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Enhancing Wind Erosion Control with Biochar-Integrated MICP

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ABSTRACT

This study examines the effectiveness of integrating biochar with Microbially Induced Calcium Carbonate Precipitation (MICP) in controlling wind erosion in a controlled laboratory setting. Wind tunnel experiments were conducted using tray samples treated with MICP alone and MICP combined with biochar. The results demonstrate a significant reduction in soil loss due to wind erosion when biochar is incorporated into the MICP technique. Quantitative analysis reveals a notable decrease in soil erosion in samples treated with biochar-amended MICP compared to MICP alone. Specifically, soil erosion decreased by an average of 29% in MICP-treated samples, whereas those treated with biochar-amended MICP experienced an average reduction of 37%. SEM imaging illustrates the formation of stable soil aggregates in biochar-MICP treated samples, indicating improved soil stability. These findings highlight the synergistic effect of biochar and MICP in mitigating wind erosion under laboratory conditions. The implementation of biochar-enhanced MICP techniques shows promise for sustainable soil management practices, particularly in wind-prone environments, offering dual benefits of erosion control and carbon sequestration.

INTRODUCTION

There is a strong correlation between increased wind erosion and soil deterioration (Kheirabadi et al., 2018). Wind erosion is a global environmental issue especially in dry and semi-arid regions. These areas feature poor cohesiveness, loosely structured soils, and little plant cover. High-speed wind may readily separate exposed surficial soil during dry seasons, which can seriously impair agricultural output and the balance of the ecosystem (Sterk et al., 2012). Moreover, the airborne particles cause sandstorms that impede vision, pollute water, and pose a health risk to individuals (Chen et al., 2004; Prospero et al., 2014; Reynolds et al., 2007). Thus, it is essential to reduce wind erosion of desert soil in arid and semi-arid regions due to the growing health, environmental, and agricultural issues.

Preventing desertification in arid regions and managing wind erosion are still major worldwide issues. A vast range of soil stabilization techniques, such as biological soil crusts (BSCs), natural or synthetic organic polymer materials, chemical agents, and straw chequerboard barriers, have been investigated to lessen wind erosion of desert soils. Even though there have been many successes, there are still certain issues that need to be resolved before they can advance farther. For instance, the employment of chemicals to the soil may disturb the nearby ecology and induce toxic elements in the surrounding environment (Kim et al., 2023). When exposed to water,

water-soluble biopolymers may become weaker and wash out of the soil, and early-stage BSCs are more likely to be eliminated by environmental degradation (Lo et al., 2020; Peng et al., 2017).

Microbially induced carbonate precipitation (MICP) is a potential substitute strategy for controlling wind-blown soil erosion in dry regions. The foundation of MICP is the formation of calcium carbonate ($CaCO_3$) crystals between soil particles by microorganism assisted mineralisation. The amount of precipitation causes the soil to become more rigid and strong (Achal et al., 2010; Chou et al., 2011; Liu et al., 2019; Mujah et al., 2019; Pham et al., 2018; Zhao et al., 2014, 2022). The majority of MICP uses to date include the induction of $CaCO_3$ crystals by urease-producing bacteria (UPB) via ureolysis, or urease-catalyzed urea hydrolysis, which is characterized by the following reactions:

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

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow \tag{2}$$

As mentioned in equation (1), ammonium (NH_4^+) and carbonate (CO_3^{2-}) are produced during the biochemical process when urea is hydrolysed enzymatically. The production of NH_4^+ raises pH, and when soluble calcium sources are available, precipitation of $CaCO_3$ crystals materialize in situ.

The precipitate of $CaCO_3$ mediated by microbes has the ability to fill voids and bind loose particles (Al Qabany and Soga, 2013; Jha, 2022). The MICP technology has been shown to be a potential solution for enhancing slope and dam stability (Chu et al., 2012; Montoya et al., 2013), remediating polluted soils (Achal et al., 2012), sealing concrete cracks (Achal et al., 2013, 2009), and reducing seepage through bench-scale laboratory testing (Gao et al., 2019). Recent evidence of the MICP's encouraging potential for suppressing fugitive dust and controlling wind erosion is encouraging. Erosion tests at 45 km/h showed weight loss of 1.29% and 0.16% for low and high bacterial concentrations, respectively, demonstrating improved erosion control with higher bacterial treatments (Maleki et al., 2016). Similarly, A bench-scale study evaluated biocementations effectiveness in stabilizing silica and carbonate sands, where; wind tunnel tests revealed that 28-day cured, single MICP-treated crustal layers resisted 20 m/s winds at 20 cm above the surface (Zomorodian et al., 2019). Erodibility studies on loess reveal that 0.5 M or >1 M urea-CaCl2 solutions minimize desiccation fractures and erosion, emphasizing the need of biotic-abiotic interactions for scalable MICP techniques (Raveh-Amit et al., 2024).

Although bacterial biocementation technique proved effective in previous researches the sluggishness of the process is an important issue that needs to be addressed (Ivanov and Chu, 2008; Jha, 2022). As a result, scientists are constantly trying to figure out how to boost the amount of $CaCO_3$ precipitation in a given amount of time while also improving the technique's effectiveness. Various amendments in the past have been used alongside MICP and their impact on the biocementation have been studied. Addition of poly-L-lysine in urea hydrolysis in the presence of $CaCl_2$affected the $CaCO_3$crystallization by increasing the amount of precipitation (Nawarathna et al., 2018). An effort was made to immobilize bacteria using sodium alginate in the MICP procedure (Wu and Zeng, 2017). They used fluorescence microscopy to demonstrate that the bacteria were effectively immobilized on the calcium alginate gel. Similarly, the effect of the Polyvinyl Alcohol (PVA) on the MICP process has been investigated. The study found that adding PVA resulted in more $CaCO_3$ than without using it (Wang and Tao, 2019). Many such add-ons have been investigated and biochar (BC) is also one such additives that has not been explored yet and may be used to accomplish the intended goal because of its high porosity and specific surface area and at the same time beneficially acting as an agricultural waste management technique.

In this study, utilizing the same methodology as adopted in previous mentioned studies for wind erosion assessment (Maleki et al., 2016; Raveh-Amit et al., 2024; Zomorodian et al., 2019); biochar was used in conjunction with the MICP method to prevent sandy soil erosion in arid and semi-arid areas. The bacteria, *Sporosarcina ureae,* has been used to enhance the sand mass assisted with little amount of biochar and study their impact on the erodibility of the sand mass in a high-speed wind environment in a laboratory wind tunnel that has been created.

MATERIALS

SAND

In the investigation, a sample of poorly graded sand (SP) was treated using MICP method. Sand was determined to have a specific gravity of 2.70 and to have fines of no more than 4% in the bulk. The soil's angle of friction was 28.42°, while the median size of the sand was 0.21 mm. Most of the sand's granules had a form that was asymmetrically angular. Figure 1 shows the sand mass's particle size distribution. It should be noted that the sand utilized in the experimentation was not sterilized.

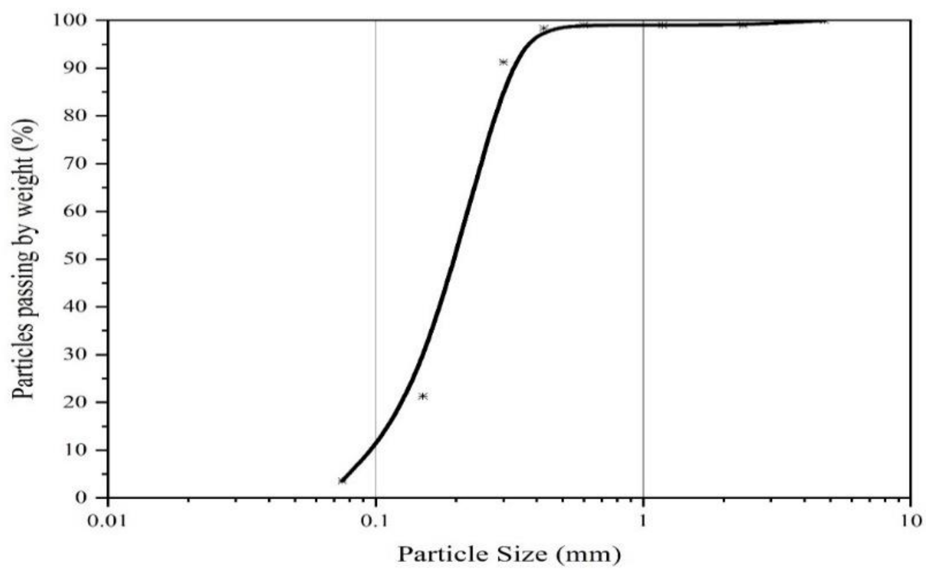

Figure 1 Particle size distribution of the sand.

BACTERIA AND NUTRIENT MEDIA

The bacterium employed in the investigation was ureolytic in nature, termed as *Sporosarcina ureae*. It was cultivated in a sterile media comprising of Luria Bertani broth for a period of 24 hours. The other supplements that were provided to bacteria to perform urea hydrolysis and consequentially form calcite units include; urea ($NH_2 - CO - NH_2$), ammonium chloride (NH_4Cl, sodium bicarbonate ($NaHCO_3$) and calcium chloride ($CaCl_2$) . The ratio between the concentration of urea and calcium chloride was specifically kept 1, as previous researches report it to be the optimum to produce good results (Naskar and Sharma, 2024; Van Paassen et al., 2010; Wani and Mir, 2021) and therefore the authors aligned their study to it. The cementation solution was prepared using 0.5 M urea and $CaCl_2$, 2.12 g/L of $NaHCO_3$ and 10 g/L of NH_4Cl. 4 g of broth was also added in a litre of cementation solution. The optical density of the bacteria post 24 hours of cultivation measured at a wavelength of 600 nm was found to fluctuate between 0.8 and 1.2.

BIOCHAR

Coconut coir derived biochar prepared by burning at 500°C was utilized in the experimentation. It constituted of micro and mesopores which significantly contributed to its high specific surface area. The biochar essentially consisted of flaky particles with approximately 66% of carbon content within it. The maximum size of the biochar particles was restricted to a maximum of 75 microns. Figure 2 shows the SEM image of the biochar indicating the porous and flaky nature of the coconut coir derived biochar.

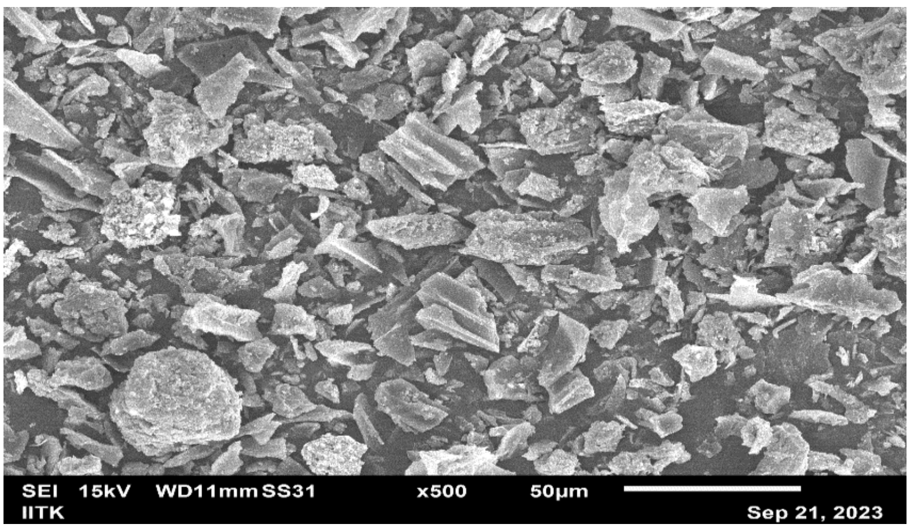

Figure 2 SEM image of the biochar

METHODOLOGY

The sand specimens for their testing of soil erosion against high-speed wind was prepared pouring sand in rectangular cardboard tray (200 × 150 × 20 mm) at 85% relative density. Prior to the filling of tray with sand, they were punched with several tiny holes with diameter not large enough to allow the passage of sand particles. Thereafter, a bacteria solution followed by cementation solution of 1.2 times of pore volume of the sand (140 mL) was carefully poured on the surface of the sand without disturbing the surface. The process was again reiterated on the 3rd and 7th day. Throughout the period the tray specimens were kept at a temperature range between 35-40°C. Similarly, other set of tray specimens were prepared, this time comprising of sand with 2% of biochar in them. The biochar was thoroughly mixed in the sand to ensure ubiquitous presence of biochar particles through the sample. The above-mentioned process of pouring the bacteria and cement solution was repeated in an identical manner as already illustrated. A control sample was also prepared where only sand was filled in the tray specimen at a relative density of 85% without any external treatment. Post 10 days, the tray specimens of all the samples were tested for their resistance against wind in a wind tunnel. The wind tunnel was fabricated in the laboratory using hard cardboards and adhered to the norms as suggested in various literatures (Diouf et al., 1990;

Genis et al., 2013). The cardboard tunnel was 30 cm in height, 25 cm in width, and 200 cm in length with an opening at its ends, creating a restricted region for regulated wind flow. An exhaust fan was added to the wind tunnel at one of the openings at the end to create the necessary high-speed wind. The fan used was a 12-inch type with an output power of 55 watts, running at 230 volts and rotating at 1325 revolutions per minute (rpm). The tray specimen was kept at 1.6 m from the source of wind. The samples were subjected to same wind conditions and their initial and final weights, 'M_i' and 'M_f', respectively, that is pre and post subjection to high velocity wind for a duration of 30 minutes, were noted for the computation of erosion. The expression utilized for the computation is given below in equation (3):

$$E = \frac{M_i - M_f}{M_i} \times 100 \tag{3}$$

where, M_i is mass of the tray specimen before wind erosion, M_f is mass of tray specimen after wind erosion and E is the percentage of soil eroded due to the action of wind.

The $CaCO_3$ precipitation was measured using acid washing technique (Choi et al., 2017). 10 gm of treated samples were washed using 1 M of HCl solution and thereafter it was oven dried to measure the loss in weight of the soil. This decrease in weight of the soil mass was attributed to the dissolution of $CaCO_3$ formed post MICP treatment. Testing was performed on atleast two samples per tray and the average value was taken as result. For morphological analysis, Scanning Electron Micrography (SEM) was utilized for the assessment of changes in the microstructure of the soil particles post treatment.

RESULTS AND DISCUSSIONS

The control sample when subjected to high-speed wind in the tunnel, showed significant loss of sand particles. The loss recorded in the soil particles was approximately, 42%. However, the MICP treated sand when subjected to wind tunnel, the decrease in the erosion percentage was approximately, 29%, that is, the loss in soil particles was somewhere around 13%. Similarly, when biochar-soil mix was tested for its erosion, the loss in soil mass reduced to 5%, decreasing the erosion by 37% (Refer to Figure 3(a)).

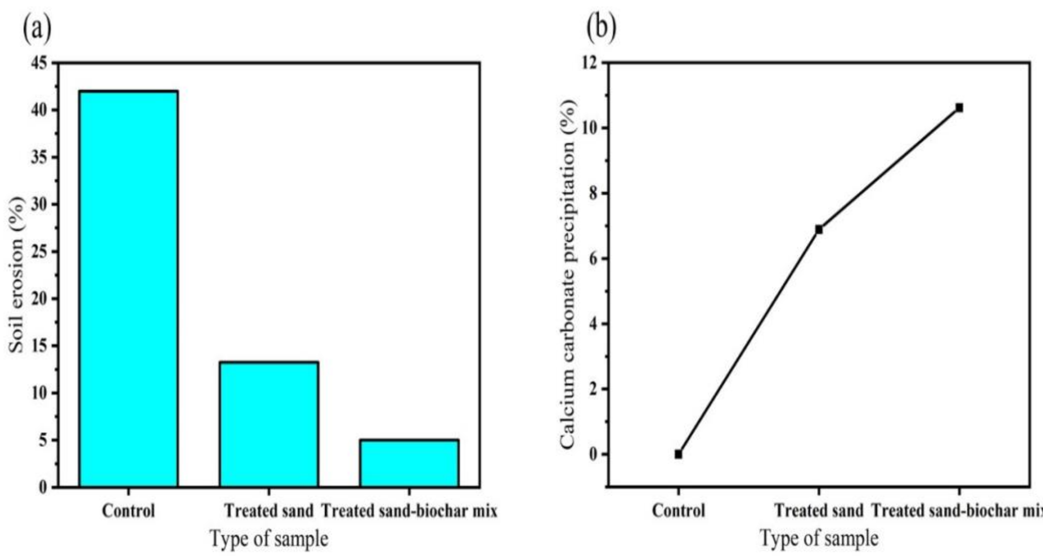

Figure 3 (a) Erosion experienced by different soil specimens, (b) Precipitation of $CaCO_3$ corresponding to the samples.

This decrease in erosion percentage can be attributed to $CaCO_3$ precipitation facilitated by ureolytic bacteria utilized which is an established fact (Achal et al., 2010; Chou et al., 2011; Liu et al., 2019; Wang et al., 2024). However, the noteworthy aspect was the reduction in erosion percentage when biochar was added. One of the primary reasons behind it is the extra precipitation of $CaCO_3$ within the soil particles, binding them together and increasing its resistance against eroding winds. This increase in precipitation of $CaCO_3$ is credited to the large surface area of biochar providing excess ground for bacteria to perform $CaCO_3$ precipitation. Moreover, the pores in the biochar also enabled storage of cementation solution within them which allowed its interaction with formed CO_3^{2-} after urea hydrolysis.

The excess precipitation caused by biochar was verified through washing method as discussed in earlier section. It was observed that for similar treatment given to sand and sand-biochar mix samples, the precipitation was found to be more in case of the sand having biochar as well (Figure 3(b)). This enhancement in $CaCO_3$ precipitation provided extra binding to the sand mass consequentially, increasing the strength of the soil to resist the impact of strong winds over its surface. The key reason for this is extra surface area provided by the biochar in soil mass to the bacterial agent to carry out urea hydrolysis.

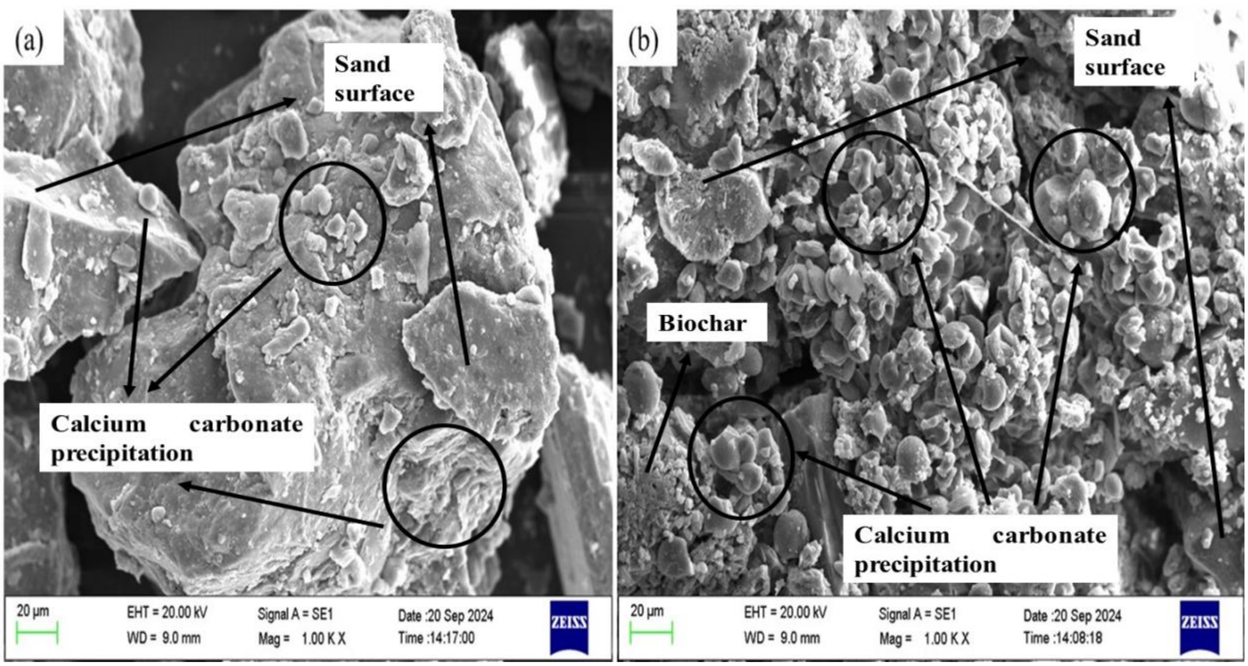

Figure 4 Scanning electron micrographs, (a) Treated sand, (b) Treated sand-biochar mix.

SEM images of the samples revealed the formation of a new substance ($CaCO_3$) on the surface of the sand particles primarily responsible for the binding action of the MICP process. The microstructural analysis as shown in Figure 4 revealed surplus formation of precipitates on the surface of the particles in case biochar as additive in soil (Figure 4(b)). The spherical particles formed in case of biochar assisted MICP, performed on sand sample are the precipitates of $CaCO_3$. These precipitates are identified as vaterite, one of the polymorphs of $CaCO_3$(Fouladi et al., 2024). These precipitates bound the particles together ensuring enhanced resistance to wind forces. It was observed that the crystals of the vaterite ($CaCO_3$) precipitate in case of biochar mediated MICP was found to be more prominent than that observed in case of MICP performed on only-sand.

Hence, it could be said that biochar significantly contributed towards improving the crystallinity of the $CaCO_3$.

CONCLUSION

The addition of biochar in soil particles enhanced the $CaCO_3$ precipitation within the soil mass when subjected to MICP treatment. This additionally precipitated $CaCO_3$ binds the soil particles altogether providing more resistance to the shear erosion caused by moving wind. The results showed that the specimen aided with biochar reduced soil erosion by 8% more in comparison to the specimen devoid of biochar. Therefore, biochar can be very effectively utilized to enhance the efficiency of MICP technique in preventing wind induced erosion and at the same time providing ground for carbon sequestration. However, its long-term feasibility needs to be studied through field grade investigation where the top crustal level soil needs to be evenly mixed with biochar and bacterial solutions, which may require specialized equipments and techniques. Regional hinderance such as soil condition, climate variation and deployment technologies will govern the scalability of biochar enhanced MICP in practical field conditions.

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