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Original article

Biocementation technology for construction of artificial oasis in sandy desert

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ABSTRACT

Artificial oasis could be supported by the trapping and retaining rainfall water by impermeable layer of artificial material. In case of average annual rainfall in Arabian or Pakistani Deserts of 100 mm the watershed area must be at least 1000 ha to ensure rainfall water supply for consumption and irrigation in the artificial oasis of 100 ha area. Minimum cost for the sealing of 1000 ha of the sand slopes with 1 mm geosynthetic liner is about 112 mln Saudi Arabian Riyal, which could be not acceptable price for 100 ha of artificial oasis land. However, this cost could be diminished to 17 mln Saudi Arabian Riyal if to coat watershed slopes with 1 mm of biocemented sand crust using a low viscosity solution of biocement. Conventional cementation is cheaper but it cannot be used to make 1 mm sand crust because of a high viscosity of the cement suspension. The novel biotechnological method is based on the formation of the sand surface crust for water collection and transportation on the surrounding slopes. Most environmentally friendly biotechnology for this biocementation is aerobic biooxidation of cheap calcium formate or calcium acetate. Biocementation of the sand crust could be used to make a low-cost artificial desert oasis fed by rainfall.

1. Introduction

The desert oases were and remain important source of water for human consumption, agricultural irrigation, and a place of recreation. Natural oases are formed in the depression of arid region, usually in former river valley, and are feeding by an underground aquifer, river, or mountain runoff to bajada, which is a landform created at the foot of the mountain in arid area. Proper ecological management, watershed management, reduction of evaporation, water-saving irrigation of the existing oases, control of land desertification are important for population welfare, maintenance of water quality, and the sustainable development for 2.5 billion people of arid regions (Reynolds et al., 2007; Xue et al., 2015). Therefore, artificial oases feeding by underground or river water are creating at present to diminish land desertification rate (Fan et al., 2004; Hao et al., 2019).

For the artificial oasis fed by rainfall, the desert watershed area has to exceed an oasis area minimum by 10–20 times to ensure sufficient water supply for consumption and irrigation. The watershed area of the artificial oasis must be coated by the water-sealing material to minimize infiltration and to collect rainfall water in the oasis reservoir. For example, in case of average annual rainfall in Arabian or Pakistani Deserts of 100 mm the watershed area must be at least 1000 ha to ensure annual 1000 mm of water supply for consumption and irrigation in artificial oasis with an area of 100 ha. The sealing of 1000 ha of the desert surface using geosynthetic liner could cost more than 100 mln Saudi Arabian Riyal (Stabnikov et al., 2016), which is not acceptable price for 100 ha of oasis land.

However, we supposed that novel, low-cost biotechnological methods of sand biocementation could be used to form the thin sand crust on the slopes that are surrounding artificial oasis and for the sealing of the oasis pond in the sandy desert (Stabnikov et al., 2015, 2016). There are known different biocements for sand slope stabilization (Ivanov and Stabnikov, 2017, 2019a,b). The most popular method of biocementation for sand sealing is microbially induced calcite precipitation (MICP) that is based on crystallization

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of calcium carbonate due to enzymatic hydrolysis of urea at molar ratio Ca: urea = 0.5–1.0 (Ivanov and Stabnikov, 2017; Sharaky et al., 2018; Gowthaman et al., 2019):

$$Ca^{2+} + (NH_2)_2CO + 2\,H_2O \rightarrow CaCO_3 \downarrow + 2\,NH_4^+ \quad (1)$$

There are known more than a hundred papers on laboratory and field testing of MICP method for soil stabilization and sealing (Ivanov and Stabnikov, 2017). It is clear from these published data that MICP method can minimize infiltration and help to collect rainfall water in the oasis reservoir. However, final consideration is that MICP method cannot be used for the construction of artificial oasis from the environmental point of view because it is accompanying with huge release of toxic ammonia and harmful hydroxide ions to environment. For example, the MICP biosealing of a dam of 100 m length, 5 m width, and 2 m height, can pollute more than 100 km^3 of air due to the ammonia release to atmosphere or more than 4.5×10^6 m^3 of drinking water (Ivanov et al., 2019a).

Therefore, the aim of this study was comparative analysis of the biotechnological methods that could be suitable for the construction of artificial oasis and experimental testing of the most suitable biotechnology for the surface sand treatment.

2. Materials and methods

The strain of calcium acetate-oxidizing bacteria VSA1 was isolated from soil and identified using 16S rRNA gene sequencing. The forward and reverse sequences were obtained in AIT Biotech using PCR with the sequencing primers 27F, 530F, 926F, 519R, 907R, 492R. The sequences were analyzed using the ABI 3730 XL analyzer (Thermo Fisher Scientific, Singapore) and were aligned using BioEdit Version 7.1.9. Top 10 Blast® Results for the sequence deposited in NCBI GenBank Database under GenBank accession number SUB5885621 seq1 MN121192 showed that the selected strain belongs to species of *Bacillus ginsengi* with the identity of 99% to 16S rRNA gene of four other known strains of *Bacillus ginsengi*.

The strain *Bacillus ginsengi* VSA1 was cultivated aerobically at 25 °C in sterile medium of the following composition: calcium acetate, 20 g/L; 10 mL of concentrated nutrients solution, and 3.5 mL of concentrated trace element solution. Concentrated nutrients solution contained, g/L: K_2HPO_4, 80; KH_2PO_4, 30; NH_4Cl, 350; $MgSO_4{\cdot}7H_2O$, 40, distilled water 1 L. Trace element solution was of the following composition: $ZnSO_4$ x$7H_2O$, 0.10 g; $MnCl_2 \times 4\ H_2O$, 0.03 g; H_3BO_3, 0.30 g; $CoCl_2 \times 6\ H_2O$, 0.20 g; $CuCl_2{\cdot}2H_2O$, 0.01 g; $NiCl_2 \times 6\ H_2O$, 0.02 g; $Na_2MoO_4{\cdot}2H_2O$, 0.03 g; distilled water 1L.

Sand treatment was done by one time or several times spaying over sand surface a solution containing calcium acetate, 100 g/L, 10 mL/L of concentrated nutrients solution, 3.5 mL/L of concentrated trace element solution, and 100 mL/L of bacterial suspension of *Bacillus ginsengi* VSA1.

The hydraulic conductivity of sand, k, was measured at water head falling from 10 to 5 cm according to the equation:

$$k = V/(t \times S)\,(m/s) \quad (2)$$

where V is a volume of liquid, t is a time of the liquid passed through sand, S is cross- sectional area of water flow through soil.

All control and experiments, as well as chemical analysis have been done in triplicate. Mean values ± standard deviations are shown for the data comparisons.

3. Results and discussion

3.1. Selection of the suitable biotechnological method for the formation of sand crust

The diversity of the biocementation methods and evaluation of their applicability for the construction of artificial oasis in sandy desert is shown in Table 1.

Table 1
Evaluation of the biocementation methods for the construction of artificial oasis in sandy desert.

Biocementation method	Conclusion on applicability of the method for the construction of artificial oasis in sandy desert
Crystallization of calcium carbonate due to aerobic microbial oxidation of calcium acetate or calcium formate: $(CH_3COO)_2Ca + 4\ O_2 \rightarrow CaCO_3\downarrow + 3\ CO_2\uparrow + 3\ H_2O$ (3)	**It is applicable method**. The optimal water content and temperature for bacterial growth has to be maintained in sand crust for few days
Crystallization of calcium and magnesium carbonates due to aerobic biooxidation of calcium and magnesium formate or acetate: $(CH_3COO)_2Ca + (CH_3COO)_2Mg + 8\ O_2 \rightarrow CaCO_3\downarrow + MgCO_3\downarrow + 6\ CO_2\uparrow + 6\ H_2O$ (4)	**It is applicable method**. The optimal water content and temperature for bacterial growth has to be maintained in sand crust for few days
Precipitation of ferric/ferrous hydroxide/ carbonate from ferrous salt or chelate due to aerobic oxidation of organic salt/chelate of ferrous: $(CH_3COO)_2Fe + 4\ O_2 \rightarrow FeCO_3\downarrow + 3\ CO_2\uparrow + 3\ H_2O$ (5)	**It is applicable method**. The optimal water content and temperature for bacterial growth has to be maintained in sand crust for few days
Crystallization of calcium carbonate minerals due to hydrolysis of urea (MICP): $Ca^{2+} + (NH_2)_2CO + 2\ H_2O \rightarrow CaCO_3\downarrow + 2\ NH_4^+$ (6)	**It is not applicable method** due to release of ammonium, ammonia, and hydroxide ions to environment
Crystallization of calcium carbonate due to decay of calcium bicarbonate and drying: $Ca(HCO_3)_2 \rightarrow CaCO_3\downarrow + CO_2\uparrow + H_2O$ (7)	**It is not applicable method** due to low solubility of calcium bicarbonate (Ivanov et al., 2019b)
Crystallization of calcium carbonate due to decay of calcium bicarbonate under action of urease on urea: $Ca(HCO_3)_2 + OH^- \rightarrow CaCO_3\downarrow + HCO_3^- + H_2O$ (8)	**It is not applicable method** due to low solubility of calcium bicarbonate (Ivanov et al., 2019b)
Biocementation based on the production of carbonates by denitrifying anaerobic heterotrophic bacteria: $(CH_3COO)_2Ca + 8/5\ NO_3^- \rightarrow CaCO_{3\downarrow} + 4/5\ N_2\uparrow + 3\ CO_2\uparrow + 3\ H_2O + 8/5\ OH$ (9)	**It is not applicable method** due to aerobic conditions in sand crust
Biocementation and sand crusting based on the production of carbonates on soil surface by phototrophic bacteria and their growth on sand surface: $Ca^{2+} + light + HCO_3^- + OH^- \rightarrow CaCO_{3\downarrow} + H_2O$ (10)	**It is not applicable method** due to slow growth and dry environment on sand surface
Crystallization of calcium phosphate (hydroxyapatite) due to the increase of the pH by urease: $10\ Ca^{2+} + 6\ H_2PO_4^- + 14\ OH^- \rightarrow Ca_{10}(PO_4)_6(OH)_2\downarrow + 12\ H_2O$ (11)	**It is not applicable method** due to low solubility of calcium phosphates (Ivanov et al., 2019b)
The combined calcite and struvite (NH_4MgPO_4) precipitation using triple superphosphate and magnesium salt to avoid the production of free ammonium and release of ammonia to the atmosphere during biocementation: $Ca(H_2PO_4)_2 + 2\ Mg^{2+} + CO(NH_2)_2 + H_2O + acid\ urease \rightarrow 2\ NH_4MgPO_4\downarrow + CaCO_3\downarrow$ (12)	**It is not applicable method** due to high pH for the reaction performance (Ivanov and Stabnikov, 2017)

Considering environmental safety, technological feasibility, market availability and cost of the raw materials, the most prospective processes for the biotechnological formation of the sand surface crust on the oasis surrounding slopes in sandy desert could be microbially-initiated precipitation of calcium carbonate due to aerobic oxidation of calcium, magnesium or iron salts of organic acids (Eqs. (3)–(5)). This biotechnology of sand calcification was previously tested only under laboratory-scale conditions (Xu et al., 2013; Ganendra et al., 2014; Ivanov and Stabnikov, 2017).

3.2. Test of the sand crust that was biocemented using aerobic oxidation of calcium acetate

Hydraulic conductivity of the biocemented sand (K, m/s) depends on the content of precipitated $CaCO_3$ (C, %, w/w) by the following equation (Ivanov and Stabnikov, 2017):

$$\lg K = -4 - 0.17C \tag{13}$$

Hydraulic conductivity of 1×10^{-6} m/s is similar to the parameter of silt on the slope (Yeh and Tsai, 2018) and could be considered as acceptable level for water collection on watershed and transportation to oasis reservoir. To reach this hydraulic conductivity the content of precipitated $CaCO_3$ in sand crust must be about 12% (w/w). The unconfined compressive strength (UCS) of this sand crust can be calculated by following equation (Ivanov and Stabnikov, 2017):

$$UCS = 0.15C = 1.8\,MPa \tag{14}$$

which is sufficient strength of the sand surface crust for water collection and transportation on the slopes to oasis reservoir.

After supply of the biocementing solution onto sand surface, the majority of $CaCO_3$ was precipitated in the upper layer with a thickness of a few mm (Fig. 1).

So, we consider that 1 mm of biocemented sand crust with the content of $CaCO_3$ about 12% (w/w) is sufficient for the collection and transportation of rainfall water on the slopes to the oasis pond. In this case, the quantity of precipitated $CaCO_3$ must be (0.001 m^3 of sand/m^2 of sand crust) × (1700 kg of sand /m^3 of sand) × (0.12 kg of $CaCO_3$/kg of sand) = 0.2 kg $CaCO_3$/m^2 of sand. To produce this quantity of $CaCO_3$ at least 0.32 kg of calcium acetate/m^2 of sand must be supplied. For this consideration, the cost of biocement for artificial oasis will be about US$1300/t of calcium acetate × 3.2 ton/ha of sand × 1000 ha = 4.5 mln USD = 16.7 mln SAR. Meanwhile, the sealing of 1000 ha with 1 mm waterproofing geomembrane (Christopher, 2014; Deepika and Rao, 2018) will cost minimum 30 mln USD = 112 mln SAR. This is too high cost for 100 ha of oasis land to be used in practice. The price of conventional cement could be cheaper than biocement but cannot be used to create 1 mm cemented sand crust by spraying because of high viscosity of the cement suspension.

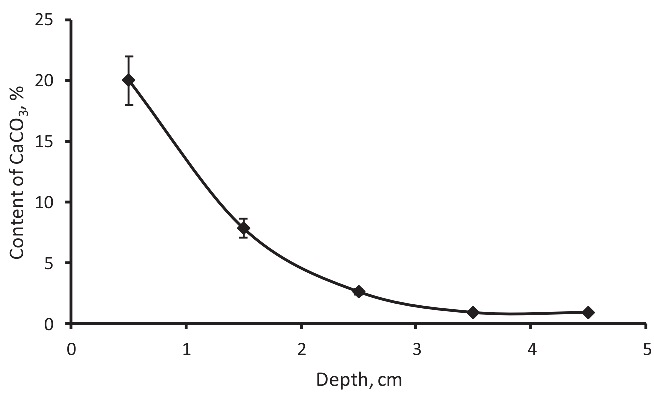

Fig. 1. Profile of precipitated calcium carbonate in sand.

3.3. Scale-up factors

Selection of the raw materials for scaled-up application must be based on both economy and environmental considerations, as well as on the local availability of the sources of calcium salts, for example: 1) such commodities as technical grade calcium formate or acetate; 2) mining waste of limestone, dolomite, cement powder, or hematite iron mine tailings that are transformed to dissolved salts by addition of organic acid or through acidogenic fermentation of organic wastes. Schematics of oasis construction

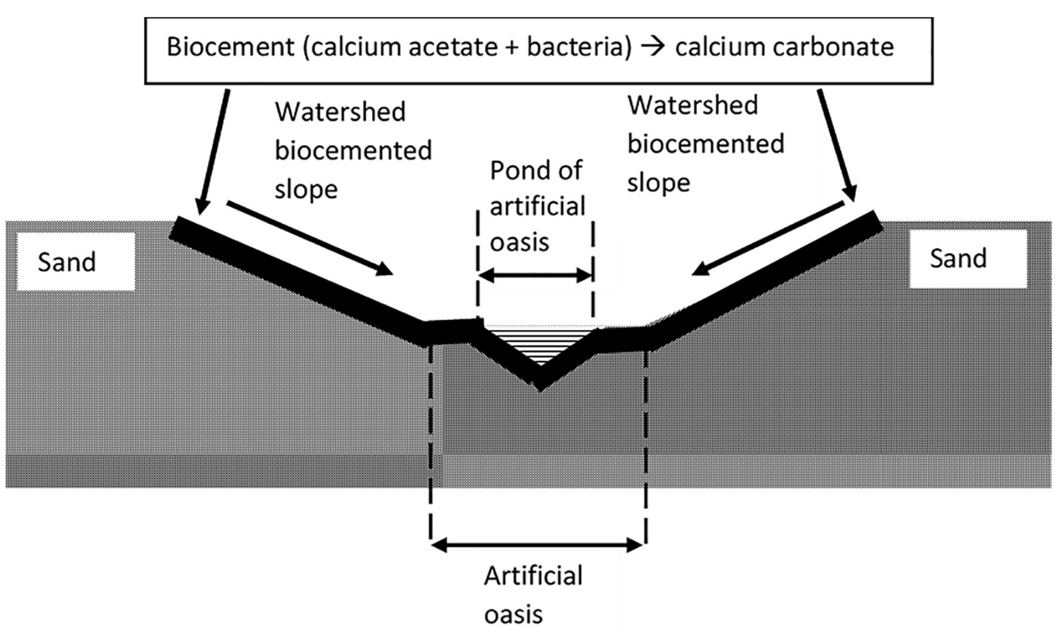

Fig. 2. Schematics of oasis with biocemented surface. The thickness of the biocemented layer of sand is aggravated to demonstrate the pattern of this layer.

using biocementation of sand surface on the slopes is shown in Fig. 2.

Optimal humidity in sand crust for growth and activity of acetate-oxidizing bacteria must be maintained for several days of biocementation. The spraying treatments of sand surface could be better repeated at night times at the optimal temperature on surface 20–30 °C to ensure several hours of continuous growth and biocementation activity of acetate-oxidizing bacteria.

4. Conclusion

The cost of biocementation of the sand crust using aerobic oxidation of calcium acetate could be several times lower than any other applicable method of the sand sealing. Therefore, this method should be tested in pilot scale for the development of large-scale biotechnology for the construction of artificial oasis in sandy desert.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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