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Evaluation of Aeolian Soil – Bacillus Brevis Induced Calcite Precipitate for Wind Erosion Application Using Bacterial Foraging Optimisation Algorithm

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Abstract — The potential of biotreated Aeolian soil using Bacillus brevis (B. brevis)-induced calcite precipitation for mitigating wind erosion was investigated through the application of the Bacterial Foraging Optimization Algorithm (BFOA). Laboratory experiments were conducted to generate the data required for the optimization analysis. Sediment flux (y) was considered the dependent variable, while B. brevis suspension density, pH, compactive effort, water content relative to optimum, and cementation conditions were considered independent variables influencing the wind-erodibility response of the treated soil. GeneXproTools 5.0 was employed to develop the fitness (objective) function describing the relationship between sediment flux and the selected independent variables. The resulting fitness function was subsequently incorporated into BFO codes developed in MATLAB 2016 to determine the combination of variables associated with minimum sediment flux. The optimization results demonstrated a strong relationship between the predicted and experimentally measured sediment-flux values, with a coefficient of determination (R^2) of 0.912. This indicates that the developed optimization model provided a satisfactory representation of the experimentally observed wind-erodibility behaviour of the biotreated Aeolian soil. The optimization process further showed that sediment flux was strongly influenced by the selected independent variables. The minimum predicted sediment flux of approximately 3.91×10^{-3} kg/m²s was obtained after 50 iterations. Based on the optimization results, treatment of Aeolian soil with B. brevis suspension and 0.75 M cementation reagent demonstrated considerable potential for reducing wind-induced sediment transport. The findings indicate that BFOA can serve as an effective optimization tool for identifying suitable microbial treatment conditions for wind-erosion mitigation, particularly in arid and semi-arid environments.

Keywords— Bacterial Foraging Optimization; Bacillus brevis; Aeolian soil; wind erosion; sediment flux; biostabilization; objective function.

I. INTRODUCTION

Wind erosion is an important form of soil degradation that occurs when soil particles at or near the ground surface are detached and transported by moving air. The susceptibility of a soil to wind-induced detachment and transportation is strongly influenced by its physical and mechanical characteristics, including particle-size distribution, surface roughness, moisture condition, cohesion, aggregate stability, and the presence of protective surface materials. In areas where vegetation cover is limited, the exposure of loose soil particles to high wind velocities can result in considerable sediment loss and progressive degradation of the soil surface. Consequently, improving the resistance of vulnerable soils to wind action has become an important consideration in soil conservation and stabilization practices (Yohanna et al., 2021).

The application of microorganisms for soil improvement has emerged as a promising biological approach for modifying soil properties through microbial activities. Unlike conventional stabilization methods that primarily depend on chemical additives, microbial-based techniques utilize biochemical reactions generated by microorganisms to alter the engineering behaviour of soil. These biological processes can promote the formation of mineral precipitates, particularly calcite, within the soil matrix. The resulting mineral deposits can bind individual soil particles together, increase interparticle bonding, and contribute to the development of a more stable soil structure (Muthukkumaran et al., 2016; Yohanna et al., 2021). Such modifications are particularly relevant to wind-erodible soils because stronger particle bonding and improved aggregation can reduce the ease with which individual particles are detached and transported by wind.

Microbially induced calcite formation can influence the physical structure of soil through the deposition of calcium carbonate around and between soil particles. The precipitation of calcite may reduce the size and continuity of soil pores while simultaneously increasing particle interlocking and aggregation. Microbial colonization and the development of biofilms can further contribute to particle binding and modification of the soil surface (Mitchell and Santamarina, 2005; Muthukkumaran et al., 2016; Yohanna et al., 2021). From the perspective of wind erosion control, these processes are important because the formation of a stronger and more coherent soil surface can increase resistance to aerodynamic forces. Thus, microbial treatment has the potential to transform a loose and easily erodible soil surface into a more stable layer capable of resisting particle detachment under increasing wind velocities.

The effectiveness of microbial soil stabilization, however, depends on the appropriate selection of treatment conditions. Factors such as microbial concentration, cementation reagent concentration, treatment duration, soil characteristics, and environmental conditions may influence the degree of mineral precipitation and, consequently, the resulting resistance of the soil to wind erosion. Therefore, identifying a suitable combination of treatment variables is essential for achieving maximum improvement in soil resistance while avoiding unnecessary use of treatment materials. This requirement introduces the need for optimization techniques capable of determining the most favourable treatment conditions from a range of possible alternatives.

Optimization refers to the systematic process of identifying the most favourable solution to a problem by maximizing or minimizing a specified mathematical function within a defined range of permissible conditions (Ehasn et al., 2014). In soil stabilization research, optimization can be employed to determine the combination of treatment variables that produces the desired improvement in soil performance. The optimal solution represents the most favourable outcome among a range of possible alternatives, based on a predetermined performance criterion. According to Ehasn et al. (2014), an optimization problem generally consists of two principal components: the objective or fitness function and a set of constraints. The objective or fitness function establishes the performance criterion that the optimization procedure seeks to maximize or minimize, whereas the constraints specify the allowable limits within which the solution must be obtained. In the context of wind-erodibility control, optimization can therefore provide a systematic means of identifying treatment conditions that produce maximum resistance to wind-induced soil detachment and sediment transport.

Certainly. I will keep the same citations, retain the discussion of BFO/BFOA and its stages, but modify the parts that are specific to hydraulic conductivity, liner/cover material, and permeability so that they are appropriate for your wind erodibility study. I will also substantially paraphrase the wording to reduce textual similarity.

The constraints represent the physical and operational limitations associated with the system or problem being optimized. An optimal solution is obtained when the selected decision-variable values satisfy the specified constraints while simultaneously producing the most desirable value of the objective or fitness function (Ehasn et al., 2014). In a wind-erodibility investigation, these constraints may represent the permissible ranges of soil, microbial, environmental, or treatment parameters within which an effective stabilization condition can be achieved.

The major stages involved in developing an optimization model can be summarized as follows:

Identification of decision variables: Decision variables are the controllable or measurable factors that influence the outcome of the problem under investigation. Their proper identification and definition constitute an important stage in the formulation of an optimization model. In wind-erodibility studies, such variables may include wind velocity, soil properties, microbial concentration, cementation reagent concentration, treatment conditions, or other factors that influence particle detachment and sediment transport. The reliability and practical relevance of the optimization results depend considerably on the selection of appropriate decision variables.

Specification of the objective or fitness function: The objective or fitness function represents the principal goal of the optimization process. It establishes the performance criterion that the optimization algorithm attempts to maximize or minimize. For wind erosion research, the objective function may be formulated around parameters such as sediment flux, soil-loss rate, threshold friction velocity, or another measurable indicator of soil resistance to wind erosion. Consequently, the fitness function provides the mathematical basis for determining the most favourable combination of the selected variables.

Definition of constraints: Constraints establish the permissible conditions that a potential solution must satisfy. They may be represented mathematically through equality or inequality relationships and serve to restrict the optimization process to physically realistic and feasible solutions. Appropriate constraints are important because they establish the boundaries within which the desired soil response can be obtained while reducing unrealistic solutions and minimizing potential errors in the optimization process.

A variety of optimization approaches have been developed and applied to engineering and scientific problems. These include neural-network-based techniques, swarm intelligence methods, random search approaches, bacterial foraging optimization, particle swarm optimization, and ant colony optimization, among others (Nitin and Dipak, 2014; Yohanna et al., 2021). Among these approaches, bacterial foraging optimization has attracted considerable attention because of its ability to search for suitable solutions by simulating the adaptive behaviour of microorganisms.

II. BACTERIAL FORAGING OPTIMIZATION THEORY

The concept of Bacterial Foraging Optimization was introduced by Prof. K. M. Passino in 2002 (Passino, 2002; Yohanna et al., 2021). The approach was developed as a nature-inspired computational algorithm based on the foraging behaviour, reproduction, and elimination-dispersal mechanisms observed in Escherichia coli (E. coli) bacteria. Passino developed the Bacterial Foraging Optimization Algorithm (BFOA) by translating these biological processes into mathematical procedures for solving optimization problems. The algorithm is therefore inspired by the manner in which bacterial populations search their surroundings for favourable sources of nutrients (Nitin and Dipak, 2014; Dharminder and Vinay, 2012; Yohanna et al., 2021).

BFOA provides a general computational framework for searching for satisfactory solutions to complex optimization problems rather than relying solely on direct analytical solutions (Yohanna et al., 2021). As a numerical bio-inspired optimization technique, BFOA forms part of the broader family of swarm-intelligence and evolutionary computational approaches (Badamchizadeh et al., 2010; Yohanna et al., 2021). Its population-based search mechanism enables the algorithm to explore different regions of a solution space and identify promising solutions. Consequently, BFOA has been applied to optimization and control problems in several engineering disciplines.

The theoretical foundation of bacterial foraging is related to the manner in which organisms search for food while attempting to obtain sufficient energy with an efficient expenditure of time and effort. From an optimization perspective, an organism seeks favourable locations that provide greater nutritional benefits while minimizing the resources required for the search. This biological behaviour can be represented mathematically and subsequently converted into a computational optimization procedure (Passino, 2002).

According to Passino (2002), organisms may employ different strategies when searching for food in their surrounding environment. Two general approaches include continuous searching, in which the organism changes its position while actively looking for food, and ambush-type searching, in which the organism remains relatively stationary and waits for suitable prey to enter its effective range. These biological strategies provide the conceptual basis for developing computational search mechanisms capable of exploring a solution space and locating favourable regions (Passino, 2002; Yohanna et al., 2021).

The Bacterial Foraging Optimization (BFO) technique has been successfully employed in a wide range of engineering applications and optimization problems (Passino, 2002; Badamchizadeh et al., 2010; Gautam and Soumya, 2012; Dharminder and Vinay, 2013; Nitin and Dipak, 2014; Yohanna et al., 2021; Kanyi, 2024; Oyelakin, 2025; Garba et al., 2025). Its application to wind-erodibility research provides an opportunity to identify combinations of influencing variables that can produce improved resistance of biotreated soil to wind-induced particle detachment and sediment transport.

1. Steps of the Bacterial Foraging Optimization Algorithm

The Bacterial Foraging Optimization Algorithm operates through a sequence of biological processes that are represented computationally. The principal stages are chemotaxis, swarming, reproduction, and elimination-dispersal.

Chemotaxis

Chemotaxis represents the movement behaviour of an E. coli bacterium as it searches for a more favourable location. The process is based on two characteristic bacterial movements: swimming and tumbling, which are facilitated by the action of flagella (Kanyi, 2024; Oyelakin, 2025; Garba et al., 2025). During the computational implementation of BFO, these movements are represented mathematically to enable individual bacteria within the population to explore different positions in the solution space.

Let $\theta_i(j, k, l)$ represent the position of the ith bacterium during the jth chemotactic step, kth reproductive step, and lth elimination-dispersal event. The parameter C(i) represents the step size associated with the movement of the bacterium in a randomly selected direction. The computational movement of a bacterium during chemotaxis can therefore be represented by:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(\Delta i)}{\sqrt{\Delta^T(i)\Delta(i)}} \quad (1)$$

Where the relevant vector (Δ) represents a unit-length vector directed along the randomly selected search direction (Nitin and Dipak, 2014).

In the context of wind-erodibility optimization, chemotaxis enables the algorithm to investigate different combinations of the selected input variables and progressively move toward combinations that produce more favourable values of the defined fitness function.

Swarming

Swarming describes the collective behaviour of bacteria as they interact and move as a population toward favourable regions. Collective behaviour has been observed in several bacterial species, particularly when bacteria are distributed within a semi-solid nutrient medium (Nitin and Dipak, 2014). In E. coli, the cells can organize their movement collectively and migrate toward areas associated with favourable nutrient conditions.

When stimulated by appropriate nutrient conditions, bacterial cells can produce attractant substances that encourage aggregation and coordinated movement. For example, cells responding to high concentrations of succinate can release the attractant aspartate, resulting in the formation of bacterial clusters and organized swarm patterns (Nitin and Dipak, 2014). This collective behaviour is represented within BFOA to improve communication and coordinated searching among the candidate solutions. The swarming mechanism therefore assists the optimization process in directing the population toward regions of the solution space with improved fitness values (Kanyi, 2024; Oyelakin, 2025; Garba et al., 2025).

Reproduction

Reproduction is the stage in which the relative fitness of individual bacteria is evaluated. Bacteria associated with poorer fitness values are progressively eliminated, while the healthier bacteria are allowed to reproduce. The surviving bacteria divide asexually to generate new bacterial individuals at or near their existing locations. Through this process, the population size is maintained while the search becomes increasingly concentrated around more favourable regions of the solution space (Nitin and Dipak, 2014).

For wind-erodibility optimization, the reproduction stage enables the algorithm to retain candidate solutions that produce better soil resistance characteristics while eliminating combinations of variables that result in less desirable responses.

Elimination and Dispersal

Elimination and dispersal represent mechanisms through which bacteria occupying particular locations are removed and redistributed to other regions of the search environment. Passino (2002) proposed that bacteria located at favourable positions may be retained, whereas other members of the population may be eliminated according to the probability of elimination and dispersal. The remaining or newly generated bacteria are subsequently introduced at different locations within the search space (Kanyi, 2024; Oyelakin, 2025; Garba et al., 2025).

This mechanism is important because it reduces the possibility of the optimization algorithm becoming trapped around a local optimum. By introducing new candidate solutions into other regions of the search space, elimination and dispersal increase the ability of BFOA to explore alternative solutions and potentially identify a better global optimum.

The aim of this study is to evaluate the potential of microbial-induced calcite precipitation for improving the resistance of soil to wind erosion using Bacterial Foraging Optimization (BFO). The study further seeks to establish the optimal combination of the selected soil, microbial, treatment, and wind-related parameters required to achieve improved resistance to wind-induced soil particle detachment and sediment transport. The application of BFO provides a computational approach for determining the combination of variables associated with the most favourable wind-erodibility response.

III. MATERIALS AND METHODS

1. Bacterial Foraging Optimization Procedure

Experimental data for the optimization analysis were obtained from laboratory investigations conducted on the biotreated soil. The measured wind-erodibility response was considered the dependent variable, while the selected soil, microbial, treatment, and environmental parameters were considered independent variables.

Depending on the experimental design, these independent variables may include wind velocity, bacterial suspension density, cementation reagent concentration, soil moisture condition, soil density, compaction energy and other relevant soil characteristics influencing wind-induced sediment transport. Similar approach were adopted by many researchers

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(Yohanna et al., 2021; Onyelowe et al., 2023; Oyelakin et al., 2025).

The experimental data were used to establish the fitness or objective function required for implementation of the Bacterial Foraging Optimization algorithm. GeneXproTools 5.0 was employed in developing the mathematical relationship representing the response of the biotreated soil to the selected independent variables.

The resulting fitness function was subsequently integrated into MATLAB 2016 to enable the BFO procedure to search for the combination of input variables associated with the most favourable wind-erodibility performance.

For the present study, the optimization objective is directed toward minimizing wind-induced sediment loss or sediment flux and/or maximizing the resistance of the biotreated soil to wind erosion, depending on the selected response variable.

The fitness function used in the Bacterial Foraging Optimization procedure is presented in Equation 2. Figures 1and 2 show the Genxprotool Expression Tree for Four Generations and flow charts for BFO, respectively.

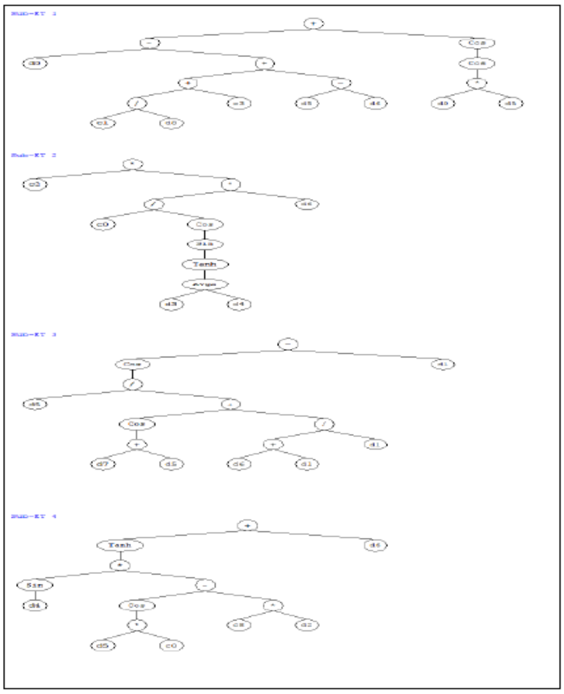


Figure 1: Genxprotool Expression Tree for Four Generations

2. Fitness/Objective function

$$y = \arctan\left[\frac{d_5}{d(d3)+d(d_5)}\right] + \left[\frac{d(d_6)+d(d_1)\cdot\exp\left(d(d_7)\right)}{2}\right] - \frac{0.122-d(d_1)+\log\left(d(d_4)\right)}{2.0} \quad (2)$$

Where: d1 = cementation solution concentration, d2 = B. brevis suspension density, d3 = compaction energy, d4 = UCS (unconfined compressive strength), d5 = urease activity, d6 = wind velocity, d7 = calcite content and y(qs) = optimum sediment flux.

3. Constraints

The constraint considered include B. brevis suspension density (d1), cementation solution concentration (d2) B. brevis suspension density (d3) compaction energy

Constraints

0.25 ≤ d1 ≤ 1, 0 ≤ d2 ≤ 2.4E-09, -1 ≤ CE ≤ 1

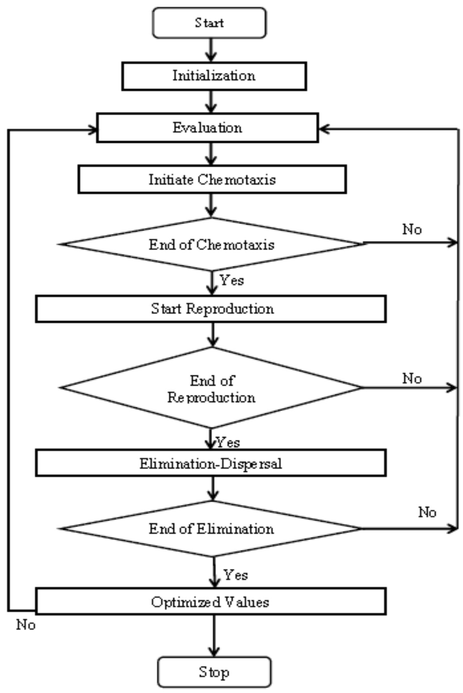


Figure 2: Flow Chart for Bacterial Foraging Optimisation Algorithm

IV. RESULTS AND DISCUSSION

The measured performance indicators for the objective function created by Gene Xpro Tools 5.0 for training (model) and validation output is presented in Table 1.

Table 1: Variables measured for fitness function created by Gene Xpro Tools 5.0

Metrics	Training (model)	Validation output
R-square	0.912	0.883
Best-fitness	821.260	732.505
RMSE	0.217	0.356
MSE	0.047	0.133
RAE	0.241	0.271
MAE	0.167	0.261
RSE	0.049	0.094
RRSE	0.220	0.307

MSE - Mean Square Error; RMSE - Root Mean Square Error; MAE - Mean Absolute Error; RSE - Residual Standard Error, RAE - Relative Absolute Error, RRSE - Root Relative Squared Error.

Bacterial foraging optimisation (BFO), was utilised to establish the optimal Y(qs) values of the bio-biotreated Aeolian soil using the laboratory factors that produced bio-biotreated aeolian soil with better resistance to wind erosion to forestall their negative impact on arid and semi-arid regions.

The relationship between the predicted sediment fluxes (Target) and the values measured in the laboratory used for the model are presented in Figures 3a and b. The fitness function with coefficient of determination (R2 = 91.2 %) was then incorporated into BFO codes in Matrix laboratory 2018 type to forecast the least sediment flux. A strong correlation exists between the measured and the predicted sediment flux the outcome displayed a strong correlation among the predicted values and the measured values in the laboratory by means of regressed line with coefficient of determination (R= 91.2 %) (Fig. 3b). The BFO algorithms recorded good outputs (Table 2).

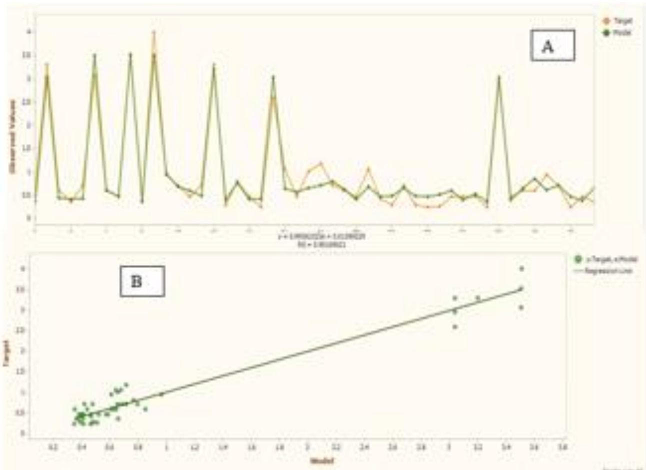
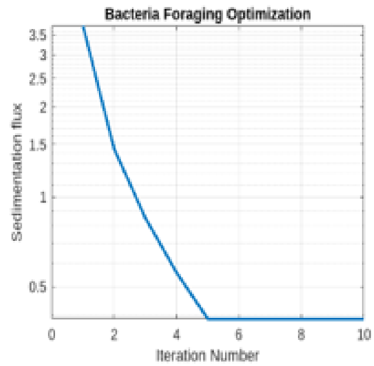
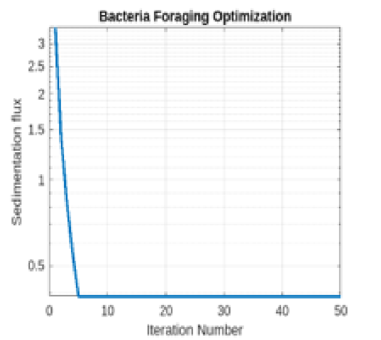


Figure 3: Relationship between predicted sediment fluxes and measured laboratory values generated using from the GenXprool Model: (A) Scatter plot (B) Comparison of measured and generated values.

The plots of sediment flux against iteration number iterations (10, 50, and 200 iterations) for BFO algorithms respectively are shown in Figures 4.



a.



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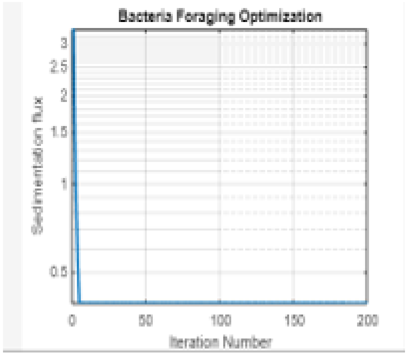

c.
Figure 4: Plots of sediment flux versus number of iterations (10, 50, and 200) for (A – C) BFO

Table 2: Bacteria foraging optimisation (BFO) results

Number of iteration	Y(q_s)	D1	D2	D3	D4	D5	D6	D7
10	3.902e−3	1.000e−9	1.136e0	9.888e−10	6.580e−7	7.400e−8	1.000e−9	3.600e−9
50	3.901e−3	9.941e−11	1.147e0	9.851e−11	2.082e−7	7.399e−9	9.990e−11	3.600e−10
100	3.902e−3	1.000e−10	1.165e0	9.887e−11	2.823e−7	7.400e−9	9.978e−11	3.600e−10
200	3.904e−3	1.000e−10	1.724e0	9.851e−11	2.823e−7	7.400e−9	1.000e−10	3.600e−10
500	3.906e−3	9.998e−11	2.174e0	9.837e−11	2.823e−7	7.400e−9	1.000e−10	3.598e−10

Y(qs) - laboratory sediment flux, a deterministic variable, d1 - cementation solution concentration, d2 - B. brevis suspension density, d3 - compaction energy, d4 – unconfined compressive strength, d5 - urease activity, d6 - wind velocity, d7 = calcite content

The optimisation results reveal that the sediment flux (qs) values, and the self-determining variables are near to one another regardless of the numeral of iterations considered especially for BFO. Nevertheless, the minimum sediment flux values of 0.003901 kg/m2s were recorded from 50, 10 and 10 iterations using BFO optimization approach. This suggests that the least iteration that is vital to minimise sediment flux of aeolian soil - B. brevis mixture is 50 iterations via BFO.

V. CONCLUSIONS

The effectiveness of Bacillus brevis (B. brevis)-induced calcite precipitation for improving the wind-erodibility resistance of Aeolian soil was evaluated using the Bacterial Foraging Optimization Algorithm (BFOA). Laboratory experiments were conducted to obtain the experimental data required for developing and validating the optimization model. Sediment flux was adopted as the principal indicator of wind-erodibility response, while the selected soil, microbial, and treatment parameters were incorporated as independent variables.

GeneXproTools 5.0 was used to establish the fitness (objective) function describing the relationship between sediment flux and the selected independent variables. The developed function was subsequently integrated into MATLAB 2016 through BFO codes to identify the combination of input parameters associated with minimum sediment transport. The comparison between the experimentally measured and BFOA-predicted sediment-flux values produced a strong relationship, with a coefficient of determination (R^2) of 0.912. This high degree of agreement demonstrates that the developed optimization model can satisfactorily predict the wind-erodibility response of the biotreated Aeolian soil.

The optimization results further established that sediment flux was strongly associated with the selected independent variables. The optimization process maintained this relationship across the investigated iteration levels, although the magnitude of the predicted sediment flux varied with the number of iterations. The lowest predicted sediment flux, approximately 3.91 × 10^{-3} kg/m²s, was obtained at 50 iterations, indicating a favourable optimization condition within the investigated range.

The results demonstrate that microbial treatment of Aeolian soil with B. brevis-induced calcite precipitation can improve resistance to wind-induced particle detachment and sediment transport. In particular, the combination of approximately 6 × 10^{-9} cells/ml B. brevis suspension density and 0.75 M cementation reagent concentration showed potential for reducing wind-erodibility. The optimized treatment condition may therefore provide a promising biological approach for wind-erosion mitigation in arid and semi-arid environments.

Overall, the study demonstrates that the Bacterial Foraging Optimization Algorithm can be effectively applied as an optimization and predictive tool for determining suitable treatment conditions and estimating sediment flux from biotreated Aeolian soil. Its application provides a computational means of identifying favourable combinations of microbial and treatment parameters while reducing dependence on extensive experimental trial-and-error procedures.

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