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Recent development on optimization of bio-cementation for soil stabilization and wind erosion control

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ABSTRACT

This paper reviews and analyzes recent research development on bio-cementation for soil stabilization and wind erosion control. Bio-cement is a type of cementitious materials by adopting natural biological processes for geotechnical and construction applications. Bio-cementation is usually achieved through microbially- or enzyme-induced carbonate precipitation (MICP or EICP). The use of soybean urease can be a cost-effective solution for carbonate precipitation and bio-cementation, which is named SICP. The produced calcium carbonate can cement soil particles and bring considerable strength improvement to soils. In this paper, the mechanisms and recent development on the technology optimization are reviewed first. The optimization of bio-cementation involves 1) altering the treatment materials and procedures such as using lysed cells, low pH, the salting-out technique; and 2) using cheap and waste materials for bio-cement treatment and bacterial cultivation. The objectives are to improve treatment uniformity and efficiency, use bio-cement in more scenarios such as fine-grain soils, and reduce costs and environmental impacts, etc. Studies on the mechanical behaviour and wind erosion performances of bio-cemented soil show that the wind erosion resistance can be improved significantly through the bio-cement treatment. In addition, the use of optimized method and additives such as xanthan gum and fibers can further enhance the strength, treatment uniformity or ductility of the bio-cemented soils. Attention should be paid to wind forces with saltating particles which have much stronger destructive effect than pure wind, which should be considered in laboratory tests. Field studies indicate that bio-cement can improve soil surface strength and wind erosion resistances effectively. Besides, local plants can germinate and grow on bio-cemented soil ground with low-concentration treatments.

1. Introduction

Land desertification is one of the most serious ecological problems in China and worldwide. The desertification area accounts for 1/4 of the entire land area globally. More than 110 countries and nearly 1 billion people are affected by desertification [25,31]. The problem is particularly serious in China. According to a recent desertification and sandy land survey, the desertification land area is 2.57 million square kilometers, accounting for 26.81% of the total land area in China [37]. Every year in China, a large number of farmlands and grasslands are damaged by wind and sand storms. Infrastructure systems and agricultural facilities such as roads, railways, reservoirs and irrigation channels in these areas are often attacked by wind-blown sand, causing huge direct and indirect economic losses. Aeolian sands in arid and semi-arid regions are mainly composed of sand particles, with few clay particles. The soil cohesion is low. In dry seasons, wind can easily blow away the loose fine particles on the surface of the sandy ground. The absence of these fine particles often leads to the loss of organic matter and other necessary nutrients for plant growth. In addition, the fine soil particles carried away by the strong wind are easily suspended in the air and transported to other places by the wind, resulting in air pollution and threatening human health.

The methods for sand fixation against wind erosion usually include engineering methods, plantations, and chemical methods [44]. Engineering methods are to construct barriers on the sandy ground surface of the sand, such as fences and straw squares, etc. Due to the limited heights of these structures, fences and straw squares can be easily buried by wind-blown sand, and thus their protection duration is short

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according to the practices for wind erosion control in Northwest China. Plantation methods are mainly planting and cultivation of drought-tolerant plants, such as grass, trees and shrubs, etc. The purposes of plantation methods involve not only reducing wind velocity, preventing wind erosion, and fixing soil particles, but also restoring vegetation, and improving the ecology and environment in arid regions. Due to the lack of water in arid areas, the survival rate of artificially planted plants is low. The plant growth rates are also relatively slow. Chemical methods refer to the spraying of chemical substances with solidification or water retention effects on the surface of sand dunes or grounds. However, this method is often relatively expensive, and some chemical reagents are toxic or non-degradable substances, which may cause environmental contaminations.

Conventional sand fixation methods have many problems in terms of technical performance, economy, environmental impacts. In recent years, soil cementation methods based on microbial or enzymatic processes have been proposed and tested for various applications. These methods have also shown potential for sand fixation and wind erosion control in deserts and arid regions. This paper first introduces the mechanisms and recent studies on the optimization of these biological soil cementation (or so-called bio-cementation) methods. Furthermore, the laboratory and field studies on the mechanical behaviour and wind erosion resistances of bio-cementation are summarized and analyzed. Bio-cementation technology has been developed for more than ten years. Relevant literature reviews include Ivanov and Chu [26], Dejong et al. [10], Dhami et al. [11], Qian et al. [39], Cheng et al. [6], He et al. [19], Liu et al. [28], etc. The focus of this article, however, is to review and analyze literature related to bio-cementation against wind erosion control, including biological processes, optimization of the treatment methods, wind erosion resistance effects and evaluation methods, etc.

2. Mechanisms and optimization of bio-cementation

2.1. Basic concepts of bio-cementation

Bio-cementation is an emerging soil improvement technology in which inorganic compounds are induced by bacteria or free enzymes to cement geotechnical materials. The effective products of the bio-cementation process are usually precipitates with cementing properties, including carbonate, phosphate, and iron hydroxide, etc. Among them, ureolysis-based carbonate precipitation is the most widely studied process to achieve bio-cementation. During this process, the hydrolysis of urea is catalyzed by the bacteria or urease enzyme, releasing a large amount of free carbonate ions into the reaction environment. With free calcium ions in the reaction system, calcium carbonate can precipitate in soil pores. The reaction process is shown as follows:

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \quad (1)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(s) \quad (2)$$

The ureolysis is an important step in the bio-cementation process. This step usually relies on urea-hydrolyzing bacteria or free urease. Depending on the type of selected catalyst, the two common processes are named microbially-induced carbonate precipitation (MICP) and enzyme-induced carbonate precipitation (EICP), respectively. In recent years, the use of soybean urease for carbonate precipitation and bio-cementation has attracted many research studies, which are named SICP. Urea-hydrolyzing bacteria are widely used in the bio-cementation process. It can adapt to various reaction environments, effectively promote carbonate precipitation, and provide nucleation sites for mineral growth [3]. The use of free urease makes the bio-cementation technology easier to conduct. Because of the smaller size of urease, it can move relatively freely in fine-grained soils. Evidences have been reported that, when using urease for the catalyzation of urea and the treatment of fine-grained soils, relatively uniform carbonate precipitation and higher strength can be obtained as compared with that using live bacteria [15]. In comparison, the MICP technology is limited by the pore size and cannot effectively treat fine-grained soils [22]. To further reduce the high cost caused by commercial urease, a series of studies have also been conducted by many scholars using plant crude extract urease as an alternative to commercial urease. For example, He et al. [22] extracted crude urease from soybean and used it to catalyze urea decomposition during SICP, and in turn effectively strengthened silty sand. Khodadadi et al. [40] also compared the effectiveness of crude extracts of jack bean, watermelon seeds and commercial urease in treating Ottawa sand, and found that crude urease was more effective than highly purified urease in improving soil strength.

The introduction of bacteria or urease can accelerate the hydrolysis of urea, promote the precipitation of carbonates, and regulate their cementation patterns. The produced carbonate can interconnect soil particles and fill soil voids, thereby improving the strength and reducing the permeability of geotechnical materials. In recent years, many scholars have successfully applied bio-cementation technology in several geotechnical engineering fields, such as ground soil strengthening [3], erosion control [21], and conservation of historic relics [17]. The ultimate effect of bio-cementation is determined by a series of factors, such as properties of soils, the concentration of the reaction solutions, and treatment methods. These factors lead to the differences in the bio-treated materials such as the amount, uniformity and cementation pattern of calcium carbonate. According to previous studies, there is a significant positive correlation between the calcium carbonate content and the strength of the specimens, and the treated specimens with higher calcium carbonate content tend to exhibit higher strength [32,38]. In addition to the total amount precipitations, the uniformity of calcium carbonate distribution is also an important factor affecting the final reinforcement effect. Uneven calcium carbonate distribution often leads to local damage in locations with less calcium carbonate content, which eventually exhibits lower overall material strength [43]. Localized excessive precipitation of calcium carbonate also causes bio-clogging problems, which hinders the subsequent treatment [5]. In addition, the cementation pattern of calcium carbonate between soil particles also has influences on the bio-cementation effect. According to the distribution state of calcium carbonate between soil particles, the cementation patterns can be roughly divided into two categories: coating and bonding, both of which exist in different proportions in the bio-cemented soils [9]. In the bonding pattern, the calcium carbonate precipitate is initially generated at localized points on the soil particles, and calcium carbonate continues to precipitate on these points as the nucleation site. Eventually calcium carbonate precipitates form bridges between two or more soil particles to improve the integrity of soil particles. In the coating pattern, calcium carbonate precipitates are evenly distributed on the surface of soil particles and even encapsulates soil particles. In this type of cementation pattern, calcium carbonate does not effectively connect soil particles and therefore only provides filling effect as compared to the bonding pattern. Thus, the bonding pattern of calcium carbonate precipitation can utilize the calcium carbonate more effectively in terms of the strength improvement.

2.2. Enhanced techniques in bio-cementation

In the bio-cementation process, there are some limitations that could lead to ineffectiveness of the treatment. To properly solve these problems, some enhanced techniques based on bio-cementation technology have been proposed. He et al. [20] used ultrasonic cell lysis technique to obtain crude urease from urea-hydrolysis bacteria and used it to treat silty sands, which overcame the limitation of bacterial size and obtained a better treatment effect than MICP. Cheng et al. [5] proposed a low-pH one-phase injection method. It can control the lag period of the bio-cementation process by adjusting the biomass concentration, urease activity and pH. This method can avoid the blockage of bio-floc formation, so that the bio-cement solution can be well distributed in the soil matrix before calcium carbonate starts to

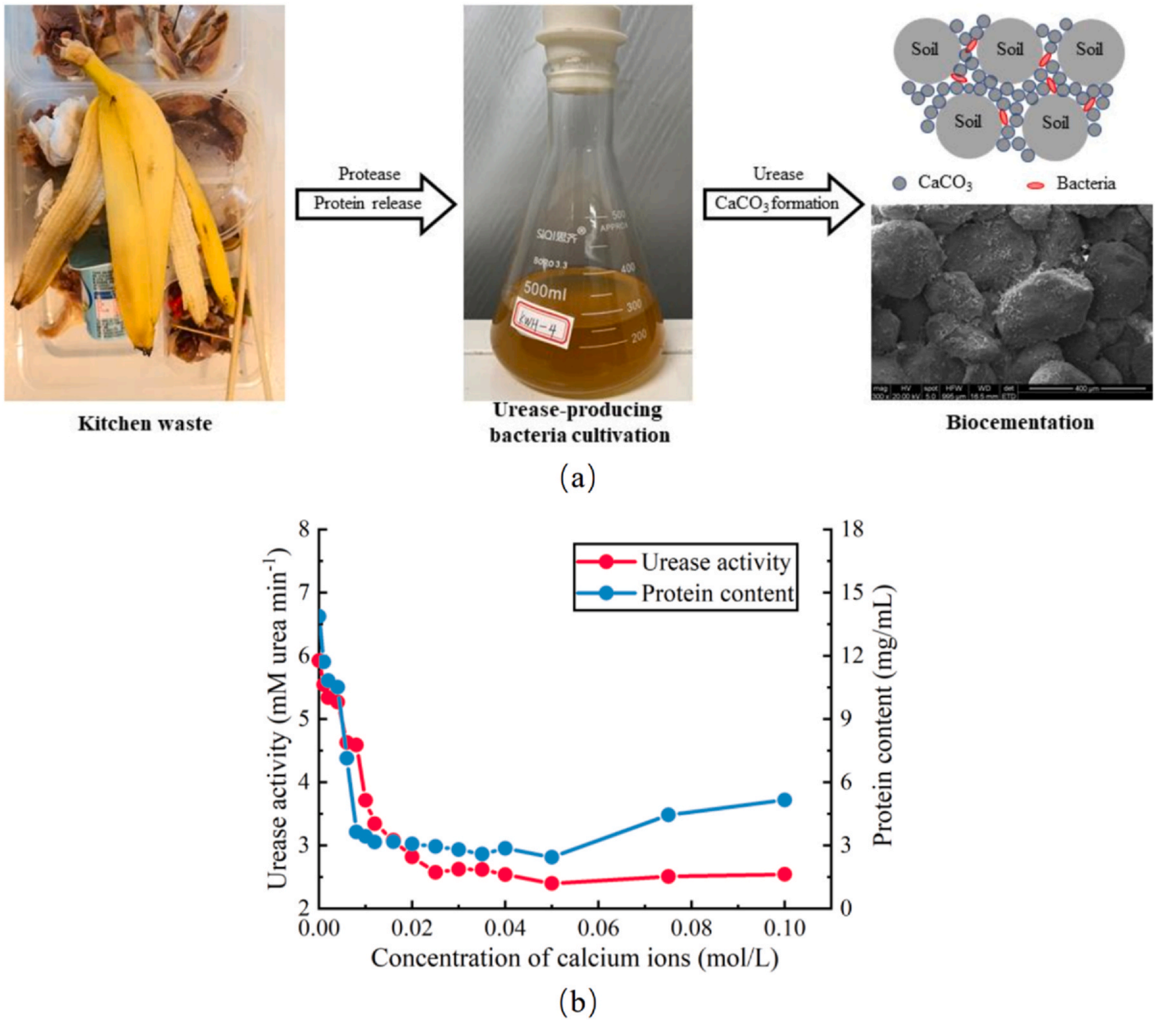

Fig. 1. Enhanced techniques in bio-cementation: (a) the production of S. pasteurii and utilization phase of MICP; (b) the salting-out method for crude soybean urease. (a) Images from Meng et al. [34]; (b) Data from Yan et al. [43].

precipitate, and thus achieve a relatively uniform MICP treatment. Yan et al. [43] proposed a modified salting-out method for crude soybean urease. This method utilized the property that proteins will aggregate and precipitate when encountering trace amounts of salt (as shown in Fig. 1b). The excess proteins can be removed in soybean urease solution in advance. Otherwise, these proteins can negatively affect the soil treatment during the bio-cementation process. Meng et al. [35] proposed a multi-phase treatment method based on the SICP process. In this method, soil was pre-mixed with soybean crude urease and the cementation solution first. Subsequently the soil underwent several times of percolation treatment using only the cementation solution. By using this method, the urease utilization rate increased by at least fourfold, and the blockage problems was alleviated, resulting in a relatively uniform SICP treatment effect.

In addition to the optimization of treatment methods, the optimization of reaction substrates has also been one of the directions for bio-cement technology development in recent years. In laboratory studies, the common reaction substrates for bio-cementation are analytically pure urea and calcium chloride reagents, which are relatively expensive. If the bio-cementation technology is to be applied to engineering practice, it is required to reduce the cost of the reaction materials. He et al. [22] conducted a meter-scale model test using industrial-grade calcium chloride and fertilizer urea for SICP treatment of silty sands. The results showed that the treatment using the above-mentioned materials has the potential to improve silty sands in engineering scale. Liu et al. [29] proposed the concept of urease enrichment degree (defined as the urease activity per gram of organic matter in the extracted urease solution) to evaluate the purity and organic matter level of crude ureases from different plant sources. It was found that the crude urease extract with a higher urease enrichment degree (e.g., jack bean crude urease) can be more effective in enhancing soil strength. In addition to the use of slightly lower quality reaction materials, obtaining calcium sources from waste instead of commercial calcium chloride is also the focus of such studies. This idea can reduce the costs and have environmental benefits a. As presented in Fig. 1a, Meng et al. [34] used enzymatic decomposition of kitchen wastes and used them to cultivate ureolytic bacteria. Then, the bacteria were used for MICP treatment and wind erosion control. He et al. [18] dissolved waste concrete in an acidic liquid to obtain liquid calcium. The liquid calcium was then used for bio-cement treatment of sand columns. The test results showed that the specimens using concrete-extracted calcium exhibited strengths close to or better than those of conventional SICP specimens with commercial calcium sources. Besides, Qi et al. [38] prepared soluble calcium by acid dissolution of industrial waste calcium carbide slag powder (CSP) and used it for the treatment of sandy soils. All these studies have shown that the bio-cementation technology based on waste or reused raw materials can not only bring similar soil improvement effect as compared those with commercial materials, but also have environmental benefits.

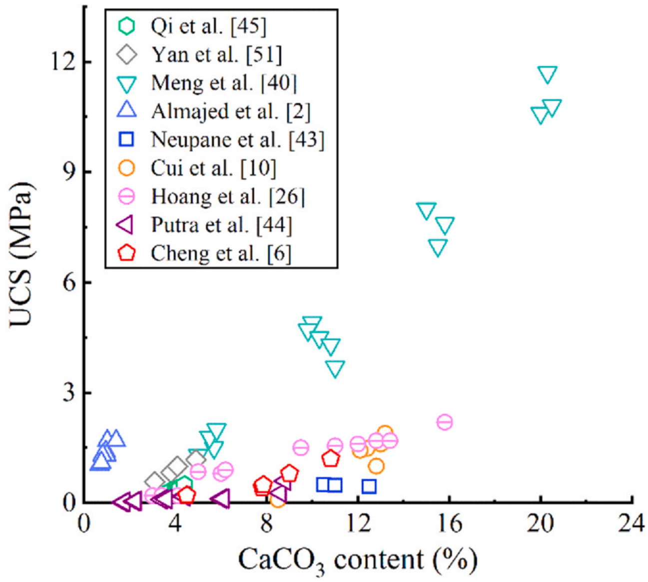

Fig. 2. The relationship between UCS and $CaCO_3$ content of bio-cemented soil.

3. Mechanical behaviour and wind erosion resistance in laboratory investigations

Numerous studies have characterized bio-cemented soils using various techniques and testing methods at multiple scales. The observed properties and their significance are discussed in this section.

3.1. Strength

The unconfined compression test has been the most used strength test for bio-cemented soils. Fig. 2 plots the unconfined compressive strength (UCS) values reported in literature against the corresponding contents of precipitated $CaCO_3$. It can be seen that, with the $CaCO_3$ content ranging from 1% to 22%, UCS varies from 0.05 MPa to 12 MPa. In general, the UCS increases with increasing $CaCO_3$ content, which proves the effectiveness of bio-cementation technology for soil improvement. Different levels of soil improvement can be obtained by controlling the mass content of calcium carbonate in the soil to meet different scenarios of applications. However, the relationship between UCS and $CaCO_3$ content is not unique, and is affected by other factors. The treatment effect using bio-cement involves many variables such as urease activity and chemical concentration. In addition, treatment schemes (such as single-phase versus multi-phase injection treatment), and the uses additives can also affect the bio-cementation effect.

The optimized bio-cementation methods have shown significant effects in improving the mechanical properties of soil. Several new methods have been tried to achieve high efficiency of bio-cementation. He et al. [20] found that crude urease obtained from the lysis of ureolytic bacteria successfully alleviates the clogging problem in conventional MICP method for the treatment of fine-grained soils. Silty sand samples treated by crude bacterial urease had higher shear strengths and more dilative stress-strain responses during the undrained shear as compared with the samples treated by live bacteria. In recent years, the crude urease extracted from plants was considered as an alternative to commercial urease in terms of ease of operation and economy. Yan et al. [43] proposed a salting-out method that could effectively improve the uniformity for soil treated with crude soybean urease. The $CaCO_3$ content of specimens treated by the salting-out method remained uniformly increased after 10-cycle treatments, and the UCS of the specimens increased to 1.2–1.3 MPa, which was approximately 12 times higher compared to the conventional method treated with the same amount of raw materials. Optimizations also have been made in the treatment processes. Cui et al. [8] proposed a modified one-phase-low-pH MICP or EICP method in order to simplify the treatment procedure and improve the efficiency of bio-cementation treatment. In this method, the low-pH bacteria or urease solution is together with the cementation solution (i.e., $CaCl_2$ and urea) for the first treatment. For the subsequent treatments, only cementation solution is used. The experimental results showed that the modified method was more efficient in enhancing the strength of sand, that is, less calcium carbonate is needed to achieve a certain soil strength. Meng et al. [35] proposed a multi-phase method consisting of a premixed of soybean crude urease and cementation solution followed by several percolations of cementation solution. The method alleviated the clogging of carbonate precipitation. The UCS of sand exceeded 10 MPa with a $CaCO_3$ content of about 20%. Additives such as xanthan gum and milk powder can adjust the distribution of calcium carbonate formation during the treatment process, and improve the treatment efficiency [1,42]. The addition of xanthan gum, fibers and other substances can also improve the strength, ductility and other mechanical properties of the treated soils. The viscosity of the xanthan gum delays the infiltration of the treatment solution, which facilitates the cementation of the surface soil. A small amount (e.g., 0.1–1 g/L xanthan gum according to Wu et al. [42]) can significantly improve the erosion resistance of the surface layer of soil. The fiber inclusion can promote the $CaCO_3$ precipitation and form more effective bonding at soil particle scale. A series of experimental results indicate that the fibers dramatically improved the ductility and toughness of specimens by a factor of 2–5, preventing the bio-cemented soil from failing in a brittle failure mode [7,14,41].

3.2. Wind erosion resistances

Wind erosion is a common soil erosion problem in arid and semi-arid areas. It often occurs in aeolian soils with poor gradation and relatively uniform particle sizes. Thus, soil erosions in deserts and arid regions are the major focus of using bio-cement for wind erosion control. In addition, other types of soil wind erosions, such as dust pollution in mining areas and construction sites, and preservation of historic sites, have also been involved in related studies [17,23]. The destructive effect of wind erosion can be divided into two types, pure wind blowing and wind erosion with saltating particles. Pure wind damages the soil surface solely by wind force. For the wind erosion with saltating particles, the sand particles saltate on the surface under the wind force, and the damages are triggered by the bombardment of the saltating particles. This process will then lead to further soil particle saltation and ground damages. Anderson et al. [2] showed that, considering the impact of saltating particles, bio-cementation treatment can improve the wind erosion resistance by 1 order of magnitude, and it can produce 2–4 orders of magnitude improvements without considering this impact. In Wu et al. [42], at a wind velocity of 15 m/s, the destructive effect of wind erosion considering the impact of saltating particles is much higher than that without saltating particles for the soil samples treated in the same way. Therefore, ignoring the impact of saltating particles will lead to a serious underestimation of wind erosion damages. To simulate the impact of saltating particles in wind erosion tests, a sand feeder is often used to artificially deliver saltating particles into the wind flow in order to artificially control the erosion intensity. For example, Fattahi et al. [12] evaluated the erosion resistance of MICP-treated soil to a wind-sand flow with a wind velocity of 6.8 m/s and a sand flux of 1 g/s. Liu et al. [32] investigated the erosion resistance of bio-cemented desert sand under wind-sand flows of 5–15 m/s with different sand fluxes. Liu et al. [30] compared the efficacy of jack bean and soybean crude urease for the mediation of carbonate precipitation on desert sand stabilization. It is found that jack bean crude urease exhibited greater surface stabilization (wind erosion control) potential under a single bio-treatment, thanks to higher urease content and suitable organic matter level. There are mainly two types of assessment methods for the soil surface erosion under wind forces. One type uses the erosion rate or erosion amount under a certain wind velocity as an assessment indicator, such as the amount of soil loss per unit area over a certain period of time. The other one is to use the threshold detachment velocity (TDV) to evaluate the wind erosion resistance. When the wind velocity is less than TDV, only a small amount of surface dust and uncemented particles will cause mass loss. If the wind velocity is greater than this value, there will be evident wind erosion, and the erosion rate is positively correlated with wind velocity. In most studies, only a single bio-treatment round is needed to significantly reduce the wind erosion rate and improve the TDV of soil.

In addition to the wind erosion test, some other test methods are also used to evaluate the wind resistance effect, such as calcium carbonate content measurement, scanning electron microscopy (SEM), mineral composition analysis, permeability, strength measurement, etc. Among them, a large number of studies have adopted the surface penetration strength test. The penetration test is effective in assessing the strength of surface soil. It is suitable for measuring the strength of hard crusts form by bio-cementation. It has been demonstrated that the penetration resistance is consistent with the results of calcium carbonate content, triaxial CD tests, etc [14,22]. Considering the difficulty of conducting wind erosion test in laboratory and field conditions, penetration test can be used to evaluate the wind erosion resistance as an easy and fast method. As shown in Fig. 3a, under certain wind velocity and duration conditions, there is a strong correlation between the TDV and the surface penetration resistance. When the surface strength reaches a certain value, it can effectively resist wind erosion.

4. Field studies on wind erosion control using bio-cement

The bio-cementation technologies have demonstrated considerable potential for controlling wind erosion in desert field trials [13,16,24,27,33,36]. Naeimi et al. [36] assessed the impact of microbially induced calcium carbonate precipitation (MICP) on in-situ sand dune fixation in Northeastern Iran. After 30 days, the penetration strength of the surface treated layer was 123 kPa at a urea-calcium chloride concentration of 0.3 M. No wind erosion occurred at a wind speed of 30 m/s. Hodges and Lingwall [24] employed the MICP method for in-situ treatment using 0.33 mol/L urea, 0.25 mol/L calcium chloride, and ureolytic bacteria. This level of treatment was enough to achieve sufficient sand fixation effect to resist wind erosion. Li et al. [27] used the MICP method in combination with the traditional straw square technique to achieve sand fixation successfully in the field. Meng et al. [33] utilized the MICP method for in-situ sand fixation and wind stabilization tests in the Ulaanbuwa Desert, China. It is revealed that spraying treatment with 0.2 mol/L urea, calcium chloride, and bacterial solution resulted in a relatively long-lasting effect on sand fixation.

Soybean urease-induced carbonate precipitation (SICP) is an effective method for improving soil strength and durability. Compared to the MICP technology, the SICP technology for wind erosion control in desert areas offers several advantages. On the one hand, it eliminates the need for large-scale on-site cultivation of ureolytic bacteria. On the

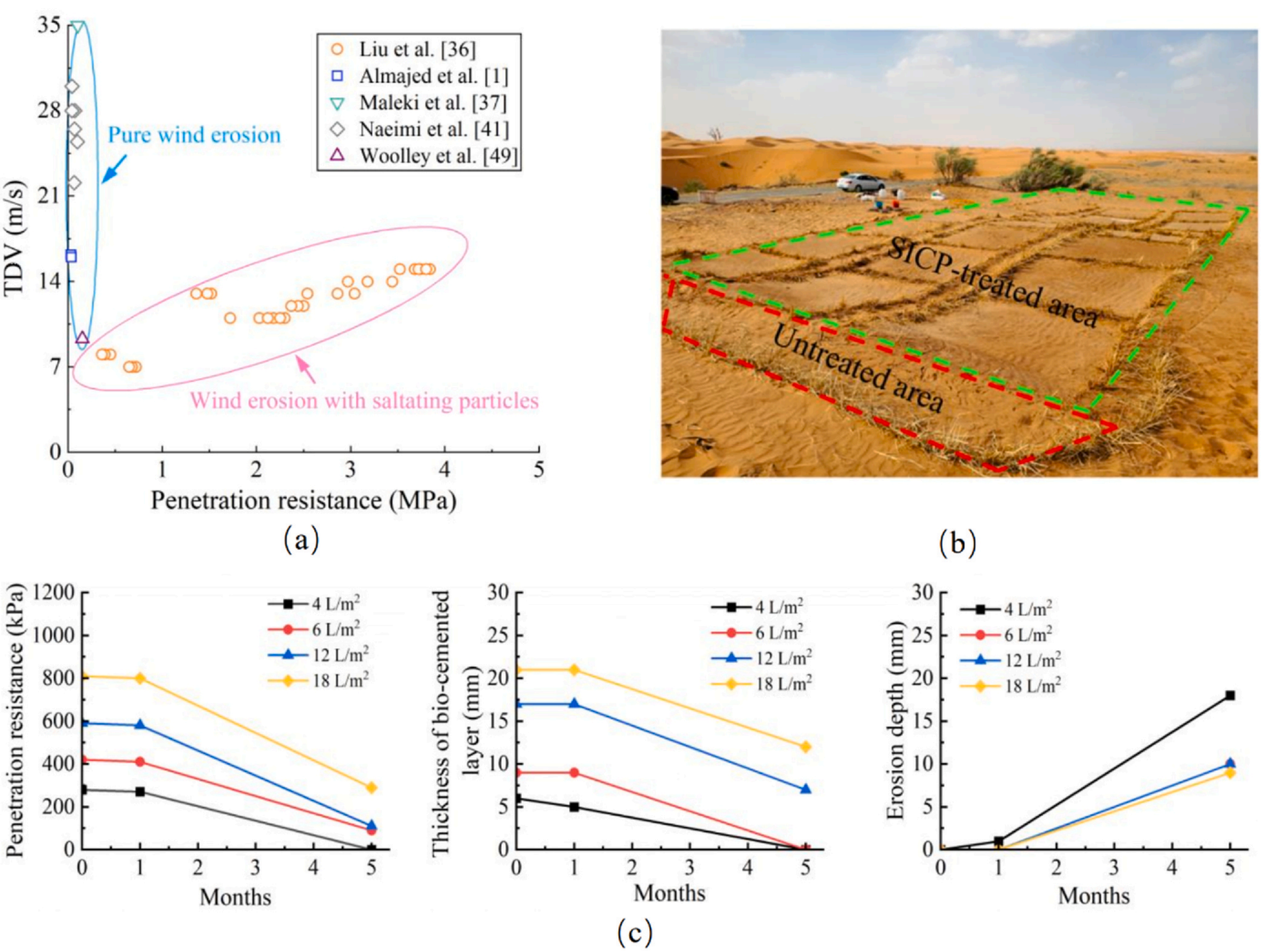

Fig. 3. Bio-treatment for wind erosion control: (a) relationship between the TDV and penetration resistance by laboratory experiments; (b) SICP treated field in Tengger Desert; (c) Surface penetration resistance, thickness and erosion depth of bio-cemented layer.
(b) Image from Gao et al. [13]; (c) Data from Gao et al. [13].

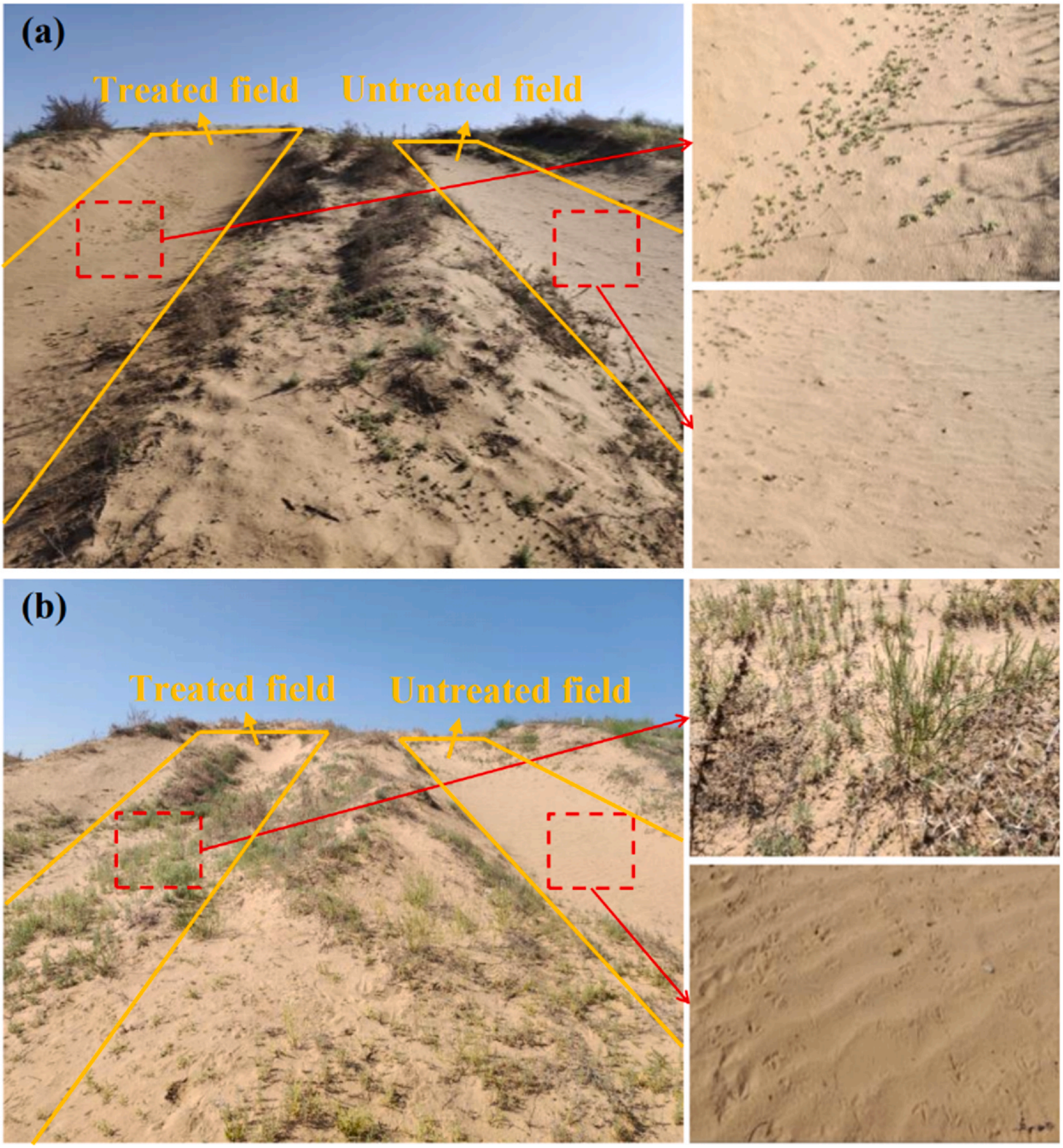

Fig. 4. The comparison between the untreated and SICP treated field in Ningxia, China after (a) 2 months; (b) 15 months.

other hand, the ecological risk of using soybean urease in desert areas is lower compared to the use of live microorganisms. Meng et al. [33] conducted a field trial in the Ulaanbuhe Desert, Ningxia Hui Autonomous Region. The results demonstrated that the SICP method significantly enhanced surface strength and wind erosion resistance of topsoil. The optimal bio-cementation solution (urea-calcium chloride) concentration was 0.2 M, and the optimal spray volume was 4 L/m^2. Under these conditions, after 30 days of SICP treatment, the $CaCO_3$ content was approximately 0.45% in topsoil, and the surface strength of the sandy soil reached 306.2 kPa. The erosion depth under natural wind was almost zero. Gao et al. [13] evaluate the feasibility and durability of SICP treatment for enhancing the wind-induced erosion resistance of desert sand in Tengger Desert. Results indicated that the ductility of SICP treatment could be improved by applying higher chemical concentrations, spraying more dosages and multiple treatment cycles in the areas where severe wind-induced erosion takes place (Fig. 3b and c). The authors' team have employed the optimized SICP method [20] in Ningxia. Experimental results revealed that the optimized SICP method reduced clogging caused by excessive organic matter in the urease solution, increased the number of SICP treatments, and enhanced the final strength of the surface cured layer. The final wind erosion resistance can thus be improved.

The long-term goal of wind erosion control in desert is to restore vegetation and ecology in desert areas. Therefore, the interaction between bio-cementation and vegetation growth has been a focus in field trials. The bio-cemented layer can provide fixation for desert plant germination and root growth. The reduction in soil surface permeability and microstructural changes can improve water retention [4]. These factors are beneficial for plant growth. However, plant growth can be limited at higher concentrations of the treatment solution. Under field conditions, MICP treatment could have an inhibitory effect on seed germination and growth of native sandy plants when the treatment solution concentration exceeded 0.2 mol/L. The excess saline could increase the osmotic pressure in soil, inhibiting plants from absorbing pore water in soil. Hodges and Lingwall [24] found in field trials that plants could still grow on MICP-treated land, but in some cases plant growth was adversely affected. The authors' team conducted a field trial using the SICP technology for sand fixation in the Ulanbu Desert, Ningxia, China. Field observations revealed that with a treatment solution concentration of 0.2 mol/L and a spraying volume of 4 L/m^2, many plants could grow in the SICP-treated area after 2 and 15 months (Fig. 4), which was in clear contrast to the untreated area. Due to the complex environments on the desert site, the effects of bio-cemented soil on plant growth and root immobilization, water retention, chemical composition alteration, require further exploration.

5. Conclusions

This paper reviews and analyzes recent research development on bio-cementation for soil stabilization and wind erosion control. Major conclusions are given as follows.

(1) The optimization of bio-cementation involves altering the treatment materials and procedures such as using lysed cells, low pH, the salting-out technique, and using cheap and waste materials for bio-cement treatment and bacterial cultivation. The objectives are to improve treatment uniformity and efficiency, using bio-cement in more scenarios such as fine-grain soils, and reduce costs and environmental impacts etc.
(2) Studies on the mechanical behaviour and wind erosion performances of bio-cemented soil show that the wind erosion resistance can be improved significantly through the bio-cement treatment. In addition, the use of optimized method and additives such as xanthan gum and fibers can further enhance the strength, treatment uniformity or ductility of the bio-cemented soils. It should also be noted that wind force with saltating particles has much stronger destructive effect than pure wind, which should be considered in laboratory tests.
(3) Field studies indicate that bio-cement can improve soil surface strength and wind erosion resistances effectively. Besides, local plants can germinate and grow on bio-cemented soil ground with low-concentration treatments. However, plant growth is negatively affected in the field treated with higher-concentrations of bio-cement materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Yufeng Gao and Jia He are editorial board members for Biogeotechnics and were not involved in the editorial review or the decision to publish this article.

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