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Sustainable biocementation of mine tailings: Reduction of urea requirements through bicarbonate-based MICP

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A R T I C L E I N F O

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A B S T R A C T

Microbially induced calcite precipitation (MICP) has emerged as a promising technique to contribute to a more sustainable management of mine tailings deposits. While ureolytic activity has been the predominant driver of conventional MICP to date, the associated release of ammonia poses significant environmental hazards. This study explores a novel, environmentally friendly approach by replacing urea with sodium bicarbonate as the carbon source for MICP, with the aim of reducing urea requirements and thus ammonia release. Leveraging the principles of the MICP, it was observed that when urea concentration was reduced to 0.7 M, by replacing it with bicarbonate, surface strength was close to 400 kPa. Furthermore, wind tunnel testing showed a significant reduction in dust emission, where the mass loss rate of the biocemented sample was below 10 kg m^{-2} h^{-1}, which means a 9-fold reduction compared to untreated samples. So, it was demonstrated that bicarbonate can effectively replace urea, achieving a relevant reduction of up to 75 % in urea use without compromising the surface strength of the biocemented tailings and reducing the environmental hazards of ammonia release. These results highlight the potential of bicarbonate-based MICP as an innovative and sustainable approach to mitigate the environmental impacts associated with tailings deposits.

1. Introduction

The development of societies globally depends on the use of minerals, which are necessary in applications such as manufacture of chemicals, glass, fertilizers, pharmaceuticals, plastics, paper and in many other types of industries (Pedro et al., 2017). As the productivity of mineral exploitation has significantly increased in the last decades, the management of wastes associated with this activity has also become more complex, costly, and time-consuming (Lottermoser, 2010). One of the most important wastes coming from mining operations is the mine tailings. They are normally stored in deposits of great dimensions, with extensive areas where material is exposed to the atmosphere. As a result, one of the main concerns associated with these tailings is the release of heavy metals through leaching (Nam et al., 2016; Proudfoot et al., 2022) and the possible emission of windblown dust, which have been shown to be

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hazardous to the environment and human health (Csavina et al., 2012; Jaishankar et al., 2014; Martín-Velázquez et al., 2022). This is specially the case of inactive or abandoned tailings deposits, where supervision or control of their condition and evolution may be absent.

Microbially induced calcite precipitation (MICP) has been reported as an effective method for the reduction of wind erosion from natural soils (Martín-Velázquez et al., 2022; Meyer et al., 2011). In recent years, MICP has also been reported as a potential effective way to control dust emissions from mine tailings (Bao et al., 2024; Buikema et al., 2018; Ehsasi et al., 2022; Lai et al., 2021; Rodin et al., 2023; Zúñiga-Barra et al., 2025). Briefly, the MICP process is based on calcium carbonate ($CaCO_3$) precipitation through the hydrolysis of urea, by the microbial urease enzyme in the presence of calcium ions (Achal and Pan, 2014; Whiffin et al., 2007). Microorganisms, through their ureolytic activity, supply the inorganic carbon essential for the precipitation of $CaCO_3$ and ammonia that lead to alkalinization of the environment, creating the conditions for this process. MICP facilitates a biocementation effect due to the $CaCO_3$ precipitation, as this reaction generates chemical bonds between the particles of mine tailings and the microorganisms (Chen et al., 2024; Meyer et al., 2011). Further details of the chemical reactions that occur during the MICP are described in Table 1.

It has been reported that the dynamics of MICP is governed by the application methodology and dosage of biocementation reagents (Buikema et al., 2018; Ehsasi et al., 2022; Rodin et al., 2023). However, to date, the urea requirement during the biocementation of mine tailings has not been fully elucidated. Available reports describe urea dosages that vary between 10 and 1000 g urea per m^2 of treated mine tailings (Zúñiga-Barra et al., 2022). Moreover, it should be noted that the typical concentration of urea used during MICP treatments for the reduction of wind erosion is close to 1.0 M (Nikseresht et al., 2020; Wang et al., 2018). So, considering that 2 moles of ammonium are released for each mole of hydrolysed urea (see Table 1, Reaction 1 and 2), significant atmospheric pollution may occur due to ammonium volatilization, with the obvious risks that this would involve. Indeed, ammonia is one of the main sources of nitrogen pollution (Kanter, 2018). It can volatilize and contribute to the formation of several aerosol compounds, which can affect climate behaviour (Erisman et al., 2011; Lelieveld et al., 2015). Ammonia can get accumulated, oxidized, and later leach into a surface water body as nitrate (NO_3^-), contributing to eutrophication and aquatic ecosystems pollution (Galloway et al., 2003). Therefore, one of the main challenges in the field of MICP is to reduce potential risk by ammonia emissions.

Limitation of urea dosage seems to be an obvious option for the control of ammonia production in the context of MICP. For example, Ashraf et al. (2021) used surface response methodology to optimize MICP during biocementation assays of a sand column, providing a reduction of 75 % in urea consumption per gram of sand, also significantly improving the compressive strength of biocemented sand columns. The use of inorganic carbon sources as a partial replacement of urea, such as $NaHCO_3$ or CO_2, has also been proposed as an alternative (Hussain et al., 2025). During bioprecipitation test (i.e., MICP test in liquid media), Kaur et al. (2016a) demonstrated the feasibility of using CO_2-fixing bacteria and CO_2 injection to produce $CaCO_3$ precipitation. However, application of CO_2-driven biocementation processes to soils or tailings can pose challenges due to mass transfer limitations. As a result, there is a need to develop practical ways to apply CO_2 in large-scale geotechnical applications (Mwandira et al., 2023). In contrast, bicarbonate can be easily added to the biocementation media. Moreover, the cost of bicarbonate is USD 208 per tonne, 50 % less than that of urea (Trading Economics, 2025a, 2025b). Then, bicarbonate seems a suitable potential carbon source for tailings biocementation applications.

This research studied the viability of urea replacement by $NaHCO_3$ as a carbon source during MICP, as a strategy to reduce urea requirements during the biocementation of mine tailings, to improve their resistance to wind erosion. Results of this research are expected to contribute to the development of an environmentally friendly MICP process that contributes to the safe management of mine tailings deposits.

2. Materials and methods

2.1. Microorganisms and growth conditions

To induce $CaCO_3$ precipitation by MICP process, the bacterium *Sporosarcina pasteurii* (NCIMB 8841) was used. Microorganism was cultivated using a culture medium containing: 5 g L^{-1} peptone, 5 g L^{-1} NaCl, 2 g L^{-1} yeast extract and 1 g L^{-1} nutrient broth (Achal et al., 2009). Culture medium was sterilized by autoclaving for 30 minutes at 121°C. Then, sterilized autoclaved solution was cooled at room temperature and supplemented with a urea solution (2 % p/p), previously sterilized using a sterile filtration system (Achal et al., 2015). The microorganism was cultivated using a 3 L bioreactor (Applikon, Schiedam, The Netherlands) with a working volume of 1.5 L. The culture was performed during 48 hours at 37°C, under aerobic conditions using an agitation rate of 300 rpm and an air flow rate of 1.5 L min^{-1}.

Table 1
Details of the chemical reactions occurring in the MICP process.

Reaction N°	Reaction	**MICP stage**
1	$CO(NH_2)_2 + H_2O \xrightarrow{Urease} NH_2COOH + NH_3$	Urea hydrolysis
2	$NH_2COOH + H_2O \rightarrow H_2CO_3 + NH_3$	
3	$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^-$	Chemical equilibrium
4	$H_2CO_3 \leftrightarrow HCO_3^- + H^+$	
5	$HCO_3^- + H^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2H_2O$	
6	$Ca^{2+} + Cell \rightarrow Cell - Ca^{2+} complex$	Heterogeneous nucleation
7	$Cell - Ca^{2+} + CO_3^{2-} \rightarrow Cell - CaCO_3 complex$	

2.2. Evaluation of urea substitution in bioprecipitation tests (MICP assays in liquid media)

Urea substitution was studied in bioprecipitation tests performed in liquid media. Design of experiments (DOE) 1 was conceived to identify the effect of calcium concentration and urea-$NaHCO_3$ ratio on MICP behaviour. Different urea and $NaHCO_3$ concentrations were tested at three $CaCl_2$ levels (12.5, 25 and 50 mM). DOE 1 was performed following a full factorial design, evaluating a total of 15 conditions. These experiments are described in Table 2. For all conditions, an equimolar total carbon (TC) - calcium ratio was used. pH was not controlled during the experiments.

The bioprecipitation tests were performed in 50 mL conical tubes, shacked at 120 rpm at 30°C. Tests lasted 24 hours. 1 mL of fresh culture broth obtained from the fermentation of *S. pasteurii* was added to each test. Note that by the end of the fermentation, a final biomass concentration of 1.96 ± 0.01 g L^{-1}, and an ureolytic activity of 92.3 ± 4.1 U mL^{-1} was obtained.

2.3. Evaluation of urea substitution in biocementation tests (MICP assays in a solid matrix)

Two sets of experiments were designed and conducted (DOE 2 and 3) to determine the feasibility of urea replacement during biocementation tests (see Table 3). DOE 2 was conceived to evaluate different TC - calcium ratios (1:1, 2:1 and 3:1) to reduce the urea dose. Whereas DOE 3 was performed to evaluate the feasibility of urea substitution by using different urea - $NaHCO_3$ ratios (2:1, 1:1 and 1:2). DOE 2 and 3 were performed following a factorial design, evaluating a total of 3 and 4 conditions, respectively. These experiments are described in Table 3. For all assays, a synthetic tailing was used, using materials commercially available in the Valparaíso region, Chile. Its characterization was previously described by Zúñiga-Barra et al. (2023) and is presented in Table S1 of Supplementary Material. Biomass used for these tests had a solids concentration of 1.3 ± 0.3 g L^{-1}, while the ureolytic activity was 34.8 ± 0.7 U mL^{-1}. Biomass was concentrated by centrifugation to achieve the conditions described in Table 3.

For DOE 2 and 3, a suspension of *S. pasteurii* biomass was added at a dose of 0.06 g of dried biomass per kg of dried soil. As a result, biomass suspension dose corresponds to 0.15 L per kg dried tailings, equivalent to 2.5 L per m^2. Biocementation media (i.e., solution of calcium and urea and/or bicarbonate) was provided in the same proportion (2.5 L per m^2). Concentrations of biomass and reagents listed in Table 3 are reported considering total added liquid volume (biomass suspension plus biocementation media).

DOE 2 and 3 were performed using 300 g of dried tailings, which were added to 350 mL polyurethane cups acting as molds. Molds were placed into an incubating room at 30°C during a curing time of 30 days. In all tests, the biomass suspension and biocementation media were added by the irrigation method, which consisted of adding the media to the top of the biocementation molds, allowing the solution to permeate through the sample without being contained.

2.4. Determination of calcium precipitation yield and $CaCO_3$ content

The quantification of remaining calcium was used to estimate the calcium precipitation yield and thus to estimate the $CaCO_3$ content of biocemented samples. Therefore, calcium precipitation yield (Eq. 1) and $CaCO_3$ content (Eq. 2) were calculated as the fraction of precipitated calcium relative to added calcium as follows:

$$Calcium\ precipitation\ yield(\%) = \frac{n_{precipitated\ Ca2+}}{n_{added\ Ca2+}} * 100 \tag{1}$$

$$CaCO_3 content(\%) = \frac{m_{CaCO_3}}{m_{sample}} * 100 \tag{2}$$

Table 2
Conditions of DOE 1: urea substitution in bioprecipitation tests.

Test	Biomass conc. (g L^{-1})	TIC - calcium ratio	Calcium conc. (mM)	Urea - $NaHCO_3$ ratio
1	1.96	1:1	12.5	1:0
2	1.96	1:1	12.5	1:0.4
3	1.96	1:1	12.5	1:0.7
4	1.96	1:1	12.5	0.7:1
5	1.96	1:1	12.5	0.4:1
6	1.96	1:1	25	1:0
7	1.96	1:1	25	1:0.4
8	1.96	1:1	25	1:0.7
9	1.96	1:1	25	0.7:1
10	1.96	1:1	25	0.4:1
11	1.96	1:1	50	1:0
12	1.96	1:1	50	1:0.4
13	1.96	1:1	50	1:0.7
14	1.96	1:1	50	0.7:1
15	1.96	1:1	50	0.4:1

Observation: The experiments presented were carried out in triplicate to check the repeatability. The results were expressed as the arithmetic mean ± standard deviation.

Table 3
Conditions of DOE 2 and 3: urea substitution in biocementation tests.

DOE	Test	Biomass (g L^{-1})	Biomass dose (g kg^{-1} dried soil)	$CaCl_2$ (M)	Calcium dose (mol kg^{-1} dried soil)	TC - calcium ratio	Urea (M)	Urea - $NaHCO_3$ ratio
2	1	0.94	0.06	1.1	0.07	1:1	1.1	1:0
	2	0.94	0.06	1.1	0.07	1:1	2.2	1:0
	3	0.94	0.06	1.1	0.07	1:1	3.3	1:0
3	1	0.94	0.06	1.1	0.07	2:1	2.2	1:0
	2	0.94	0.06	1.1	0.07	2:1	1.5	2:1
	3	0.94	0.06	1.1	0.07	2:1	1.1	1:1
	4	0.94	0.06	1.1	0.07	2:1	0.7	1:2

Where n_i and m_i are the moles and mass of each specie.

2.5. Biocementation effect

To evaluate the biocementation effect by $CaCO_3$ precipitation during DOE 2 and 3, surface strength and wind erosion resistance of the biocemented samples (inside the polyurethane mould) were quantified using cone penetration test and wind tunnel test, respectively. Different reports have shown that MICP may lead to the formation of different $CaCO_3$ crystalline phases, such as calcite or vaterite (Behzadipour and Sadrekarimi, 2023; Kaur et al., 2016; Lai et al., 2021). Therefore, scanning electron microscopy (SEM) analysis was used to observe the crystal morphology of $CaCO_3$.

2.6. Analytic methods

The cone penetration assay was performed with an electric compression press (ELE international, mod. T-1325A-4) to measure the surface strength of the biocemented tailings, as described by Zúñiga-Barra et al. (2023). Likewise, the wind tunnel test was performed on a laboratory-scale equipment at wind speed of 8.5 m s^{-1} for 30 minutes as described by (Zúñiga-Barra et al., 2025). The wind tunnel consisted of two sections: the first section was 1.2 m long, with a cross-section of 0.2 m in width and height. The second section was 2.0 m long with a cross-section of 0.3 m width and height. A detailed schematic of the laboratory-scale wind tunnel is shown in

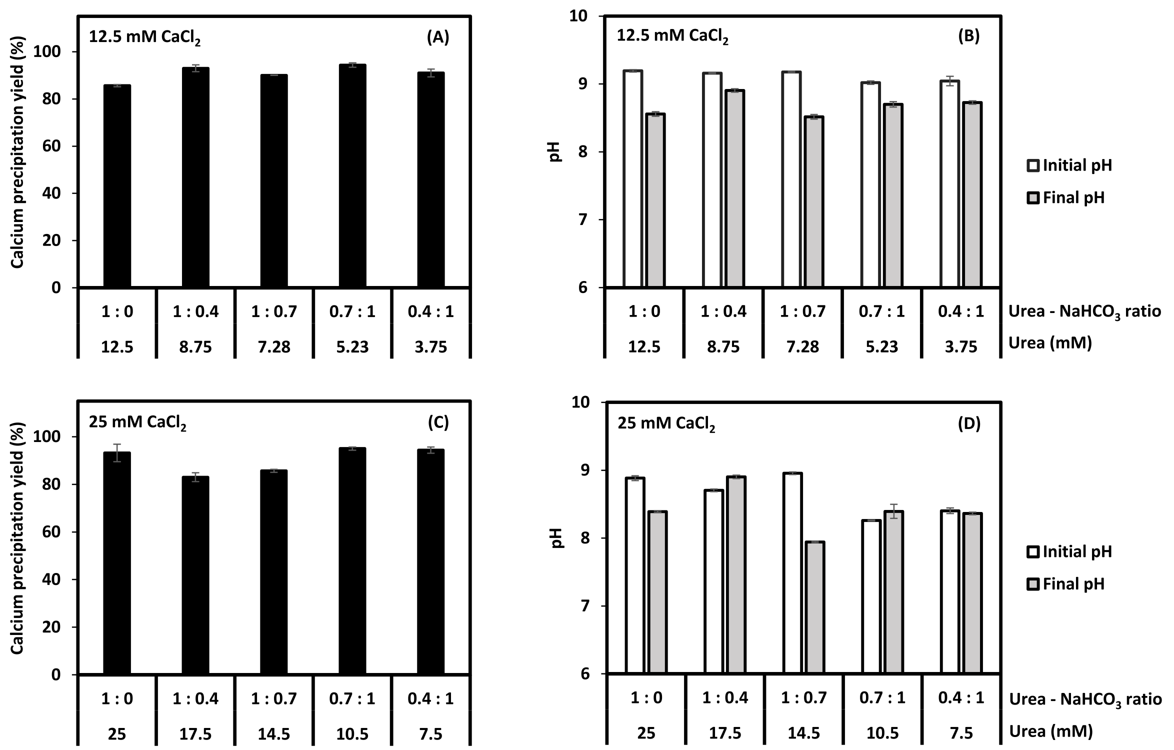

Fig. 1. (A-C) Calcium precipitation yields and (B-D) pH changes observed during bioprecipitation tests (DOE 1), at different levels of $CaCl_2$ and urea - $NaHCO_3$ ratio. Reported values after 24 hours. In all cases an equimolar TC - calcium ratio of 1:1 was provided. Error bars represent the standard deviation between triplicates.

Figure S1 of the Supplementary Material.

Calcium precipitation yield (Eq. 1) and the $CaCO_3$ content (Eq. 2) were determined by determining the remaining calcium by titration with EDTA to determine the concentration of dissolved calcium (APHA, 2005).

The micrographic characteristics of the precipitated crystals were observed by scanning electron microscope analysis using a HITACHI SU3500 at accelerating voltages of 10 kV and working distance (WD) of 6 mm. The electron micrographic characteristics were observed by secondary electron (SE) and backscattered electron (BSE) detectors.

2.7. *Statistical analysis*

Hypothesis testing was carried out in order to determine the existence of statistical differences between the responses observed at the different tested conditions. Student's *t*-test were performed for that purpose. Differences between responses were considered to be statistically significant at p-values < 0.05. Statistical analysis of the data were performed using MINITAB software.

3. Results and discussion

Fig. 1 presents calcium precipitation yield, and initial and final pH of the assays involved in DOE 1. All the results were compared with a reference condition (i.e., conventional MICP). The later was defined as the experiments where urea - $NaHCO_3$ ratio was 1:0, which means that only urea and $CaCl_2$ were added. As can be observed in Fig. 1A, when 12.5 mM of $CaCl_2$ was added, calcium precipitation yields close to 90 % were achieved. Fig. 1B show a slight decrease of pH, from around 9.2 to about 8.7. Despite this, in all cases, data suggest that the alkaline pH was suitable to favour the $CaCO_3$ precipitation.

Fig. 1C and 1D show the behaviour of the precipitation tests, when 25 mM of $CaCl_2$ was applied. Similar responses were obtained in comparison with assays involving 12.5 mM of $CaCl_2$. Calcium precipitation yields were like those reported by other authors (Kaur et al., 2016; Stocks-Fischer et al., 1999). For example, Kaur et al. (2016) reported a calcium precipitation yield of 80 %, after 24 hours of reaction, when using 25 mM of TC and 13:1 urea - $CaCl_2$ ratio (333 mM of urea). Results in Fig. 1 proves that, at 12.5 and 25 mM of $CaCl_2$, a urea reduction of up to 70 % was possible. Moreover, data showed that urea - $NaHCO_3$ ratio was not a statistically significant factor (p value > 0.05) for the calcium precipitation yield, implying that at this stage no relevant differences were detected in the performances of bicarbonate-based MICP and conventional MICP.

During the assays reported in Fig. 1 (DOE 1) an equimolar ratio of TC and calcium was provided. This ratio, combined with the high observed precipitation yield, means that carbon released during urea hydrolysis was insufficient to fulfil the requirements of calcium

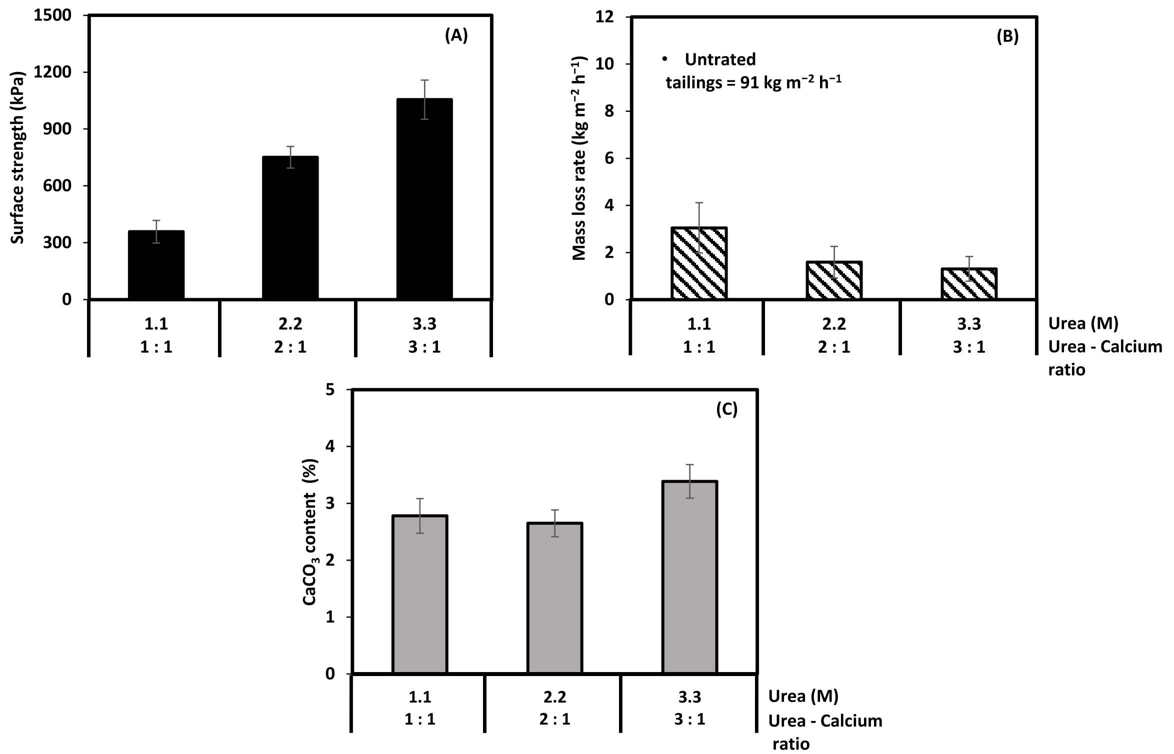

Fig. 2. (A) Surface strength determined by cone penetration method, (B) mass loss rate determined by wind tunnel test performed for 30 minutes at 8.5 m s^{-1} and (C) $CaCO_3$ content observed during biocementation test (DOE 2), applied to synthetic tailings samples when 1.1 M of $CaCl_2$ was provided, at different levels of urea - calcium ratio. Error bars represent the standard deviation between quadruplicates.

carbonate precipitation. Then, it is inferred that at least part of the inorganic carbon from bicarbonate participated in the precipitation phenomenon. As a result, the data from Fig. 1 provides strong evidence that substitution of the inorganic carbon donor is possible by replacing part of the urea with bicarbonate, without negatively impacting the calcium precipitation yield.

Subsequently, the reduction of the urea dose was evaluated during the biocementation test (DOE 2), in which 1.1 M of $CaCl_2$ and different urea - calcium ratios were evaluated (see Table 3). Note that DOE 2 corresponds to a conventional MICP treatment. Fig. 2A show that when urea - calcium ratio was increased from 1:1–3:1, a 4-fold increment of the surface strength of biocemented tailings was observed (statistically relevant difference, p-value < 0.05). In general terms, a higher surface strength was observed in comparison with other reported studies, when similar conditions were used. For example, Rodin et al. (2023) reported biocemented tailings with a surface strength of 73 kPa, using a urea - calcium ratio of 2:1, when using 1.0 M of $CaCl_2$ and a similar irrigation level (4 L m^{-2}). Differences in the data provided by existing reports can be attributed to the diversity of physical and chemical characteristics of tested materials, such as particle size or mineral, as described by Chae et al. (2021).

Fig. 2 also presents data on mass loss rate using wind tunnel test, performed at 8.5 m s^{-1}, for 30 minutes. Dust emission rate below 4 kg m^{-2} h^{-1} was observed, suggesting that the application of a urea - calcium ratio as low as 1:1 can be applied, without impairing the wind erosion resistance of the biocemented tailings. Mass loss rate for the untreated tailings was 91 kg m^{-2} h^{-1}. Therefore, the results show that a conventional MICP treatment of tailings substantially improves the surface strength, leading to extremely low dust emissions, which is consistent with that reported by Zúñiga-Barra et al. (2025). This response is obviously attributed to the biocementation effect due to calcium precipitation that act as a bridge between the particles, which is consistent with previous reports (Lai et al., 2021; Meng et al., 2021).

Fig. 2C shows that at all tested conditions, $CaCO_3$ content was close to 3 %, equivalent to a calcium precipitation yield of around 50 %. In fact, different levels of $CaCO_3$ content have been reported in the literature. For example, Meng et al. (2021) observed that by supplying a biocementation medium with 0.4 M $CaCl_2$, a $CaCO_3$ content of 0.8 % was achieved when biocementing sand samples. Similarly, Omoregie et al. (2019) reported a $CaCO_3$ content of 7 %, when treating sand with 0.25 M $CaCl_2$ This $CaCO_3$ content is probably because the biocementation media was allowed to permeate through the sample, carrying away some of the calcium that did not precipitate.

The above results also demonstrate the possibility of reducing urea dose during biocementation without greatly compromising treatment performance. In addition, Fig. 3 presents the results of the assays testing urea replacement during tailings biocementation assays. Note that conventional MICP corresponds to the experiments in which the urea - $NaHCO_3$ ratio was 1:0, which means that only urea and $CaCl_2$ were added. It shows that when urea concentration was reduced from 1.5 to 0.7 M, surface strength was close to 400 kPa, showing no relevant changes. Mass loss rate of the samples, when tested in the wind tunnel, were in all cases below 10 kg m^{-2} h^{-1},

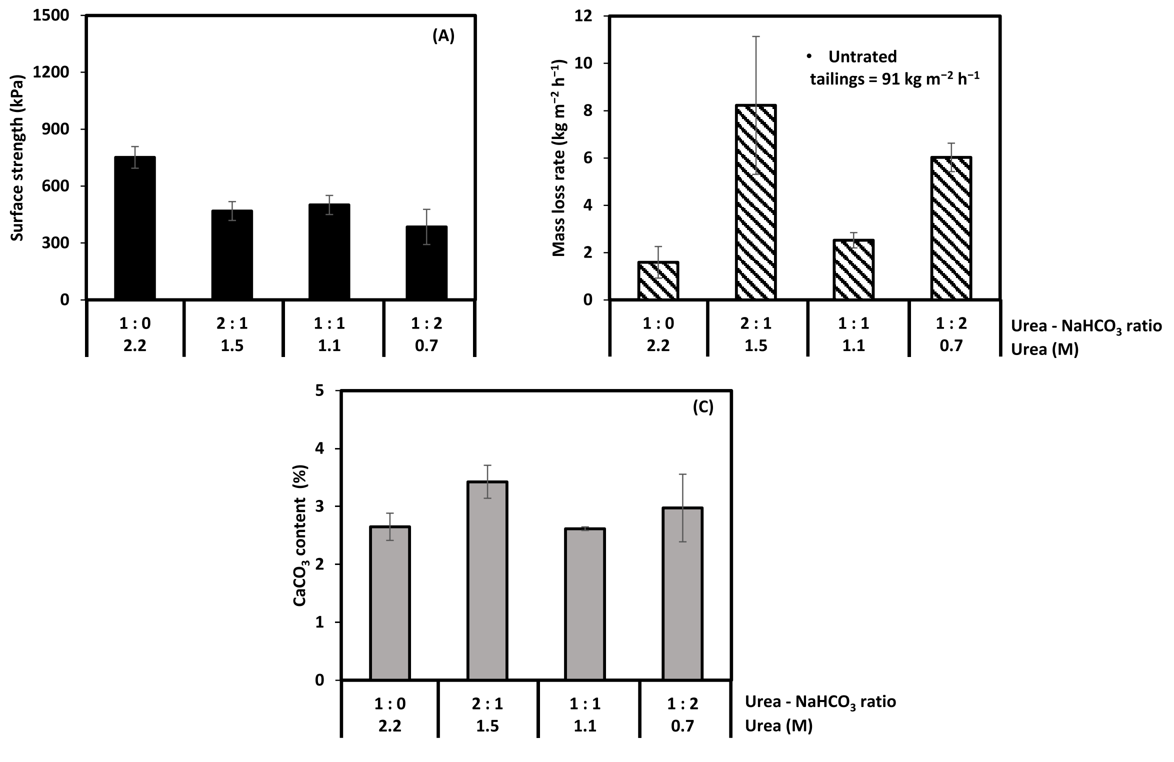

Fig. 3. (A) Surface strength determined by cone penetration method, (B) mass loss rate determined by wind tunnel test performed for 30 minutes at 8.5 m s^{-1} and (C) $CaCO_3$ content observed during biocementation test (DOE3) applied to synthetic tailings samples, when 1.1 M of $CaCl_2$ was provided at different levels of urea - $NaHCO_3$ ratio. In all cases a TC - calcium ratio of 2:1 was added. Error bars represent the standard deviation between quadruplicates.

which means a 9-fold reduction compared to untreated samples. Finally, Fig. 3 also show that $CaCO_3$ content of biocemented samples were close to 3 %, value very similar to those presented in Fig. 2C, involving assays with no urea replacement.

The results show that the urea - $NaHCO_3$ ratio was a statistically significant factor (p-value < 0.05) when the surface resistance was considered as response. This implies that, when compared with conventional MICP (urea - $NaHCO_3$ ratio 1:0), urea substitution may induce a slightly lower bearing effect in terms of surface strength. Anyhow, results presented in Fig. 3 demonstrate that even when providing a relevant level of urea substitution by $NaHCO_3$ (75 %), it is possible to maintain a good performance of the biocemented tailings in terms of mass loss rate, reaching values that are comparable with conventional MICP (i.e. urea - $NaHCO_3$ of 1:0). This is an unpublished response that confirms that bicarbonate-based MICP can be carried out during bioprecipitation and biocementation treatments, reducing the environmental hazards of ammonia release from conventional MICP.

Fig. 4 presents the EBDS images of precipitates formed during bioprecipitation test (DOE 1), using 25 mM of $CaCl_2$, at two different urea - $NaHCO_3$ ratios. Observations revealed the development of precipitates presenting different microstructures. Fig. 4A shows that during conventional MICP, the microstructure of precipitates formed aggregates of spherical microcrystals of 10–15 μm in diameter (indicated by yellow circles), like those presented by Rodriguez-Blanco et al. (2011), which they attribute to vaterite spheres crystals. On the other hand, Fig. 4B shows that when replacing urea by $NaHCO_3$, the microstructure of formed precipitates was composed by irregular euhedral crystals (indicated by red circles), which may be products of the calcite crystals, which also agrees with that reported by Rodriguez-Blanco et al. (2011).

During conventional MICP, it is inferred that formation of vaterite crystals occurs during the initial stage of the reaction, when supersaturation and pH increase, induced by the activity of the microorganisms (Chekroun et al., 2004; Jiménez-López et al., 2001a). Then, the vaterite crystal phase leads to the formation of the calcite crystal phase as the reaction proceeds (Jiménez-López et al., 2001b). On the other hand, during bicarbonate-based MICP initial addition of inorganic carbon increases supersaturation. Moreover, bicarbonate acts as a reservoir providing carbonate ions that can accelerate $CaCO_3$ formation. Consequently, bicarbonate addition may facilitate nucleation and growth of calcite crystals, which is consistent with the calcite crystals observed in Fig. 4B.

The above results indicate that the use of $NaHCO_3$ as a source of inorganic carbon could favour the transformation rate of $CaCO_3$ crystals and, consequently, the type of crystals produced. This would be especially beneficial to improve the performance of the MICP process when a biocementation effect is sought in a short period of time in practical applications.

Surface microstructure of tailings was also observed by SEM analysis. Fig. 5 presents EBDS images of untreated biocemented tailings using the irrigation method, at two conditions: urea - $NaHCO_3$ ratios of 1:0 and 1:2. Images show structures of irregular shapes and relatively dispersed precipitates, some of which are deposited on the surface of the tailings particles (indicated by yellow arrows). In addition, it can be observed that both biocemented samples also exhibit bonding patterns due to the presence of irregularly shaped precipitates between the tailings particles, presumably acting as bridges (indicated by red squares), which agrees with the observations of previous reports (Bu et al., 2018; Duo et al., 2018). This response allows us to demonstrate that the reduction of wind erosion could be due to bridging between tailings particles (by precipitated $CaCO_3$) and that this effect can even occur by replacing urea with bicarbonate, as shown in Fig. 3B.

Results show how MICP may indeed be employed to control wind erosion in mine tailings deposits. Moreover, that important part of the urea can be replaced by bicarbonate, with minor effects on superficial strength and wind erosion resistance achieved, a response not reported so far.

Visualization of the effect of urea replacement on potential ammonia emissions can be done comparing two of the scenarios tested during DOE 2 and 3. Table 4 presents data from 2 assays using a $CaCl_2$ concentration in the biocementation media of 1.1 M, one with and one without urea replacement (Urea - $NaHCO_3$ ratios of 1:0 and 1:2). If the applied irrigation of biocementation media is combined with urea and bicarbonate concentrations, then maximum potential ammonia releases can be estimated, assuming complete urea

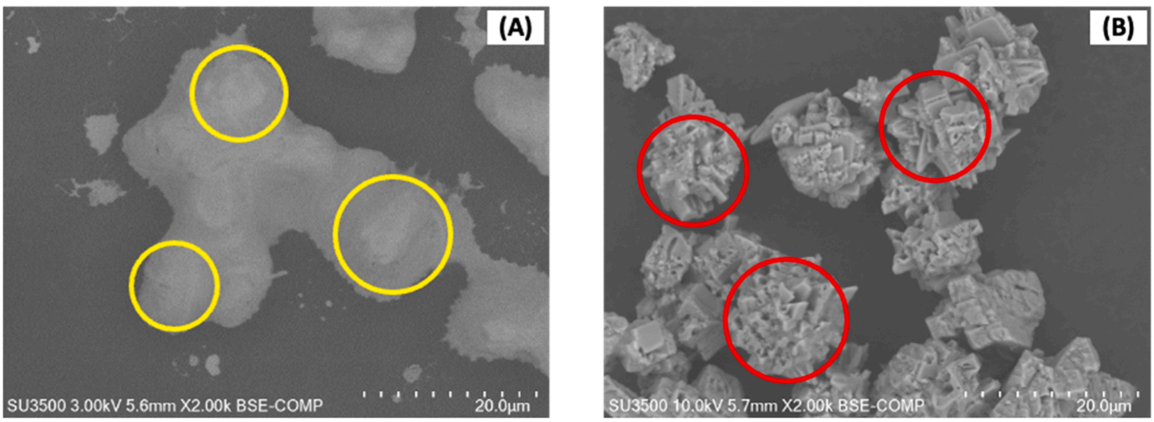

Fig. 4. EBSD images of precipitates from DOE 1. (A) 25 mM $CaCl_2$ and 25 mM urea (urea - $NaHCO_3$ ratio of 1:0). (B) 25 mM $CaCl_2$, 7.5 mM urea (urea - $NaHCO_3$ ratio of 0.4:1). Yellow circles indicate the presence of spherical aggregated precipitates attributed to vaterite crystals. Red circles indicate the presence of irregular euhedral aggregated precipitates attributed to calcite crystals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

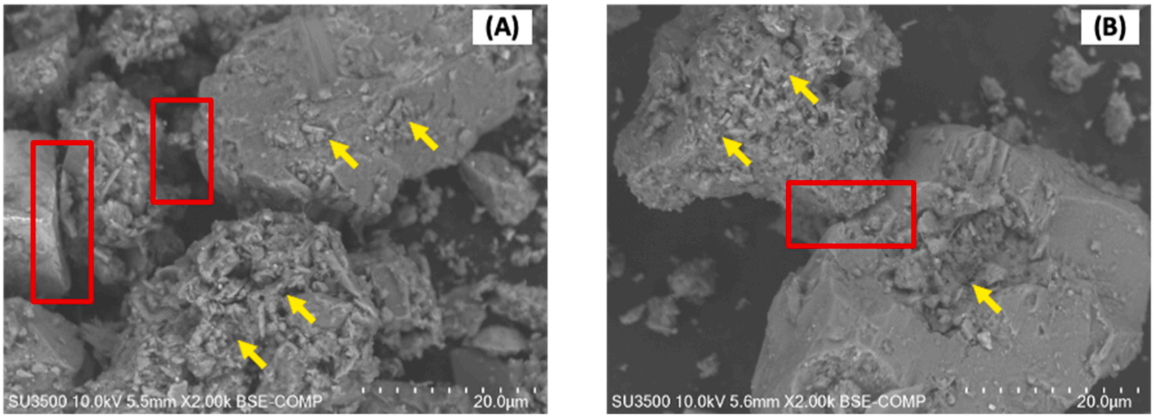

Fig. 5. EBSD images of biocemented sample from DOE 2 and 3. (A) 1.1 M $CaCl_2$ and 2.2 M urea (urea - $NaHCO_3$ ratio of 1:0). (B) 1.1 M $CaCl_2$, 0.75 M urea (urea - $NaHCO_3$ ratio of 1:2). Red squares indicate the presence of binding patters between biocemented tailings particles. Yellow arrows indicate the presence of irregularly shaped precipitated on biocemented tailings particles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Estimation of maximal potential ammonia emission during MICP applied to biocementation of a mine tailings deposit when only urea is used as carbon source and when urea is replaced by bicarbonate.

Scenario	$CaCl_2$ (M)	Irrigation (biocementation media plus biomass suspension) (L m^{-2})	Urea (M)	$NaHCO_3$ (M)	Potential maximum ammonia release (g m^{-2})
1	1.1	5.0	2.2	0	374
2	1.1	5.0	0.73	1.47	124

conversion. As can be seen in Table 1, the potential maximum ammonia release in the scenario with urea replacement is equivalent to 124 g per m^2 of treated soil, which corresponds to one third of the of that for conventional MICP. This represents a significant and relevant reduction of the risks associated with potential ammonia pollution when biocementation by MICP is applied.

Despite the potential benefits of bicarbonate-based MICP, its full-scale application for the effective biocementation of tailings faces few challenges. Scaling-up is certainly one of them, especially considering the large scale of mining operations, especially in countries such as Chile. Long term stability of precipitates formed during cementation and the persistence of its effect to agglomerate tailings also needs to be further studied, in order to determine the need for the application of consecutive treatments. Finally, cost-benefit and sustainability analyses would be required before effective implementation. As a result, it is inferred tat future research would need to be directed to address these aspects.

4. Conclusions

This study investigated the feasibility of replacing urea by $NaHCO_3$ as a carbon source for MICP, to reduce urea requirements during the biocementation of mine tailings, to improve their wind erosion resistance. The following conclusions can be drawn from this work:

- Results of the micrographic analysis showed that, for the bioprecipitation test, there are relevant differences in the morphology of the precipitated $CaCO_3$ crystals when urea is substituted, which allows inferring that, when bicarbonate is added, the transformation rate of the $CaCO_3$ crystals from vaterite to calcite tends to be faster.
- Under the conditions used during the bioprecipitation test, solid evidence was obtained that urea substitution is indeed possible. In fact, the results show that using an equimolar ratio of total carbon - calcium, when bicarbonate is added in substitution to urea, at least part of the inorganic carbon coming from the bicarbonate participated in the precipitation phenomenon, since the carbon released from the hydrolysis of urea was not sufficient to satisfy the calcium carbonate precipitation levels obtained.
- This possibility of replacing urea with bicarbonate was also demonstrated in biocementation tests. First, the possibility of reducing urea doses during treatment without greatly compromising treatment performance was validated. In fact, the substantially improved surface strength of the biocemented tailings was maintained, resulting in extremely low dust emission. Second, it was possible to drastically replace the addition of urea with bicarbonate as a source of inorganic carbon. These findings highlight the potential of bicarbonate-based MICP as a more environmentally friendly approach, which contributes to the safe management of mine tailings deposits.

CRediT authorship contribution statement

Rivas Mariella: Writing – original draft, Resources, Project administration, Funding acquisition, Conceptualization. **Jeison David:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Velastegui Edgar:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Martínez-Ruano Jimmy Anderson:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Pardo-Vásquez Camila:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zúñiga-Barra Héctor:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: David Jeison reports financial support was provided by National Agency for Research and Development. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2025.104255.

Data availability

Data will be made available on request.

References

Achal, V., Mukherjee, A., Basu, P.C., Reddy, M.S., 2009. Strain improvement of Sporosarcina pasteurii for enhanced urease and calcite production. J. Ind. Microbiol. Biotechnol. 36, 981–988. https://doi.org/10.1007/s10295-009-0578-z.

Achal, V., Mukherjee, A., Kumari, D., Zhang, Q., 2015. Biomineralization for sustainable construction - A review of processes and applications. Earth Sci. Rev. 148, 1–17. https://doi.org/10.1016/j.earscirev.2015.05.008.

Achal, V., Pan, X., 2014. Influence of calcium sources on microbially induced calcium carbonate precipitation by Bacillus sp. CR2. Appl. Biochem Biotechnol. 173, 307–317. https://doi.org/10.1007/s12010-014-0842-1.

APHA, 2005. Standard methods for the examination of water and wastewater. Stand. Methods. ISBN 9780875532356.

Ashraf, M.S., Hassan Shah, M.U., Bokhari, A., Hasan, M., 2021. Less is more: optimising the biocementation of coastal sands by reducing influent urea through response surface method. J. Clean. Prod. 315, 128208. https://doi.org/10.1016/J.JCLEPRO.2021.128208.

Bao, S., Di, J., Dong, Y., Gao, Z., Gu, Q., Zhao, Y., Zhai, H., 2024. Experimental study on the effect of cementation curing time on MICP bio-cemented tailings. Constr. Build. Mater. 411, 134263. https://doi.org/10.1016/j.conbuildmat.2023.134263.

Behzadipour, H., Sadrekarimi, A., 2023. Effect of microbial-induced calcite precipitation on shear strength of gold mine tailings. Bull. Eng. Geol. Environ. 82. https://doi.org/10.1007/s10064-023-03357-3.

Bu, C., Wen, K., Liu, S., Ogbonnaya, U., Li, L., 2018. Development of bio-cemented constructional materials through microbial induced calcite precipitation. Mater. Struct. 51, 30. https://doi.org/10.1617/s11527-018-1157-4.

Buikema, N.D., Zwissler, B.E., Seagren, E.A., Oommen, T., Vitton, S., 2018. Stabilisation of iron mine tailings through biocalcification. Environ. Geotech. 5. https://doi.org/10.1680/jenge.16.00006.

Chae, S.H., Chung, H., Nam, K., 2021. Evaluation of microbially induced calcite precipitation (MICP) methods on different soil types for wind erosion control. Environ. Eng. Res. 26. https://doi.org/10.4491/eer.2019.507.

Chekroun, K.Ben, Rodríguez-Navarro, C., González-Muñoz, M.T., Arias, J.M., Cultrone, G., Rodríguez-Gallego, M., 2004. Precipitation and growth morphology of calcium carbonate induced by Myxococcus xanthus: implications for recognition of bacterial carbonates. J. Sediment. Res. 74. https://doi.org/10.1306/050504740868.

Chen, S., Kang, B., Zha, F., Chen, X., 2024. Synergistic solidification of heavy metal tailings by polyethylene glycol (PEG) and microorganisms. Environ. Technol. Innov. 36, 103788. https://doi.org/10.1016/j.eti.2024.103788.

Csavina, J., Field, J., Taylor, M.P., Gao, S., Landázuri, A., Betterton, E.A., Sáez, A.E., 2012. A review on the importance of metals and metalloids in atmospheric dust and aerosol from mining operations. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2012.06.013.

Duo, L., Kan-liang, T., Hui-li, Z., Yu-yao, W., Kang-yi, N., Shi-can, Z., 2018. Experimental investigation of solidifying desert aeolian sand using microbially induced calcite precipitation. Constr. Build. Mater. 172, 251–262. https://doi.org/10.1016/j.conbuildmat.2018.03.255.

Ehsasi, F., van Paassen, L., Wang, L., 2022. Stabilization of mine tailings using microbiological induced carbonate precipitation for dust mitigation. Treat. Optim. Durab. Assess. https://doi.org/10.1061/9780784484012.034.

Erisman, J.W., Galloway, J., Seitzinger, S., Bleeker, A., Butterbach-Bahl, K., 2011. Reactive nitrogen in the environment and its effect on climate change. Curr. Opin. Environ. Sustain. https://doi.org/10.1016/j.cosust.2011.08.012.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J., 2003. The nitrogen cascade. Bioscience. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2.

Hussain, A., Ali, D., Koner, S., Hseu, Z.-Y., Hsu, B.-M., 2025. Microbial induce carbonate precipitation derive bio-concrete formation: a sustainable solution for carbon sequestration and eco-friendly construction. Environ. Res. 270, 121006. https://doi.org/10.1016/j.envres.2025.121006.

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B., Beeregowda, K.N., 2014. Toxicity, mechanism and health effects of some heavy metals. Interdiscp. Toxicol. https://doi.org/10.2478/intox-2014-0009.

Jiménez-López, C., Caballero, E., Huertas, F.J., Romanek, C.S., 2001a. Chemical, mineralogical and isotope behavior, and phase transformation during the precipitation of calcium carbonate minerals from intermediate ionic solution at 25°C. Geochim Cosmochim. Acta 65. https://doi.org/10.1016/s0016-7037(01)00672-x.

Jiménez-López, C., Caballero, E., Huertas, F.J., Romanek, C.S., 2001b. Chemical, mineralogical and isotope behavior, and phase transformation during the precipitation of calcium carbonate minerals from intermediate ionic solution at 25°C. Geochim Cosmochim. Acta 65, 3219–3231. https://doi.org/10.1016/s0016-7037(01)00672-x.

Kanter, D.R., 2018. Nitrogen pollution: a key building block for addressing climate change. Clim. Change 147. https://doi.org/10.1007/s10584-017-2126-6.

Kaur, G., Dhami, N.K., Goyal, S., Mukherjee, A., Reddy, M.S., 2016. Utilization of carbon dioxide as an alternative to urea in biocementation. Constr. Build. Mater. 123. https://doi.org/10.1016/j.conbuildmat.2016.07.036.

Lai, Y., Yu, J., Liu, S., Liu, J., Wang, R., Dong, B., 2021. Experimental study to improve the mechanical properties of iron tailings sand by using MICP at low pH. Constr. Build. Mater. 273. https://doi.org/10.1016/j.conbuildmat.2020.121729.

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525. https://doi.org/10.1038/nature15371.

Lottermoser, B.G., 2010. Mine wastes (third edition): Characterization, treatment and environmental impacts, Mine Wastes (Third Edition): Characterization, Treatment and Environmental Impacts. https://doi.org/10.1007/978-3-642-12419-8.

Martín-Velázquez, S., Rodríguez-Santalla, I., Ropero-Szymañska, N., Gomez-Ortiz, D., Martín-Crespo, T., de Ignacio-San José, C., 2022. Geomorphological mapping and erosion of abandoned tailings in the Hiendelaencina Mining District (Spain) from aerial imagery and LiDAR data. Remote Sens. 14. https://doi.org/10.3390/rs14184617.

Meng, H., Gao, Y., He, J., Qi, Y., Hang, L., 2021. Microbially induced carbonate precipitation for wind erosion control of desert soil: field-scale tests. Geoderma 383. https://doi.org/10.1016/j.geoderma.2020.114723.

Meyer, F.D., Bang, S., Min, S., Stetler, L.D., Bang, S.S., 2011. Microbiologically-Induced Soil Stabilization: Application of Sporosarcina pasteurii for Fugitive Dust Control. https://doi.org/10.1061/41165(397)409.

Mwandira, W., Mavroulidou, M., Gunn, M.J., Purchase, D., Garelick, H., Garelick, J., 2023. Concurrent Carbon capture and biocementation through the carbonic anhydrase (CA) activity of microorganisms -a review and outlook. Environ. Process. 10, 56. https://doi.org/10.1007/s40710-023-00667-2.

Nam, I.-H., Roh, S.-B., Park, M.-J., Chon, C.-M., Kim, J.-G., Jeong, S.-W., Song, H., Yoon, M.-H., 2016. Immobilization of heavy metal contaminated mine wastes using Canavalia ensiformis extract. Catena 136, 53–58. https://doi.org/10.1016/j.catena.2015.07.019.

Nikseresht, F., Landi, A., Sayyad, G., Ghezelbash, G., Schulin, R., 2020. Sugarecane molasse and vinasse added as microbial growth substrates increase calcium carbonate content, surface stability and resistance against wind erosion of desert soils. J. Environ. Manag. 268. https://doi.org/10.1016/j.jenvman.2020.110639.

Omoregie, A.I., Palombo, E.A., Ong, D.E.L., Nissom, P.M., 2019. Biocementation of sand by Sporosarcina pasteurii strain and technical-grade cementation reagents through surface percolation treatment method. Constr. Build. Mater. 228, 116828. https://doi.org/10.1016/j.conbuildmat.2019.116828.

Pedro, A., Ayuk, E.T., Bodouroglou, C., Milligan, B., Ekins, P., Oberle, B., 2017. Towards a sustainable development licence to operate for the extractive sector. Miner. Econ. 30. https://doi.org/10.1007/s13563-017-0108-9.

Proudfoot, D., Brooks, L., Gammons, C.H., Barth, E., Bless, D., Nagisetty, R.M., Lauchnor, E.G., 2022. Investigating the potential for microbially induced carbonate precipitation to treat mine waste. J. Hazard Mater. 424, 127490. https://doi.org/10.1016/j.jhazmat.2021.127490.

Rodin, S., Champagne, P., Mann, V., 2023. Pilot-scale feasibility study for the stabilization of coal tailings via microbially induced calcite precipitation. Environ. Sci. Pollut. Res. 30. https://doi.org/10.1007/s11356-022-22316-1.

Rodriguez-Blanco, J.D., Shaw, S., Benning, L.G., 2011. The kinetics and mechanisms of amorphous calcium carbonate (ACC) crystallization to calcite, via vaterite. Nanoscale 3. https://doi.org/10.1039/c0nr00589d.

Stocks-Fischer, S., Galinat, J.K., Bang, S.S., 1999. Microbiological precipitation of CaCO3. Soil Biol. Biochem 31. https://doi.org/10.1016/S0038-0717(99)00082-6.

Trading Economics, 2025. Soda Ash - Price [WWW Document]. ⟨https://tradingeconomics.com/commodity/soda-ash⟩ (accessed 3.16.25).

Trading Economics, 2025. Urea - Price [WWW Document]. ⟨https://tradingeconomics.com/commodity/urea⟩ (accessed 3.16.25).

Wang, Z., Zhang, N., Ding, J., Lu, C., Jin, Y., 2018. Experimental study on wind erosion resistance and strength of sands treated with microbial-induced calcium carbonate precipitation. Adv. Mater. Sci. Eng. 2018. https://doi.org/10.1155/2018/3463298.

Whiffin, V.S., van Paassen, L.A., Harkes, M.P., 2007. Microbial carbonate precipitation as a soil improvement technique. Geomicrobiol. J. 24. https://doi.org/10.1080/01490450701436505.

Zúñiga-Barra, H., Toledo-Alarcón, J., Torres-Aravena, Á., Jorquera, L., Rivas, M., Gutiérrez, L., Jeison, D., 2022. Improving the sustainable management of mining tailings through microbially induced calcite precipitation: a review. Min. Eng. https://doi.org/10.1016/j.mineng.2022.107855.

Zúñiga-Barra, H., Ortega-Martínez, E., Toledo-Alarcón, J., Torres-Aravena, Á., Jorquera, L., Rivas, M., Jeison, D., 2023. Potential use of microbially induced calcite precipitation for the biocementation of mine tailings. Minerals 13. https://doi.org/10.3390/min13040506.

Zúñiga-Barra, H., Velastegui, E., Toledo-Alarcón, J., Jorquera, L., Rivas, M., Jeison, D., 2025. Investigation of the key factors favouring the biocementing effect of microbially induced calcite precipitation when applied to mine tailings. Appl. Geochem. 179. https://doi.org/10.1016/j.apgeochem.2024.106258.