested as an alternative method to prevent soil erosion and for revitalization, taking into consideration engineering and environmental aspects. Even as a relatively small part of the soil mass (i.e., 0.5–1.0%), biopolymers in soil have the positive potential to significantly reduce the erodibility of soil by enhancing inter-particle cohesion. Moreover, biopolymer treatment also improves both vegetation germination and soil water retention characteristics against evaporation, and therefore can provide suitable environments for plants and crops used as a desertification countermeasure in arid and semi-arid regions where annual precipitation is limited. We suggest combining biopolymers with pre-existing anti-desertification efforts (e.g., afforestation and windbreaks) on desert fronts (i.e., boundaries between arid and semi-arid regions) for best efficiency.

1. Introduction

Annually, 12 million ha of the Earth's landmass (the same size as the state of Mississippi) turn into new deserts (United Nations Environment Programme, 2006). Currently, more than 30% of the Earth's dry land is affected by desertification, and this trend, transforming land into deserts, is expanding into semiarid regions. From the perspective of geoscience and geotechnical engineering, the critical factors affecting land erosion and desertification are limited precipitation and the removal of soil particles (especially fines < 0.002 mm) (Schlesinger et al., 1990).

The mechanism of soil erosion is generally known to be an interaction between the drag force of fluids (e.g., wind or water) and soil shear resistance (Morgan, 2005). Although water erosion is the largest source of global soil erosion, wind erosion is the major geomorphological force in desertified regions (Blanco and Lal, 2008). Airborne particles produced by wind erosion consist of high amounts of clay minerals (Gillette and Walker, 1977), and most global aeolian dust originates from North Africa (58%), the Middle East (12%), and West China (11%), regions which directly coincide with desertified areas (Tanaka and Chiba, 2006; UNEP/RIVM, 2004). Nonetheless, water erosion is another serious problem, because the immediate intensity of soil erosion produced by water is reported to be higher and more critical than wind erosion in areas that are undergoing desertification (e.g., grasslands in semi-arid regions) (Breshears et al., 2003). Moreover, the total amount of erosion produced by water is reported to be two times larger than the amount affected by wind erosion worldwide (Lal, 1995). Therefore, not only control of aeolian dust, but also enhancement of soil resistance to water erosion (i.e., undrained shear strength) should be considered in desertification prevention approaches.

Generally, greater amounts of clayey particles and higher organic content in soils promote higher erosion resistance, by enhancing structural binding and aggregation between soil particles (Blanco and Lal, 2008). An investigation of the particle size distributions and compositional data from 88 sites around the world (Fig. 1) shows that desertification has a high correlation with change in soil composition (i.e., loss of fine particles). Soils from 'stable regions' (i.e., low vulnerability, such as tropical or rain forests) are well graded and have very fine soil contents,

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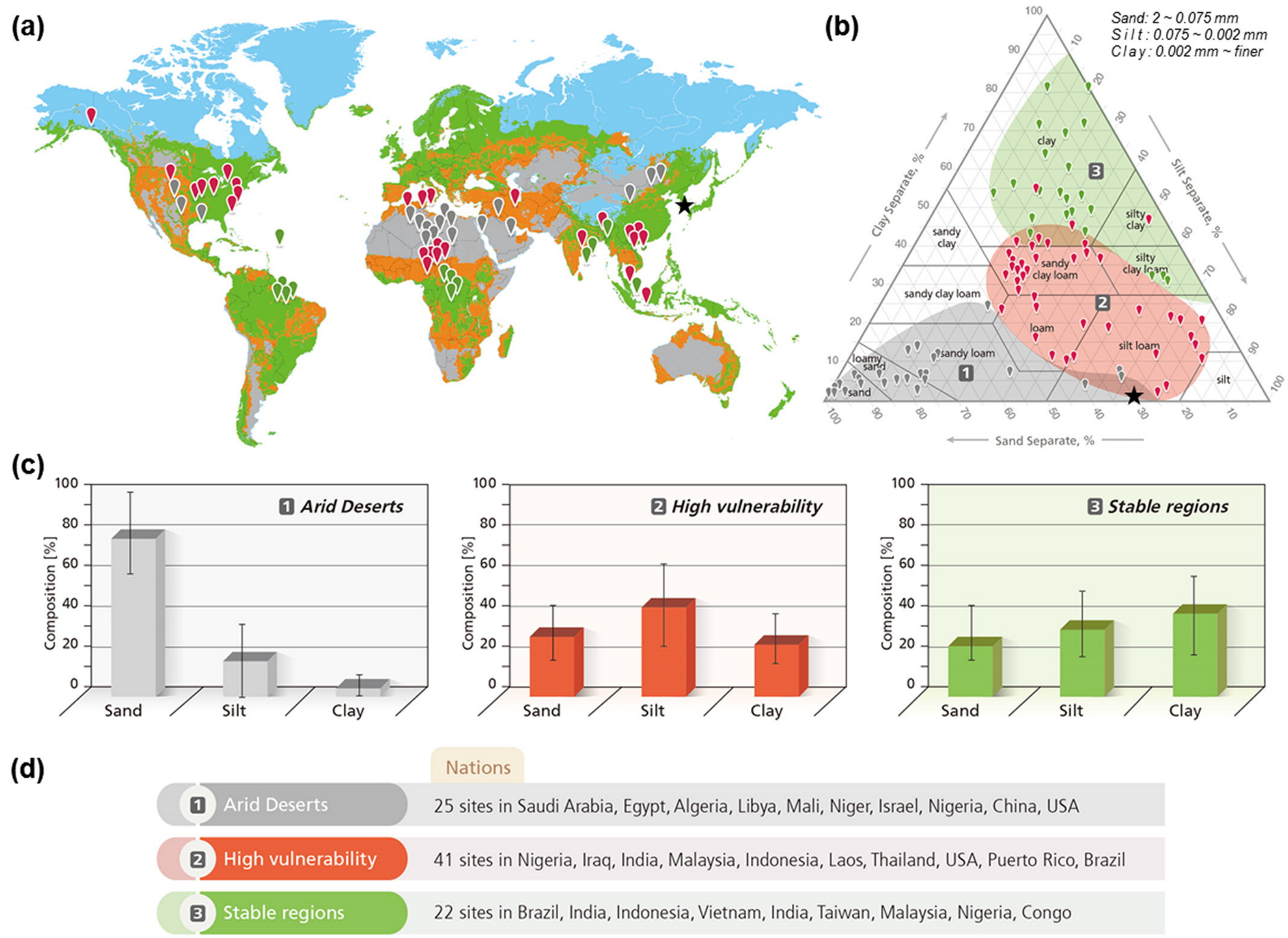

Fig. 1. Relationship between desertification and soil composition transfer (★ indicates the soil used for laboratory testing in this study). (a) Desert vulnerability map. (b) Tripartite graph of soils collected from 88 sites. (c) Soil composition. (d) Nations with sites investigated.

while 'arid desert' soil becomes poorly graded with a biased soil component (i.e., sand).

The classification of 'arid deserts', 'high vulnerability', and 'stable regions' comes from the desert vulnerability map (United Nations Environment Programme et al., 1997) which classifies regions in terms of destruction of vegetal cover, ground erosion, reduction in surface flow, loss of soil productivity, etc. (Reich et al., 1999). The evolution of soil composition illustrated in the soil tripartite graph (Fig. 1) shows that desertification involves the transformation of well graded soil in stable regions into poorly graded soil (sand content higher than 50%) due to the loss of fine soil particles (annually 3–80 tons/ha in highly vulnerable regions) by water or wind erosion (Balba, 1995; Reich et al., 1999). Thus, the loss of clay particles (i.e., decrease of interparticle cohesion of soil) is the most critical problem in desertification. This explains why deserts are generally composed of sand and rocky surfaces with a sparseness of vegetation.

In terms of geoscience the recovery of soil strength by enhancing soil cohesion is therefore very important as a countermeasure to desertification. However, in practical terms, it is impossible to supplement the sands of all arid or semi-arid regions with cohesive fine soils. As an alternative, we present herein a new concept to enrich soil cohesion using biological materials (i.e., biopolymers).

Sugar based biopolymers (polysaccharides) produced by microorganisms are widely used in food (e.g., dairy products) and medical industries. Previous studies have shown the possibility of using biopolymers to reduce soil erosion (Agassi and Ben-Hur, 1992; Gu and Doner, 1993; Orts et al., 2000), strengthen soil (Chang and Cho, 2012; Chang et al., 2015), and control water infiltration (Ben-Hur and Letey, 1989; El-Morsy et al., 1991) in agricultural and geotechnical practices. This paper reports several experimental studies which were performed to obtain a better understanding of the effects of biopolymer treatment for comprehensive soil revitalization and prevention of desertification. When a soil was mixed with even a little amount of biopolymer, we found that the presence of these hydrophilic biopolymers produced interesting soil characteristics, especially relevant in terms of anti-desertification.

2. Materials and methods

2.1. Microbial excrements: biopolymers

In this study, commercial β-glucan (Polycan™, β-1,3-glucan from *Aureobasidium pullulans*) and xanthan gum (CAS No. 11138-66-2) were used to represent high molecular chain type, and gel (gum)-forming (i.e., hydrocolloid) type biopolymers, respectively. The β-glucan (molecular weight: 1000–2000 kDa) from *A. pullulans* is a homopolysaccharide consisting of β-1,3-glycosidic linked glucose units with some branched β-1,6-glucose, which can exceed 150–5400 kDa depending on the continuity of glucosidic bonding between D-glucose monomers (Hamada, 1990). In contrast, anionic xanthan gum (molecular weight: 2000–20,000 kDa) secreted by *Xanthomona campestris* is a heteropolysaccharide with a primary structure consisting of repeated pentasaccharide units formed by two glucose units, two mannose units, and one glucuronic acid unit, which undergo self-aggregation through hydrogen bonding, rendering high viscosity gels (García-Ochoa et al., 2000).

2.2. Soil

Korean red yellow soil, which is classified as inorganic silty loam (*ML*) due to its particle composition (i.e., sand 30%, silt 68%, and clay 2%; R_{200} = 30%), chemical characteristics (i.e., pH = 7.3, electrical conductivity = 27.1 mS/m), and Atterberg limit values (i.e., LL = 43%, PL = 32%), was used to represent wind eroded soil in arid/semi-arid regions (★ in Fig. 1).

2.3. Laboratory precipitation and stream erosion simulation

Water erosion was used to evaluate the erosion resistance of soil in this study, as this approach is more convenient than wind tunnel simulation. Soil erosion was simulated using a precipitation and stream erosion test device (i.e., a precipitation sprinkling device above a soil tray having the dimensions 300 mm in length, 150 mm in width, and 50 mm in depth). As previously noted, the water soluble biopolymers β-glucan (Polycan™, Glucan Inc., Busan, Korea) and xanthan gum (Sigma-Aldrich® G1253) were used in this study.

Both untreated natural soil and biopolymer mixed soil specimens were prepared for the experiments. The untreated natural soil specimens were prepared by mixing 1500 g of dried natural soil and 900 g of distilled water (i.e., 60% initial water content, which is higher than the *LL* of soil) to form a uniform soil structure. For biopolymer mixed soil samples, the same amount of dried natural soil (w_s = 1500 g) and distilled water (w_w = 900 g) were applied, and an additional 7.5 g of biopolymer (i.e., both β-glucan and xanthan gum) was added to form a w_b/w_s = 0.5% biopolymer–soil mixture, where w_b and w_s indicate the masses of biopolymer and soil, respectively. All mixtures were placed in the soil erosion simulator tray described above.

Both untreated natural and biopolymer mixed soil specimens were air dried at room temperature without exposure to sunlight to equalize the initial water content before laboratory simulation, to avoid any possible disruptions due to different initial water contents. In detail, the change in gravimetric water content was observed by checking the weight change of the erosion tray over time. All specimens gradually converged to a certain density and moisture content (i.e., dense soil with a void ratio (e) = 0.85 and water content below 2%) depending on the mixing conditions (i.e., the untreated natural case dried faster than the biopolymer mixed-specimens).

The soils' erosion responses to exposure to short-term severe precipitation (i.e., rainfall intensity: 8000 mm/h; duration: 5 s) were evaluated by applying 500 mL of water in 5 s uniformly on a 300 mm × 150 mm soil surface in the soil tray. The soil trays were inclined at 20° to induce thorough surface stream (i.e., runoff). Water was applied using a water sprinkler which produced a uniform fall of water on the soil surface from a height of 30 cm (i.e., kinetic energy of a droplet: 1.18×10^{-5} J), inducing sheet flow on the soil surfaces. Then the entire eroded slurry was collected to determine the ratio of surface runoff and the amount of soil loss due to the rain simulation event. The next precipitation simulation event was performed after a 48 hour time interval. In total, 9 precipitation simulation events were applied consistently for each soil specimen. By controlling the duration of water application and surface flow the different erosion conditions remained comparable under equal droplet and splash energy.

Long-term (e.g., continuous) severe precipitation was simulated for the same soil conditions by applying the same rainfall intensity and duration (i.e., 8000 mm/h during 5 s; 500 mL in 5 s) but with a different time interval between rain events. The same quantity of water (500 mL in 5 s) was applied, but with increased frequency, that is, with an extremely short time interval (i.e., 10 min) between sprinklings. Subsequent rain steps were performed without allowing the specimens to dry between events. 15 precipitation simulation events were performed on the same soil specimen within a total 140 min. Thus, the soil moisture content increased simultaneously with the 15 iterations of rainfall.

In addition, new loose soil samples (i.e., dry ground soil without pre-wet mixing and dehydration steps) were also included to compare the erosion behavior for different soil densities (i.e., void ratio = 1.93).

Every simulation was repeated 3 times to ensure replicability and reliability. In this study the erosion ratio for each event was defined to be the ratio of the dry weight of eroded soil (i.e., the solid part from the eroded slurry or colloid) to the dry weight of all the soil in the erosion tray before raining (Morgan, 2005).

2.4. Vegetation cultivation

The effects of the biopolymer on the cultivation of vegetation were also investigated. The same soil (i.e., Korean red yellow soil 1500 g) and mixing conditions (i.e., biopolymer treatments — untreated, 0.5% β-glucan, 0.5% xanthan gum) as mentioned above were used to compose a biopolymer–soil culture medium. For comparison, an artificial culture soil (i.e., potting soil; Blumenerde™, Gramoflor GmbH & Co.) was also prepared in the same manner.

The same soil trays (i.e., length 300 mm × width 150 mm × depth 50 mm) used in the laboratory precipitation and stream erosion simulations were used as seedbeds for vegetation cultivation. Oats (Seed Solutions™) were chosen as the target crop, and 600 seeds were sowed uniformly. The seeds were covered with a thin layer (i.e., 10 mm) of soil and placed in a greenhouse for isothermal–isohumidity (27 °C; 55%) cultivation. No nutrients (e.g., manure) were applied, and only 300 mL of pure water was supplied daily. The number of germinated seeds and the average height of sprouts were measured every 24 h. After 28 days of cultivation, a short-term precipitation simulation (i.e., 500 mL in 5 s; interval: 48 h; slope angle: 20°; total 8 times) was performed to evaluate the erosion behavior of the vegetation-covered biopolymer-treated soils.

2.5. SEM images

Untreated natural and 0.5% β-glucan mixed Korean red yellow soil below the vegetation covered surface (i.e., containing oats roots) were sampled into 0.5 cm^3 (i.e., length 10 mm × width 10 mm × height 5 mm) cubes without disturbance after performing the precipitation erosion simulation on vegetation-covered soils. Soil samples were shade-dried for 24 h to remove the moisture content. Specimens were coated with gold (20 nm) using a sputter coater (Emitech K550X) to avoid electron scattering. Microscopic images of the biopolymer-treated soil were recorded using a SEM (Philips XL30SFEG) device with an accelerating voltage of 7 keV in high vacuum and secondary electron (SE) image mode.

2.6. Soil water evaporation rate

Three different soil mixtures were prepared in a glass petri dish (D 100 mm × H 15 mm). Based on the same initial gravimetric water content (i.e., 60%; 90 mL of water, and 150 g of soil), specimens were distinguished by different biopolymer contents (i.e., 0.5% β-glucan, 0.5% xanthan gum, and none). Separate specimens were then dried isothermally in an oven at 20, 40, and 60 °C. The amount of moisture loss (i.e., evaporation) was measured continuously every 30 min. Five replications of each test were performed to obtain an average result.

3. Results

3.1. Biopolymer effect on soil erosion

It has been a longstanding hypothesis that soil erosion behavior depends on soil porosity (i.e., whether the soil is loose or densely packed) and moisture conditions (Iverson et al., 2000). Different exposures to rain create different volumetric water content conditions in the soil with time, which becomes important in resistance to soil erosion. Likewise, in this study, it was found that the erosion ratio (i.e., dry weight of eroded soil/dry weight of the soil before raining for each event) of soil increased simultaneously with an increase in the volumetric water content. The soil erosion responses for short-term and long-term severe precipitation simulations are shown in Fig. 2. For consideration in this study, the short-term precipitation simulation is assumed to be relevant to low intensity and sustained erosion in an environment where wind is dominant, while the long-term precipitation simulation is related to severe erosion via continuous sheet or gully flows induced by annual instant heavy rain in arid and semi-arid regions.

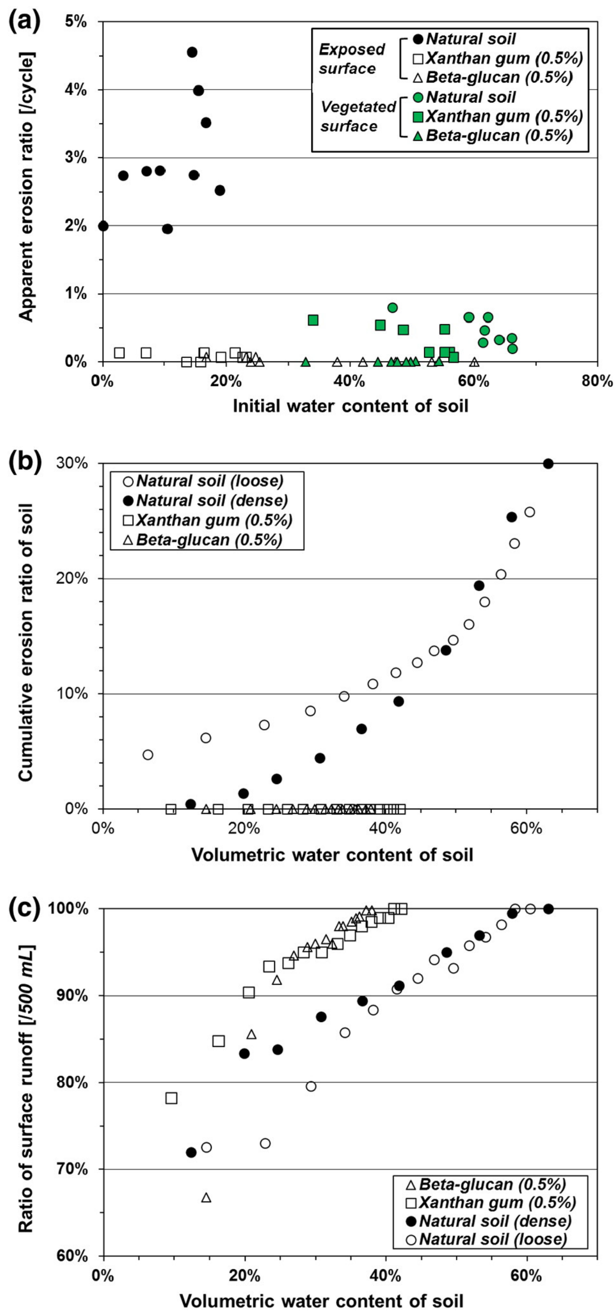

Fig. 2. Responses of soil erosion according to short-term and long-term precipitation simulations. (a) Erosion with short-term precipitation. (b) Erosion with long-term rain. (c) Surface runoff with long-term rain. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

For the short-term precipitation shown in Fig. 2(a), the 0.5% (i.e., w_b/w_s, biopolymer ratio to soil ratio in mass) biopolymer-treated soils (□ and △) demonstrated low erodibility (i.e., high erosion resistance) compared to untreated natural soils (● and ●), regardless of both the initial water content and surface vegetation conditions of the soil. The erosion ratio of the untreated natural soil was significantly affected by its initial water content, while the erosion ratio of the biopolymer-treated soils remained quite small and constant (i.e., less than 0.2%) regardless of their initial water content.

Vegetation (colored symbols) cover also prevents erosion by reducing the surface flow intensity (e.g., total runoff, runoff speed). Vegetated surfaces generally show low erodibility (i.e., ratio of soil loss below 1%); however, the results herein emphasize that the surfaces of biopolymer-treated soil effectively provided high erosion resistance, regardless of the surface vegetation conditions of the soil.

For the long-term rain simulation shown in Fig. 2(b), the cumulated erosion ratio (i.e., the cumulative total amount of eroded solids during all previous events) of untreated natural soils (i.e., both loose $e = 1.93$ and dense $e = 0.85$, where e = void ratio) exceeded 30%, whereas that of the biopolymer-treated soils remained less than 2%, indicating that excellent resistance to heavy and continuous rain was conferred by the biopolymer treatment. For the untreated natural soils, loose soil (i.e., low density) shows higher erosion than dense soil (i.e., high density) in the low volumetric water content ranges (<40%). This is due to its loose packing, and a structure which is controlled by the relatively large pore spaces between soil particles, which also induces higher infiltration (i.e., lower surface runoff as a result) due to its relatively higher hydraulic conductivity (Bryan, 2000). With an increase in water content, the soil becomes loosened by reducing capillarity-induced inter-particle forces, resulting in detachment of adjacent particles (Bryan, 2000; Cho and Santamarina, 2001). Both loose and dense soils showed similar patterns of severe erosion above 50% volumetric water content (i.e., 80–90% degree of saturation).

Moreover, for both loose and dense soils, the ratio of surface runoff increased as the volumetric water content of the soil increased (Fig. 2c). The higher surface runoff accelerates rill erosion, which expedites particle transformation to produce a larger amount of soil loss (Le Bissonnais et al., 1995). However, the biopolymer-treated soils showed little erosion, even though they had higher surface runoff than the untreated natural soils: this reflects surface coating characteristics and lower infiltration due to the biopolymers in the soil.

The erosion tendency of biopolymer-treated soils remained relatively low (i.e., below 1%) regardless of the soil moisture increment (Fig. 2b), even under high surface runoff (Fig. 2c). This can be explained as a combination of the surface coating effect and enhancement of soil inter-particle binding induced by biocompounds (Stokes et al., 2010).

In the presence of water, biopolymers start to absorb it to form hydrogels with a high degree of swelling (i.e., Q = Final volume of hydrogel after water absorbance (V_f) / Initial volume before water absorbance (V_i)). This is caused by hydrogen bonding between the water molecules and biopolymers due to their hydrophilic surface characteristic (Yoshida et al., 1993). When the volumetric water content is lower than 100% (i.e., $\theta = V_{water}/V_{Total} < 1$), the volumes of swelled hydrogels still remain less than the volume of pores without any overall soil volume expansion, while the hydrogels reduce the hydraulic conductivity of soil via pore filling. When soil is fully saturated, the biopolymers absorb as much water as they can, producing significant volumetric swelling (i.e., xanthan gum shows $Q = V_f/V_i = 150 \pm 10$) (Bueno et al., 2013). Thus, the biopolymer-treated soil showed volumetric swelling with hydrogels fully filling the pores (i.e., $\theta = V_{water}/V_{Total} = 1$). This is why biopolymers such as xanthan gum are used in drilling muds.

The expansion of bound water induces pore filling, which decreases the hydraulic conductivity of soil. At the equilibrium state of surface hydration, biopolymers can have hydrophobic surfaces with a hydrogen bonding edge (Hoffman, 2002; Li et al., 2001), as a result of the changes in the clustering bound water zone. In this state, unbound (i.e., free) water molecules outside of the boundary no longer interact with the biopolymers and therefore become free-molecules, resulting in higher surface runoff.

3.2. Biopolymer effect on vegetation growth

Vegetation cover is an important factor in resistance to soil erosion and desertification. Surface vegetation acts as windbreaks and shelterbelts, reducing the strength of wind and preventing the shifting of sand dunes (Qiu et al., 2004), while the root system reinforces soil to resist particle detachment. Accordingly, the most common approach worldwide to revitalize deserts is the planting of vegetation. However, large-scale afforestation efforts have been reported to have failed due to insufficient regional precipitation and uncontrollable windblown sand, which kills the newly planted trees (Cao, 2008). Soil revitalization using vegetation with faster growth (i.e., stabilization) is therefore a prerequisite for anti-desertification efforts.

As shown in Fig. 3, the cultivation test performed with oats demonstrated that biopolymer treatment promoted both initial seed germination (i.e., 300%) and overall sprout growth. Examination of the actual features of vegetation growth on biopolymer-treated culture soils at 7, 10, 14, and 21 days (Fig. 3a) showed that the untreated natural soil was not suitable for seed germination due to its small pore spaces and massive surface desiccation crusts. However, the presence of biopolymers stimulated seed germination and growth in both natural and cultured soil.

Moreover, results for the average number of germinated seeds (Fig. 3b) indicate that the β-glucan biopolymer treatment of natural soil induced a higher initial germination ratio as compared to the untreated culture soil medium. In addition, analysis of the growth behavior (Fig. 3c) indicates that although culture soil medium conditions render proper growth results (i.e., growth rate and increment), beta-glucan treatment provides a satisfactory (i.e., promoted) vegetation growth environment in the natural soil. Thus, it seems that biopolymer treatment has a potential to provide suitable environment for vegetation growth. This phenomenon is in accordance with the known promotional effect of polysaccharides or oligosaccharides on germination, growth, and defense mechanisms against harsh environments and/or pathogens of plants (Ceron-Garcia et al., 2011; Yvin et al., 2002).

The factors affecting germination include temperature, water, oxygen, and illumination. In particular, the organic matter in soil affects water retention, soil structure, and the activity of plant roots (Christensen, 2001). The microstructure of untreated natural soil (Fig. 4a) showed dense face-to-face particle alignment due to desiccation, which has a negative impact on plant root penetration inside the soil (Dexter, 2004). In contrast, biopolymer treatment resulted in larger pore spaces (i.e., biopolymer-treated soil showed higher porosity than untreated natural soil) in dry conditions (Fig. 4b). This is due to the hydrogels, which become stronger and stiffer via dehydration, enhancing the inter-particle stresses between soil particles, causing resistance to the volumetric attraction and therefore producing higher pore spaces. The larger pore spaces and enhanced water retention due to the presence of biopolymers provide both a suitable structural environment (e.g., hydroscopic swelling of biopolymer matrices, and loose particle stacking) for root penetration, and growth inside the soil. Moreover, with the presence of water biopolymers in soil exist as hydrogels, which enhance the growth and drought tolerance of seedlings even under limited irrigation conditions by returning its adsorbed water back into the soil due to the high osmotic pressure of the water in the swollen hydrogels (Hüttermann et al., 1999).

3.3. Biopolymer effect on soil moisture retention

Water retention is also important for desert afforestation by increasing the effective usage of limited precipitation. Although the biopolymer-treated soils were more porous, and thus provided more paths for vapor transport (Fig. 4b), they also delayed the evaporation

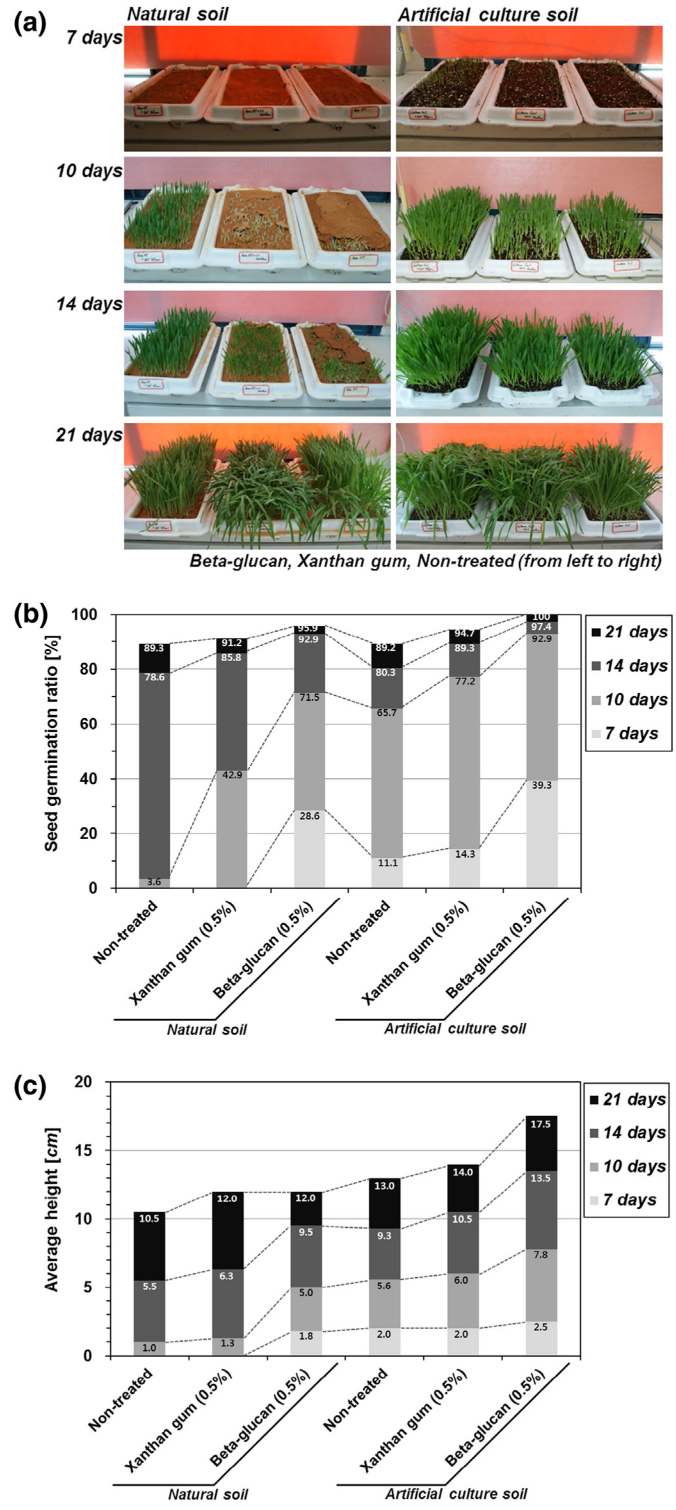

Fig. 3. Results of vegetation (oats) culture in biopolymer treated soils. (a) Actual vegetation growth at 7, 10, 14, and 21 days. (b) Average seed germination over time. (c) Average growth over time.

of water from the soil. A previous study showed that the microstructure of organic matter and hydrophilic hydrogels in soil includes extremely high specific surfaces with electrical charges which provide stronger bonding with water molecules (Chang et al., 2010; Narjary et al., 2012; Sharma et al., 2014).

As a result, the soil water retention efficiency with biopolymer treatment was more than 9% higher than untreated natural soil at room

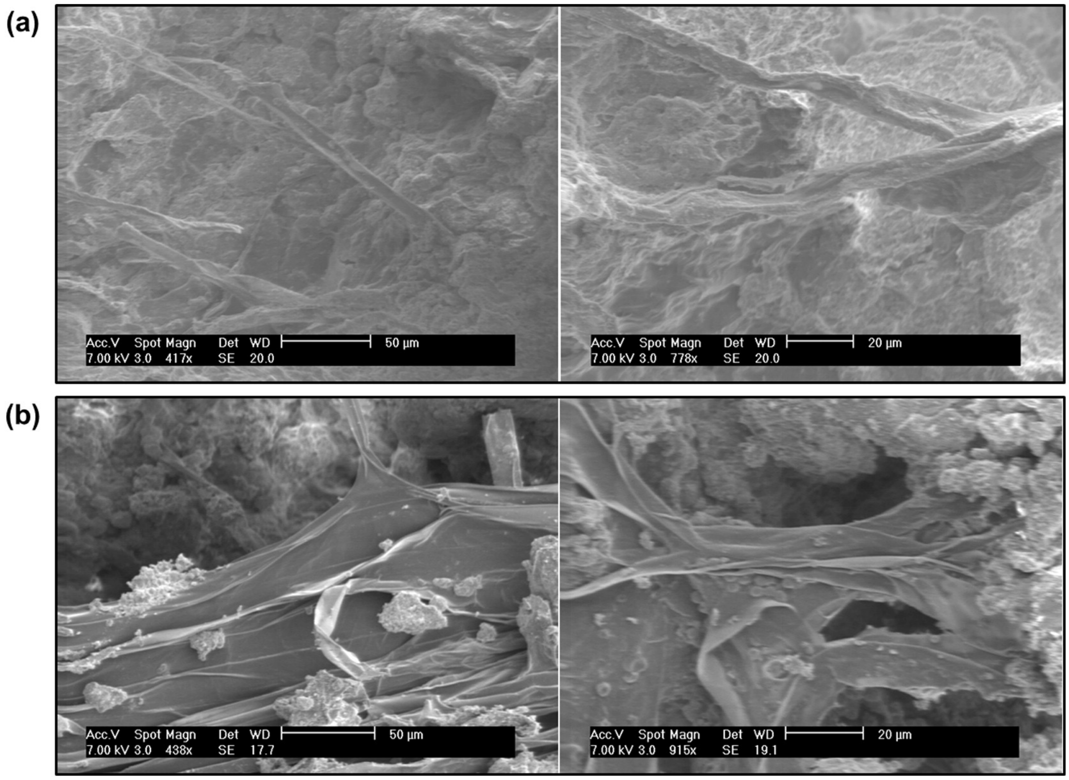

Fig. 4. SEM images of soil with oat roots. (a) Natural soil. (b) Biopolymer (i.e., beta-glucan) treated soil.

temperature. Decreases in retention efficiency to 5% and 3% were observed with higher temperatures (40 °C and 60 °C, respectively), which accelerated dissociation of the bound water from the biopolymer hydrogels (Yoshida et al., 1993). However, the mean temperature of arid and semiarid deserts is about 22 °C, with a daily range of 7 °C–40 °C. Therefore, biopolymer treatment is expected to be suitable for promoting water retention and a practical approach for the soils of arid and semiarid regions with limited irrigation (Al-Darby, 1996).

3.4. Combined mechanism of biopolymer treated soil

The series of laboratory simulations demonstrated that the presence of biopolymers has the potential to enhance soil erosion resistance and vegetation growth in arid and semi-arid regions via provision of inter-particle cohesion, relatively higher soil porosity under dry conditions, and soil moisture retention due to the unique hydrogel characteristics of the biopolymers.

The interaction between soil particles and biopolymers is affected by the following: (1) the surface characteristics of the soil particles, which result in direct or indirect bonding with biopolymers; (2) the structural flexibility of the biopolymers, which allows Van der Waal's interactions to take place with higher effectiveness; (3) the number of hydroxyl (OH^-) groups on the surface of both the soil and biopolymers, which enhances hydrogen bonding; and (4) the presence of acid groups (e.g., carboxyl $COOH^-$), which induce ionic binding between cations or positively charged fine particle edges (Martin, 1971). Thus, when biopolymer-treated soil is placed in drying conditions (i.e., unsaturated conditions), the concentration (or viscosity) of hydrogels continuously increases, attached to the surfaces of particles and forming firm and stiff surface coats and menisci on and between the particles. The dehydrated biopolymer matrices are strong and stiff enough to resist the volumetric attraction of soil particles, allowing more pores to remain open inside the soil as a result. Therefore, biopolymer-treated soil can show higher porosity than untreated natural soils in dry conditions, providing more paths for vapor transport and root penetration.

In particular, the interaction characteristics between the biopolymers, soil, and water create a distinctive soil rheology, characterized by hydrophilic adsorption and bound water, pore filling and low drainage, and temporal hydrophobic surface coating, resulting in high runoff. This combined phenomenon is schematically described in Fig. 5. Natural soils lose fine particles via surface fluid flows (e.g., wind or water) (Fig. 5a), while biopolymer treatment improves inter-particle adhesion (i.e., cohesion), resulting in higher resistance against ordinary erosive forces (Fig. 5b).

Meanwhile, in cases of occasional heavy downpour, the hydrophilic biopolymers adsorb the sudden water to form a surrounding bound water zone (Fig. 5c), which can attenuate the formation of flash floods which produce massive surface erosion in arid areas. Finally, the enlarged biopolymers (e.g., hydrogels) in soil fill pores, reducing infiltration (i.e., hydraulic conductivity) via bio-clogging by temporarily exposing hydrophobic surfaces, which then act as a surface coating to promote surface runoff without particle erosion (Fig. 5d). Moreover, biopolymer treatment was found to yield desirable effects on plants due to the soil's improved ability to absorb water under precipitation (Fig. 5e) and improved soil moisture retention in environments of intense heat (Fig. 5f).

The erosion simulations performed here have some limitations, due to differences between the mechanisms of wind erosion and water erosion (Breshears et al., 2003). However, erodibility (i.e., the resistance of the soil to both detachment and transport) is an inherent soil property depending on soil texture, aggregate stability, shear strength, infiltration, and organic/chemical contents (Morgan, 2005). Thus, erosion simulation using water is appropriate for evaluating the erodibility of soil when the wind tunnel approach is impractical. Moreover, the most intensive erosion in arid and semi-arid regions is reported to be from water erosion, resulting from sudden localized heavy rain (Lal, 1995).

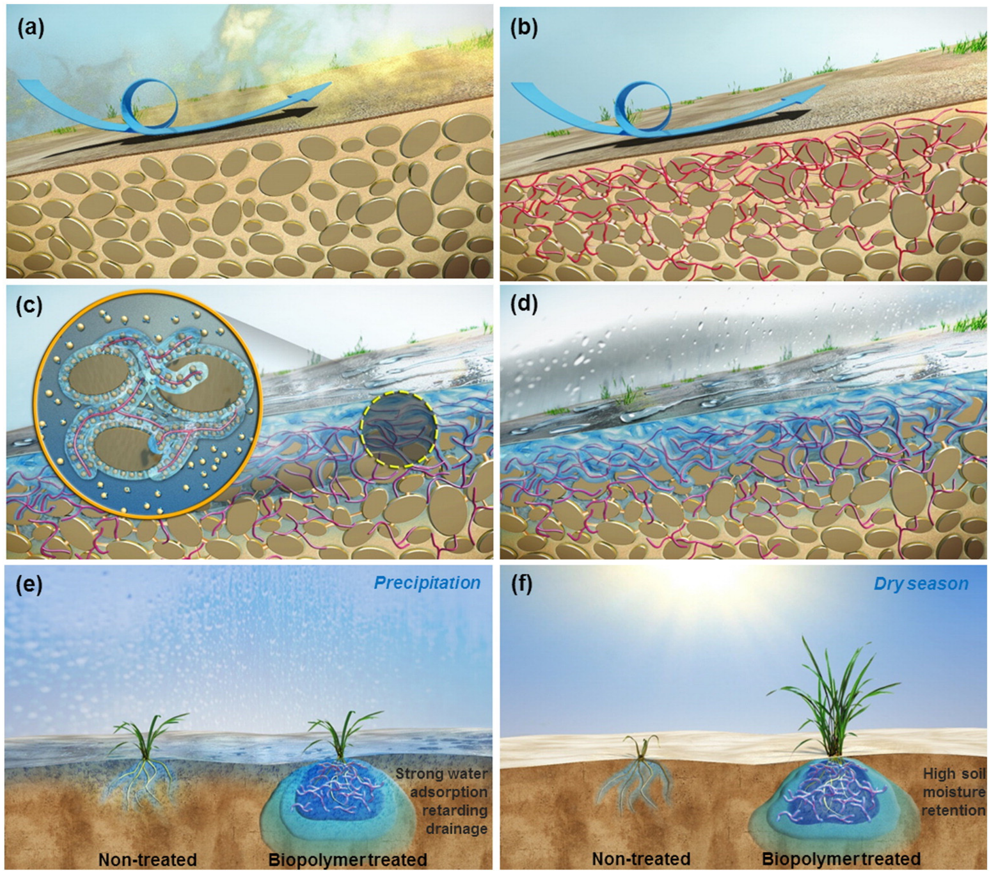

Fig. 5. Erosion resistance model of biopolymer treated soil. (a) Erodible natural soil. (b) Improved biopolymer treated soil. (c) Bound water zone via hydrophilic adsorption. (d) Surface coating effect. (e) High water adsorbability under precipitation. (f) Soil moisture retention under an intense heat environment.

The results of simulations of both high- and low-intensity precipitation performed in this study demonstrate that biopolymer treatment has the positive potential to reduce the erodibility of soil in deserts or areas threatened by desertification.

4. Discussion

4.1. Possible implementations of biopolymer treatment in the field

The most feasible use of biopolymer treatment in arid and semi-arid regions is to improve the soil erosion resistance, as well as and the survival rate and growth of afforested crops during their initial growth stages (i.e., before roots reach ground water) (Hogan et al., 2004). Thus, long-term durability seems to be less important when a biopolymer is applied in the field with other technical desertification countermeasures such as afforestation and drip irrigation systems together. Nonetheless, the photolysis, pyrolysis, and microbial degradation characteristics of the biopolymers must be considered before practical application.

Even so, the laboratory simulations showed promising results, in that the biopolymers effectively enhanced the inter-particle structure of soil under dry or wet conditions, also preventing soil erosion by forming fine particle–polysaccharide matrices or particle coats and inter-particle bridges inside the soil and continuous polysaccharide coating on exposed surfaces. In addition, results from the long-term precipitation simulation showed that biopolymer treatment has the potential to prevent severe soil erosion induced by monsoon-type flash flooding due to localized heavy rain, which typically occurs in some arid regions around the world (e.g., the North American Monsoon in Arizona). Although only two types of biopolymers were considered in this study, beta-1,3/1,6-glucan and xanthan gum represent high-molecular weight chain type and gel (i.e., hydrocolloid) type biopolymers, respectively. Both beta-1,3/1,6-glucan and xanthan gum biopolymers enhance soil erosion resistance in the same manner, while beta-1,3/1,6-glucan treatment results in better vegetation growth than xanthan gum. Thus, it can be cautiously recommended that high-molecular weight chain type biopolymers (e.g., glucan-type polysaccharides; dextran, glycogen, cellulose, curdlan) are preferred for practical implementation in arid and semi-arid regions.

The results from this study can be used to examine biopolymer treatment as a promising supplement or alternative countermeasure for various aspects of soil preservation and desertification prevention, including improvement of soil erosion resistance, retention of soil moisture, and promotion of cultivation. For instance, during the last half century the Chinese government has engaged in a large-scale (i.e., 2.2 billion ha) afforestation program called the "Three North's Forest Shelterbelt". However, the costly effort has yielded little success, while concurrent expansion of the deserts in China has occurred, with inexorable growth ratios of 1560 km^2/yr (1950–1975), 2100 km^2/yr (1976–1988), and 3600 km^2/yr after 1998 (Wang et al., 2008, 2010). One of the biggest reasons for this failure is known to be that previous massive planting efforts were performed without addressing the recovery of soil cohesion and moisture. An individual tree planted in cohesionless arid or semiarid soil can disturb the flow of air, creating turbulence and localized wind erosion on the ground around the tree trunk. As a result, trees roots were exposed and withered under the strong sunlight and limited moisture (Cao, 2008). The failure of previous attempts provides a lesson about the importance of both inter-particle cohesion and soil moisture retention for soil revitalization in afforestation projects in arid and semi-arid regions. Thus, by providing ground improvement, biopolymer treatment could possibly be combined with the aforementioned large-scale afforestation efforts to increase the survival rate of trees or crops. However, as the suggested ideas of this study are derived from a restricted feasibility study, more detail investigations on the microinteraction between biopolymers, soils, and plant roots are required in further studies.

Practical implementation is also an important concern for biopolymer usage in anti-desertification efforts. Spreading, spraying, or mixing approaches on arid deserts using plow-type or flying machines can be envisioned. However, we suggest combining biopolymers with pre-existing anti-desertification efforts (e.g., afforestation and windbreaks) on desert fronts (i.e., boundaries between arid and semi-arid regions) for higher efficiency and pragmatism.

4.2. Economic feasibility of biopolymers and future outlook

The current biopolymer industry still occupies a small market due to its restricted field of applications (i.e., mostly for food or medical purposes). The present cost of biopolymers (i.e., beta-glucan: 45–50 USD/kg in powder type; xanthan gum: 3 USD / kg in food grade) would require budgets to be extremely higher than those for ordinary construction materials (e.g., cement) to treat a unit area (i.e., 1 km^2 with 2.5 cm depth) of soil. In detail, a mixture of 0.5% biopolymer would cost between 600,750 USD (xanthan gum) and 9,011,250 USD (beta-glucan) to treat the 40,050 tons of dried sand estimated to be contained in the unit area, while 10% cement would take only 240,600 USD/km^2. However, the global biopolymer market is projected to increase from 420 kton (in 2011) to 1350 kton by 2016 with an annual growth rate of 22% (BCC Research, 2013).

Nonetheless, to form a 1 cm thick biopolymer-soil crust on a 1 km^2 area with 0.5% biopolymer to soil ratio in mass, the required biopolymer would weigh (w_b) = 80.1 tons. Thus, the entire global production in 2011 (420 kton) could only treat 5242 km^2, while the expected rapid growth of the global biopolymer market could increase coverage to a 3 times larger area (i.e., 16,855 km^2) in 2016. However, even at that scale, the global biopolymer supplement could only cover 0.2% of the Sahara desert. Therefore, the treatment of an entire geographic area with biopolymer alone is as yet economically infeasible and impractical. More realistically, biopolymers could be used as a supplement to enhance the efficiency and performance of pre-existing desertification countermeasures such as afforestation, windbreaks, and wind belts by enhancing soil erosion resistance and vegetation growth.

Over the long term, however, the economic feasibility of biopolymer treatment will gradually improve due to the rapid growth of the global biopolymer market. For example, due to increasing production during the last decade there was an 80% reduction in the price of biopolymers, and further reduction will be possible with projected expanding demand (JEC Group, 2008). Moreover, the production price of biopolymers can be reduced by more than half by removing the requirement for food or medical grade material (i.e., with lower levels of purification or filtering). The introduction of new fields and broader biopolymer application, which was the main purpose of this study (i.e., usage in soil preservation and anti-desertification purposes), should also be a driving force in reducing the cost of biopolymers, via mass production.

Biopolymer usage for soil erosion reduction and anti-desertification efforts can become a promising method not only for soil protection and global climate protection, but also for the environmentally sound and sustainable development of the Earth and human beings. The United Nations warns that the global population will exceed 7 billion by 2030, at which time more than 3 billion will suffer from food shortages or starvation. As shown in this study, biopolymers can be used to promote the production of agricultural grains and greens in preparation for future food shortage problems. At the same time, by recycling or extracting biopolymers from food wastes (Morgan et al., 1990), biopolymer usage in mega-scale soil preservation attempts can contribute to the reduction of global food waste (e.g., 20% in dairy products, 30% in cereals, and 45% in fruits and vegetables (Food and Agriculture Organization of the United Nations, 2013)) in the near future.

5. Conclusion

In geological and geotechnical terms, the loss of clay particles via erosion, which decreases the inter-particle cohesion of soil, is a critical problem in desertification. An alternative method to improve soil inter-particle cohesion using environmentally-friendly microbial polysaccharides (i.e., biopolymers) for anti-desertification purposes has been introduced in this study. A series of laboratory simulations demonstrated that the presence of biopolymers has the potential to enhance soil erosion resistance and vegetation growth in arid and semi-arid regions by simultaneously improving inter-particle cohesion, producing relatively higher soil porosity under dry conditions, and increasing soil moisture retention, due to the unique hydrogel characteristics of the biopolymers.

The results from this study can be used to examine biopolymer treatments as a promising supplement or alternative countermeasure for various aspects of desertification prevention, including improvement of soil erosion resistance, retention of soil moisture, and promotion of cultivation. For practical implementation, we suggest combining biopolymers with pre-existing anti-desertification efforts (e.g., large-scale afforestation efforts and windbreaks) to increase the survival rate of trees or crops via ground improvement on desert fronts (i.e., boundaries between arid and semi-arid regions). Moreover, the current rapid growth of the global biopolymer market and production volume assures bright prospects for the economically feasible application of biopolymers for various anti-desertification projects or efforts in the near future. However, detailed further studies on the microinteraction between biopolymers, soils, and crops are required to ensure and enhance the reliability and applicability of biopolymers for actual applications.

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