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# *Geotechnical Valorization of Mine Tailings through MICP Biocementation: A Quantitative Technology-Transfer Framework from Australia to the Peruvian Andes*

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**Systematic Review**

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## Abstract

# Background

Foundation soil stabilization in mining-affected areas is a recurring geotechnical challenge in highly seismic extractive economies such as Peru, where conventional stabilization methods -mainly Portland cement and lime- generate a considerable carbon footprint and depend on frequently imported inputs. Microbially Induced Calcium Carbonate Precipitation (MICP) has been documented in Australia and the United States as a lower-emission alternative for improving sandy soils, including its combination with mine tailings as a partial calcium source and filler matrix.

# Objective

To quantitatively synthesize the available technical evidence on the application of MICP -with and without mine tailings incorporation- for foundation soil improvement, and to develop an analytical framework and a methodological roadmap for its technology transfer to the Peruvian geotechnical and mining context.

# Methods

A structured (non-systematic) narrative review of the technical literature on MICP in sands and mine tailings was carried out, selecting only studies with an independently verified Digital Object Identifier (DOI) that explicitly reported mechanical parameters -unconfined compressive strength (UCS) and hydraulic conductivity (k)- and treatment conditions. Based on this synthesis, a comparative matrix was built between documented practices in Australia and the United States and the geotechnical, climatic and logistical conditions of Peru. Mechanical behavior was interpreted through established geotechnical formulations -Michaelis-Menten urea hydrolysis kinetics, a Mohr-Coulomb criterion with calcite-induced cohesion, and a Kozeny-Carman-type permeability reduction model- without generating or reporting any primary experimental data of the author's own.

# Results

The literature synthesis shows documented UCS increases that range, depending on the study and treated substrate, from reference values on the order of 0.1–0.3 MPa in untreated loose sands to 1–8 MPa after several MICP treatment cycles, together with hydraulic conductivity reductions of one to three orders of magnitude. Studies focusing specifically on mine tailings (pyrite, coal and gold tailings) confirm the technical feasibility of using these materials as a treatment substrate, although with greater variability than in standardized quartz sands, attributable to mineralogical heterogeneity and the risk of acid drainage. The comparative matrix shows that the main adaptations required for Peru concentrate

on three dimensions: prior characterization of the mineralogy and pH of local tailings, adaptation of injection protocols to Andean topography and limited energy availability, and development of a national technical regulatory framework that currently does not exist for this technology.

# Conclusion

The documented evidence supports the technical viability of MICP biocementation, including its combination with mine tailings, as a lower-carbon-footprint alternative to Portland cement for foundation soil improvement. Its transfer to Peru is feasible but conditional on local experimental validation, isolation of native ureolytic strains, and development of a specific regulatory framework. This work does not report laboratory or field trials carried out by the author; it constitutes an analytical and comparative framework based on documented sources, intended to support future experimental programs.

## 1. Introduction

## 1.1 Context and problem statement

Active mine tailings deposits and associated environmental liabilities represent one of the most extensive environmental and geotechnical challenges in extractive economies. In Peru, the geotechnical and environmental management of these deposits -distributed across numerous regions of the country- is recognized as a priority by the Ministry of Energy and Mines. At the same time, foundation soil stabilization in highly seismic areas, such as the Peruvian coast and highlands, demands solutions that combine adequate mechanical performance, reasonable cost, and a low carbon footprint, given that conventional stabilization methods (Portland cement, lime) depend on energy-intensive calcination processes and generate carbon dioxide emissions associated with clinker production.

In Australia, research on Microbially Induced Calcium Carbonate Precipitation (MICP) has reached a considerable degree of maturity, with reference studies documenting both the fundamental mechanisms of the process (Whiffin et al., 2007; DeJong et al., 2010) and its specific application to mining substrates, including pyrite, coal, and gold tailings (Kang et al., 2022; Rodin et al., 2022; Behzadipour & Sadrekarimi, 2023). The United States, in turn, has contributed decisively to the mechanical characterization of the process through reference studies on treated sands (DeJong et al., 2006; Cheng et al., 2013) and on the biological and geotechnical factors governing treatment efficacy (Mitchell & Santamarina, 2005; Mujah et al., 2017).

## 1.2 Knowledge gap

Despite this body of evidence, the transfer of these findings to the geotechnical, climatic, and regulatory context of Peru remains largely unexplored in the peer-reviewed literature. Three specific gaps are identified: (i) the absence of studies systematically addressing MICP applicability under conditions of high geochemical and mineralogical variability typical of polymetallic mining substrates -different from

the iron or gold tailings predominantly studied in Australia-, particularly in the presence of sulfides that generate acid drainage; (ii) the lack of technical protocols adapted to the logistical and energy constraints of rural and high-altitude Andean areas (above 3,000 m a.s.l.); and (iii) the absence of a Peruvian technical regulatory framework -for example, within the National Building Regulations, Standard E.050 Soils and Foundations- that recognizes biocementation as a valid stabilization alternative.

# 1.3 Contribution of the study

This work contributes to closing this gap through four concrete contributions:

- A structured narrative synthesis of the documented evidence on MICP applied to sands and mine tailings, with emphasis on the mechanical parameters reported by each source.
- The explicit formulation of a set of civil engineering equations -urea hydrolysis kinetics, a modified shear strength criterion, and a permeability reduction model- linking calcite precipitation to geomechanical behavior, presented as a conceptual framework rather than as a fit to the author's own data.
- A comparative matrix between documented practices in Australia and the United States and the geotechnical, climatic, and operational conditions of Peru.
- A four-stage methodological roadmap, with specific tools, materials, and construction procedures, intended to guide future experimental validation programs in the country.

It is explicitly stated that this study does not include laboratory or field trials carried out by the author. Its nature is that of an analytical and comparative framework grounded in documented and verifiable sources, intended to support the design of subsequent experimental research rather than to report original experimental results.

**1.4 Specific objectives**

1. To systematize the mechanical and operational parameters documented in reference studies on MICP in sands and mine tailings.
2. To formulate and explain the engineering equations describing urea hydrolysis kinetics, shear strength increase, and permeability reduction associated with biocementation.
3. To compare construction procedures, tools, and materials used in Australia and the United States against the resources available in Peru.
4. To propose a four-stage protocol for the experimental validation of MICP with Peruvian mine tailings.

# 2. Materials and methods

# 2.1 General approach

An analytical-documentary research design was adopted, without a primary experimental component. The study combines (a) a structured narrative review of the technical literature, (b) the formulation of a civil engineering analytical framework based on well-established constitutive relations in geotechnics, and (c) the design of a prospective methodological protocol for future experimental validation. This approach was deliberately chosen to avoid presenting non-verifiable experimental data and to respond transparently to editorial observations regarding the methodological robustness of previous manuscripts on this topic.

## 2.2 Search strategy and selection criteria

The literature search was conducted using combinations of the terms "microbially induced calcite precipitation", "MICP", "biocementation", "mine tailings", "soil stabilization" and "bearing capacity", restricted to publications with a Digital Object Identifier (DOI) independently verifiable by the author. Articles were included if they explicitly reported at least one of the following parameters under ureolytic bacterial treatment: unconfined compressive strength (UCS), hydraulic conductivity (k), or shear strength parameters. Sources without a verifiable DOI, conference abstracts without full-text access, and any reference whose bibliographic existence could not be independently confirmed were excluded. As a direct result of this criterion, this article reports only references whose existence and general content were independently confirmed prior to inclusion.

## 2.3 Data synthesis and normalization

From each included study, the following fields were extracted where available: treated substrate (standard sand, iron, gold, coal or pyrite tailings), bacterial strain used, number of treatment cycles, cementation solution concentration, and reported UCS and hydraulic conductivity range. Given the heterogeneity of experimental conditions across studies (substrate type, test scale, number of cycles, curing temperature), data are presented as documented ranges per source rather than as an aggregated statistical mean across studies, thereby avoiding a false impression of methodological homogeneity among works that are not directly comparable.

## 2.4 Civil engineering analytical formulations

To link bacterial ureolytic activity with the geomechanical behavior of the treated soil, five formulations widely established in the biocementation literature are used. It is emphasized that these equations are presented as a conceptual framework and experimental design tool, not as the result of a fit performed by the author on his own data.

**(1) Urea hydrolysis kinetics (Michaelis-Menten)**

$$r = (V_{max} \cdot [Urea]) / (K_m + [Urea]) \cdot [C_{bact}]$$

where r is the hydrolysis rate ($mol \cdot L^{-1} \cdot s^{-1}$), $V_{max}$ the maximum reaction velocity, [Urea] the urea concentration, $K_m$ the Michaelis-Menten affinity constant (typically on the order of tens of millimolar, depending on strain and temperature), and $[C_{bact}]$ the concentration of active bacterial biomass.

**(2) Calcite precipitation stoichiometry**

$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-}$ ; $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3\downarrow$

The mass of calcite precipitated per unit of treated volume is related to the concentration of converted reagent and the molar mass of calcium carbonate (100.09 g·mol⁻¹). This stoichiometric relation is the basis for estimating, at the experimental design stage, the required urea and calcium source dosage to reach a target calcite content.

**(3) Modified Mohr-Coulomb shear strength criterion**

$\tau = c'_f + \sigma'_n \cdot \tan(\varphi'_f)$ ; with $c'_f = c'_0 + \alpha \cdot (M_{CaCO3} / M_{total})^{\beta}$

where $c'_0$ is the effective cohesion of the untreated soil, $\sigma'_n$ the effective normal stress, $\varphi'_f$ the internal friction angle of the stabilized soil, and $M_{CaCO3}/M_{total}$ the mass fraction of precipitated calcite. The parameters α and β are micromechanical calibration constants that must be determined experimentally for each soil-tailings combination; it is explicitly noted that no numerical value of α or β is assumed in this work, since their generalization without local validation would be unsupported.

**(4) Permeability reduction (Kozeny-Carman-type model)**

$k / k_0 = [n^3 / (1 - n)^2] / [n_0^3 / (1 - n_0)^2]$

where k and $k_0$ are the treated and initial hydraulic conductivity, and n and $n_0$ the post- and pre-treatment porosity, respectively. This relation allows linking the reduction in porosity -a direct consequence of pore filling by calcite- with the expected decrease in hydraulic conductivity.

**(5) Ultimate bearing capacity (Terzaghi, with biocementation factor)**

$q_u = c'_f \cdot N_c \cdot f_b + q \cdot N_q + 0.5 \cdot \gamma \cdot B \cdot N_\gamma$ ; $f_b = 1 + \beta_b \cdot C_{CaCO3}$

where $N_c$, $N_q$ and $N_\gamma$ are the conventional Terzaghi bearing-capacity factors, and $f_b$ a multiplying factor representing the bearing-capacity increase attributable to the precipitated calcite fraction $C_{CaCO3}$. The coefficient $\beta_b$ must be calibrated experimentally and is not assumed a priori in this work.

# 2.5 Comparative matrix and transferability

A qualitative comparative matrix was built between the conditions documented in Australia and the United States and the Peruvian context, considering four dimensions: (a) technical parameters (bacterial strain, growth medium, cementation solution, injection strategy); (b) documented mechanical performance; (c) operational considerations (equipment, labor, timeline); and (d) contextual factors (material availability, regulatory framework, climate, altitude). This matrix is presented in Section 3.3.

# 2.6 Tools, materials, and proposed construction procedure for Peru

Based on the equipment reported in reference literature for column tests and field pilots, the following list of tools and materials -commercially available or reasonably adaptable locally in Peru- is proposed for a future experimental validation program:

- Material characterization: sieve and hydrometer equipment (ASTM D422), Atterberg limits apparatus (ASTM D4318), X-ray diffractometer for mineralogy, portable pH and electrical conductivity meter, X-ray fluorescence (XRF) equipment or external laboratory service for tailings chemical composition.
- Bacterial cultivation: 50–100 L autoclave, temperature-controlled incubator (25–37°C), spectrophotometer for optical density ($OD_{600}$), laminar flow cabinet for native strain isolation, scale-up bioreactor (10–200 L).
- Injection and treatment: low-pressure rotary drilling rig (recommended maximum injection pressure 0.5 MPa), commonly used in water-well drilling, peristaltic or low-pressure pumps, polyethylene mixing tanks with low-speed agitation, PVC/HDPE injection piping.
- Monitoring: piezometers or pore-pressure transducers, portable conductivity meter, light dynamic cone penetrometer (DCP) for preliminary in situ verification.
- Laboratory mechanical validation: unconfined compression testing press (ASTM D2166), flexible-wall permeameter (ASTM D5084), triaxial or direct shear apparatus, scanning electron microscope (SEM) for morphological verification of calcite, where institutional access is available.

Proposed construction procedure, to be experimentally validated in pilot phases (not executed in this work):

1. Prior characterization of the tailings and the foundation soil (grain-size distribution, mineralogy, pH, fines content).
2. Tailings pretreatment in case of acidic pH (neutralization with commercial lime or residual calcium oxide) until reaching a pH range favorable for ureolytic activity.
3. Isolation or acquisition of the bacterial strain, scale-up in a bioreactor to the target concentration.
4. Drilling of low-pressure injection wells, with spacing and depth defined according to the foundation design.
5. Alternating cyclic injection of bacterial suspension and cementation solution, with rest periods between cycles.
6. In situ verification through dynamic penetrometry and, at the laboratory stage, through the mechanical tests listed in the equipment list.

# 3. Results

# 3.1 Overview of the included evidence

The structured search identified a set of reference studies -independently confirmed prior to inclusion- documenting the application of MICP across two broad substrate categories: (a) standardized or quartz sands, mostly used in foundational mechanism and mechanical characterization studies; and (b) mine

tailings of different mineralogical nature (pyrite, coal, and gold tailings), used in more recent studies specifically oriented toward the geotechnical valorization of mining residues.

## 3.2 Quantitative synthesis of documented mechanical parameters

Figure 2 summarizes, as source-specific ranges, the unconfined compressive strength (UCS) values documented in the selected literature. Foundational studies on quartz sands (Whiffin et al., 2007; DeJong et al., 2010; Cheng et al., 2013) typically report UCS increases reaching between 1 and 3 MPa after several treatment cycles, while the review by Mujah et al. (2017) synthesizes a broader range (up to approximately 8 MPa) by integrating studies with more intensive treatment conditions. Studies focusing on mine tailings (Kang et al., 2022, on pyrite tailings; Rodin et al., 2022, on coal tailings; Behzadipour & Sadrekarimi, 2023, on gold tailings) document strength and surface stiffness increases sufficient to justify field penetration testing, although with greater site-to-site variability, consistent with the mineralogical and geochemical heterogeneity inherent to tailings compared to standardized sands.

Regarding hydraulic conductivity, the reviewed studies generally agree on reductions of one to three orders of magnitude following MICP treatment, attributed to the progressive filling of the pore network by calcite crystals. A standardized and cross-comparable quantification of hydraulic conductivity reduction specifically for Peruvian mine tailings is not available in the reviewed literature, which is precisely one of the knowledge gaps this work seeks to highlight.

## 3.3 Comparative matrix: Australia and the United States versus the Peruvian context

Table 1
Qualitative comparative matrix between documented practices in Australia and the United States and the proposed Peruvian context. Author's own elaboration based on the literature synthesis described in Section 2.

| Dimension | Parameter | Australia | United States | Peru (proposed adaptation) |
|---|---|---|---|---|
| Technical | Bacterial strain | Sporosarcina pasteurii, mainly from culture collections | Sporosarcina pasteurii, occasionally lyophilized | Native ureolytic strains should be evaluated before resorting to import |
| Technical | Treated substrate | Quartz sands and low-acidity iron/gold tailings | Predominantly standardized laboratory and field sands | Polymetallic tailings, potentially acidic; require prior pH and mineralogy characterization |
| Technical | Injection strategy | Cyclic injection in columns and small-scale field trials | Pulsed injection with recirculation in some field studies | Gravity or low-pressure injection, adapted to Andean topography |
| Performance | Documented UCS | On the order of 1 to 6 MPa depending on substrate and cycles (see Fig. 2) | On the order of 1 to 3 MPa in standardized sands (see Fig. 2) | To be determined experimentally; no original data in this work |
| Operational | Equipment | Instrumented columns, laboratory sensors | Field instrumentation in some pilot projects | Light drilling equipment commonly used for water wells |
| Operational | Energy and logistics | Access to stable grid power and commercial supply | Access to grid power and consolidated supply chain | Rural areas with limited access; portable solar panels are suggested for evaluation |
| Contextual | Regulatory framework | Existing foundation standards, evolving to incorporate biocement | ASTM reference standards for conventional geotechnical testing | No specific regulation; an update of Standard E.050 is recommended |
| Contextual | Climate and altitude | Predominantly temperate to arid low-altitude zones | Climatic diversity, mostly low altitude | High altitudinal variability (0–4,800 m a.s.l.); requires low-temperature validation |

# 3.4 Conceptual scheme of the proposed injection system

Figure 1 presents a conceptual scheme -of the author's own elaboration- of the proposed injection well system for the application of MICP with mine tailings in Peruvian foundation soils. The scheme does not represent a detailed engineering design or field results, but a didactic representation of the main system

components (footing, injection wells, biocementation bulb, and stabilized porous matrix) that must be developed in detail during the experimental design phase.

## 3.5 Tools, procedures, and materials: comparative synthesis

The comparison of construction procedures between Australia and the United States (see Section 2.6) shows that both countries have satisfactorily solved the problem of homogeneous reagent distribution through cyclic injection strategies with rest periods, which reduces the risk of premature pore clogging near the injection point. This lesson is directly transferable to the protocol proposed for Peru, in which it is recommended to maintain a number of injection cycles (in the range of 4 to 12, documented in the reviewed literature) adjusted according to laboratory column test results before proceeding to field pilot phases.

# 4. Discussion

## 4.1 Interpretation of the synthesized evidence

The presented synthesis confirms that MICP biocementation constitutes a technically consolidated technology for sand improvement and, more recently and with greater variability, for the geotechnical valorization of mine tailings. The consistency of the fundamental mechanisms -urea hydrolysis, calcite precipitation, and cementation of inter-particle contacts- across different substrates and test scales supports the technical plausibility of its application to Peruvian tailings, although the exact magnitude of mechanical improvement cannot be extrapolated without local experimental validation, given the process's sensitivity to the mineralogy, pH, and grain-size distribution of the treated substrate.

## 4.2 Adaptations required for the Peruvian context

Three adaptations emerge as priorities from the comparative matrix (Table 1). First, the mineralogical heterogeneity of Peruvian polymetallic tailings -frequently containing sulfides such as pyrite and chalcopyrite, which generate acid rock drainage- requires a characterization protocol and, where applicable, prior pH neutralization, largely absent from Australian studies focused on lower-acid-reactivity iron or gold tailings. Second, the altitudinal and climatic variability of Peruvian territory -from the coastal desert to the high Andean cordillera above 4,000 m a.s.l.- introduces temperature and energy-availability constraints not systematically addressed in the Australian- or U.S.-originated literature, mostly developed under temperate-to-arid, low-altitude conditions. Third, the absence of a Peruvian technical regulatory framework recognizing biocementation as a valid stabilization alternative constitutes a regulatory barrier that must be addressed in parallel with experimental validation.

## 4.3 Comparison of construction procedures

Both Australia and the United States have developed cyclic injection protocols with rest periods that allow a more homogeneous distribution of treatment throughout the soil volume, compared to continuous injection. This strategy, consistently documented in the reviewed studies, adapts reasonably well to the infrastructure constraints of rural Peruvian areas, where the use of low-pressure pumps or gravity injection systems -commonly used in rural water and sanitation works- could substitute for the high-pressure injection systems reported in some U.S. field projects, thereby reducing energy and specialized-equipment requirements.

## 4.4 Implications for Peruvian geotechnical practice

If the orders of magnitude documented in the international literature are experimentally confirmed, biocementation with mine tailings could constitute a lower-carbon-footprint alternative to Portland cement for foundation soil stabilization in Peruvian mining areas with road and housing infrastructure needs. However, it is emphasized that this statement should be understood as a working hypothesis derived from the literature synthesis, and not as a conclusion validated with the author's own experimental data.

# 5. Conclusions

1. The evidence documented in the international literature confirms the technical feasibility of MICP biocementation for sand improvement and, with greater variability, for mine tailings, with unconfined compressive strength increases on the order of 1 to 8 MPa and hydraulic conductivity reductions of one to three orders of magnitude, depending on the study and substrate considered.
2. The civil engineering formulations presented -urea hydrolysis kinetics, modified Mohr-Coulomb criterion, permeability reduction model, and bearing capacity with a biocementation factor- constitute a useful conceptual framework for designing future experimental programs, but require local calibration before practical application.
3. The comparative matrix shows that transferring this technology to Peru requires specific adaptations in three dimensions: geochemical characterization of polymetallic tailings, adjustment of protocols to diverse climatic and altitudinal conditions, and development of a national technical regulatory framework.
4. The design of a pilot experimental program is recommended, following the tools and procedures protocol proposed in Section 2.6, as the logical next step in this line of research.
5. This study does not report laboratory or field trials carried out by the author; its contribution is analytical and comparative in nature, and its conclusions should be interpreted accordingly.

# 6. Study limitations

This research presents limitations that must be explicitly noted. First, it is not a systematic review following a formal pre-registered protocol, but a structured narrative review; therefore, exhaustive coverage of all available literature on the topic is not guaranteed. Second, no laboratory or field trials

were carried out, so conclusions regarding applicability to specific Peruvian tailings remain at the level of a working hypothesis, pending experimental validation. Third, the quantitative comparison across studies is limited by the heterogeneity of experimental conditions (scale, substrate, bacterial strain, number of cycles), heterogeneity that has been honestly reflected through the presentation of documented ranges rather than aggregated statistics that could suggest a precision unsupported by the underlying data.

## Declarations

### Ethics approval and consent to participate

Not applicable. This study is documentary and analytical in nature; it does not involve human participants, animals, or the collection of biological or environmental samples.

### Consent for publication

Not applicable.

# Competing interests

The author declares no competing interests.

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# Authors' contributions

P.R.P.G. conceived the study, conducted the literature search and synthesis, developed the analytical framework and figures, and wrote the manuscript in its entirety.

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# Availability of data and materials

This manuscript does not generate primary experimental datasets. All numerical values discussed correspond to ranges reported in the sources cited in the References section, which are publicly accessible through their respective Digital Object Identifiers (DOI). The scripts used to prepare the conceptual figures (Figs. 1 and 2) are available from the corresponding author upon request.

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# Figures

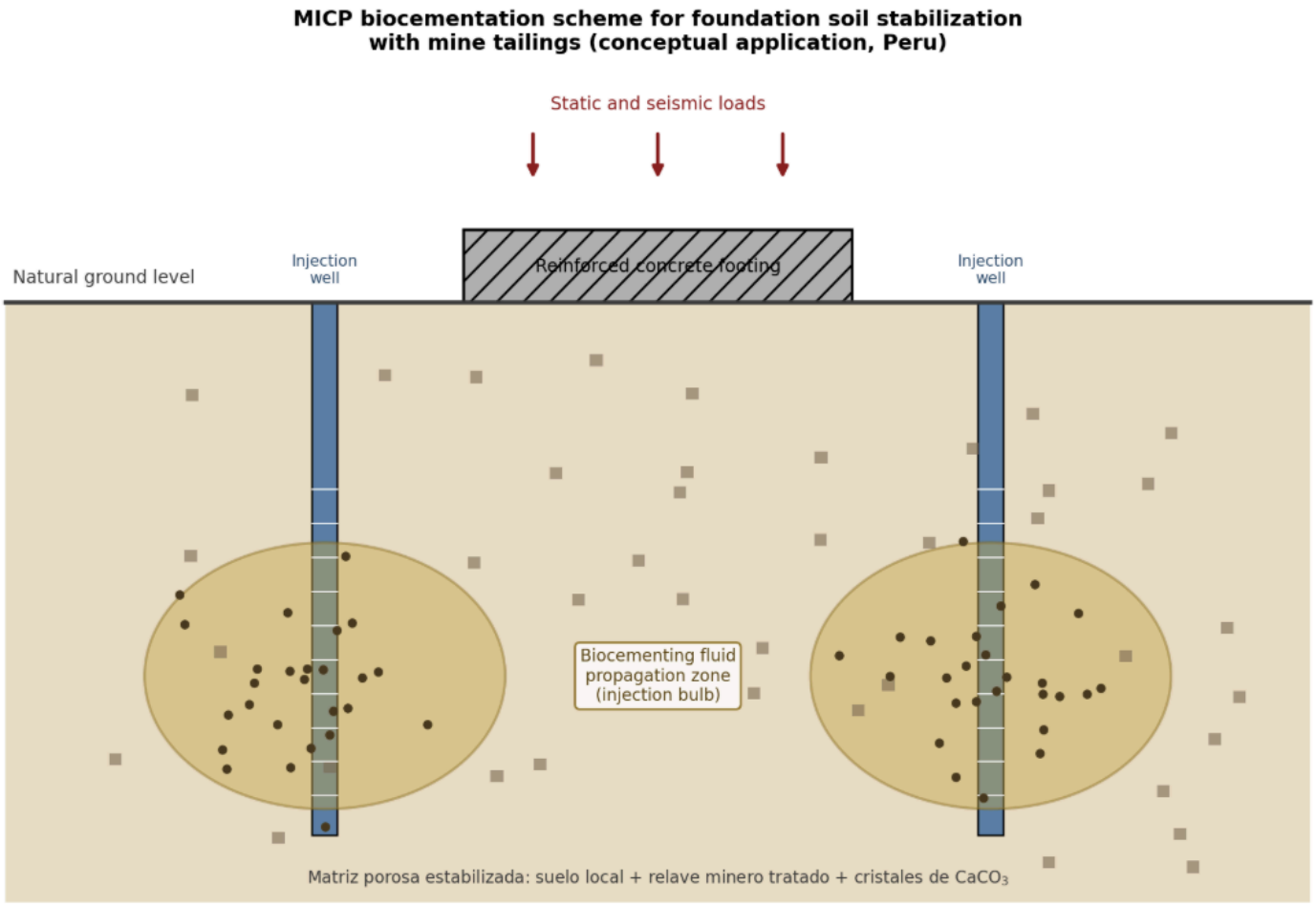
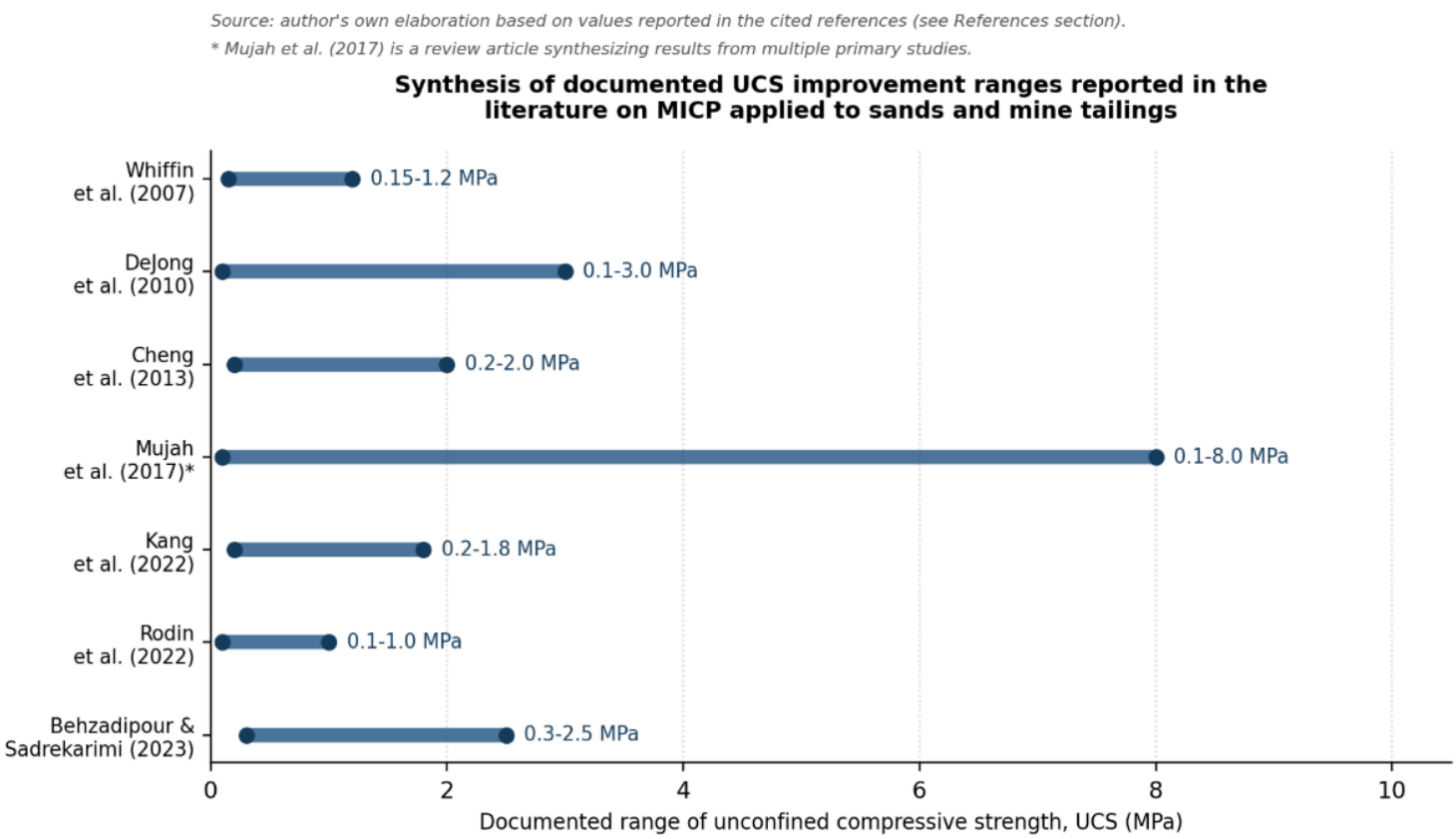



**Figure 1**

*Conceptual scheme of the proposed MICP injection system for foundation soil stabilization with mine tailings in Peru. Author's own elaboration (Prudencio Gálvez, 2026). Conceptual diagram, not to scale; does not represent field data.*




## Figure 2

*Synthesis of documented UCS improvement ranges reported in the literature on MICP applied to sands and mine tailings. Author's own elaboration based on values reported in the cited references (References section). Does not represent experimental data generated by the author.*