Engineering Mine Tailings for Environmental Recovery

A Critical Review of Climate Resilient Techno sols, Carbon Sequestration, and Sustainable Mine

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Abstract

Traditional approach to the management of mine tailings is as a long-term geotechnical/environmental liability. This is a review of another, but conditional proposition: that a select tailing can be engineered into a functional soil system, a mineral-carbon storage medium, and a climate resilient closure landform. The proposition is appealing because it integrates the areas of mining engineering – tailings deposition, tailing drainage, tailing stability, materials handling and tailing closure design – with environmental engineering – pollutant control, water quality, ecological recovery, carbon accounting, and life-cycle performance.

It's also a matter of being carried away. Evidence is variable and it is difficult to sustain in the short-term. All four of these distinctions are therefore made before a field observation can be differentiated from a laboratory demonstration, carbon capacity from carbon uptake, surface revegetation from whole facility closure performance, and so on.

Based on the synthesis, three coupled design domains are identified. In the first place, tailing-based Techno sols should be operational as designed root-zone/support-horizon systems. Their performance is affected by physical structure, water balance, salinity and acid generating potential, mobility of contaminants, plant establishment and longevity of amendments.

Second, global capacity estimates are not to be confused with deployable net carbon removal, and mineral carbonation is credible and durable in Mg or Ca rich tailings, especially ultramafic systems. Third, for any facility to be safe to close and for a carbon permanence claim to be made, the facility must be climate resilient, as future drought, high intensity rainfall, erosion, deep percolation changes, and altered biogeochemistry could alter facility safety and environmental exposure pathways. A critical review of the evidence suggests that there are some good early site-specific outcomes: a 20 year bauxite-residue field study suggests early stage soils, an alkaline iron-ore tailings glasshouse study shows pH changes, organic carbon and aggregate formation in the short term, passive carbonation at Mount Keith and Thetford Mines demonstrates early stage soil mineralization, and climate-aware studies indicate material changes in closure water-balance demand.

None sets a template or a generic carbon credit. The review suggests an integrated decision-making framework, a minimum monitoring and measurement reporting and verification (MRV) dataset, and a priority research program focused on multi-hectare, multi-decade, climate-stressed demonstrations. The main finding is that the defensibility of tailings recovery is only possible if the ecological, geochemical and carbon functions and tailing-facility safety functions are designed, tested and governed as a single closure system.

Keywords

Mine tailings; Techno sols; mine closure; mineral carbonation; carbon sequestration; climate resilience; tailings storage facility; Phyto stabilization; water balance; environmental engineering.

2. Introduction

Mining's strategic significance is growing with the global need for metals to build infrastructure, electrify networks and enable energy transition, and with a focus on the waste created by mining. The small pieces of rock or mineral that remain after they have been processed are called tailings. They can be held in impoundments, valleys, thickened deposits, filtered piles or historic piles.

They are regulated by the mineralogy, grain size, water content, deposition history, geochemistry, climate, and the containment configuration and downstream receptors. The term "tailings" by itself is

not useful from an engineering point of view. Closure strategies are often quite different for a carbonate rich iron-ore residue, ultramafic nickel tailings, bauxite residue, sulfidic polymetallic tailings and saline desert tailings.

In practice, the closure of mines often has considered rehabilitation of land, tailings safety, seepage management and post-mining land use as separate workstreams. This separation is getting harder to justify. Soil cover which provides vegetation but enhances deep percolation may change seepage and contaminant movement.

A chemically effective cover which splits or breaks apart during a major storm event may become a geotechnical and water quality issue. Mineral-carbonation intervention that results in an increased formation of carbonate can alter the pore structure, the drainage and strength. In contrast, a low seepage, stable tailings landform may be environmentally compromised when salts accumulate in the root zone of the tailings or when dust is emitted from the tailings, which may impede ecological recovery or move metals to plants and food chains.

The closure endpoint, therefore, must be a coupled physical–chemical–biological system instead of independent controls. There are two major pathways for a waste management challenge to provide environmental restoration: tailings-derived Techno sols and mineral carbonation. Techno sols are soils that have been significantly impacted by anthropogenic material or material that has been introduced to the soil surface.

The World Reference Base identifies a Techno sol diagnostic route consisting of artefacts that satisfy specific abundance and depth thresholds, such as a weighted average threshold of at least 20% artefacts by volume in the top 100 cm beneath the relevant route. Classification is not proof of fertility, contaminant safety, carbon permanence or closure success. Nevertheless, it should be remembered that engineered mineral materials can be made to have soil functions if their constraints are managed intentionally. The environment is a big challenge.

The most common reviews of Phyto stabilization of mine tailings, such as the one I cited, found that studies have reported concentrations ranging from 1 to 50 g kg−1 with the highest concentration of 22 dS m^{-1} in arid environments. Tailings also can have very low water-holding capacity, be sodiated, have poor aggregation, generate acid and contain high levels of As, Cd, Cu, Pb, Zn or other contaminants. These properties limit plant establishment and can establish long duration exposure pathways via dust, drainage, groundwater, surface runoff, vegetation and wildlife. [2] At the same time, tailings frequently have properties that can be used rather than merely suppressed.

They possess a high mineral content, can have reactive Fe, Ca or Mg phases, are frequently already finely ground and can be layered during operation. A suitable system may be able to give a structured root zone that turns a sterile surface into an organic and mineral soil through selected vegetation and microbial processes. Selected Mg-rich tailings have the potential to sequester atmospheric carbon into stable solids by dissolution and precipitation of carbonate minerals.

These opportunities should be considered as provisional designs. They are believable if they enhance—rather than diminish the credibility of the tailings storage facility (TSF) safety case, water balance, controls on contaminants and long-term closure obligations. Four practical questions are addressed in this review.

How to screen and engineer mine tailings for use in climate-resilient Techno sols. Second, what are the evidences that support mineral carbonation as an environmental and closure co-benefit and what are the evidences that are limited to laboratory only and/or modelled. Finally, what are the interactions among future climate hazards, tailing landforms, cover systems, water management and carbon permanence?

In the end, what is the proper metric, governance and research architecture to bring the idea of defensible mine-closure practice to life? The emphasis is intentionally interdisciplinary, with mining engineering supplying the materials, placement, and stability considerations; environmental engineering establishing the boundaries of water, contaminants, ecosystems, and carbon that permit recovery.

2.1 Evidence interpretation and analytical boundaries

There are a number of terms used in the literature in various ways, including rehabilitation, reclamation, Phyto stabilization, ecological engineering, constructed soil, soil cover, mine-waste valorization and carbon mineralization. There are no semantic differences. A vegetated cover may lower the amount of dust, but will not build a self-sustaining soil.

A lab column may demonstrate fast sorption of metals but it may not represent the performance in the root zone. A field carbonate sample is proof of mineralization, but not of annual mineralization or additionality. A climate model is able to describe the future hydraulic load but does not necessarily show the survival of a specific landform.

This review maintains those distinctions without collapsing all of the evidence into one single performance score. A set of three boundaries frame the analysis. The material boundary distinguishes tailings, mine spoil, waste rock, imported soil, organic amendments and engineered reactive media.

The system boundary is used to define a root zone, the tailings support horizon, a local treatment cell, a cover system and the complete TSF. The time boundary is between short experiments and multi-year field trials and post closure design life. Often the most useful inference is not whether a technology "works" or "fails" but whether a particular process has been proven under the following material, scale, duration and climate conditions.

Field and long-term field observations are necessary, but are relatively limited and very site-specific. Laboratory and glasshouse studies provide mechanism and formulation evidence, but cannot simulate inter-weather variability, tailings-landform heterogeneity, hydraulic gradients, construction traffic, wildlife interaction or rare extreme events.

Standards and guidance do not give a material specific performance coefficient. The figures and tables in this review are therefore given in their original units and evidence classes are not pooled together into a false meta-analysis.

2.2 Why integrated design is necessary

The key design conflict can be seen at the boundaries of the built root zone and the tailings under it. Root-zone amendments can enhance plant establishment and nutrient availability and improve structure. They can also change the infiltration, hydraulic conductivity, redox conditions, mobility of dissolved organic carbon and metals.

A dense or low-permeability cover can help minimize oxygen and water entering potentially acid-generating tailings, but may not allow roots to penetrate or result in perched water or lateral seepage into the tailings. A gas accessible tailing layer can improve the chances for mineral carbonation while at the same time providing for dust emissions or lowering the capillary storage. There is no universal physical/chemical target per se that is considered "green" as its value is dependent on the conceptual model of closure.

Huang, Baumgartl and Mulligan presented this problem as the necessity to consider the rhizosphere horizon and the support horizon of the tailings as a two-component system. Salts, acidity or contaminants may travel upward from below while vegetation is strong in a shallow amended layer. Also, a dry surface layer may show no signs of change, but seasonal movement of pore water can convey metals away from the root zone.

The correct design answer is to specify the function for each horizon and the interface between them: water storage, drainage, root penetration, capillary break, oxygen ingress, contaminant sorption, erosion resistance or access for monitoring or maintenance [3]. The rest of the review is structured around this holistic interpretation. The evidence from Techno sol and mineral-carbonation is discussed in Sections 2 and 3. The concept of climate-resilient closure is covered in section 4.

In section 5 and 6 a design, monitoring and research agenda are synthesized. Its purpose is not to mandate a single standard tailings-recovery technology. It is to show the evidence conditions under which a mine can make a defensible decision to pursue, modify or reject an environmental-recovery pathway.

3. Tailings derived techno sols: engineering a functional root zone

3.1 Material constraints and design objectives

A tailings-derived Techno sol can be best viewed as a dynamic soil–plant ecosystem designed by humans. It could be a modified tailing matrix, a multi-layered root zone over tailings, a blend of mine waste and imported material, or an alternative application, a reactive medium to treat tailing water. These configurations shouldn't be used interchangeably.

A fixed-bed experiment with a reactive techno sol that adsorbs metals from a solution does not demonstrate a self sustaining rehabilitated landform, it only indicates adsorption under a given contact time. A profile of a limestone-spoil pasture may show pedogenesis and carbon accumulation but this does not necessarily mean it will be the case with acidic, saline or metal-rich tailings. The first design step is characterization.

These include total and leachable metal(loid)s, acid–base accounting, mineralogy, particle-size distribution, soluble salts, exchangeable sodium, pH, redox potential, saturation behavior, water-retention curve, saturated and unsaturated hydraulic conductivity, bulk density, shear and penetration resistance, dust propensity, radionuclides (where appropriate) and likely effects of weathering. Characterization should address the spatial aspects. The characteristics of tailings can differ from ore zone to ore zone, processing campaign to processing campaign, method of deposition, beach to pond position, and age.

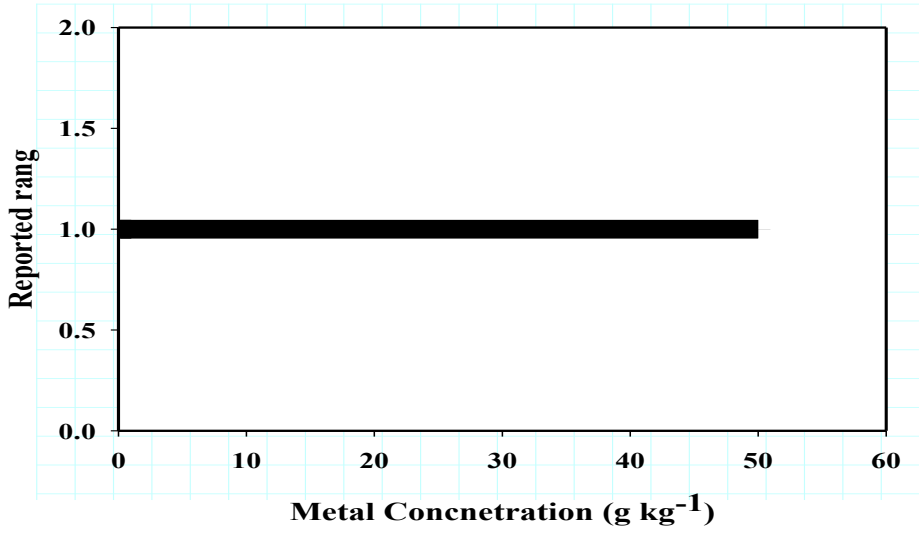
A closure basis is often limited to just one composite sample. The second step is to convert these data into closure functions. A choice of an organic amendment can be made to promote aggregate stability, microbial substrate, moisture holding and nutrient release.

An amendment of carbonate or alkaline can be chosen to neutralize acidity or alter sodicity. An iron-rich phase can be chosen to enhance the ability to sorb oxyanions or metals. A coarse layer can be chosen for drainage or as a capillary break.

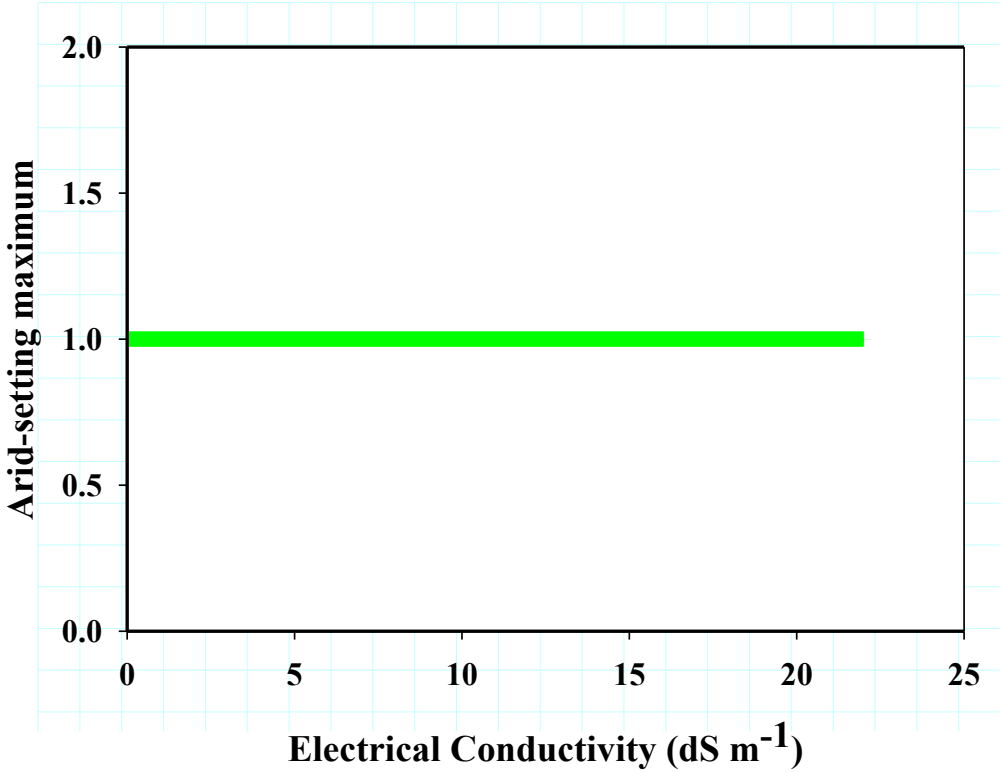
Plant mix can be chosen for root reinforcement, surface cover, drought resistance or low shoot uptake. All selections must contain a failure hypothesis, which is a potential source of failure that could be associated with the selected technology, such as mineralization of organic matter, nutrient leaching, amendment heterogeneity, salt redistribution, iron reduction, pore clogging, root-zone drought, erosion, fire, and invasive plants or seepage quality changes. Figure 1 shows the spectrum of environmental constraints that stimulates engineering and not just simple revegetation.

The concentration and salinity values reported are not design targets. They show why a "topsoil and seed" solution is not sufficient for extreme chemistry of the tailings. The right targets need to come from a source–pathway–receptor model, anticipated post mining land use, criteria and regulatory requirements, and the TSF closure plan.

This review uses the following key terms and decision boundaries, which are defined in Table 1. It is based on the WRB soil classification, the tailing's root zone review and guidance from GISTM and ICMM [1, 3, 9, 10]. The definitions at the beginning help maintain consistency in the review, and provide clarity on the boundaries between tailings recovery and formal soil formation or regulated closure.



(a)



(b)

Figure 1. Reported tailings constraints motivating engineered Techno sols: (a) metal concentrations of 1–50 g kg^{-1} in reviewed tailings studies and (b) electrical conductivity up to 22 dS m^{-1} in arid settings. Values are literature context, not universal thresholds. Data source: Mendez and Maier [2].

Table 1. Definitions and decision boundaries used in the review. Sources: WRB classification, tailings-root-zone review, GISTM and ICMM guidance [1, 3, 9, 10].

Term	Working meaning	What it must demonstrate	What it does not establish by itself
Tailings-derived Technosol	Engineered soil system containing tailings or related mine material as a parent or support material.	Root-zone function, compatible hydrology, chemical safety, vegetation performance and constructability.	Automatic classification, natural-soil equivalence, carbon credit or TSF safety.
Root-zone horizon	Surface or near-surface layer designed for roots, water storage, nutrients and biological activity.	Water availability, low exposure risk, stable structure and acceptable plant uptake.	Isolation from tailings chemistry without measuring the support horizon.
Support horizon	Underlying tailings or engineered layer that controls drainage, capillarity, gases and pore-water chemistry.	Compatibility with seepage, stability, oxygen and solute controls.	A passive substrate merely because it is below vegetation.
Mineral carbonation	Precipitation of carbonate minerals from CO_2 and reactive Ca/Mg-bearing phases.	New carbonate formation, source attribution, net emissions balance and environmental compatibility.	A generic negative-emissions claim from total inorganic carbon alone.
Climate-resilient closure	Closure design tested against non-stationary climate hazards and adapted over time.	Hydraulic, geotechnical, geochemical and ecological performance under stated scenarios.	A one-time climate-screening exercise without monitoring or governance.
Passive closure	Post-closure condition intended to require no ongoing active intervention for safety and environmental protection.	Credible landform, water-management and governance case meeting applicable criteria.	Absence of monitoring, assurance or residual-risk responsibility.

3.2 Physical and hydraulic design

Physical function is frequently the constraint to rehabilitating tailings. A fine particle size and low organic matter may result in dense, poorly-structured surfaces that offer little infiltration, have limited aeration, and have poor seedling emergence. For other tailing, however, high hydraulic conductivity or cracking may lead to fast preferential flow and the avoidance of the intended sorption or buffering areas.

The size of a root zone needs to be big enough to allow plants to survive dry spells but not allow salt or metals to migrate down to ground water. It should be sheet, rill and wind erosion resistant, allow for settlement, wet-dry cycles, animal disturbance and construction traffic. The water-retention curve is thus more useful than a moisture value.

It relates the matric potential to water content so that the designer can make an estimate of water available to the plant, as well as drainage and the length of the saturation period. The hydraulic conductivity function should be evaluated over the range of saturation conditions of interest, since the hydraulic conductivity of a material can vary dramatically during a drought if it has low hydraulic conductivity during saturation. The water balance over time is often more important question than a single lab measurement of permeability in tailing covers.

A useful root-zone water balance can be expressed as:

$$q_D = P - \mathrm{ET} - \Delta S - q_R \quad (1)$$

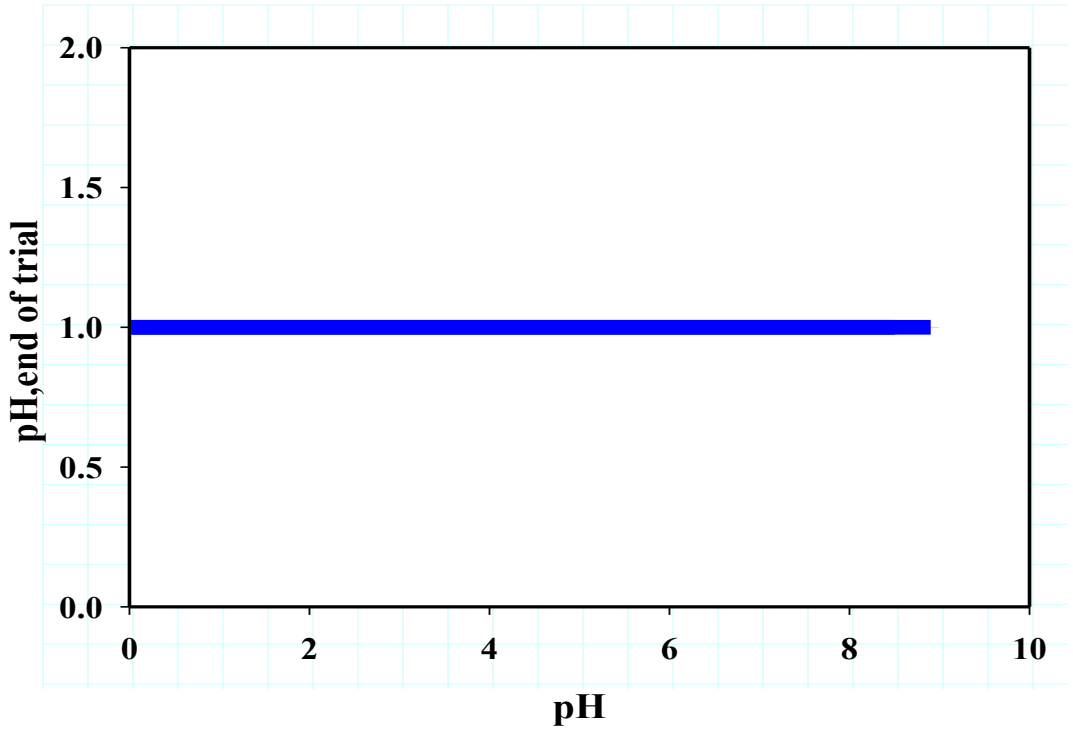
where q_D is deep drainage, P is precipitation and applied water, ET is evapotranspiration, ΔS is the change in root-zone water storage, and q_R is runoff. This identity does not replace a site water-balance model. It makes clear that a successful surface cover can still increase deep drainage if precipitation rises, evapotranspiration is limited by drought-stressed vegetation, storage is exceeded or runoff is intentionally reduced.

Therefore, the components should be measured and modelled under the observed climate conditions as well as future climate conditions. These flows can be contained by engineered layers. Fine textured amendments can enhance the plant available water, but can also have an increase in shrink – swell behaviour or decreased gas diffusion.

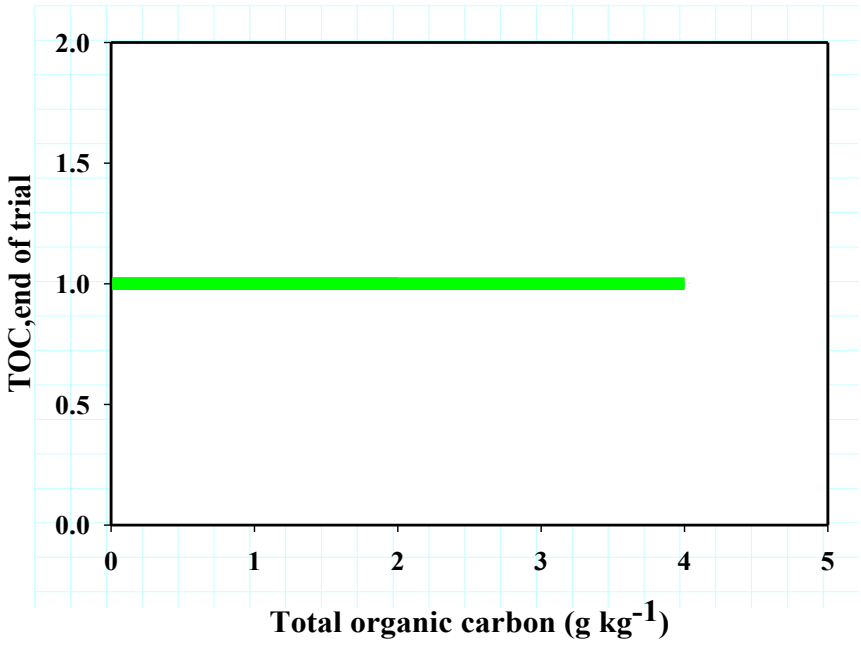
If not well graded or not laterally controlled, the coarser layers can conduct water, but can prevent capillary rise. Organic amendments have the potential to decrease bulk density and increase aggregation and can mineralize, shrink and release dissolved organic carbon after some time. Geosynthetics are able to control water and gases and add interface stability, puncture, ageing and repair problems.

Often the best profile is not the most impermeable or permeable. It is the profile that best satisfies the site-specific water, chemistry, stability and ecological objectives with an acceptable level of uncertainty. The example of iron ore tailings in Figure 2 is helpful because of the potential opportunities as well as the challenges.

In a short-term glasshouse experiment, the alkaline magnetite tailings were modified by 2% lucerne hay, native microbes, and pioneer plants, the pH was lowered from above 9.5 to 8.5–8.9, and the total organic carbon (TOC) increased from < 0.5 to 2–4 g kg−1. The study gives evidence to the aggregation and weathering mechanisms caused by micro organisms and plants. Does not define the establishment of hectare scale mixing, persistence of amendments in the long-term, drought response, contaminant flux and post-closure water balance [6].



(a)



(b)

Figure 2. Short-term ecological-engineering response in alkaline magnetite Fe-ore tailings amended with 2% lucerne hay and native microbes. pH is shown as a lower-bound initial value and a reported end-range midpoint; TOC is shown as reported ranges. Glasshouse evidence only. Data source: Wu et al. [6].

3.3 Geochemical safety and contaminant pathways

The total metal concentration is not a sufficient criterion for assessing a tailings derived technosol. Total concentrations are required for inventory and regulatory screening, but exposure is dependent on (among others) mineral association, pH, redox potential, ionic strength, DOC, sulfate, competing ions, particle entrainment, uptake by biota and hydrological transport. A batch formulation which decreases soluble metal concentrations may later liberate metals due to changes in pH, sorption sites, the reduction of Fe phases, or decomposition of organic matter.

Acid–base accounting is not enough for potentially acid-generating tailings; in these cases, there is a need for kinetic testing and field monitoring studies to consider both reaction rates and flow pathways. Pathways to pore-water leaching, runoff, dust, upward capillary movement, direct contact, plant uptake, and transfer in the food-web should be identified in the source–pathway–receptor model. This model can then be used to establish measurable performance criteria.

For instance, a phytostabilization project may be expected to result in a reduction in dust flux, in no trend toward rising concentrations of metals in the pore water below the root zone, in maintenance of plant cover without regular irrigation, in plant concentrations below a screening limit for the receptor, and in no statistically significant rise in metal concentrations in downgradient groundwater. The successful growth chamber biomass result is not enough to satisfy this set of criteria. The quality-assurance challenge comes with amendments.

Potential sources of valuable carbon, nutrients or mineral surfaces include compost, biosolids, biochar, industrial by-products, waste rock fines, and dredged materials. They may also add salts, pathogens, microplastics, PFAS, trace metals, contaminants of emerging concern (CEC) and variable particle-size distributions. They may have significant emissions and transport connected with their supply chain.

The value of separating functions is shown by Reactive Technosols, which can be used to accept materials with the stipulation that they are intended for certain uses, rates and contact pathways with the soil and that they will undergo certain ageing processes. [8] A medium of 97% iron-rich native soil and 3% Fe/FeS nanoparticles for an Ecuadorian bench study removed an average of 70% of the metals in a fixed-bed test at 30 minutes, and 80% in batch removal tests at six minutes. These numbers apply to tailings polishing and/or tailing treatment.

Don't have a vegetated cover or ecological closure system. The appropriate engineering implication is that reactive media can be given a specific water-treatment role in an integrated closure design, with the caveat that any manufacturing, handling, ageing, and residual disposal of nanoparticles is considered [7].

3.4 Biological function and ecological recovery

Biological recovery is more than a rapid increase in green cover. The local climate tolerance, root structure, ecological role, low transfer of contaminants and the post-mining land use should also be considered when selecting a plant community that is closure-relevant. Native species with drought adaptation traits might be better suited to survive under water limiting conditions than high biomass species picked from a greenhouse screen in arid and semiarid environments.

Field evidence for copper-tailings-derived Technosols in Chile correlates vegetation cover with available water, fine particles and organic matter, and indicates that low water availability, high relative density, nutrient limitation and high Zn limited vegetation cover. Plant–microbe interactions can facilitate aggregation, nutrient cycling and weathering, but can also cause uncertainty. Microbial community can produce organic matter, alter redox, and can increase infiltration or create barriers; rhizosphere acid can alter the availability of metals, depending on the mineral system; and roots can alter infiltration or create barriers. A resilient ecological design requires functional diversity, rather than just the number of species.

Should contain early establishment, reproduction, drought and high rainfall persistence, root depth, litter inputs, soil biological indicators, invasive-species control and exposure monitoring. The 20 year field experience with bauxite-residue is of interest. Incipient soil horizons were formed with amendment treatments and sewage sludge was more effective than yard waste or topsoil on selected chemical properties.

However, the system created in the study was described as being in the early stages of soil development, rather than as a natural soil equivalent. The result points emphasize the importance of monitoring field trajectories on time scales relevant to closure and also demonstrates the potential for long-term transformation. The same consideration is warranted for the Brazilian limestone-spoil Technosol for which 20-year profiles of pastures revealed high levels of organic carbon. That material is a low-hazard carbonate-bearing 'spoil analogue' and the carbon concentration can't be reproduced in sulfidic tailings and concentration is not a carbon stock; it is not bulk density and it is not a coarse-fragment fraction and it is not a depth and it is not an area [5].

3.5 Engineering performance metrics and carbon accounting

A useful Technosol performance specification is a combination of physical, chemical, biological and carbon metrics. Physical properties are bulk density, penetration resistance, aggregate stability, water retention curve, hydraulic conductivity, runoff, erosion and settlement. Chemical parameters are: pH, electrical conductivity, alkalinity, sulfate, dissolved and bioavailable metals, major ions, redox state, pore-water flux and acid-generation rate.

Biological indicators are vegetation cover, species composition, recruitment, root depth, microbial activity and shoot concentrations. Organic and inorganic carbon stocks, fluxes of greenhouse gasses, amendment-origin carbon, loss of carbon due to erosion, and energy and emissions from amendment

supply, transport, placement and maintenance are all carbon indicators. An area-based soil-carbon stock can be expressed as a function of a fixed depth or equivalent soil mass:

$$C_{stock} = C_c \times \rho_b \times (1 - f_{cf}) \times z \quad (2)$$

where C_c is carbon concentration, ρ_b is bulk density, f_{cf} is the coarse-fragment or artefact fraction by volume, and z is sampling depth.

The equation above is a reminder that a percentage organic-carbon result alone is not a sequestration claim. Other requirements include a defensible baseline, spatial replication, sampling design, carbon-source attribution, erosion accounting and net greenhouse-gas balance. If carbonate minerals are present, total carbon needs to be broken down into organic and inorganic carbon and newly formed carbonate needs to be separated from inherited carbonate.

Table 2 gives a screening matrix for judging whether tailings can be used to make techno sols, drawing on [2, 3, 4, 6, 8, 9]. It is meant as a decision aid at the early stage, so it does not replace site-specific characterization or the acceptance criteria set by regulators.

Table 2. Tailings-derived Technosol material-screening matrix. The matrix is a decision aid, not a substitute for site-specific characterization or regulatory acceptance criteria. Sources: [2, 3, 4, 6, 8, 9].

Screening domain	Key measurements	Design implication	Example trigger for redesign or exclusion
Mineralogy and reactivity	XRD/QXRD, MLA, neutralization potential, acid-generating potential, secondary carbonate baseline.	Defines acid control, carbonation potential, amendment choice and metal speciation.	Reactive sulfides, inaccessible reactive phases or inherited carbonates not resolved.
Salinity and sodicity	EC, soluble ions, sodium adsorption ratio, exchangeable sodium percentage, capillary-rise potential.	Controls plant selection, leaching strategy, texture and drainage design.	Salt redistribution or EC trend incompatible with root-zone/receptor criteria.
Particle size and physical state	PSD, bulk density, water-retention curve, hydraulic conductivity, dustiness, shrinkage/cracking.	Defines mixing, lift thickness, root penetration, storage and erosion controls.	Unacceptable dust, low trafficability, cracking or preferential flow.
Contaminants and exposure	Total/leachable metals, pH-dependent leaching, pore-water chemistry, ecotoxicity, plant uptake.	Links chemistry to source-pathway-receptor controls.	Uncontrolled leachate, dust or biomass-transfer pathway.
Amendment quality	Nutrients, salts, trace contaminants, stability, provenance, pathogen/organic-contaminant screening.	Supports circular sourcing with explicit quality assurance.	Amendment adds risk or lacks supply-chain/LCA justification.
Climate and water balance	Observed baseline, downscaled scenarios, P-ET-storage model, erosion and drainage calculations.	Tests drought, rainfall intensity, water demand and deep percolation.	Performance depends on a stationary-climate assumption.
Constructability and governance	Material volumes, blending tolerance, placement QA/QC, access, monitoring locations, financial provision.	Translates pot-scale formulation into operable closure design.	No workable scale-up, quality-control or post-closure ownership plan.

4. Mineral carbonation: opportunity, limits and environmental safeguards

4.1 Carbonation mechanisms and suitable feedstocks

Mineral carbonation is a method of CO_2 sequestration in solid carbonate minerals. Tailing's process is dependent on dissolution of Ca/Mg-containing phases, dissolution and transport of CO_2 and carbonate species, and precipitation of carbonate minerals. The most promising feedstocks consist of easily accessible brucite, olivine, serpentine and other reactive Ca–Mg silicates.

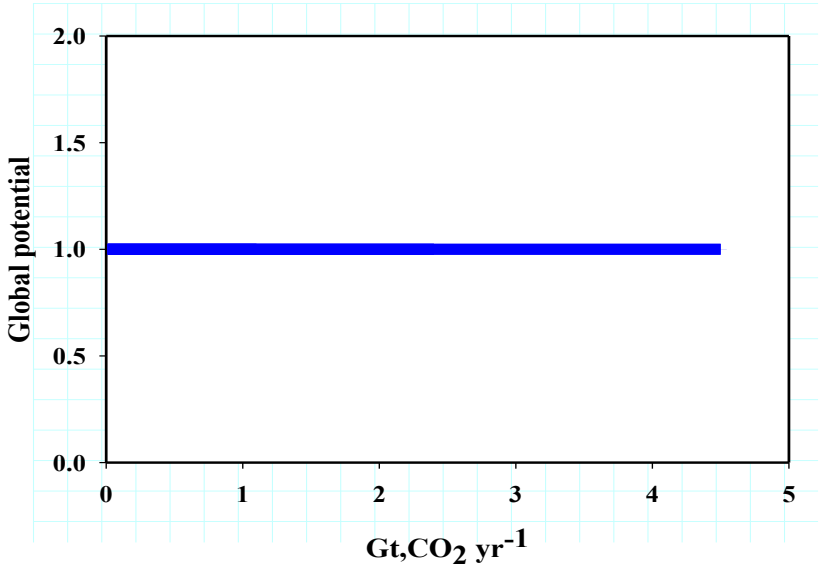
The comminution of the ores can be beneficially used to provide fresh surface area and particle sizes that are often in the 50–500 μm range. But even small particle size does not mean that there are no kinetic controls, reaction may be rate-limited by dissolution, diffusion of CO_2, water availability, passivating silica or Fe-rich coatings, carbonate crust formation and heterogeneous mineral distribution. It is helpful to differentiate passive, enhanced and active routes. The passive carbonation is based upon the CO2 in the atmosphere and the exposure of naturally available water and mine-waste.

In terms of enhancing in-place carbonation, the following methods may be used to increase access: lift geometry, wet dry cycling, controlled deposition, water recirculation, and biologically mediated changes and/or low-intensity gas supply. These active processes may be ex-situ reactors, direct gas injection, acid leaching, pH-swing extraction, selective processing and carbonate-product routes. The former can obtain a reaction rate that is more rapid but demands energy, reagents, handling systems and waste disposal.

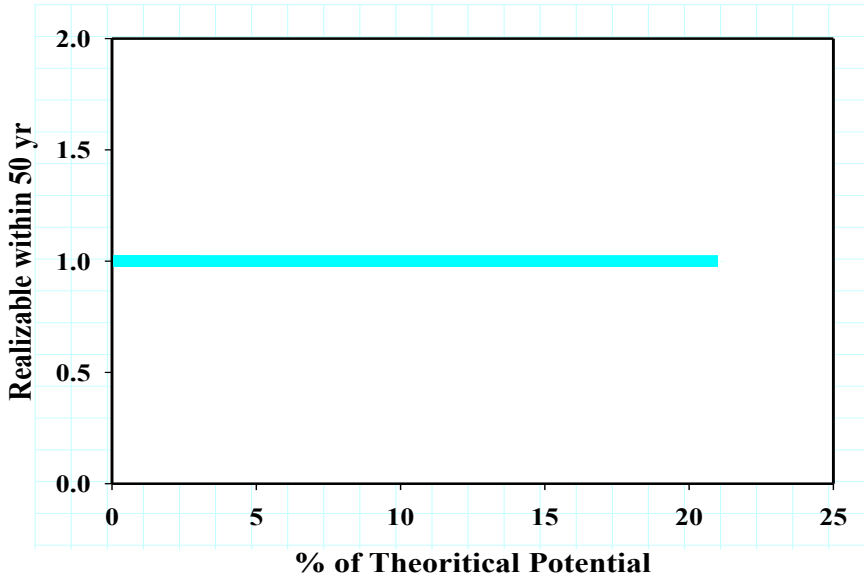
High gross uptake can be associated with low net climate (electricity, acid, compression or pumping emissions are high). The global size is encouraging and on the other hand, it can be deceptive. Bullock et al. determined a potential for mine-waste enhanced weathering of 1.1-4.5 Gt CO_2 yr^{-1} (best estimate 2.4 Gt CO_2 yr^{-1}).

The same evaluation has estimated that only about 3-21% of this potential can be achieved within 50 years, with current kinetic knowledge. The figures are screening estimates and do not reflect global removal. They illustrate the value of mine waste as a carbon-management opportunity and the challenges of mineral availability and time [13].

The potential for increased weathering of mine waste and the proportion that can be achieved by weathering kinetics within 50 years (Bullock et al. [13]) are compared in figure 3, which demonstrates that substantially less than the screening potential can be achieved in reality.



(a)



(b)

Figure 3. Theoretical global mine-waste enhanced-weathering potential and the fraction estimated to be potentially realized in under 50 years. Data source: Bullock et al. [13].

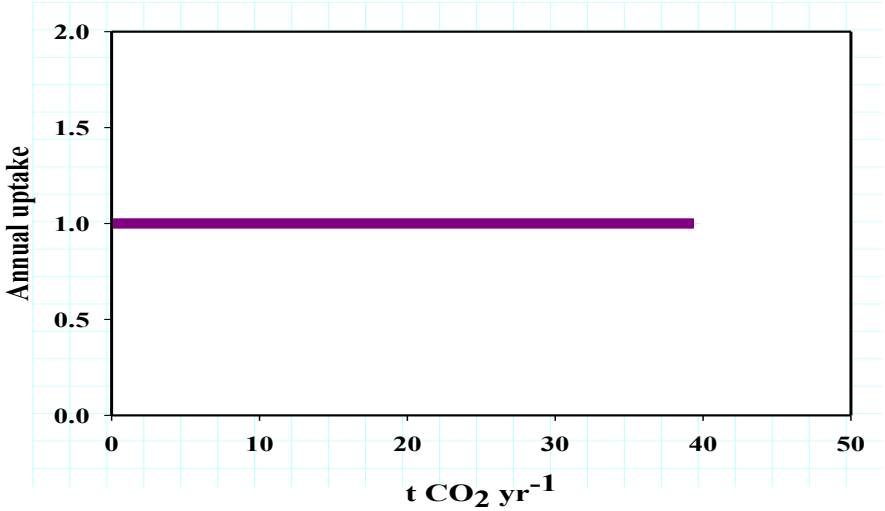
4.2 Field evidence and the importance of system boundaries

Several ultramafic tailing systems have demonstrated passive carbon mineralization. However, in the field, at Mount Keith Nickel Mine in Western Australia, a value of about 11% of annual greenhouse-gas emissions from the mine was reported as annual uptake of atmospheric CO_2, which amounts to nearly 39,800 t. However, modern atmospheric carbon was verified as the source of most of the carbon in the hydro magnesite through isotopic evidence.

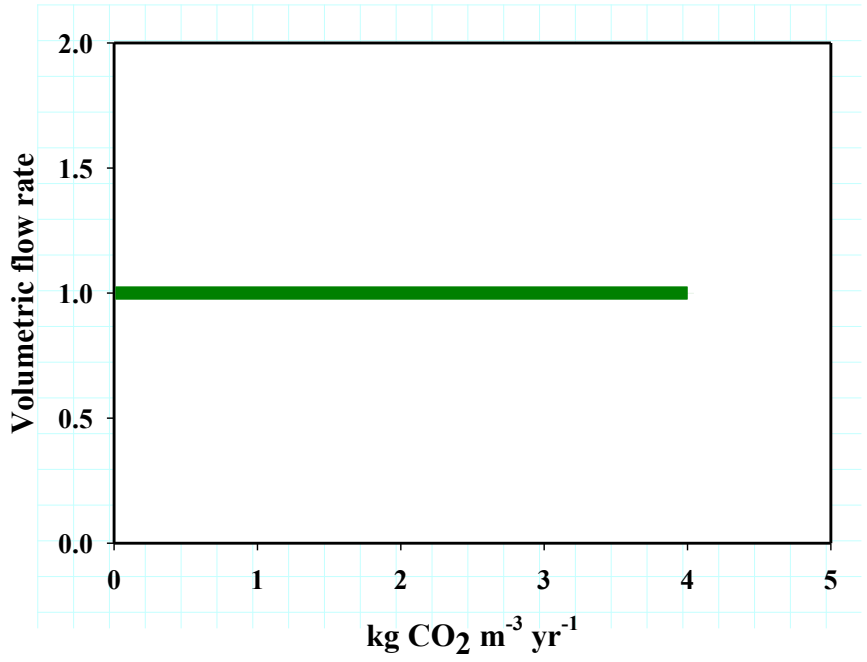
The estimated CO2 release for instrumented field cells was 4 kg CO_2 m^{-3} yr^{-1} at Thetford Mines, Canada. The following are significant demonstrations as they take place in real mine-weathering conditions. They have different units, boundaries and materials, and so cannot be aggregated into a single transferability coefficient. These reported metrics are intentionally separated by panel in [11, 12] because most of them are related to the base system, and only a few are related to the variable systems.

The comparison is not meant to determine a "best" site. Denominator, monitoring method, mineralogy, depth, climate and time basis is emphasized. The cell volume rate and the annual mine-wide uptake estimate are different answers to different questions. Both can be useful, provided the claim is stated precisely.

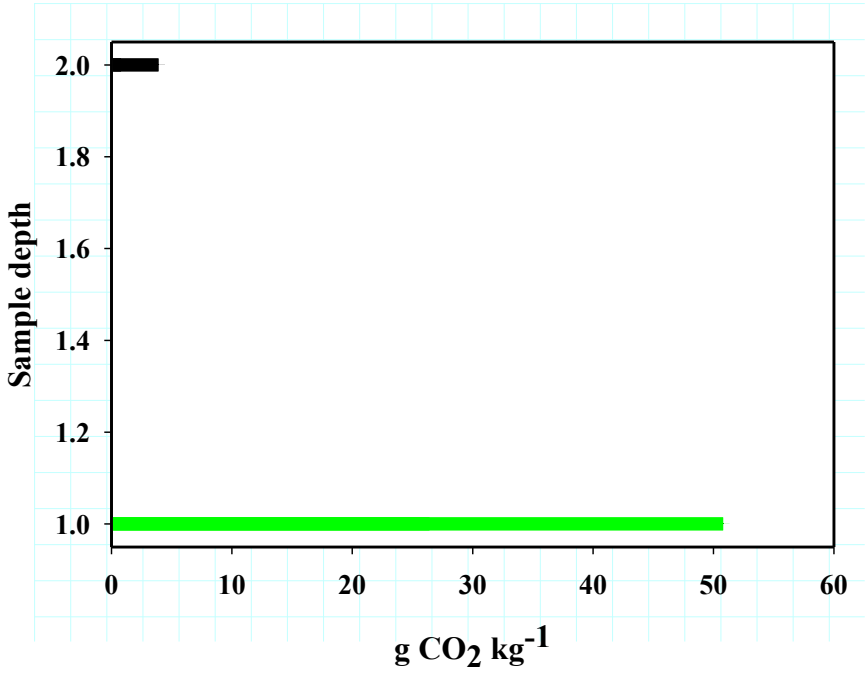
Reported passive-carbonation performance is highly site and sampling dependent, as shown in Figure 4. Mount Keith annual uptake [11] is based on different boundaries than the Thetford Mines volumetric rate [12] and the vastly higher carbonate concentrations in the surface crust at Woodsreef compared with shallow tailings [17] make it impossible to pool or transfer the data between sites without stratified and site specific measurement.



(a)



(b)



(C)

Figure 4. Passive-carbonation metrics at three sites: (a) Mount Keith annual CO_2 uptake [11], (b) Thetford Mines sequestration rate [12] and (c) Woodsreef crust versus tailings carbonate [17].

4.3 Laboratory acceleration and coupled physical stabilization

Laboratory tests have demonstrated that several processes may be used to accelerate the carbonation process. CO_2 can be supplied directly and raise the formation of carbonate when there is reactive brucite. Mineral-stored CO_2 doubled in 4 weeks compared to passive field carbonation over about 30 years in Woods reef columns exposed to 10% CO_2.

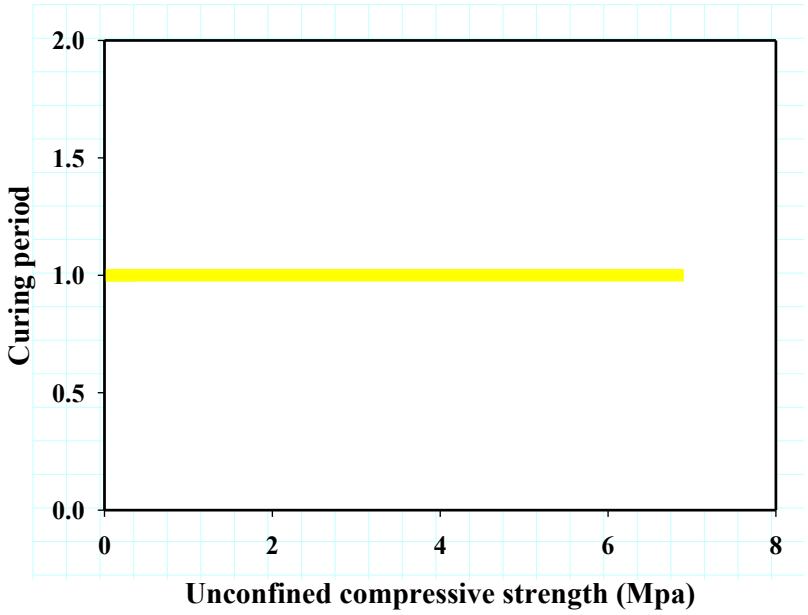
This yields a mechanism demonstration, not a full-scale annual rate, given under controlled gas concentration and column conditions. Acid heap leaching has been shown to release Mg more rapidly, but the same study indicated that sulfate mineral formation was not a problem since it reduced carbonate precipitation. The more there is dissolved, the more stable carbonate is not being stored. A special coupling is the management of water.

There is a need for water for dissolution and ion transport, while high saturation may inhibit gas transport. In Thetford field cells the concentration of CO_2 inside the cells ranged between 5–50 ppmv, with approximately 400 ppmv in the atmosphere, meaning that the CO_2 was being consumed; volumetric saturation was 0.40–0.65. The engineering challenge is not just to add water, or to increase the porosity.

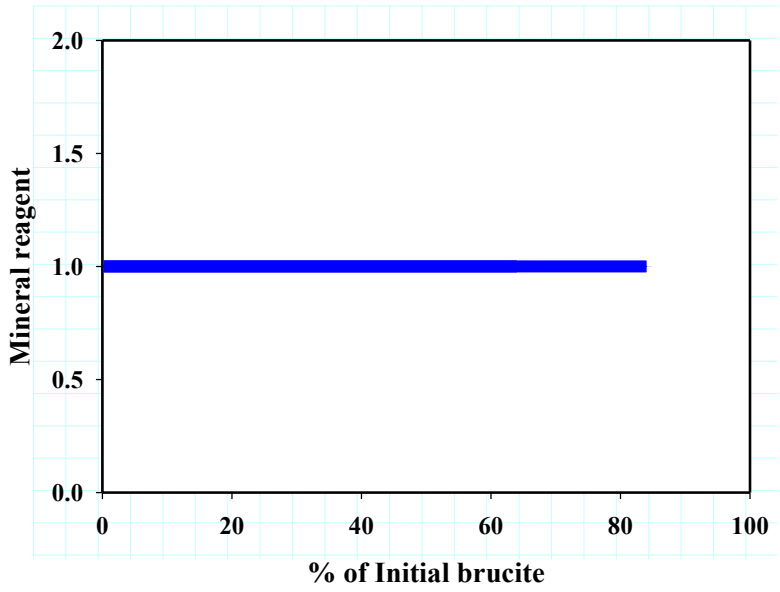
The challenge is to develop a transport regime for gas, liquid and solids that will result in a net carbonate formation, while simultaneously maintaining dust control, seepage, slope stability, tailings deposition and tailings closure cover performance. The carbonation also has a significant impact on the physical behavior of tailings. [12, 19] After 10 weeks of carbonation, the UCS values of the brucite-containing tailings, in laboratory cylinders, ranged from 0.4 to 6.9 MPa, brucite consumption was 64 to 84%, and the total inorganic carbon content was increased by 0.17 to 0.84 wt%. The findings are consistent with the hypothesis that carbonate cementation can be physically stabilizing in addition to its role in bio stabilizing.

They are not intended to substitute for a stability assessment specific to a TSF. Cementation can be non-uniform, can lower the permeability in local areas, and should be assessed under wetting/drying, settlement, freeze/thaw if applicable, seismic demand, construction disturbance and erosion [15].

Figure 5 demonstrates that the carbonation of brucite-bearing tailings for 10 weeks removed brucite and raised the concentration of inorganic carbon and strengthened the tailings, however these results are only for one laboratory system and should not be specified as design values for other tailings.



(a)



(b)

Figure 5. Ten-week carbonation of brucite-bearing tailings: (a) compressive strength and (b) brucite consumption and inorganic-carbon gain [14-16, 35].

4.4 Net removal and closure value

The climate claim that matters is net removal, not gross carbonate formation. A simplified accounting identity is:

$$C_{net} = \Delta C_{inorg} + \Delta C_{org} - E_{supply} - E_{operations} - E_{maintenance} \quad (3)$$

where ΔC_{inorg} and ΔC_{org} are additional inorganic and organic carbon retained within the accounting boundary, while the E terms represent lifecycle emissions from materials, energy, transport, water management and ongoing intervention. The identity is intentionally simplified.

An assessment can also include methane and nitrous oxide fluxes, carbon erosion, carbonate dissolution, indirect land-use effects, adding carbon credits for additionality and uncertainty. The practical value is that it doesn't allow a closure program to report on the formation of the mineral, but fail to report on the emissions required to produce the mineral. For many mines, the most feasible short-term goal is not an independent CO_2 removal plant.

It is "co-optimization": consider if a low-energy in-place requirement for closure is also beneficial for durable mineral storage, stabilization of a surface, control of dust and/or reduction of a long-term liability. These are more believable if the intervention is clearly based on a baseline, has a testable increment, and a water and geotechnical design that remain compatible, and a monitoring plan that endures with changes of ownership. It is less believable when it assumes a world-wide capacity, high-carbon energy input or a poorly characterized reagent.

Selected quantitative evidence on tailing recovery and carbon mineralization are compiled in table 3, with each value reported in its original system boundaries and evidence class [5-7, 11-17, 23-26]. These are based on various scales, methods and assumptions, and represent the range of reported performances and should not be combined into a single comparable performance factor.

Table 3. Selected quantitative evidence for tailings recovery and carbon mineralization. Values retain their original system boundaries and evidence class; they must not be pooled into a common performance factor. Sources: [5–7, 11–17, 23–26].

Evidence setting	Reported value	System and interpretation	Critical qualification
Long-term field	20 years	Bauxite residue amended with sewage sludge, yard waste or topsoil; early-stage soil development observed.	One residue and climate; not natural-soil equivalence.
Glasshouse	pH above 9.5 to 8.5–8.9; TOC below 0.5 to 2–4 g kg^{-1}	Alkaline magnetite Fe-ore tailings with 2% lucerne hay, native microbes and plants.	Short-term mechanism evidence only.
Field / operational	39,800 t atmospheric CO_2 yr^{-1}; 11% of mine GHG	Mount Keith passive carbonation.	Site-specific annual estimate and mine-emissions context.
Field cell	4 kg CO_2 m^{-3} yr^{-1}	Thetford ultramafic milling-waste cells.	Volumetric cell estimate, not a mine-wide total.
Global model	1.1–4.5 Gt CO_2 yr^{-1}; ~3–21% realizable in under 50 years	Mine-waste enhanced-weathering screening.	Theoretical capacity and kinetic scenario, not observed removal.
Laboratory	0.4–6.9 MPa UCS; 64–84% brucite consumed	Brucite-bearing tailings after 10 weeks of carbonation.	Material-specific; requires geotechnical scale-up.
Field-calibrated climate model	Summer PMP +18–30%; peak discharge up to +49%	Canadian Malartic mine-waste system, RCP8.5 by 2100.	Scenario result, not a universal climate factor.

5. Climate-resilient mine closure: water, stability, ecology and governance

5.1.Closing under a non-stationary climate

Records often are used to design the closure of a mine, and their statistical properties are assumed to be stationary. The idea is undermined by climate change challenges. The IPCC estimates water-related risks are high-confidence to rise due to warming, and there is high-confidence of changes in the intensity of precipitation and drought/flood risk in many regions.

Local hydroclimate, snow, permafrost, weathering and water demand and receiving environments determine mining implications. The concluding landform question is whether the end product (TSF and ecological system) is physically and environmentally capable of functioning within credible future drought, heavy rain events, hot and dry conditions, wildfire, freeze–thaw, and extended wet periods, not just the historical averages. But what does it mean to be resilient in a changing climate?Climate resilience needs to be expressed in terms of modes of failure. Some of the above may apply for a TSF: overtopping, exceedance in diversion channels, loss of freeboard, loss of pore pressure, seepage, erosion, differential settlement, water-treatment demand.

Reclamation may involve reclaimed landforms (rilling, gullying, slope failure, generation of dust, salinization of the root zone, revegetation failure, change in infiltration, and acid rock drainage and transport of metals). These include erosion of carbon-rich material, loss of vegetation, decrease in mineral-carbonation rate, carbonate dissolution, and increased lifecycle maintenance emissions, for a carbon-bearing system. The process for closure starts with the observation of a local baseline and the use of a multi-models ensemble of future scenarios.

The climate variables have to be expressed as engineering variables such as design rainfall, probable maximum precipitation, intensity–duration–frequency curves, peak discharge, evapotranspiration, soil-water storage, erosion potential, drought duration, fire weather, and permafrost thaw or snowmelt-rainfall coincidence. Now it's time to experiment with design variations and the potential failures. Importantly, a high-resolution climate grid will not necessarily generate a high-confidence site design.

It needs to be bias corrected and linked to local hydrogeology, landform geometry, material properties and operational information.

5.2 Quantified climate stressors in mine closure studies

Modelling at the Canadian Malartic mine-waste storage system was calibrated based on field-based data and was used to simulate the increase in probable maximum precipitation for the summer season by 2100 under RCP8.5, which was estimated at 18-30%, or the peak discharge, which was estimated at up to 49%. Model was calibrated with field rainfall and runoff data. The results are not predictions for all mines.

These are a significant example of how future hydraulic loading has been sufficient to necessitate reassessment of diversions, spillways, freeboard, containment dikes and erosion protection. A similar water-balance issue is evident in reclamation-cover studies in northern Alberta. Reclamation covers versus natural sites are compared under downscaled climate projections using field monitoring and modelling with the computer program Hydrus-1D. A related five-site analysis showed that the maximum increases in growing-season precipitation (25.5%) and potential evapotranspiration (11.9%) in 2071–2100 were under RCP8.5, with increases in net percolation at all sites.

A cover that was optimized to maximize plant-available water under historic climate conditions, may not match the future condition where water storage is more often exceeded or where evapotranspiration is limited by plant stress. These values are presented in Figure 6, but not combined into a common effect size. The Canadian values are for extreme rainfall and peak discharge design demand. The Albertas are related to growing season water balance.

Both reinforce the need to model water controls under multiple climate stressors. Neither supplies a generic percentage to add to a design storm at another mine.

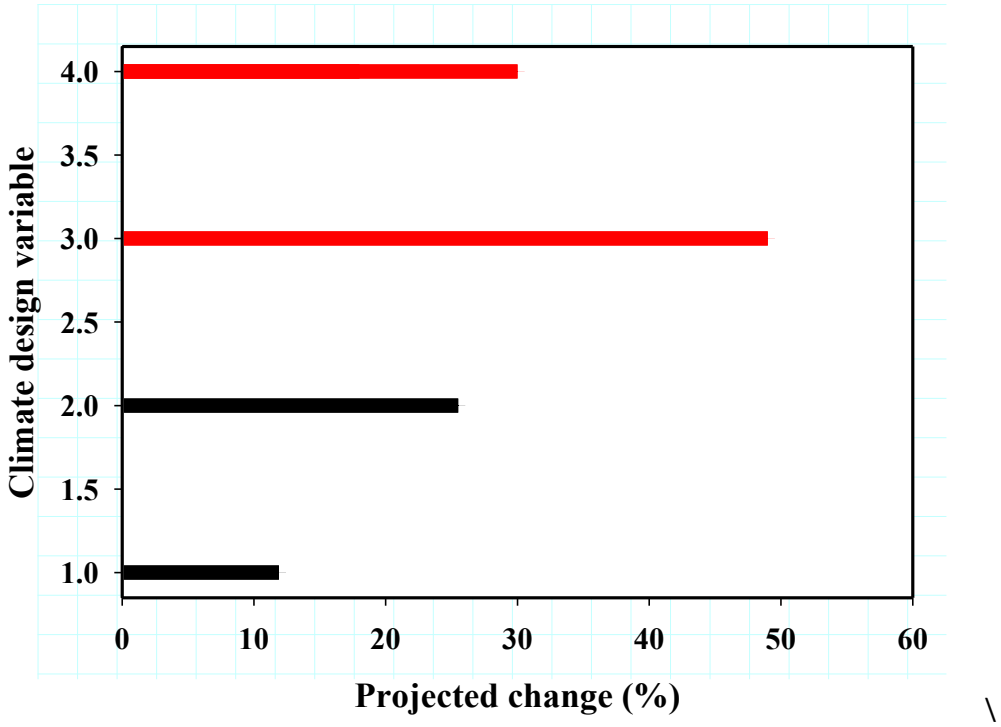


Figure 6. Projected climate changes for mine-closure water balance at Canadian Malartic [23], northern Alberta [25] and Queensland [26].

5.3.Tailings standards and passive closure requirements

The Global Industry Standard on Tailings Management (GISTM) calls on operators to consider climate change knowledge in the facility lifecycle, include the consideration of climate change in water-balance and water-management models, and show safe closure. The standard distinguishes operating (active-closure) conditions from passive closure conditions. The flood-design criteria increase in proportion to consequence class for operations and closure by flooding, with the criteria for passive closure being set at 1/10,000 for each consequence class.

It is not a standard in place of that of a jurisdiction or the local design. It's good to remember a vegetation outcome does not override hydraulic safety for a tailing facility. For the active-closure criteria, Figure 7 presents them in return-period equivalent terms. The log scale shows that the value of the design basis used for the low-consequence classification is quite large compared with the value used for the extreme-consequence classification.

This figure does not have to be of value because it is the governance point, not the visual ranking that must be controlled documents. They need to be revised if the factual situation of the closure changes significantly due to an assessment of performance or climate knowledge.

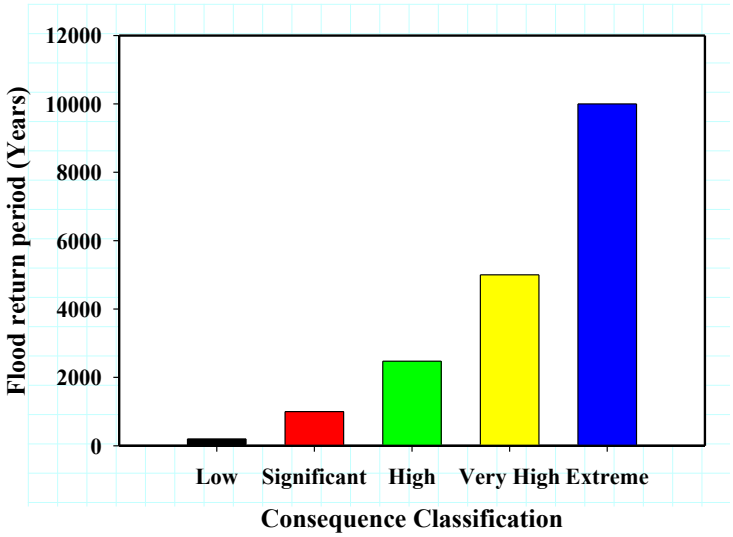


Figure 7. GISTM flood-design return periods by consequence class for operations and active closure; passive closure requires 1/10,000 annual exceedance probability [9,10.30,32].

5.4 Techno sols, water quality and carbon permanence under climate stress

Climate resilience is a condition for ecological and carbon performance. The benefit of a Techno sol that sequesters organic carbon through vegetation and aggregation is lost once the fine fraction is removed by erosion, the fine fraction is lost due to drought, biomass is destroyed by fire, or heavy rains form gullies, and/or prolonged saturation causes changes in redox conditions. Similarly, during

a dry period mineral carbonation can be limited by a lack of water, and during a saturated period by a lack of gas transport.

Not that Techno sols or carbonation are necessarily climate solutions, but that they can be. It is that their performance should be assessed in the context of closure boundaries for climate change. The problem with the record length is depicted in figure 8.

In one of the studies in the north of Alberta, less than about 10 years of field monitoring data were used to calibrate ~60 years of cover-design modelling. This is a natural phenomenon of closure engineering and is often impractical to do field monitoring over the decades prior to closure decision. The answer is not to give up modelling.

It's about being explicit about the mismatch, accounting for uncertainty, tracking leading indicators and continually refining the model as more information surfaces in the field [24].

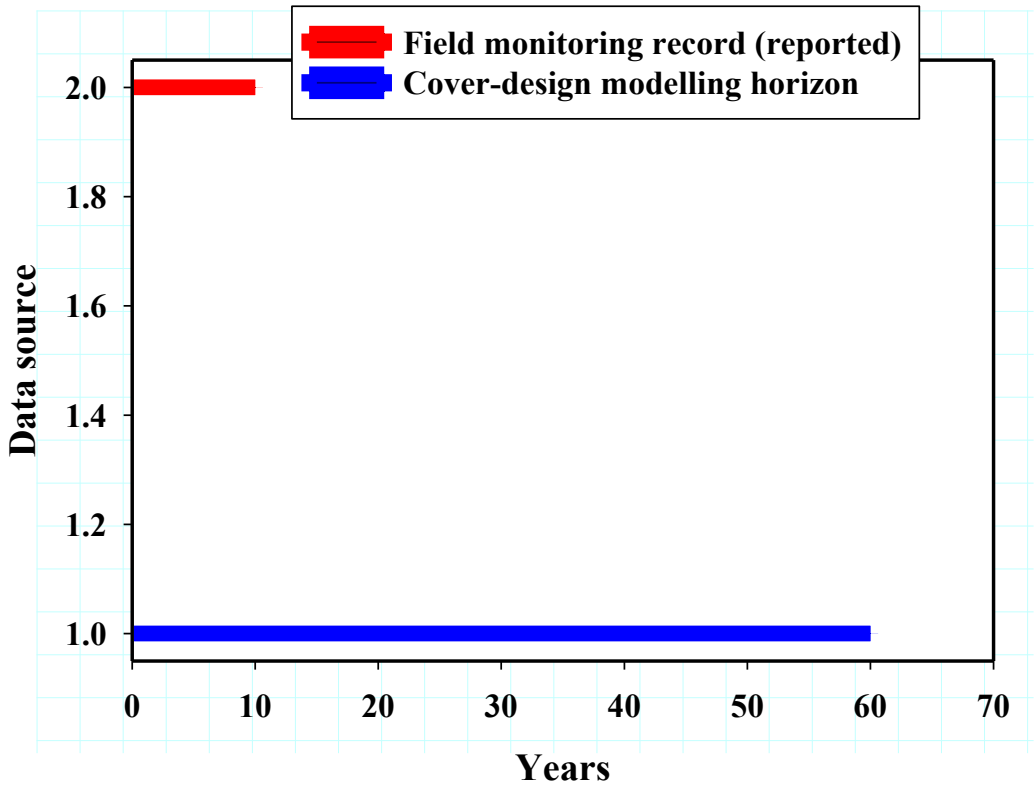


Figure 8. Northern Alberta reclamation-cover study: less than about 10 years of field monitoring versus a modelling horizon of about 60 years [24].

6. Integrated design and performance assurance

6.1.A phased decision framework

An integrated closure pathway starts in operations and not at the relinquishment. Operational deposition provides chances to establish baseline data, define monitoring infrastructure, stage amendments and identify reactive fractions, as well as to map material variability. It also establishes an obligation not to make intervention more complicated in the future, with respect to safety. The decision framework below has been designed to be used to connect mining and environmental engineering, one by one.

Phase 1: characterize and exclude. Identify and map the inventory of tailings by material domain. Measure mineralogy, acid generation potential, salinity, contaminants, hydraulic properties, inherited carbonates, geotechnical condition and climate setting. Exclusions: such as material with unmanageable contaminant mobility, an unsuitable stability, no viable amendment supply or an intervention that is not compatible with the design of the TSF closure. This stage creates a space for an eco-circular story to not push an inappropriate material into the land-use receptor.

Phase 2: conceptual models and candidate functions. Develop connected conceptual models related to safety of tailing facilities, water balance, geochemistry, ecology and carbon. Specify the function of each intended layer or treatment: root zone growth, capillary break, oxygen control, drainage, erosion armour, sorption, dust control, mineral carbonation or water polishing. Detect interfaces and failure modes. If a candidate is only capable of performing a desirable function and an undesirable, then it should be revised or eliminated.

Phase 3: Replicated field demonstration. Narrowing/Formulation should be done in the lab and not announced as a closure success. Field trials should be repeated, incorporate conventional closure comparators, involve instrumented profiles, involve measurement of material mass balance, and be long enough to experience relevant wet and dry seasons. Trials should be conducted within a hydraulically representative tailings domain where possible, and should be designed to ensure that the scaling up of the trial to hectares is not inappropriate for the mixing, placement and drainage assumptions made.

Phase 4: climate stress testing & lifecycle assessment. Test water balance, erosion, seepage, vegetation and carbon performance with the use of climate ensembles. Assess an intervention's net greenhouse gas balance, water usage, contaminant pathways, material inputs, transport and maintenance. Run extreme rainfall, drought, high wind and fire sensitivity cases, as well as sensitivity cases for cases of prolonged saturation. Identify the after closure land use and receptor scenario that would enable a residual risk acceptable to the public.

Phase 5: assurance, adaptive management and relinquishment. Identify performance criteria, monitoring sites, QA/QC, trigger-action-response plans, financial provisions and governance

framework to remain with change of operator. The transition from active to passive closure should only be made with confirmed evidence in the field of the conditions for safety and the environment required for closure. Relinquishment should be done based on performance and not just time.

6.2 Monitoring, MRV and trigger-action-response planning

The monitoring should be used for decisions, not to make an archive. The underlying premise of an assurance system is a series of hypotheses connecting a measured indicator to a closure goal and a specific response. For example, if the electrical conductivity of the root zone increases, it may lead to capillary rise investigations or irrigation water quality investigations; if the concentration of the metals in pore water in the deep root zone increases, it may lead to leachate-source investigations and/or treatment; if vegetation diminishes due to drought, then it may lead to investigations of stabilizing and/or reseeding the area or making a new irrigation design that is consistent with the closure plan or redesigning the water-storage layer.

The trigger should not be set to material variability or measurement uncertainty, but only because of its ease of sampling. The mineral carbonation MRV requirements are very strict. The following elements must be identified in a claim: treatment baseline, counterfactual, sampling frame, depth intervals, tailings mass, mineralogical methods, inorganic-carbon inventory, uncertainty calculation, and carbon-source attribution.

A portable XRD method can enhance the practicality in the field, however, it requires calibration and representativeness checking. Soil-carbon stock calculation, fluxes of greenhouse gases, assessment and accounting for amendment emissions must also be included when a claim contains carbon from the organic component of the soil. These boundaries are not supported by the evidence of gross carbonate formation. Climate input selection should also be transparent [11, 17].

The CMIP6 documentation products from Queensland indicate that 11 global climate models and 15 regional climate-model members are available for products at 5 km for daily biophysical modelling, 10 km for mean-climate and hazard indices, and 20 km for hourly CORDEX-compliant data. This shows that different resolution and ensemble should be used for different purposes of closure model. It is not intended to imply that local observed data or site instrumentation or engineering judgement may be replaced by a regional product [42].

Table 4. Minimum integrated monitoring and trigger-action-response plan for a tailings-recovery closure system. Sources supporting the measurement logic include GISTM, ICMM, climate-aware cover studies and mineral-carbonation field accounting [9, 10, 17, 23–25].

Objective	Core measurements	Interpretation / trigger example	Indicative response
TSF and landform safety	Water level, pore pressure, deformation, settlement, diversion performance, erosion mapping.	Trend or event response outside design envelope; loss of freeboard or accelerated erosion.	Inspect, re-model, repair drainage/erosion works, revise closure risk case.
Root-zone hydraulic function	Matric potential, water content, infiltration, runoff, hydraulic conductivity, crack survey.	Storage deficit during drought or excess deep drainage after storms.	Adjust surface protection, grading, layer design or vegetation strategy.

Objective	Core measurements	Interpretation / trigger example	Indicative response
Geochemical containment	pH, EC, sulfate, major ions, dissolved/bioavailable metals, redox and pore-water flux.	Upward/downward adverse trend relative to receptor criterion or baseline.	Identify source/pathway, verify with speciation, modify barrier/treatment/monitoring density.
Ecological recovery	Cover, recruitment, root depth, species composition, biomass, shoot concentrations, invasive species.	Loss of functional cover, poor recruitment or unacceptable uptake pathway.	Stabilize surface, use local species, revise amendment or exposure controls.
Carbon MRV	Inorganic/organic C stocks, mineralogy, carbonate baseline, fluxes, treatment mass balance, LCA inventory.	Claim uncertainty or additionality not supported; carbon loss or unexpected emissions.	Suspend claim, expand sampling, recalibrate accounting boundary or change intervention.
Climate adaptation	Rainfall intensity, drought indices, ET, weather-driven erosion, updated projections and model residuals.	Observed conditions exceed stress-test range or model residuals grow.	Update water balance and hazard model; revise design/financial provision.
Governance and assurance	QA/QC records, audit findings, corrective-action closure, financial provision, ownership and stakeholder reporting.	Unresolved actions, inadequate funds or unclear post-closure responsibility.	Escalate management decision; revise assurance plan before passive closure.

6.3 A closure performance dashboard

Table 4 can be used to create a closure performance dashboard. A strong dashboard will not involve a single composite index since the implications of a declining index are not the same as an increasing pore pressure trend; a small ecological decline is one thing, while the trend of an increasing pore pressure could be a more urgent engineering concern. Rather, a performance category (in envelope, early warning, action required or critical) is assigned to each domain, along with a threshold, uncertainty band and decision authority.

Leading and lagging indicators need to be reported on the dashboard. Some leading indicators are soil moisture, crack density, early erosion features, pore-water chemistry, vegetation recruitment, climate anomalies and model residuals. Lagging indicators are gully formation, downgradiment contamination of groundwater, vegetation mortality or need for emergency maintenance.

Where there are decades long outcomes, it is particularly important to focus on leading indicators. It offers a chance to take action before a situation becomes a long term commitment. There needs to be an element of social and governance issues in assurance.

Climate impacts may manifest and shift the use of land after mining, cultural values, access, water requirements and monitoring obligations. Community and Indigenous knowledge might enhance the local understanding of the hydrology, fire cycles, land use and residual risk they can accept. These factors are not meant to supplant geotechnical or geochemical analysis.

They set the basis for the environmental performance that's being evaluated in the receptor environment and enhance the legitimacy of the post-closure stewardship.

7. Evidence gaps and a research agenda

7.1. The central gap: scale, duration and integration

The biggest research deficit is not that there are no plausible mechanisms. Previous published reports have demonstrated that plants, microbes, organic amendments, mineral phases and carbonation reactions can modify tailings. The gap is represented by the integrated field evidence at closure scale.

In the majority of studies, one process is isolated for weeks, months or a few growing seasons. Multiple processes are needed to ensure compatibility over decades in a changing climate, under changing tailings domains, with operation restrictions, rare events and governance transitions. This space has four aspects.

Scale: pot, column and small-plot studies are not a true replication of material blending, placement, trafficability, variable lift thickness, drainage and landscape connectivity. Second, duration: initial plant establishment does not create persistence of amendments or contaminant retention, or carbon permanence or resilience to extreme-event sequences. Third, Coupling: studies tend to collect data for soil chemical, vegetation, carbonation and water balance as separate entities when in fact they are all coupled.

Fourth, comparability: inconsistent reporting of mineralogy, bulk density, depth, carbon basis, climate, amendment mass and field layout and monitoring data do not allow for useful meta-analysis. The priority research response is a network of multi-hectare demonstration sites with instrumentation for a variety of tailing types and climate domains. In each site a conventional closure comparator, a Techno sol treatment, a carbonation-oriented treatment where mineralogy allows it, and a combined treatment only in the case of an interface where it is safe.

A design should include the requirements of mass balance, material quality, construction method, energy and water consumption, weather, root-zone and support-horizon data, pore-water chemistry, gas flux, mineralogy, carbon stocks, erosion, and vegetation and safety indicators relevant to the TSF. These studies are more costly than short trials, but they directly minimize closure uncertainty and may avert late stage redesign and costs.

7.2. Research questions that connect mining and environmental engineering

What are strategies to manage material heterogeneity?. Tailings deposition domains should be mapped at resolution that is relevant to both the carbonation potential and the root-zone risk. Mineralogy based on grain size fractions, acid–base accounting, secondary-carbonate baseline, hydraulic properties and leachability should be correlated to the digital mine model. The question to address is whether it is better to segregate and selectively treat a reactive fraction or treat the entire deposit, with consideration to energy and materials handling.

How can root zones and support horizons be co-designed? Future experiments should measure root, matric potential, oxygen, redox, pore water chemistry and solute flux continuously at the interface. The question of whether a surface can plant successfully is not the only one. It is if the seasonal wetting, capillary rise, salt redistribution, redox reversal or root penetration moves a negative tailings signal into the root zone or toward a receptor.

Is it possible to convey climate stress realistically?. A combination of controlled mesocosms is available, but should involve sequences: drought–high intensity rainfall; wet/dry cycles; wind exposure; fire analogues; and freeze thaw in appropriate regions. Climate stations and design-storm observations on the field trials. Ensembles and scenario periods should be utilized in closure models but results should be compared to field water balances and erosion surveys as the climate record grows.

What is the meaning of a credible carbon claim? In mineral carbonation research, the amount of new carbonates, tails mass, accessibility of the reactive phases, reaction depth, carbon source, energy consumption, water consumption and metal fate should be measured. In the case of Technosol carbon, it should measure stocks per equivalent soil mass, GHG flux, amendment-origin carbon and erosion loss. The overarching research question concerns the question whether this net benefit remains once the emissions from the supply chain and maintenance are subtracted.

What will happen to contaminants in the long run?. Aging of organic amendments, iron phases, carbonate minerals and reactive media under fluctuating pH and redox should be evaluated in long duration leach columns, as well as in lysimeters and field pore water transects. Routine assessment of inorganic contaminants, salinity, sulfate, emerging contaminants and, if applicable, asbestos/fibre hazards should be performed on the system. An environmental recovery treatment that results in a nice short-term leaching effect and a noncontrolled late-term source is not an environmental recovery treatment.

What are the construction and economic limits? Reporting at the field-scale should contain: Amendment supply distance, Quality variance, Mixing tolerance, Water demand, Placement productivity, Dust, Equipment, Settlement, Access and costs. Environmental engineering needs lifecycle inventories, mining engineering needs constructability and production realism. These two are required prior to any formulation being deemed scalable.

7.3.A proposed minimum evidence standard

The following evidence standard is suggested for tailings-recovery interventions before the project is represented as a sustainable closure solution. The operator should demonstrate: (1) a material-specific conceptual model and exclusion screening; (2) a TSF safety and water-balance compatibility assessment; (3) field evidence beyond a single growing season; (4) an explicit receptor and post-mining land-use context; (5) contaminant and ecological exposure data; (6) climate stress testing; (7) a lifecycle inventory and net carbon calculation if climate claims are made; (8) a monitoring and

trigger-action-response plan; and (9) clear post-closure ownership and financial provision. This standard takes a deliberate challenge.

Doesn't demand that all mines be implementing all the technologies. It avoids the other error: defining a short term revegetation or carbonation observation as 'sustainable mining' without proving that safety, water, contaminants and carbon are acceptable throughout the closure phase. Imperial's unworkable mines can still use traditional, risk-based closure.

Mines capable of meeting it can generate real environmental recovery value, and lower long-term liabilities. The additional evidence from other disciplines confirms that finding. Material and biological conditions that must be addressed before a tailing-derived soil can be closure ready are discussed in several additional Phyto stabilization, revegetation, microbial-ecology, amendment-ageing and landform studies [45-62].

There are additional mineral-carbonation works that deal with reaction mechanisms [63–67], activation [68–80], gas–liquid–solid transport [81–88], microbial mediation [89–92], pilot-scale processing [93–96], consequences of being a lifecycle process [97–98], and techno-economic constraints [99–100]. These studies corroborate the idea of moving away from a technology-label-based approach: carbon and ecological co-benefits are legitimate only if they are compatible with water, contaminant and physical-stability controls that will be maintained over long periods of time.

Table 5 outlines a priority research programme for climate resilient tailings recovery. It is based on the gaps of evidence from the field, reviewed in the laboratory, climate studies and governance studies reviewed here [3–7, 11–19, 23–32]. When taken together, these priorities indicate that further laboratory optimization is not enough for progress. It is equally important to validate the progress in the field under representative climatic conditions with the adoption of effective governance and monitoring frameworks.

Table 5. Priority research program for climate-resilient tailings recovery. Evidence gaps are synthesized from the reviewed field, laboratory, climate and governance literature [3–7, 11–19, 23–32].

Priority	Research design	Minimum outputs	Decision enabled
1. Multi-hectare trials	Replicated Technosol, conventional cover and, where appropriate, carbonation treatments across material domains.	Construction records; 5–10+ years of coupled performance data and failure observations.	Whether to scale, redesign or reject a closure treatment.
2. Coupled horizon instrumentation	Measure roots, moisture, O2/redox, pore water and solute flux above and below the root-zone/support interface.	Interface transfer model and early-warning indicators.	Compatibility of soil function with geochemical containment.
3. Climate sequence stress tests	Drought–storm, wet–dry, erosion, fire and freeze–thaw experiments linked to field weather.	Thresholds for cover, aggregate and contaminant performance.	Climate-resilient material and landform design.
4. Carbon MRV protocol	Stratified mineralogy and C sampling, baseline, isotope/complementary attribution, GHG flux and LCA.	Uncertainty-bounded net C balance.	Whether any claim is sufficiently additional and durable.

Priority	Research design	Minimum outputs	Decision enabled
5. Contaminant ageing	Long-term leach, lysimeter and field studies through pH/redox cycles.	Speciation, flux and receptor-risk trajectories.	Selection of safe amendments and reactive media.
6. Scale-up engineering	Mass balance, blending trials, equipment productivity, water/energy demand and QA/QC.	Hectare-scale constructability and cost range.	Operational feasibility and closure-cost provisioning.
7. Model calibration and updating	Ensemble climate, water balance, erosion and reactive transport models updated with monitoring.	Transparent residuals, sensitivity and intervention triggers.	Adaptive management and financial assurance.
8. Common reporting standard	Minimum metadata for tailings, climate, soil, carbon, water and ecological indicators.	Comparable open datasets and reproducible methods.	Cross-site synthesis and transferability assessment.

8. Conclusions

Based on this review, it is concluded that tailings engineering for environmental recovery is a feasible research and closure stream that should be considered a part of the mining and environmental engineering problem, not as a standalone closure stream. Measurable advantages of Tailings Derived Technosols, mineral carbonation and climate-resilient design. But each one is subject to local material characteristics, transport phenomena and long-term uncertainty. This evidence therefore confirms the need for an integrated, climate-oriented (closure) approach rather than generic solutions. The following are conclusions of the key findings.

1. Engineered Technosols can be used to function as the root zone and to enhance erosion control and ecological recovery on tailing surfaces. They are affected by the entire soil profile, not just the top layer, especially by the relationship of the root zone with the underlying tailings support horizon.
2. In selected Mg- or Ca-rich tailings, mineral carbonation can provide durable inorganic carbon storage, with potential co-benefits for physical stabilization. Its practical value is constrained by:
    a. energy and reagent demand
    b. mineralogy and reaction kinetics
    c. the quality of measurement, reporting and verification (MRV)
    d. contaminant fate
    e. water and gas transport
3. Climate resilience is not an add-on to design but part of it. It regulates hydraulic loading, water balance, erosion, vegetation persistence, transport of contaminants and permanence of stored carbon. Projected climate extremes have already been demonstrated to significantly increase the demand for mine closure designs in the field.
4. Standards and guidance currently in place are lifecycle and climate responsive for the closure of tailing storage facilities (TSF). But even with that performance at a specific location, it still requires detailed characterization of the material and stress testing for future climate scenarios, long-term monitoring, and adaptive governance.
5. The first priority is not a recipe of all tailings to all soil, or a generic carbon factor. What is required are multi-hectare multi-year instrumented field demonstrations. Together, these should cover geotechnical safety, hydrology, geochemistry, ecology, carbon accounting and climate scenarios.

6. The integrated demonstrations will be needed to distinguish between treatments that might look promising, but actually do not result in superior closure performance over realistic time periods.

7. The most defensible closure approach is the tailings management system that is designed for environmental protection and/or post-mining recovery.

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