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Vegetation growth promotion and overall strength improvement using biopolymers in vegetated soils

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Abstract

Planting vegetation is a sustainable and eco-friendly method for shallow slope stabilization. However, in water-limited regions, this method is facing challenges like retarded vegetation growth, which leads to unprotected soils. Biopolymer, with potentials in both vegetation growth promotion and soil strength enhancement, is therefore tested in this paper with regard to its possibility in assisting soil reinforcement with vegetation through vegetation cultivation and direct shear tests. Both sugar-based and protein-based biopolymers improved water availability to growing plants and nutrient uptake. The most suitable polysaccharide xanthan gum was adopted to further explore the effects of treatment condition (i.e., blending content) and external environment (i.e., precipitation) on the vegetated soil performances. Under a variety of water supply, xanthan gum with a medium blending content of 0.5% (i.e., with respect to dry soil mass) led to the most substantial improvement in the ability to resist shear loading. This indicates that the appropriate dosage of biopolymer used at the initial stage of plant growth, should provide moderate bond strength between soil particles, whilst not impeding root penetration. Supported by the obtained results, biopolymer is suggested to be used in combination with plants for soil reinforcement for the best efficiency.

Key words: vegetation, biopolymer, clayey soil, shear strength, water retention.

1. Introduction

Plants are extensively involved in the stabilization of shallow slopes and the control of soil erosion (Veylon et al. 2015; Pollen-Bankhead and Simon 2010; Świtala et al. 2018). They provide mechanical reinforcement through frictional interlocking and interaction between plant roots and soil particles (Roering et al. 2003; Reubens et al. 2007; Stokes et al. 2009), and meanwhile increase soil effective stresses by elevating the level of matric suction via plant transpiration (Leung et al. 2015; Ng et al. 2016a; Ng et al. 2016b; Ni et al. 2019). However, soil stabilization using plants is always facing with the problem of scarce water resources. It has been reported that the lack of a stable equilibrium between water consumption (e.g., evaporation and transpiration) and water supply (e.g., local precipitation and soil water reserve) is responsible for unsatisfactory planting practices (Glenn et al. 1998; Jackson et al. 2002; Cao et al. 2007, 2008).

Biopolymer treatment is known to provide a better soil environment for vegetation growth (Chang et al. 2015a). Biopolymer hydrogels in soils allow great water retention under irrigation or precipitation, thus alleviating the impact of wetting-drying cycles on vegetation growth (Carminati et al. 2010; Zickenrott et al. 2016; Tran et al. 2019; Rajanna et al. 2022). Biopolymers have an abundance of sugar molecules and elements like nitrogen and phosphorus which can serve as soil nutrients to stimulate vegetation germination and growth (Schachtman et al. 1998; García-Ochoa et al. 2000). Soil particles glued by viscous hydrogels are less susceptible to wind erosion (Wu et al. 2020) and water erosion (Orts et al. 2000). When hydrogels undergo dehydration and become stiffer, they may help to increase the soil resistance to the volumetric attraction, which is beneficial to soil aeration (Chang et al. 2015a).

Meanwhile biopolymers exhibit considerable impacts on altering soil geotechnical properties. For sandy soils, viscous biopolymer hydrogels can remarkably improve soil cohesions immediately after a thorough mixing (Chang and Cho 2019). For clayey soils, biopolymers with high molecular weight can adsorb to several clay particles to cause flocculation and/or aggregation (Kang et al. 2019a; Kang et al. 2019b). The mechanism that governs the adsorption process depends on biopolymer types. For non-ionic biopolymers (e.g., guar gum), hydrogen bonding is the dominant method of adsorption, while for anionic biopolymers (e.g., xanthan gum) and cationic biopolymers (e.g., chitosan), electrostatic attraction dominates the interaction between functional groups of biopolymers and charged clay particles. Previous studies have shown that biopolymers at concentrations of 0.5%~1.5% by weight of dry soil mass have great potentials in improving the soil performances under unconfined compression (Chang and Cho 2012; Fatehi et al. 2018; Vydehi and Moghal 2022; Ni et al. 2022; Cheng and Geng 2023), triaxial compression (Khatami and O 'Kelly 2013), direct shear (Chang and Cho 2019; Chen et al. 2019a), interface shear (Lee et al. 2020), tension (Muguda et al. 2017), three-point bending (Aguilar et al. 2016; Nakamatsu et al. 2017), and split (Aguilar et al. 2016; Nakamatsu et al. 2017). In addition, water resistance of soils can be enhanced by using thermo-gelation biopolymers, e.g., gellan gum, agar gum, and carrageenan (Chang et al. 2015b; Chang et al. 2017; Nakamatsu et al. 2017), as well as hydrophobic biopolymers, e.g., casein (Chang et al. 2018).

As biopolymers show possibilities of reinforcing soil mechanical performances and supporting vegetation growth, their usage is expected to increase the efficiency of soil reinforcement with vegetation, especially at the initial stage of vegetation growth when the plant root system is not well developed and is more vulnerable to the variation of water supply. Different from other existing researches (Chang et al. 2015a; Tran et al. 2019) in which the effects of biopolymers were largely evaluated with respect to reducing soil erosion and promoting plant growth, a preliminary work proposed by Ni et al. (2020a) also focused on the impact of biopolymer on the geotechnical behaviours of the vegetated soil. This current work is an extension of Ni et al. (2020a), to investigate the influencing factors including treatment conditions (i.e., biopolymer type and blending content) and external environment (i.e., precipitation) on the biopolymer performances in terms of stimulating vegetation growth and improving the overall strength of the vegetated soil.

2. Materials and methods

2.1. Clayey soil

The clayey soil obtained from a deltaic deposit (Shanghai, China) was used in this study. It contained both coarse-grained and fine-grained soils, consisting of sand (33.4%), silt (54.9%), and clay (11.7%) particles. The basic properties include liquid limit w_L = 38%, plastic limit w_P = 22%, optimum moisture content w_{opt} = 23%, maximum dry density $\rho_{d,max}$ = 1.59 kg/m^3, and specific gravity G_s = 2.73. According to ASTM D2487, the clayey soil was classified as sandy lean clay. Further detailed information of this clayey soil can be found in Ni et al. (2020b).

2.2. Plant

Oats (*Avena sativa* L.) were chosen as a representative of herbaceous species for soil reinforcement. They usually show a simple root structure (Edmaier et al. 2014), which is typical of many species at their early growth stages (Mickovski et al. 2007). They also possess a relatively fast germination process, e.g., germination of oat seeds can occur 30 h after sowing (Edmaier et al. 2014). In addition, oats have strong resistance to harsh environment, leading to high yields and popularity in most areas of China (Yang 2010). In order to better control the quality of commercially available oat seeds, seed screening was carried out manually before sowing by picking out the small grains, as well as seeds of other plants mixed in, such as barley, highland barley, grass seed and buckwheat.

2.3. Biopolymer

Both sugar-based biopolymers also called polysaccharides (i.e., xanthan gum, guar gum, agar gum, and beta-glucan) and protein-based biopolymer (i.e., casein) were used in this study. Their main chemical components, solubility in cold water, and performances in soils are summarized in Table 1.

Xanthan gum is an anionic polysaccharide biopolymer produced by fermentation of sucrose or glucose by using *Xanthomonas campestris*. It has a leading chain consisting of a linear β-1,4-linked D-glucose backbone with every two elements possessing a trisaccharide side chain (Jansson et al. 1975; Sutherland 1994). Xanthan gum in a small concentration can greatly increase the viscosity of aqueous systems (Hassler and Doherty 1990; Nugent et al. 2009). Incorporation of xanthan gum into soils helps to increase soil strength (Latifi et al. 2016; Chen et al. 2019; Ni et al. 2020b), reduce soil erosion (Chang et al. 2015a), and increase water resistance (Chen et al. 2020).

Guar gum is a non-ionic galactomannan polysaccharide extracted from guar seeds. It has a backbone consisting of β-1,4-linked D-mannose. Every second mannose possesses a short side branch made of α-1,6-linked D-galactose residues (Mudgil et al. 2014; Mandal et al. 2023). Guar gum is soluble in water and has a potential to improve soil strength when it is used in soils (Ayeldeen et al. 2016; Muguda et al. 2017).

Agar gum is a polysaccharide that is commonly extracted from marine red algae. It is composed of alternating sequences of β-1,3-linked D-galactose and α-1,4-linked 3,6-anhydro-L-galactose residues. Agar gum has a low solubility in cold water, but dissolves in hot water (> 85 °C) and starts to form a gel when cooled to 32~43 °C (Normand et al. 2000; Ryou and Jung 2023). Other biopolymers that resemble this similar property (i.e., referred as thermo-gelation biopolymers) include carrageenan (Nakamatsu et al. 2017; Ni et al. 2022) and gellan gum (Chang et al. 2015b; Chang et al 2017; Chang and Cho 2019). The usage of agar gum in soils helps to raise soil strength (Khatami and O'Kelly 2013) and water resistance (Chang et al. 2015b).

β-1,3/1,6 glucan (beta-glucan) is found in a variety of natural sources, e.g., fungi, yeast, mushrooms, seaweeds, and bacteria. It comprises glucose units mainly linked by β-1,3 bonds with a side chain joined by β-1,6 linkages (Chen and Seviour 2007; Wu et al. 2016; Uchiyama et al. 2020). Beta-glucan is water soluble and has possibilities to enhance soil strength (Chang and Cho 2012) and reduce soil erosion (Chang et al. 2015a).

Casein is used to refer a family of phosphoproteins typically found in mammalian milk. It is generally found as a suspension of casein micelles which are held together by calcium ions (Schmidt 1982; Holt 1992). Casein has a low solubility in neutral water (pH = 7). Due to the hydrophobic bonds of the nonpolar side chains of amino acids in its protein structures, casein molecules have limited interactions with water molecules (Nemethy and Scheraga 1962). Therefore, the usage of casein in soils can improve water resistance of soils (Chang et al. 2018; Fatehi et al. 2018) as well as soil strength (Ni et al. 2022).

2.4. Experimental program

The experimental program consisted of Test series I and II which were conducted on the biopolymer-treated vegetated soils (Table 2). Test series I aimed to testify the feasibility of the method and assess the performances of various biopolymers in vegetated soils. The blending content, precipitation, and number of seeds in Test series I were the same as adopted by Ni et al. (2020a). Based on the results from Test series I, the most suitable biopolymer was selected for Test series II, which was designed to probe the effect of blending content on vegetated soils under the impact of precipitation.

For each test series, the behaviors of the biopolymer-treated vegetated soils were explored from the following three aspects: (1) pore fluid, i.e., volumetric water content and electrical conductivity; (2) plant growth, i.e., seed germination ratio, sprout height, and root content; and (3) mechanical properties in direct shear tests.

2.4.1. Vegetation cultivation

Referring to the Standard for Geotechnical Test Method (GB/T 50123-2019 China), the procedures for sample preparation are described as follows. The clayey soil was oven dried at temperature 105 ± 5 °C for 24 h, crushed down gently on a rubber plate with wood hammer, and sieved through a 2 mm sieve to became base soil. The base soil was thoroughly mixed with the biopolymer powder with certain blending content (defined as the mass of biopolymer powder with respect to the mass of base soil), before adding tap water. The optimum moisture content was employed as the initial water content for sample preparation according to Ng et al. (2014) and Ng et al. (2016b). In addition, as indicated by Ni et al. (2020b), biopolymer-induced soil strengthening effect hardly occurred for initial soil water contents smaller than the optimum moisture content, probably due to the poor workability of highly viscous hydrogels (Chang et al. 2015c). To increase the solubility, the water was heated to 85 °C for dissolving agar gum. A metal trowel was used for mixing manually for about five minutes until a homogeneous biopolymer-soil mixture was obtained. The mixture was then placed into a plastic tray (length × width × height = 205 mm × 150 mm × 80 mm), covered with a piece of filter paper and statically compacted to a degree of compaction of 80% (defined as the ratio of compacted soil dry density to the maximum dry density) with a wood panel. After compaction, the filter paper and wood panel were removed, and 160 oat seeds were evenly sowed on the soil surface. A thin layer of the biopolymer-soil mixture (1 cm) was placed on top to cover the oat seeds. The volumetric moisture content (defined as the volume percentage of water in the soil per unit volume) of the soil was 25.5% after seeding.

Higher degrees of compaction (> 90%) were not adopted because of the following two reasons. On one hand, higher degrees of compaction might inhibit vegetation growth (Ng et al. 2014), due to the increased mechanical resistance of root penetration (Bengough and Mullins 1990; Lipiec and Hakansson 2000), as well as the reduced oxygen diffusion rate in soils (Granovsky and McCoy 1997) caused by the reduction of average soil pore size (Romero et al. 1999). On the other hand, higher degrees of compaction tend to increase the water-holding capacity of soils (Romero et al. 1999; Ng et al. 2014; Ng and Peprah-Manu 2023), and then the effect of biopolymers on helping in retaining moistures would be less important, whilst the increased mechanical strength would also minimize the contribution from biopolymers. Biopolymers should therefore be more beneficial at lower degrees of compaction, when vegetation growth is not impeded so much.

The trays of the biopolymer-treated soils embedded with oat seeds were placed at a controlled environment (i.e., temperature of 20 °C and relative humidity of 75%) for a cultivation period of 14 d. Precipitation simulation was performed by providing designated amount of tap water on the 1st, 2nd, 3rd, 8th, 9th, and 10th days. It should be noted that only tap water without any additional nutrient was supplied during the vegetation growth. Multiple holes, each with a diameter of 5 mm, were made at the bottom of the plastic tray to allow free drainage and to collect any water percolated from the base during watering.

2.4.2. Measurement of volumetric water content and electrical conductivity

The volumetric water content and electrical conductivity of the biopolymer-treated vegetated soils were recorded every 24 h using a multi-functional soil sensor produced by Jingxun Changtong Electronic Technology Co., Ltd (Weihai, China).

2.4.3. Measurement of seed germination ratio and sprout height

The number of germinated seeds and the height of sprouts above the soil surface were recorded every 24 h.

2.4.4. Direct shear test

At the end of vegetation cultivation, a cutting ring (diameter × height = 61.8 mm × 20 mm) and a square hoe were used for sampling. The detailed sampling process is described as follows with a schematic diagram (see Fig. 1). Firstly, the upper seedlings above the surface (Fig. 1a) were cut off with scissors, after which a cutting ring was pushed into the soil where the sprouts were relatively uniformly distributed (Fig. 1b). The soil near the edge of the tray was excavated out so that the square hoe could be inserted below the cutting ring following the direction of arrows as shown in Fig. 1b. Then the sample was taken out (Fig. 1c). The excessive soil above and below the cutting ring was removed and then both surfaces of the sample were levelled off. It should be noted that all the samples were taken 1.5 cm below the soil surface, as shown in Fig. 1c, in order to ensure that there were no oat seeds in the cutting ring. In addition, the roots were pruned to extent 0.5 cm out of the cutting ring so as to assure the anchoring effect of the root system (Zhou et al. 2016).

The reinforcing effect of the combination of oat roots and biopolymer on the shear performances of the clayey soil was determined using direct shear tests following the

Standard for Geotechnical Test Method (GB/T 50123-2019 China). The shear stress was applied on the saturated sample at a rate of 0.8 mm/min under undrained condition, during which the overburden stress (i.e., 50, 100, and 150 kPa) was applied. For herbaceous species, the majority of roots are found in near surface soils (Jackson et al. 1996). When nutrients and/or water are limiting, roots tend to grow deeper (Jackson et al. 1996), e.g., up to several meters (Stokes et al. 2009). Therefore, the overburden stress up to 150 kPa which was also adopted by (Gonzalez-Ollauri and Mickovski 2017) was used here as it could cover the root depth of herbaceous species at extreme conditions. The root architecture and density near the soil surface will likely be very different from those at depth, as roots have a heterogeneous spatial distribution in soils (Jackson et al. 1996; Reubens et al. 2007; Stokes et al 2009). However, this effect of spatial root distribution on the shear resistance of the vegetated soil is not considered within the scope of this study. After the direct shear test, the root-containing damaged samples were dried in the oven at 80 °C for 48 h (Cornelissen et al. 2003). Then the dry mass of roots and dry mass of soil were weighed separately. The ratio of the dry mass of roots to the dry mass of soil in the specimen was determined as the corresponding root content.

3. Results and analysis

3.1. Test series I

3.1.1. Plant growth

The actual features of oat growth in biopolymer-treated soils examined every two days are shown in Fig. 2a. The germination of oat seeds was first found in the soil treated with xanthan gum followed by guar gum. It is seen in Fig. 2b that at the end of cultivation, xanthan gum was observed the most efficient biopolymer in promoting vegetation growth in terms of increasing the seed germination ratio (defined by the ratio of the number of germinated seeds to total number of seeds) by 300%, and raising the average sprout height by 31%, compared with the untreated soil. Guar gum, casein, agar gum, and beta-glucan were in a descending order by effectiveness in stimulating seed germination and sprout growth. Even the least efficient biopolymer (beta-glucan) increased the seed germination ratio and average sprout height by 101% and 15%, respectively. Therefore, all the biopolymers were proved able to exert a favorable influence on the soil environment for plant growth to certain extent.

3.1.2. Water content and electrical conductivity

Although biopolymers may induce large pore spaces into soils (Chang et al. 2015a), and thus lead to more paths for moisture transport, they help to delay the moisture evaporation from soils, mainly attributed to the formation of hydrogen bonds between functional groups of biopolymers and water molecules (Narjary et al. 2012).

Normally, precipitation, soil evaporation, and vegetation transpiration are the primary factors affecting the moisture level in soils. The volumetric water content w at any given time can be expressed by:

$$w = w_0 + \Delta w_p - \Delta w_e - \Delta w_t \quad (1)$$

where w_0 is the initial volumetric water content; Δw_p, Δw_e, and Δw_t are the changes in volumetric water content due to precipitation, soil evaporation, and vegetation transpiration respectively. Since vegetation transpiration releases about 95% of the water absorbed by the roots (Nobel 2009; Mcelrone et al. 2013), the soil moisture absorbed by oat roots could be represented by Δw_t in eq. 1. Since w_0 and Δw_p were the same for all the treatment conditions in Test series I, w was then only influenced by Δw_e and Δw_t. Δw_e is affected by the water-holding capacity of the biopolymer used for soil treatment (Chang et al 2015a; Muguda et al. 2017). Δw_t is largely affected by the leaf area index (LAI) of vegetation (Jarvis and Mcnaughton 1986). When LAI is high, the total number of stomata on the leaves is also high, leading to a significant increase in water absorption from soils. In this sense, higher seed germination ratio and average sprout height can lead to higher Δw_t. It should be noted that there was hardly any water drained out from the drainage holes and therefore the impact of percolation on volumetric water content was not included in eq. 1. This might be partly attributed to the relatively low amounts of precipitation adopted in the current study. In addition, upon precipitation, hydrophilic biopolymers help to adsorb the sudden water and swell, which leads to filling of soil pores and reduction in hydraulic conductivity via bio-clogging (Chang et al. 2015a).

The variations of volumetric water content during cultivation are presented in Fig. 3a. The vegetated soils treated with casein and agar gum respectively had the highest and the second highest values of *w*. This is because both casein and agar gum were less effective in promoting seed germination and sprout growth compared with xanthan gum or guar gum as shown in Fig. 2, which resulted in medium vegetation transpiration. In addition, although casein and agar gum have poor water solubility, they have strong water-absorbing and water-holding capacity, which helped to reduce soil evaporation. The vegetated soils treated with xanthan gum and guar gum respectively had medium values of *w* (Fig. 3a) due to an increased vegetation transpiration caused by highly promoted germination of oat seeds and sprout growth (Fig. 2). The untreated vegetated soil, although experienced the lowest level of plant transpiration corresponding to the worst plant growth (Fig. 2), had the smallest value of *w* (Fig. 3a), indicating the highest level of soil evaporation due to lowest water-holding ability.

In the past, the electrical conductivity of biopolymer-treated soils has been rarely investigated, although the information could be potentially useful for soil scientists, geotechnical and environmental engineers. Figure 3b shows the variations of electrical conductivity of the vegetated soils during vegetation growth. The electrical conductivity is affected by a variety of soil properties, including the nature of solid grains, arrangement of voids, degree of water saturation, and electrical conductivity of the pore fluid (Samouëlian et al. 2005). Pore fluids containing different biopolymers could yield different electrical conductivities. In addition, the physicochemical interaction between functional groups of biopolymer molecules and charged clay particles could lead to different patterns of soil particle association (i.e., aggregation and/or flocculation), and in turn different arrangements of voids. Therefore, the values of initial electrical conductivity were not identical for the vegetated soils treated with various biopolymers (Fig. 3b). By comparison of Figs. 3a and 3b, it is seen that the electrical conductivity was positively correlated with the volumetric water content, implying its strong dependence on degree of saturation. Generally, the electrical conductivity of tap water is between 125 to 1250 μs/cm. The tap water used in the current study has an electrical conductivity of 483 μs/cm, which is much higher than the electrical conductivity of air (i.e., air medium is an insulator). Thus, increasing the water-filled porosity raised the soil electrical conductivity and vice versa.

3.1.3. Direct shear test

Figure 4 presents the relationships of shear stress-shear displacement of the vegetated soils with or without biopolymer treatment at overburden stresses of 50, 100, and 150 kPa. The enhanced shear behaviors due to the presence of biopolymers were noticeable. The vegetated soil with the addition of casein or agar gum had a greatly elevated shear strength (defined as the shear stress at 9 mm displacement) and exhibited a larger stiffness at the initial loading stage (i.e., < 3 mm displacement) compared with the control group. Xanthan gum and guar gum also effectively improved the shear strength and stiffness of the vegetated soil, albeit not as remarkable as casein or agar. Beta-glucan slightly increased the resistance of the vegetated soil to shear loading.

In the current study, the root-containing samples were sheared under the saturated condition and therefore soil suction as a component of soil strength was not considered. The question that then comes to mind is whether it could be possible that the untreated vegetated soil had a higher strength than the biopolymer-treated one if soil suction was included, because the untreated vegetated soil appeared to have the lowest water content (Fig. 3a) and therefore could have the greatest contribution from soil suction to mechanical performance. We think it could be largely unlikely because (1) there are evidences (Zha 2014; Muguda et al. 2017; Cao et al. 2018; Tran et al. 2019) indicating that biopolymer-treated soils exhibit higher suctions than untreated soils, due to the viscosity of biopolymer hydrogels and adhesive force between biopolymer hydrogels and solid surfaces; (2) under the unsaturated condition with lower water contents, the strengthening effect of biopolymers would be more remarkable due to the dehydration-induced strength gain and rigidity enhancement of biopolymer hydrogels, and closer interaction between biopolymer molecules and soil particles (Chang and Cho 2012; Latifi et al. 2016). To sum up, the reinforcing effect of biopolymers was underestimated to some extent in the current study due to the adopted testing method.

3.1.4. Evaluation of different biopolymers

As discussed above, all the selected biopolymers positively contributed to the soil reinforcement with plants. After comparing xanthan gum, casein, and agar gum that had better performances either in facilitating vegetation growth or increasing overall soil strength, it was determined to adopt xanthan gum for further study based on the following reasons, e.g., reinforcing effect, implementation, and cost. (1) The strength of the vegetated soil treated with casein or agar gum was less dependent on the plant growth compared with the vegetated soil treated with xanthan gum (Figs. 2 and 4). Biopolymers are biodegradable from a long-term aspect, and hence the vegetated soil with a less developed root system could be more adversely affected when the direct mechanical reinforcement contribution from biopolymers wanes with time. By contrast, xanthan gum was the most effective polysaccharide in assisting plant growth (Fig. 2) and had also satisfactory performances in strengthening the vegetated soil (Fig. 4), and therefore the usage of xanthan gum is considered superior for improving the engineering behaviors of the vegetated soil. (2) Agar gum is a thermo-gelation biopolymer and hence hot water is needed for the preparation of agar gum-soil mixtures, which brings certain difficulties for implementation practices in field. Casein, on the other hand, has a low solubility in neutral water and exhibits cheesy state when mixed with water (Fatehi et al. 2018; Ni et al. 2022), which might lead to poor workability with soil. By comparison, xanthan gum has excellent solubility in cold water and other desirable functions like pH stability, storage stability, and ionic salt compatibility (Barrére et al 1986; Rosalam and England 2006). (3) Xanthan gum has been produced and used in large quantities with a relatively low price. Over the last three decades, the cost of soil treatment with 0.5% xanthan gum (i.e., 5 kg of xanthan gum per ton of soil) has decreased from approximately 70 USD to 10 USD (Mendonça et al. 2021).

3.2. Test series II

3.2.1. Plant growth, water content and electrical conductivity

The results of vegetation cultivation performed on the xanthan gum-treated soils under the impacts of blending content and precipitation are presented in Fig. 5. The earliest oat seed germination was observed on the second day of cultivation. Within the first five days, the majority of oat seeds germinated except for the highest blending content (i.e., 1.00%) with low to medium precipitations (i.e., 25 and 50 mL). Due to the variation in both blending contents and precipitations, seed germination ratios changed broadly from 35% to 85% at the end of cultivation. Medium precipitations (i.e., 50 and 75 mL) allowed more seeds to germinate (Fig. 6a), while excessive water (i.e., 100 mL) lowered the seed germination ratio probably due to oxygen deficiency caused by the decreased air-filled porosity. On the other hand, low to medium blending contents (i.e., 0.25% and 0.50%) were more effective in stimulating seed germination (Fig. 6b). Medium to high blending contents (i.e., 0.75% and 1.00%) were prone to form more viscous hydrogels that might increase the root penetration resistance. The high viscosity of the biopolymer hydrogels with 1.00% blending content may also be responsible for the delayed seed germination as shown in Fig. 5.

During the vegetation cultivation, the volumetric water content was M-shaped with two peaks (Fig. 7). For precipitations larger than 50 mL, the second peak value was higher than the first one, implying that precipitation exceeded the moisture loss due to soil evaporation and plant transpiration. For the minimum precipitation (i.e., 25 mL), the second peak value was lower than the first one. While increasing precipitations remarkably increased volumetric water contents (Fig. 8a), raising blending contents had a relatively small effect (Fig. 8b). Variations of electrical conductivity during vegetation cultivation is shown in Fig. 9. The impacts of precipitation and blending content on the electrical conductivity are shown in Figs. 10a and 10b, respectively. The electrical conductivity showed a positive correlation with both influencing factors.

The volumetric water content was affected by precipitation, soil evaporation and plant transpiration. For a fixed xanthan gum blending content (Fig. 11), the moisture loss due to soil evaporation Δw_e could be deemed identical. Then the volumetric water content was mainly influenced by precipitation and vegetation transpiration. Taking Fig. 11a for an example, the volumetric water content had a small increment as the precipitation increased from 25 to 50 mL. This was a resultant value from a positive Δw_p in eq. 1 due to the increased precipitation and a positive Δw_t in eq. 1 due to the promoted plant growth. When precipitation increased from 50 to 100 mL, the volumetric water content had a more remarkable increment as the sign of Δw_t changed from positive to negative in eq. 1. Alternatively, for a fixed precipitation (Fig. 12), the moisture increment due to precipitation Δw_p was identical. Then the volumetric water content was mainly influenced by soil evaporation and vegetation transpiration. Taking Fig. 12b for example, the volumetric water content had a small decrement as the blending content increased from 0.25% to 0.50%. This is a resultant value from a negative Δw_e in eq. 1 due to the decreased soil evaporation and a positive Δw_t in eq. 1 due to the promoted plant growth. When the blending content increased from 0.50% to 1.00%, the volumetric water content had a small increment as the sign of Δw_t changed from positive to negative in eq. 1.

3.2.2. Direct shear test

The effect of precipitation on the relationship between shear stress and shear displacement for different xanthan gum blending contents are presented in Fig. 13. It was observed that the precipitation corresponding to the highest curves at 50, 100, and 150 kPa overburden stresses increased as the blending content increased. For example, 50 mL precipitation led to the best improved shear resistance for the soils treated with low to medium blending contents (e.g., 0.25% and 0.50%, see Figs. 13a and 13b) and 75 ml precipitation for those treated with medium to high blending contents (e.g., 0.75% and 1.00%, see Figs. 13c and 13d), respectively. The dependence of shear performance on precipitation was in accordance with that of seed germination ratio on precipitation (Fig. 6a). For low to medium blending contents (i.e., 0.25%, 0.50%, and 0.75%), the stiffness of the xanthan gum-treated vegetated soils decreased gradually with the increasing shear displacement. While for 1.00% blending content, there was a more apparent change in the stiffness around 1 to 2 mm shear displacement, which might be due to the least satisfactory vegetation growth (Fig. 6b). The effect of blending content on the relationship between shear stress and displacement for different precipitations are shown in Fig. 14. The blending content leading to the highest strengths at 50, 100, and 150 kPa overburden stresses was observed to be a fixed value (i.e., 0.50%) regardless of the precipitation. Similarly, this result can be linked to the trend of seed germination ratio, i.e., 0.50% was the optimum dosage to facilitate plant growth (Fig. 6b).

The variations of internal friction angle and cohesion against root content (defined as the root mass with regard to the soil mass within the cutting ring) for different blending contents are provided in Figs. 15a and 15b, respectively. Fine oat roots actively increased the internal friction angle of the soil (Fig. 15a). When root content increased from 0.10% to 0.50%, the internal friction angle increased from 20º to 35º. By observing Fig. 15b, it was discovered that for each blending content, the dependence of cohesion on root content was not obvious. However, by comparing different soil groups, it is not difficult to find that the soil group containing more oat roots had higher soil cohesions, i.e., 0.50% xanthan gum-treated soil group had the highest cohesion followed by 0.25% XG-treated soil group, and the other two soil groups.

4. Discussion

4.1. The role of biopolymers in the vegetated soil

A schematic diagram is provided for elucidating the biopolymer-treated vegetated soil system in which many aspects are transient, e.g., plants grow and biopolymers degrade (Fig. 16). At the initial stage after planting, there is primarily a biopolymer/soil composite. Biopolymer plays a dual role in the soil (i.e., promoting vegetation growth and improving soil strength). Once seeds geminate and roots grow, there exists a biopolymer/root/soil composite, or more precisely a biopolymer/mucilage/root/soil composite. Mucilage is a range of organic materials secreted by plants and associated microorganisms (Naveed et al. 2017; Naveed et al. 2019). Both mucilage and biopolymer have been shown to facilitate the adhesion of soil grains to plant roots and enhance the interparticle bonding of the soil grains in the rhizosphere, forming a root-associated soil region (Gregory 2006; Hinsinger et al. 2009; Chen et al. 2019b). Due to the presence of biopolymer in the periphery of the rhizosphere, the diameter of soil region associated with roots could be further enlarged. Under shearing, the movement of a root relative to the soil will therefore take directly or indirectly adhered grains with it, increasing the shear plane area between soil and roots and consequently raising the shear resistance of the biopolymer/mucilage/root/soil composite. Owing to the degradable nature of biopolymer, the biopolymer/mucilage/root/soil composite will be ultimately replaced with the mucilage/root/soil composite.

4.2. Effect of biopolymer type

Polysaccharides and protein-based biopolymers have great water-holding abilities. It is seen from Fig. 3a that although biopolymers promoted vegetation growth, which in turn accelerated the water transportation from soil to plants through transpiration, they helped to increase the water use efficiency and had an overall beneficial effect on improving water availability to plants.

In addition, various biopolymers contain a variety of nutrients which are essential for plant growth. For example, polysaccharides chemically consist of repeated sugar units. These chemical components are not directly available to plants; polysaccharide degradation is normally required first to permit the uptake and usage of these components by plants. Products of enzymatic xanthan gum degradation caused by xanthan gum-degrading microorganisms include glucose, glucuronic acid, mannose, pyruvated mannose, acetylated mannose, and unidentified oligo- and polysaccharides (Hou et al. 1986), most of which can be utilized for plant photosynthesis and respiration (Meléndez-Hevia et al. 1996; Oexle et al. 1999; Berg et al. 2002; Valpuesta and Botella 2004; Buchanan et al. 2009; Ceron-Garcia et al.

2011). Other polysaccharides (e.g., guar gum, agar gum, and beta-glucan) contain chemical species that are needed for plant metabolism as well; however, the diversity of nutrient components of these biopolymers is not comparable with xanthan gum (Table 1). This might be the reason that xanthan gum was observed the most efficient polysaccharide in promoting seed germination and sprout growth. A different result was obtained by (Chang et al. 2015a), saying that beta-glucan had a better performance than xanthan gum in promoting plant growth.

Casein is a protein-based biopolymer comprising phosphoproteins. Both nitrogen and phosphorus are the most frequently limiting macronutrients for the growth of terrestrial plants (Schachtman et al. 1998; Capek et al. 2018). In available forms (e.g., mediated by soil microbes) for plant uptake, nitrogen can be used to produce chlorophyll which is essential for plant photosynthesis, while phosphorus can raise biomass production (Moeneclaey et al. 2022). Due to the strong interactions of nitrogen and phosphorus in biogeochemical processes, increasing the availability of either nitrogen or phosphorus promotes the uptake of the other one by plants (Xia et al. 2023). Therefore, casein also helps to stimulate plant growth by supplying nutrient elements. However, the contribution of casein might not be as great as xanthan gum or guar gum, as sugars are the most vital biomolecules and play the most important role in metabolism of plants (Ng 2017; Ahmad 2019).

4.3. Effect of biopolymer blending content

Xanthan gum hydrogels can either lubricate the interface of roots and soil particles or increase mechanical impedance of plant roots depending on the blending content. Xanthan gum was used by Chen et al. (2019b) to mimic plant mucilage which provides root tip lubrication and helps to mobilize beneficial chemical components for plant uptake (Jones et al. 2009). For low to medium blending contents (i.e., 0.25% and 0.50%), xanthan gum was observed effective in stimulating seed germination under varying water supplies (Fig. 6b), suggesting that the blending content up to 0.50% might not be restrictive for root penetration. By contrast, medium to high blending contents (i.e., 0.75% and 1.00%) adversely impacted seed germination ratios (Fig. 6b); the highest blending content of 1.00% combined with the minimum precipitation of 25 mL retarded seed germination (Fig. 5). This is mainly because that the highly viscous hydrogels (especially upon drying) could result in the formation of a rigid soil crust at surface. It is deduced that there existed a relationship between vegetation growth and shear resistance of the vegetated soil. The inclusion of xanthan gum with 0.50% blending content which maximized the biomass production, was also corresponding to the highest soil shear strength (Fig. 14) due to both increased internal friction angle and cohesion (Fig. 15).

Therefore, higher blending contents do not necessarily lead to a higher reinforcing efficiency when vegetation is involved. As illustrated in Fig. 16, when biopolymers were initially mixed with soils, they dominated the role of soil reinforcement to a large extent, thereby 1.00% blending content was expected to create the maximum soil reinforcing effect owing to the increased soil cohesion and bonded soil particles. However, upon dehydration, the soil treated with 1.00% biopolymer might become excessively stiff which was restrictive for root elongation, resulting in a less protected soil from the long-term perspective. By comparison, an appropriate blending content (i.e., 0.25% and 0.50%) will provide a moderate reinforcing effect while ensuring a long-term plant-reinforced soil system.

In a biopolymer/mucilage/root/soil composite, both biopolymer and mucilage can offer beneficial effect on soil stabilization. The mucilage secreted by plants and associated microbes, although is biodegradable in nature, is produced continuously and there exists a consistent level of total mucilage estimated 0.005% to 5% with regard to the dry soil mass (Zickenrott et al. 2016). Therefore, the higher mucilage contents associated with the better vegetated soils (i.e., treated with 0.25% and 0.50% blending contents) should be taken into account when the effect of blending content of xanthan gum on shear strength indices is analyzed (Fig. 15).

4.4. Effect of precipitation

Precipitation had a greater effect on the soil water content than the biopolymer blending content, by comparing Figs. 8a and 8b. Precipitation of 25 mL led to the least amount of available water to the growing plants (Fig. 8a) and the worst vegetation growth (Fig. 6a), which could be attributed to the water stress under which plant metabolism was restricted. The highest precipitation of 100 mL resulted in the highest volumetric water content (Fig. 8a), but not the best plant growth (Fig. 6a). This might be attributed to the fact that upon precipitation, biopolymer hydrogels absorbed water, swelled, and clogged the pore spaces, which decreased the air-filled porosity and in turn led to an unbalanced air-water circulation. Precipitations of 50 and 75 mL allowed the highest seed germination ratios to occur for low to medium blending contents (i.e., 0.25% and 0.5%) and medium to high blending contents (i.e., 0.75% and 1.00%), respectively (Fig. 6a), and led to efficiently improved strength (Fig. 13). This suggests that moderate soil moisture contents (Fig. 8a) may satisfy the requirements of both water demand for plant metabolisms and soil aeration.

4.5. Economic feasibility of biopolymer usage in vegetated soils

The economic feasibility of biopolymer usage in geotechnical engineering has been reviewed by Chang et al. (2016), Chang et al. (2020), and Mendonça et al. (2021). Over the last thirties years, the cost of xanthan gum has dropped approximately from 14,000 USD/ton to 2,500 USD/ton. The expanded applications of biopolymers in geotechnical engineering as well as in other fields (e.g., food, medicine, cosmetics, farmland irrigation, and construction) and the resultant mass product intend to further reduce the cost of biopolymers. In addition, the price of biopolymers can reasonably be expected to decrease when they are produced specifically for the purpose of geotechnical engineering, e.g., by reducing the high levels of food-grade purity of biopolymers as they are unnecessary for geotechnical applications.

5. Conclusion

The application of biopolymers in vegetated soils to promote vegetation growth and improve overall strength is evaluated in this paper. Both polysaccharide and protein-based biopolymers improved water availability to the growing plants. In addition, they contain sugars and elements like nitrogen and phosphorus which in available forms (e.g., monosaccharides and oligosaccharides) can be utilized by plants for photosynthesis and respiration. It has been revealed that polysaccharide xanthan gum with 0.5% blending content greatly facilitated plant growth and improved overall vegetated soil strength under a variety of water supplies. Higher blending contents, although provide a greater soil reinforcing effect at the initial sage, may increase the root penetration resistance and hinder the formation of root-soil composite from a long-term perspective. From the obtained outcomes, biopolymers are suggested to assist in the plant-reinforced soil system especially at the initial stage of vegetation growth when the plant roots do not actively reinforce the soil and are more vulnerable to water stress.

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Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that there are no competing interests.

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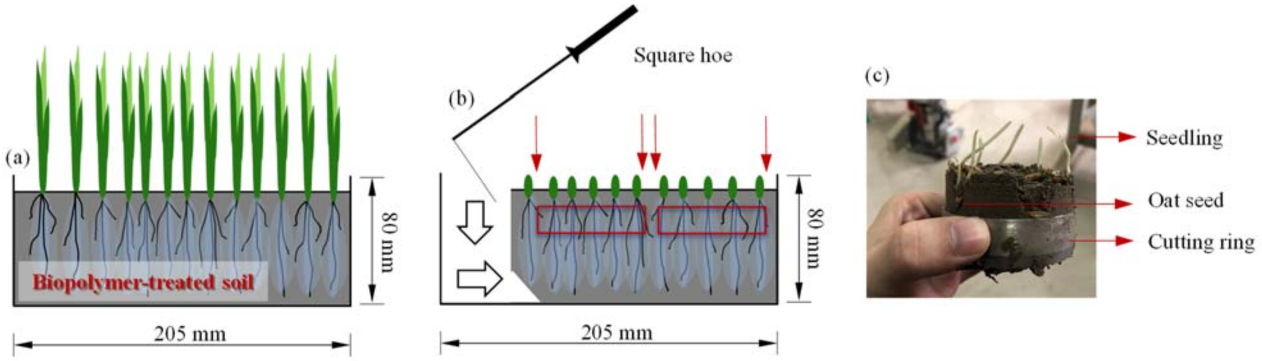

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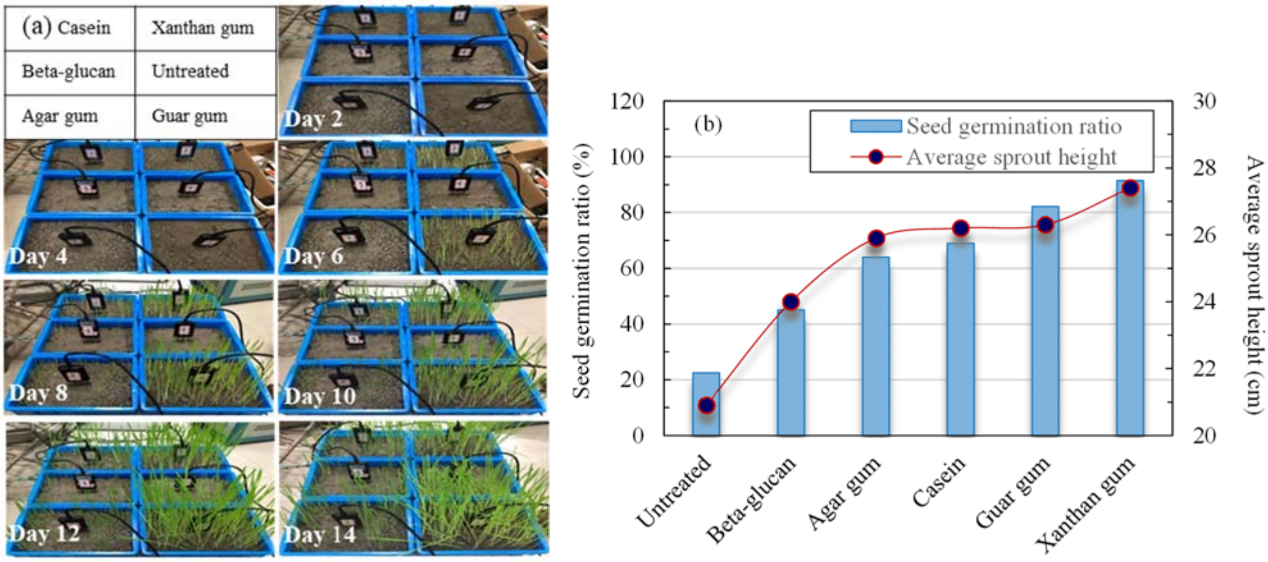

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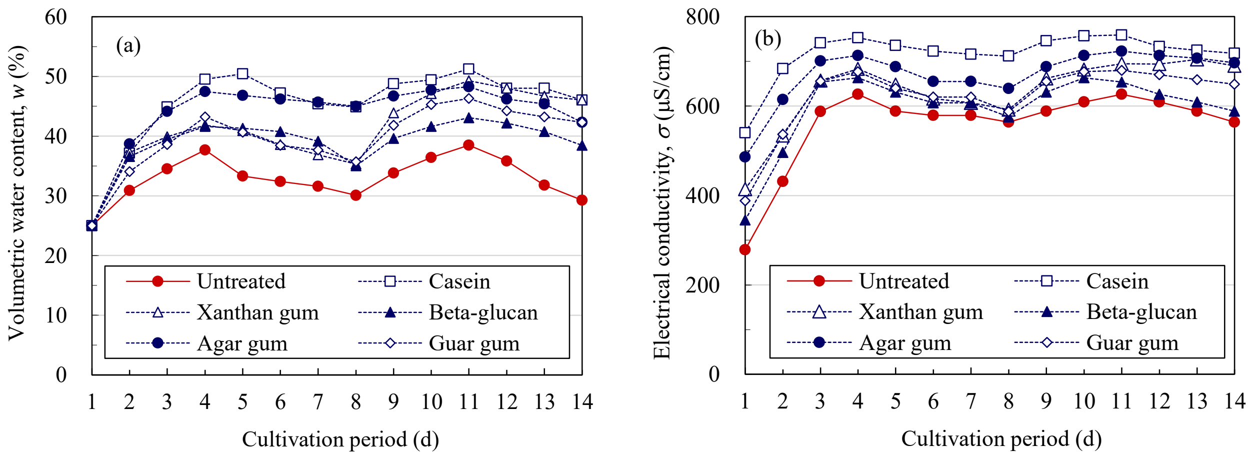

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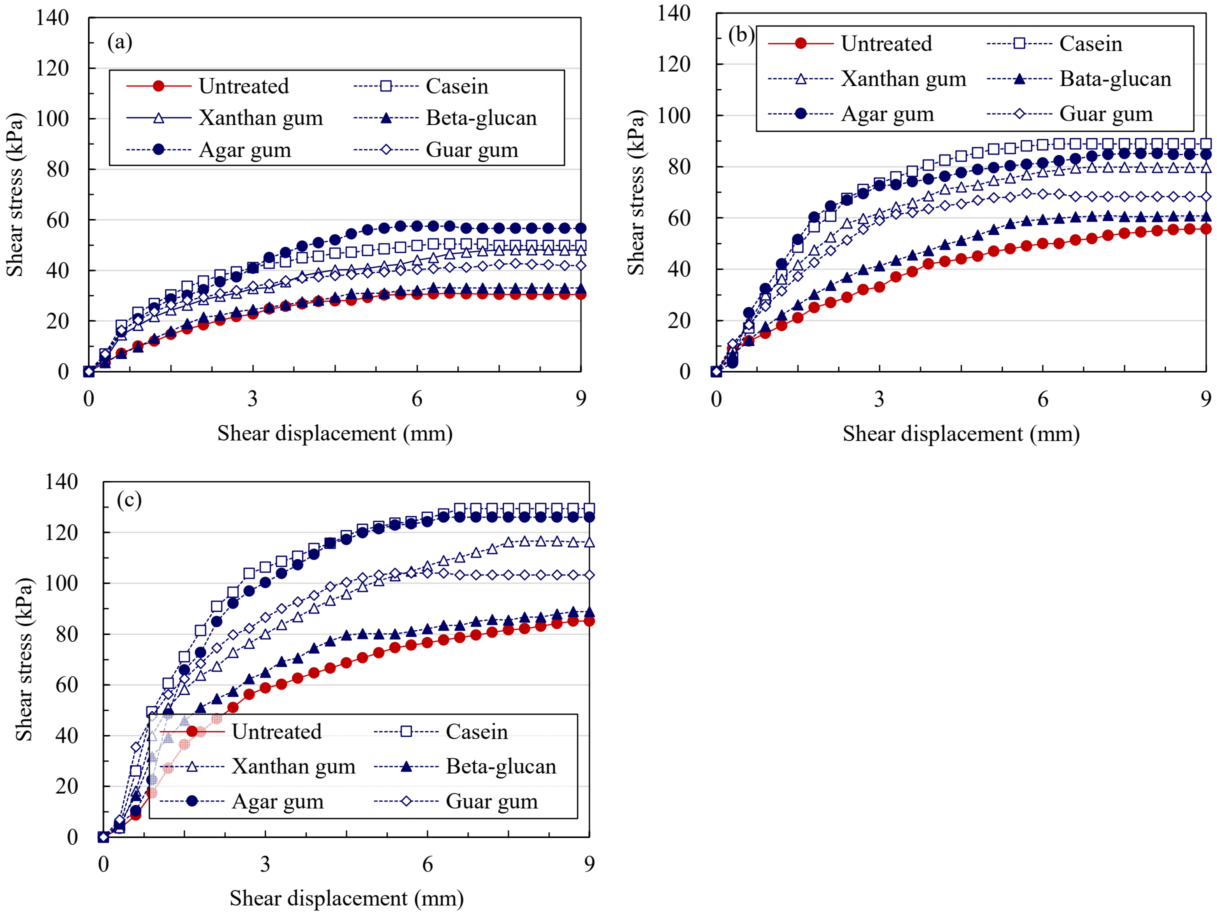

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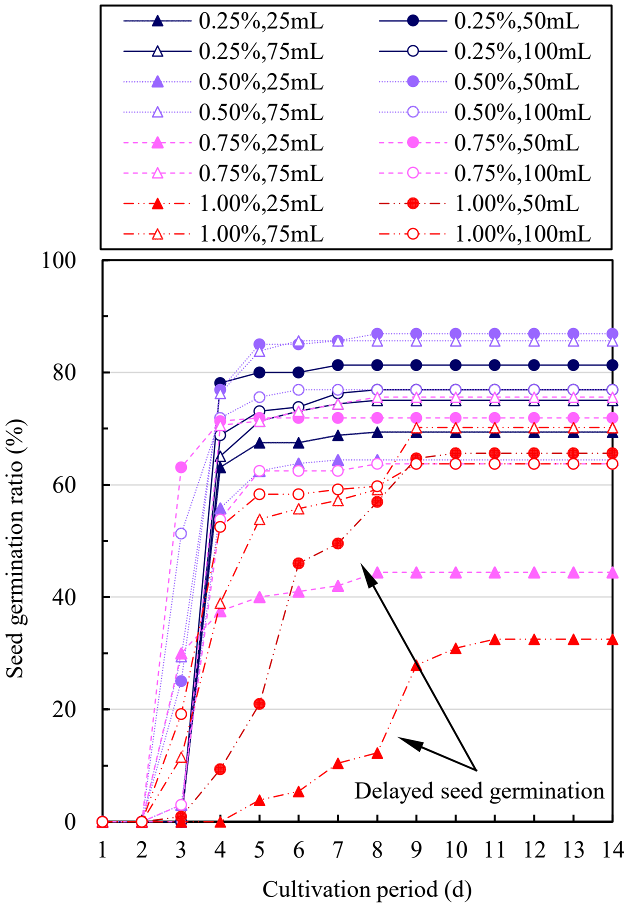

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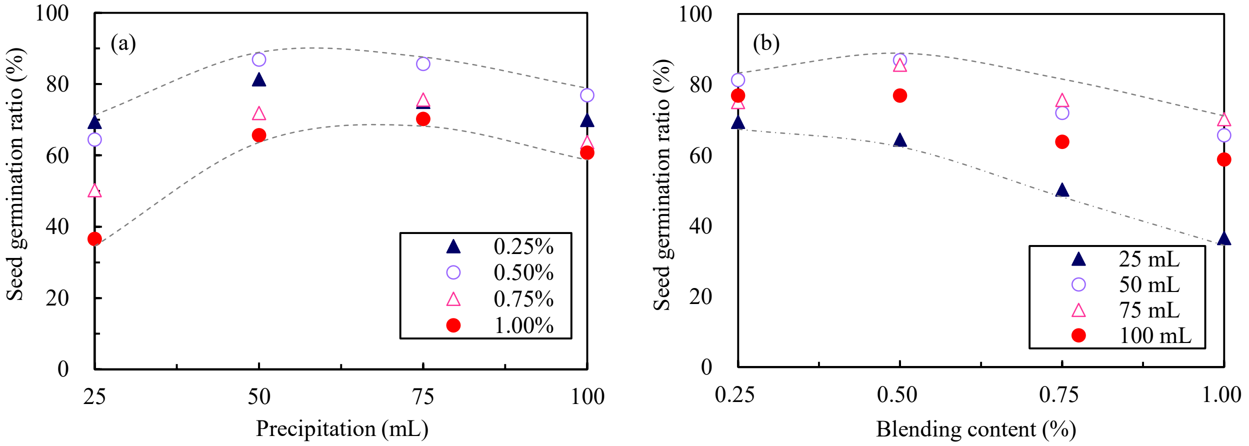

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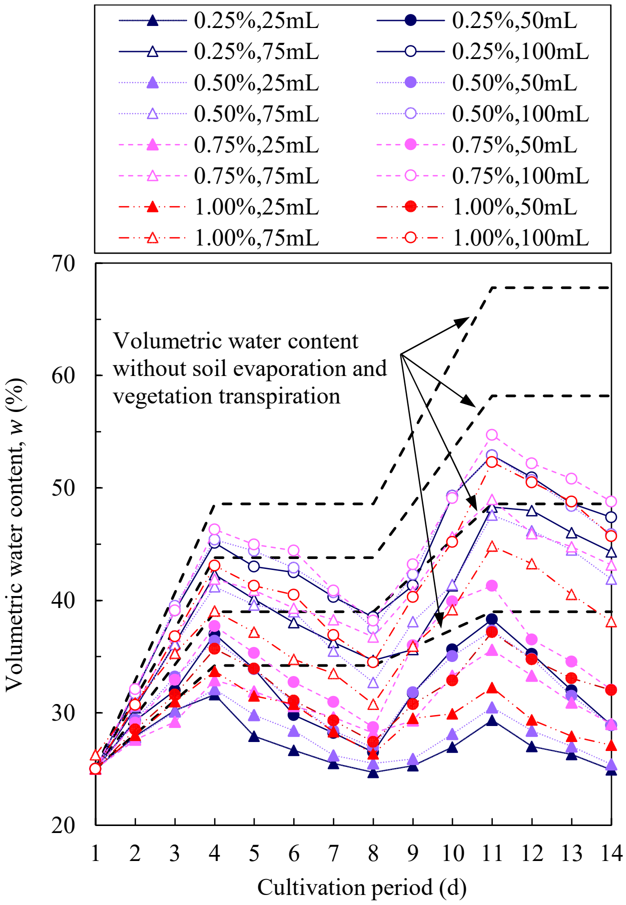

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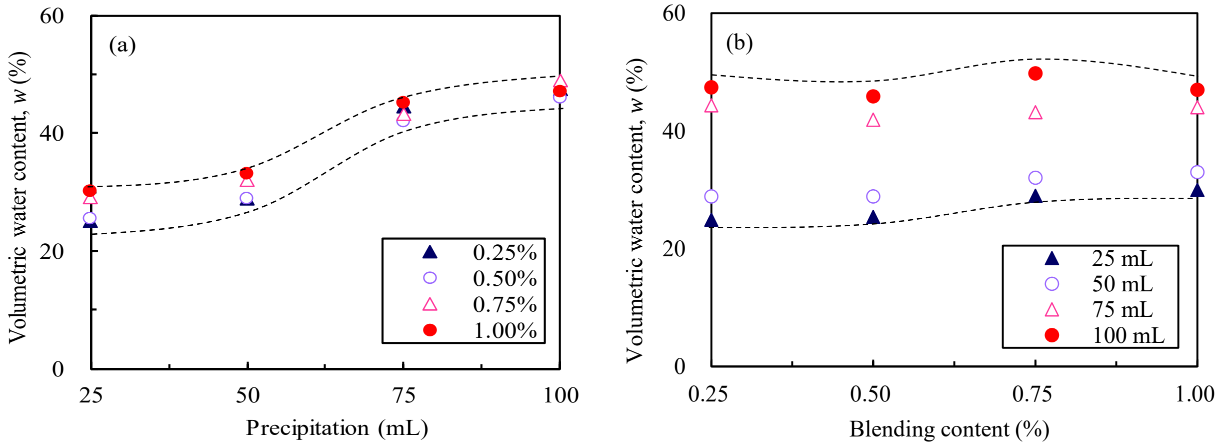

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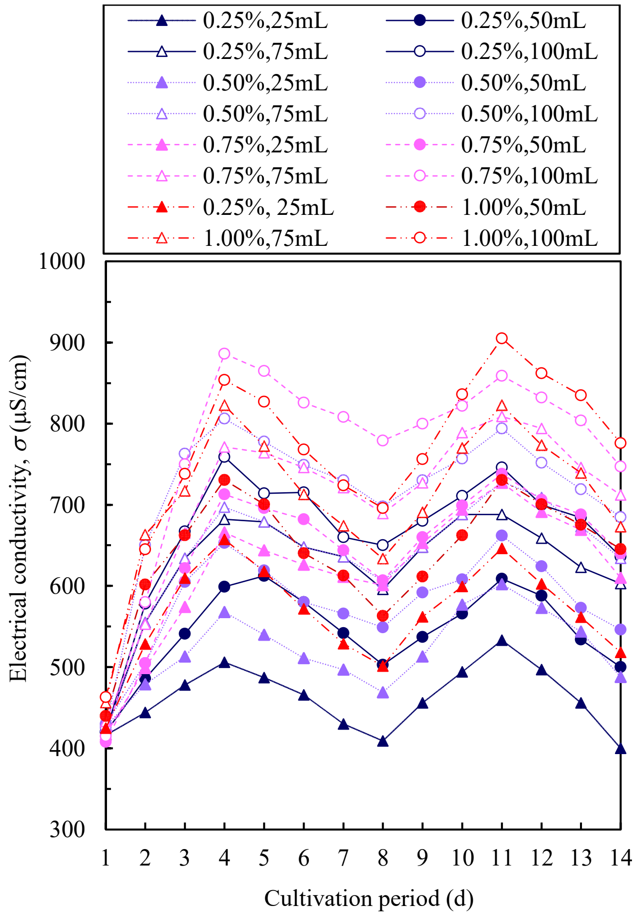

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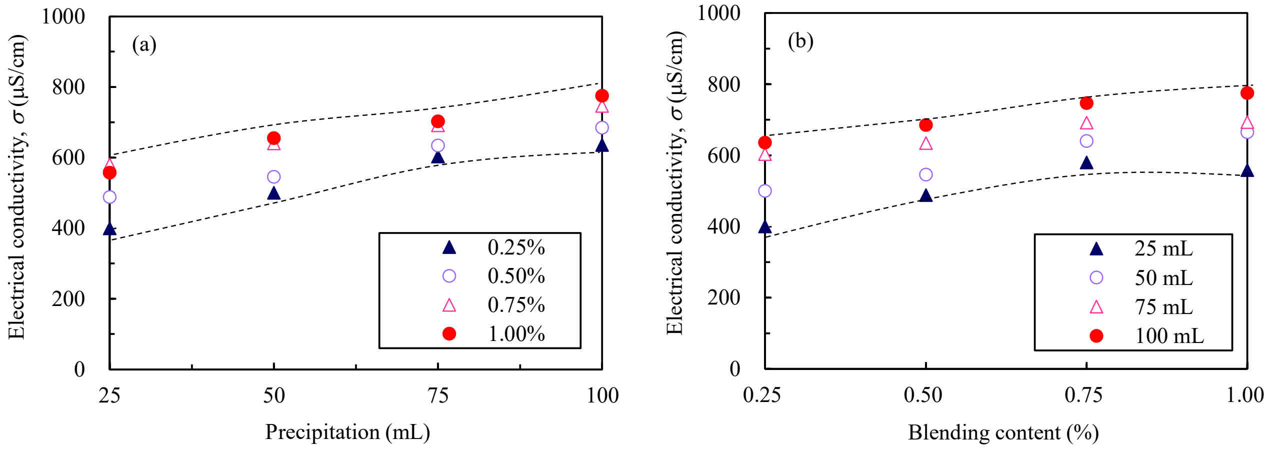

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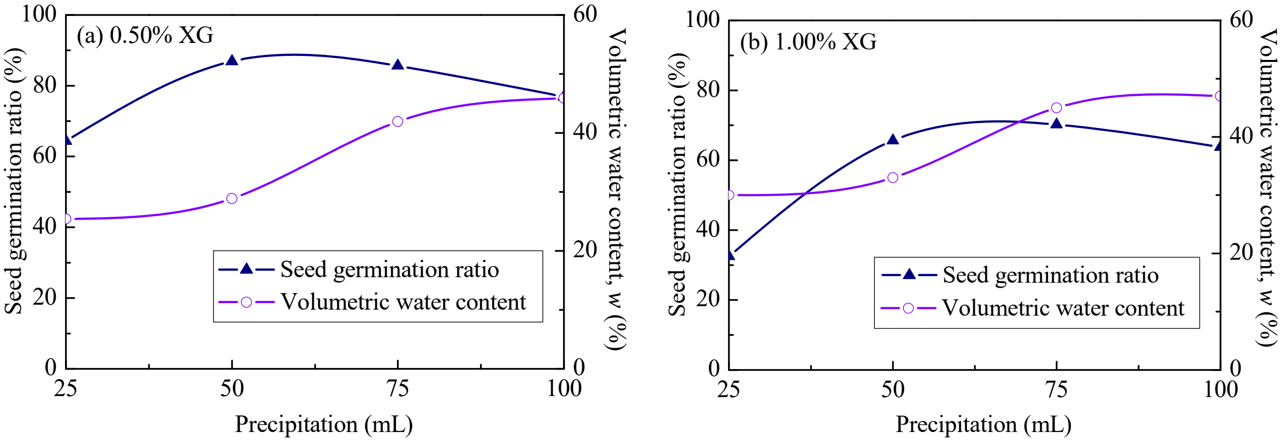

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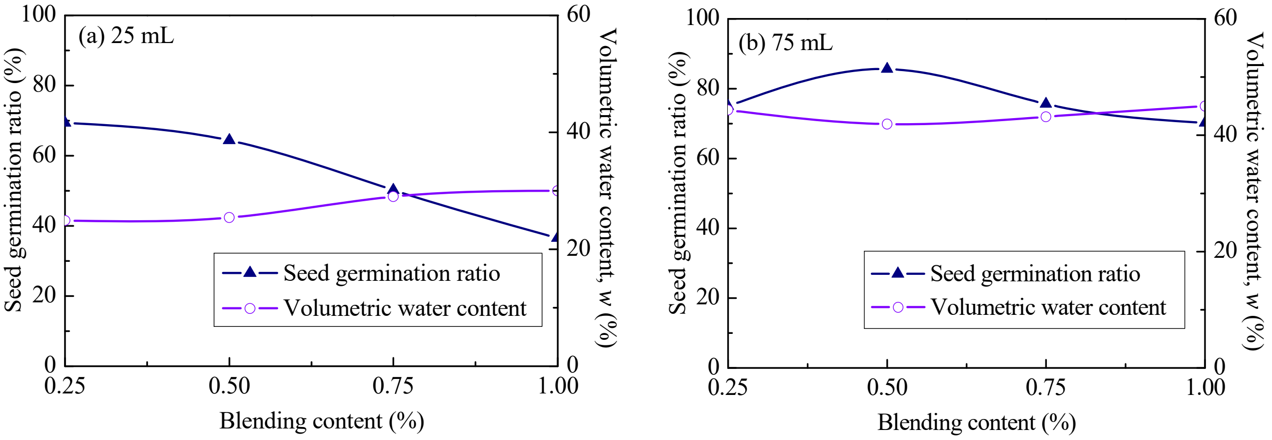

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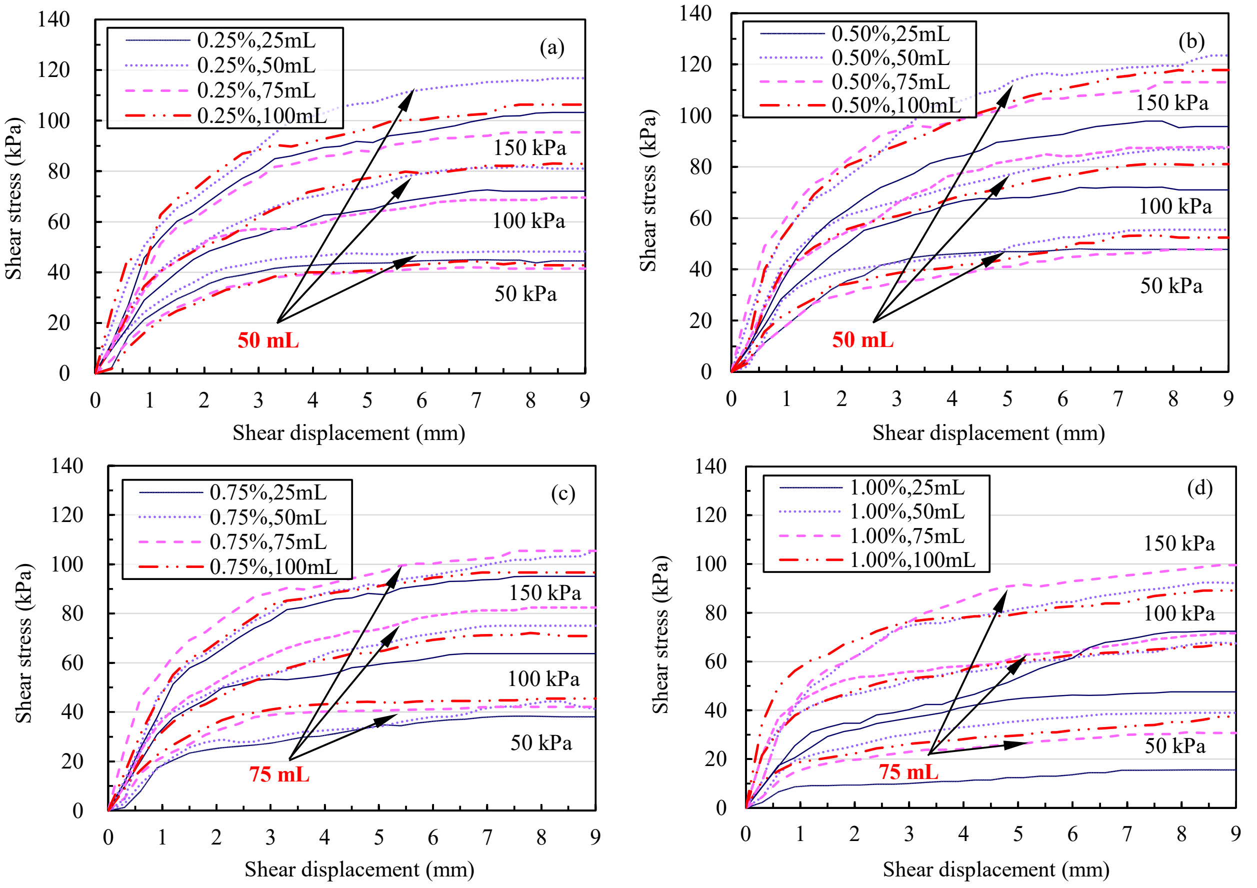

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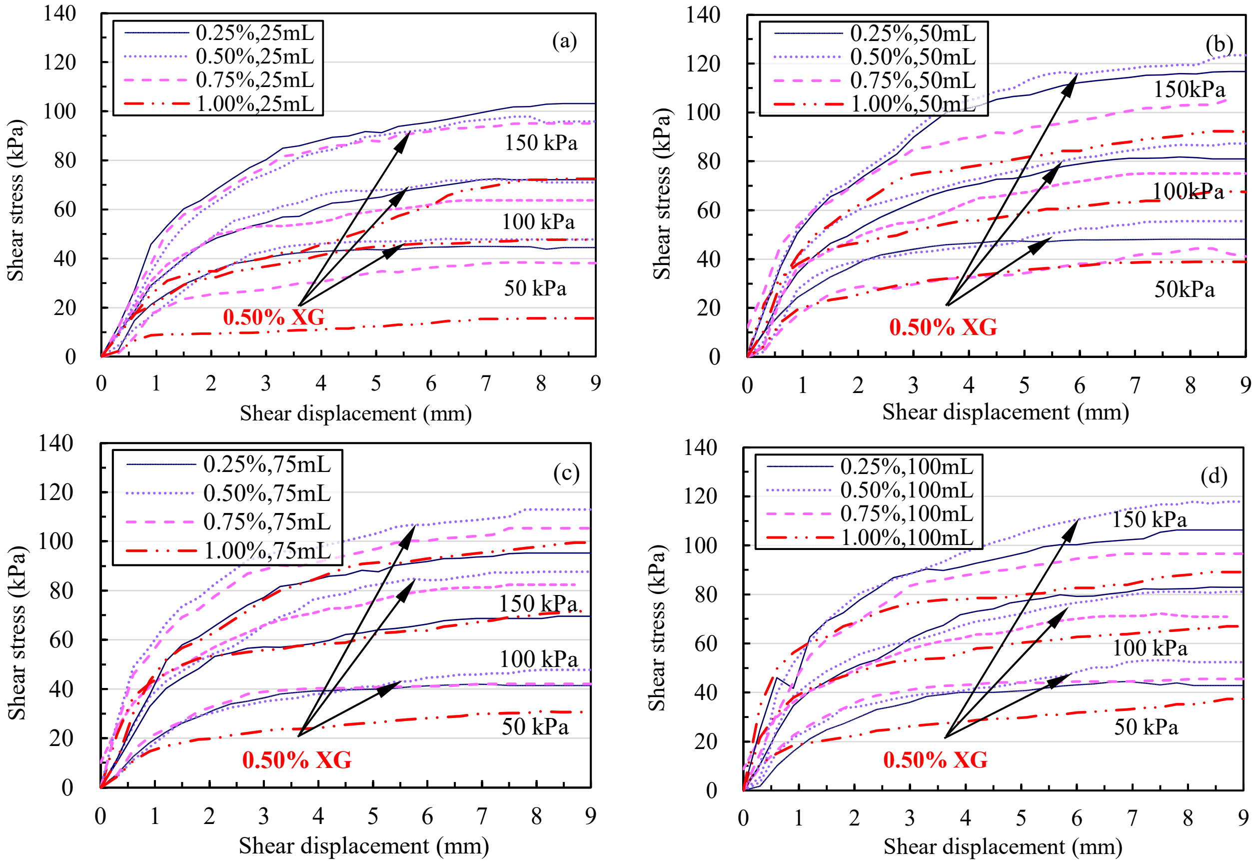

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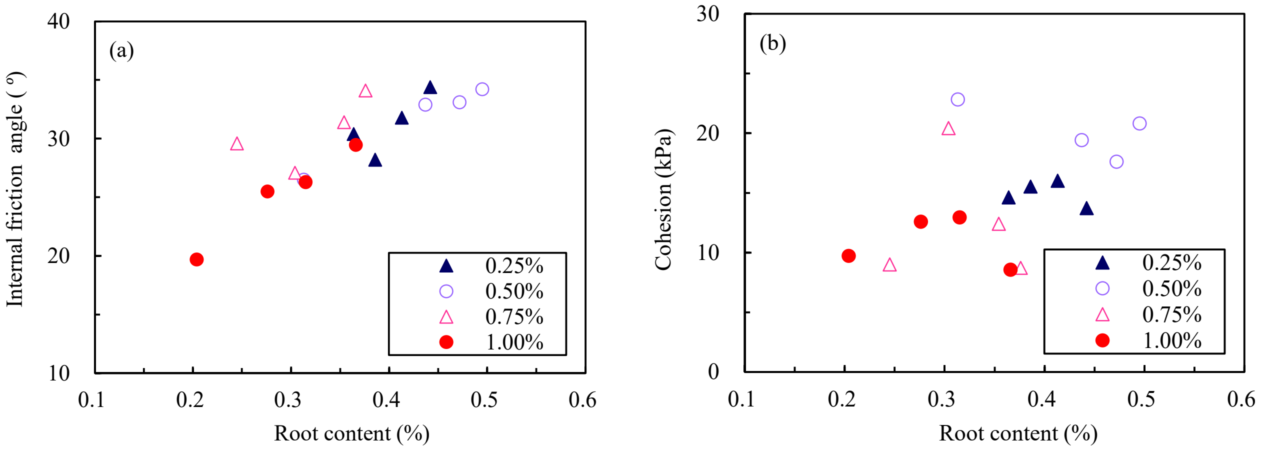

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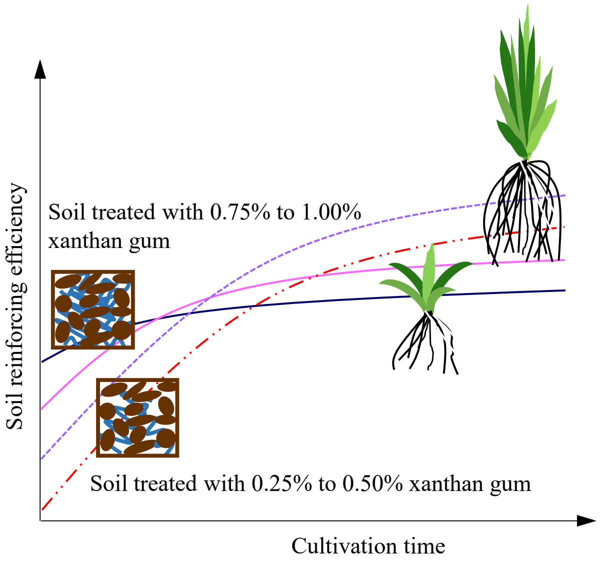

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Table 1. Properties of various biopolymers used in this study.

Biopolymers	Chemical components	Solubility (g/100 mL water)	Performances with soils
Xanthan gum	Glucose, mannose, and glucuronic acid	0.5~1.5	Strengthening (Latifi et al. 2016; Chen et al. 2019; Ni et al. 2020b) Erosion reduction (Chang et al. 2015a) Water resistance (Chen et al. 2020)
Guar gum	Mannose and galactose	0.5~1.5	Strengthening (Ayeldeen et al. 2016; Muguda et al. 2017)
Agar gum	Galactose	0.01~0.5	Strengthening (Khatami and O'Kelly 2013) Water resistance (Chang et al. 2015b)
Beta-glucan	Glucose	0.5~1.5	Strengthening (Chang and Cho 2012) Erosion reduction (Chang et al. 2015a)
Casein	Aggregates of micelle (α-, β-, and κ-casein) and phosphate calcium	0.01~0.5	Strengthening (Chang et al. 2018; Fatehi et al. 2018; Ni et al. 2022) Water resistance (Chang et al. 2018; Fatehi et al. 2018)

Table 2. Experimental program for two test series.

Variables	Test series I	Test series II
Plant	Oat	Oat
Biopolymer type	Xanthan gum, guar gum, agar gum, beta-glucan, casein	Xanthan gum
Blending content, %	0.50	0.25, 0.50, 0.75, 1.00
Precipitation, mL	70	25, 50, 75, 100
Number of seeds	160	160