Repurposing enhanced rock weathering for brownfield cleanup: a practical carbonate–silicate remineralization method for stabilizing cationic metals in shallow soils

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Abstract

Brownfield, mining-impacted, urban fill, and legacy agricultural sites often contain cationic metals concentrated in shallow soil horizons, where they sustain direct-contact, dust, and leaching risk and can complicate redevelopment. This paper reframes enhanced rock weathering (ERW), originally advanced for carbon dioxide removal, as a practical remineralization approach for immobilizing cationic metals in soil. The proposed method is not simply another mineral amendment. It uses controlled carbonate–silicate blends to accelerate soil-aging processes, acid neutralization, increased negative surface charge, Ca and Mg occupation of exchange sites, hydrolysis, sorption, and secondary Fe–Al mineral formation that shift metals from labile and leachable pools toward less mobile forms. The framework is grounded in a watershed-scale Vermont field deployment of low-Ni, Fe–Al-rich basalt and in prior liming, wollastonite, and ERW literature. Across these lines of evidence, silicate remineralization behaves as a slow-release liming system, hydrologically connected receiving zones can show strong buffering signatures, and metal lability can decline where alkalinity and base cations accumulate. Building from that evidence, this paper presents a field-executable remediation method covering site screening, feedstock selection, blend design, hotspot targeting, application, vegetative cover, verification, and boundary conditions. The method is best suited to shallow soils in which cationic metals such as Pb, Zn, Cu, Cd, and Ni are major risk drivers and where in situ stabilization is preferable to full excavation. Key practical recommendations are to use low-Ni, Fe–Al-rich mafic feedstocks, bench-test carbonate fractions to control pH trajectory, align placement with the contaminated depth interval, and verify performance using leachability tests together with mechanistic indicators such as soil pH, exchangeable acidity, exchangeable aluminum, and Ca:Al. Soil health improvement, local sourcing from quarry fines, reduced hauling, and incidental carbon sequestration may provide additional value, but remediation endpoints should govern design.

Keywords: brownfield remediation; enhanced rock weathering; remineralization; cationic metals; basalt

Practice relevance

- Design the remedy around lability and leachability rather than total metal mass alone.
- Use screened low-Ni, Fe–Al-rich silicate fines with a modest carbonate fraction to combine rapid neutralization with slower long-term buffering.
- Verify performance with the toxicity characteristic leaching procedure (TCLP) and synthetic precipitation leaching procedure (SPLP) plus soil pH, exchangeable acidity, exchangeable aluminum, and Ca:Al; monitor receiving zones only where hydrologically relevant.

Introduction

Brownfield, mining-impacted, urban fill, and legacy agricultural sites commonly contain cationic metals concentrated in shallow soil horizons, where they sustain direct-contact, dust, and leaching risks and can delay redevelopment (Berman et al., 2022; Hou et al., 2023). For many of these sites, excavation and off-site disposal remain effective but costly, disruptive, and carbon-intensive, especially when contamination is shallow but laterally extensive (Elnakat, 2015; Song et al., 2019). In situ stabilization is therefore attractive when the practical objective is to reduce lability, bioaccessibility, and leachability rather than remove all metal mass from the site (Davidson, 2013; Gupta et al., 1996).

Most mineral-based stabilization systems rely on single-phase alkaline materials such as lime or cement. Those remedies can work, but they often deliver a rapid chemical pulse rather than a controlled geochemical trajectory, and they are not always optimized for heterogeneous shallow-soil metal problems or for long-term soil function (Goulding & Blake, 1998; Hale et al., 2012). What is still needed is a practical framework that combines rapid risk reduction with slower, more durable buffering; that can be sourced from abundant local mineral byproducts; and that can be verified using the same regulatory and risk-based metrics that drive remedial decisions.

Enhanced rock weathering (ERW) was originally advanced as a carbon dioxide removal strategy, but the underlying geochemistry is directly relevant to remediation. Finely milled Ca–Mg silicate fines consume acidity, release base cations, raise pH, increase negative surface charge, and can promote secondary Fe–Al mineral formation (Beerling et al., 2020; Calabrese et al., 2022; Lewis et al., 2021). Those are the same processes that govern the lability of many cationic metals in soil (Alloway, 2012, 2013). This paper argues that ERW can be repurposed as a remineralization-based remediation method: not primarily for carbon accounting, but for rebuilding buffering capacity and accelerating soil-aging pathways that move cationic metals from more labile pools toward more stable mineral-associated states.

The method presented here emerged from a watershed-scale basalt deployment at a Vermont headwater catchment supported by the Yale Center for Natural Carbon Capture. Although the original experiment was designed as a carbon-capture study, it served as a sentinel system for remediation logic. Low-Ni, Fe–Al-rich basalt behaved as a slow-release liming amendment in upland soils, while hydrologically connected receiving zones exhibited stronger buffering signals and lower cationic metal lability. Combined with prior liming, wollastonite, and ERW literature (Beerling et al., 2024; Cho et al., 2010; Gu et al., 2017; Johnson et al., 2014; Likens et al., 1998), those observations support a field-executable method for shallow-soil metal stabilization on brownfields and related sites.

This is a methods-focused synthesis rather than a new brownfield pilot report. Its purpose is to translate the geochemical and field evidence into a practical, deployable framework that remediation practitioners can evaluate, test, and adapt site by site.

Why remineralization can stabilize cationic metals

At its core, the method exploits the fact that environmental risk from metals depends more on lability and leachability than on total mass alone (Davidson, 2013; Gupta et al., 1996). As soil pH rises, variable-charge mineral surfaces and organic functional groups deprotonate, net negative surface charge increases, competition from H^+ declines, and exchangeable acidity and Al^{3+} are reduced. Base cations released from weathering, especially Ca^{2+}, then occupy exchange sites and shift the exchange complex away from acidic conditions that favor metal mobility

(Goulding & Blake, 1998; Hale et al., 2012; Wolf & Beegle, 2011). For polyvalent cationic metals such as Pb^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}, and Ni^{2+}, higher pH and stronger Ca/Mg saturation generally increase sorptive retention, hydrolysis, and transfer into less labile pools (Alloway, 2012, 2013).

What differentiates this approach from a conventional lime-only treatment is that the goal is not a one-time pH correction. The goal is controlled acceleration of pedogenic stabilization pathways. In this sense, the approach can be viewed as a nature-based stabilization strategy that accelerates naturally occurring soil-forming processes rather than relying on synthetic binding systems. As reactive silicates weather, they add alkalinity and silica, sustain Ca/Mg delivery through time, and may promote precipitation, aging, or transformation of Fe- and Al-rich secondary phases that provide high-affinity sorption and occlusion sites for metals (Cho et al., 2010; Gu et al., 2017; Johnson et al., 2014; Lewis et al., 2021). Watershed-scale calcium silicate additions have been shown to shift aluminum from exchangeable pools to more strongly bound organic and mineral-associated forms over decadal timescales, demonstrating that base-cation additions can drive durable changes in metal binding rather than transient pH effects alone (Gu et al., 2017). In practical terms, the method expedites soil aging: it encourages the soil to evolve toward a more buffered geochemical state in which cationic metals are less exchangeable, less leachable, and less bioavailable. This is why low-Ni, Fe–Al-rich mafic feedstocks are attractive: they do not merely neutralize acidity; they can also create the reactive mineral context needed for longer-term stabilization (Dupla et al., 2024; Dupla et al., 2023).

A carbonate–silicate blend provides a practical way to manage time. Carbonate fines supply rapid early neutralization when immediate risk reduction is needed. Silicate fines weather more slowly and self-throttle as pH approaches neutrality because proton-driven dissolution slows as exchangeable acidity is depleted (Cho et al., 2010; Goulding & Blake, 1998). The result is a fast-slow buffering system rather than a single alkaline pulse. For remediation, that matters because it helps avoid overshoot into highly alkaline conditions that can damage vegetation or mobilize oxyanion-forming metalloids such as As or Se (Christ et al., 1999; Jihad & Saeed, 2023). In other words, the blend is designed not simply to increase pH, but to control the time-evolution of pH and exchange-site occupation.

Because these processes operate in parallel and evolve through time, the approach does not rely on a single reaction pathway or transient chemical condition, which may contribute to more stable long-term outcomes under variable field conditions. Viewed this way, the approach is not just another mineral amendment. It is a managed geochemical treatment that uses multiple mechanisms, acid neutralization, exchange-site occupation, surface complexation, hydrolysis, and secondary mineral formation, to reduce metal lability through time.

Field and literature basis for the method

The sentinel Vermont deployment that motivated this framework provides three transferable lessons. First, a single 20 t ha^{-1} surface application of Ca-rich meta-basalt increased upland soil pH by 0.15–0.24 units and exchangeable Ca by up to 12% in the upper 15 cm within 13 months, with the largest response in more acidic landscape positions (Zacharias, Rioux, Sun, Tatge, Pihlap, et al., 2026). Second, hydrologically connected riparian soils downslope of treated areas showed stronger buffering signatures than the treated uplands, including higher pH, higher Ca, and sustained increases in shallow groundwater Ca and alkalinity. Third, those receiving zones also showed lower extractable Ni, Al, and Pb as Ca:Al increased. The remediation lesson is not that every site will respond identically, but that low-Ni, Fe–Al-rich silicate fines can drive the system toward lower lability rather than simply add metals.

Those field observations sit within a broader body of evidence. Watershed liming and calcium silicate additions at Hubbard Brook and related systems showed that Ca-based mineral additions can suppress Al, alter exchange chemistry, and create multi-year changes in soil and soil-solution behavior (Gu et al., 2017; Johnson et al., 2014; Likens et al., 1998). Recent ERW studies likewise show that well-chosen basaltic feedstocks can behave as slow-release liming materials in temperate agriculture and can do so without driving major increases in plant-available Ni or Cr at agronomic rates (Beerling et al., 2024; Dupla et al., 2024; Lewis et al., 2021). Conversely, ultramafic or olivine-rich materials with higher intrinsic Ni and lower reactive Fe–Al supply are more likely to sustain metal release or require stricter stewardship (Dupla et al., 2023; Flipkens et al., 2021).

Hydrologic connectivity is an especially important lesson for practitioners. The Vermont deployment showed that receiving zones can express stronger and more durable geochemical signals than the amendment footprint itself. For remediation, this implies that stabilization processes are not confined to the treated soil volume but can extend along hydrologically connected pathways where weathering products accumulate. In many contaminated landscapes, these receiving zones correspond to areas where metals have been redistributed through prior leaching or runoff, suggesting that mineral-based stabilization may preferentially reinforce geochemical conditions in these high-risk compartments. At the same time, this behavior requires that verification programs be designed as transport-and-transformation frameworks rather than as one-time soil pH checks (McGlynn et al., 1999; Naiman & DeCamps, 1997; Power et al., 2025).

A field-executable carbonate–silicate remineralization method

The method is intended for shallow cationic-metal problems where the remedial objective is to reduce risk in place, not universally replace excavation. It is often most attractive either as a stand-alone shallow-soil stabilization remedy or as a polishing step after removal of discrete hotspots. A central objective of the framework is to improve the reliability of in situ stabilization by controlling amendment delivery, reaction pathways, and verification against regulatory endpoints. Table 1 summarizes the design sequence, and Tables 2 and 3 outline feedstock screening and verification. In this context, the framework expands the decision space between full excavation and in situ stabilization by providing a more controlled and potentially more reliable stabilization pathway that practitioners can evaluate alongside conventional remedies.

Site screening and conceptual site model

Start with the decision, not the amendment. Delineate Areas of Concern (AOCs), identify the depth interval carrying exposure risk, and define the remediation endpoint, whether to reduce leachability (e.g., toxicity characteristic leaching procedure (TCLP) and synthetic precipitation leaching procedure (SPLP)), reduce extractable metal, reduce bioaccessibility, support vegetative cover, or achieve compatibility with intended land use (Berman et al., 2022; Defoe et al., 2014). For many legacy Pb and mixed cationic-metal problems, the critical interval will be the upper 5–30 cm, where direct contact, dust generation, and shallow runoff originate. Baseline pH, exchangeable acidity, exchangeable aluminum, and the labile or extractable fraction of the target metals should be mapped because the method relies on acid-neutralization demand and exchange chemistry rather than on total metal mass alone.

Contraindications must be screened early. Oxyanion-forming metalloids (especially As and Se), PFAS, chlorinated solvents, and mixed organic contamination can require separate remedies, modified prescriptions, or paired sorbents (Christ et al., 1999; Davidson, 2013; Song et al., 2019). The method is strongest where cationic metals are the primary risk drivers. It is not a license to raise pH indiscriminately across complex mixed-waste sites.

Feedstock selection and quality screening

Feedstocks should be treated as engineered inputs, not generic rock dust. Prefer low-Ni, Fe–Al-rich mafic fines, basalt, meta-basalt, diabase, gabbro, or similarly reactive Ca–Mg silicate fines, with enough Fe and Al to favor scavenging and secondary-phase development (Dupla et al., 2023; Lewis et al., 2021). Position along the Goldich weathering series provides a useful framework for interpreting feedstock behavior, as mafic, Fe–Al-rich materials tend to promote net scavenging of cationic metals, whereas more ultramafic, olivine-rich materials are more likely to sustain metal release. Bulk geochemical proxies such as Mg:Si ratio can therefore be used as preliminary screening indicators, but should be interpreted alongside mineralogical composition and trace-metal content rather than used as stand-alone selection criteria (Zacharias, Rioux, Sun, Tatge, Warren, et al., 2026). Quarry fines, crusher dust, and washed fines can be excellent candidates because they are locally available and often low-value byproducts, but only after screening for mineralogy, trace-metal burden, asbestos, sulfides, and batch consistency (Bakken et al., 2000; Dahlin et al., 2015; Flipkens et al., 2021).

Particle size should be selected to balance reactivity against field handling and worker protection. Weathering rates are strongly surface-area dependent, so material that is too coarse may not influence soil chemistry within a practical remediation time frame, whereas material that is too fine can create dust and handling challenges. In practice, this generally requires a substantial fine fraction, often including particles below ~100 μm, to provide sufficient reactive surface area for meaningful alkalinity generation over months to years. Specific surface area (e.g., Brunauer–Emmett–Teller [BET]) provides a more direct measure of reactive surface area than particle size alone and can help explain differences in weathering behavior among materials with similar grain-size distributions. Where available, BET measurements can therefore be used as a supporting indicator of expected reactivity, but should be interpreted alongside particle-size distribution and field handling considerations rather than used as a stand-alone design criterion. For example, the basalt used in the Vermont deployment exhibited a BET surface area of ~4.3 m^2 g^{-1}, consistent with a fine, reactive material capable of influencing soil chemistry over annual timescales (Zacharias, Rioux, Sun, Tatge, Pihlap, et al., 2026).

As a practical rule, high-Mg ultramafic materials, obvious olivine- or spinel-rich feedstocks, or sulfide-bearing materials should trigger heightened scrutiny rather than routine use. Feedstock screening should include total metals, where relevant feedstock leach tests, particle-size distribution, moisture and dustiness, and simple mineralogical review. If the amendment itself introduces a trace-metal liability, the remedy loses credibility before it reaches the site.

Bench- and small-scale testing and blend design

Bench- and small-scale testing is where the remedial design becomes real. Batch tests, short columns, small pots, or microplot trials can be used to calibrate dose, carbonate fraction, pH trajectory, extractable-metal response, and leachability response for the specific soil and contaminant profile (Campisano et al., 2017; Dupla et al., 2025). The purpose is not to force every site into a universal formula but to determine how much fast alkalinity is needed up front and how much slower silicate buffering is needed to hold the system in a desirable operating window.

In most cases, a modest carbonate fraction is best treated as a starting lever rather than a fixed recipe. As an initial bench-scale starting range, a small carbonate addition on the order of low-single-digit weight percent to roughly 10 wt.% of the total amendment can be evaluated to accelerate early neutralization, while the silicate fraction supplies slower long-term buffering. Final blend ratios can be set by site tests, not by theory alone. The design target is usually a buffered near-neutral soil, often around pH 6.5–7.5, rather than the highest pH that can be achieved (Cho et al., 2010; Goulding & Blake, 1998). Overshooting pH can undermine revegetation and may worsen metalloid mobility.

Application design and field execution

Match placement to contaminant distribution. For most brownfield and urban fill problems, treating the upper 5–30 cm is more sensible than deep mixing because that is where dust generation, direct contact, and many legacy Pb inventories are concentrated (Defoe et al., 2014). Where access and disturbance allow, shallow incorporation improves soil-amendment contact. Where disturbance is constrained by utilities, compaction, pavement remnants, or occupancy, surface top-dressing coupled with a vegetative cap can still function as a lower-disturbance stabilization strategy.

Application rate should also be bench-calibrated, but practical field starting ranges are generally in the same range as aggressive liming or remineralization programs rather than trace fertilizer additions. For shallow soils, many sites will likely fall within approximately 5–50 t ha−1 total amendment, with more modest rates often appropriate for already buffered zones and higher rates reserved for acidic hotspots or for hybrid ex situ mixing scenarios. Variable-rate application is especially useful because the strongest response often occurs where exchangeable acidity and labile metal are already highest (Burke et al., 1999; Hartmann et al., 2013). In practice, agricultural lime spreaders, construction spreaders, municipal V-notch or salt spreaders, or ex situ batch mixing equipment can all be used, depending on site access and the desired degree of uniformity.

Dust control is a design requirement, not an afterthought. Wetting, tarping, limiting drop heights, staging on prepared pads, and sequencing application around wind conditions should be part of the construction plan. Where uniform in situ mixing is not feasible, excavate the target interval, blend ex situ and return the material to grade. Where higher uniformity or tighter process control is required, excavation and ex situ blending using equipment such as pug mills, ribbon mixers, or batch mixing systems can provide a more controlled and verifiable treatment approach. This configuration allows amendment dose and distribution to be tightly managed before re-placement, which may be advantageous for sites requiring higher confidence in performance or regulatory signoff. For many brownfields, this hybrid approach may be easier to verify than attempting perfect in-place incorporation.

Vegetative cover, co-amendments, and hybrid remedies

A vegetative cap adds more than erosion control. Vegetation reduces dust, limits surface runoff, moderates pH excursions through rhizosphere processes, and supports the re-establishment of soil function in future reuse scenarios (Song et al., 2019). For brownfield applications, grasses or mixed cover crops that can establish quickly are usually more valuable than species richness during the initial weathering period.

Co-amendments should be used strategically. Activated carbon or biochar can be paired with mineral buffering where hydrophobic organics co-occur (Bai et al., 2013). Phosphate or reactive Fe-oxide additives may be useful where specific metals or metalloids dominate (Fleming et al., 2013). Just as important, the method does not need to replace excavation to be useful. In practice it may be most defensible as a shallow-soil stand-alone remedy for laterally extensive low-to-moderate contamination, or as a polishing step after hotspot removal, especially when the objective is to reduce residual lability and disposal volume rather than eliminate all soil handling (Hou et al., 2023; Song et al., 2019).

Verification and monitoring

Verification should be built around the remedial decision. If the objective is hazardous-waste classification relief, prioritize leachability tests such as TCLP or SPLP. In cases where regulatory classification is governed by leachability criteria, reducing TCLP concentrations below hazardous-waste thresholds may allow treated soils to transition from Subtitle C hazardous waste to Subtitle D non-hazardous classification, subject to site-specific regulatory approval. If the objective is risk-based soil management for reuse, pair those tests with regionally accepted extractable-metal assays and mechanistic indicators of buffering (Eckert & Sims, 1995; Grubinger et al., 2011; Wolf & Beegle, 2011). The most useful routine metrics are soil pH, exchangeable acidity, exchangeable aluminum, the extractable fraction of target metals, and Ca:Al as a simple indicator that the exchange system is moving away from Al dominance and toward base-cation buffering.

In hydrologically connected settings, add porewater or shallow groundwater measurements only where they are relevant to exposure or stewardship. Alkalinity, Ca, dissolved Al, and selected metals can reveal whether weathering products are propagating to receiving zones or whether early-time mobilization is occurring (Chapman et al., 2002; Geibe et al., 2006; McGlynn et al., 1999; Naiman & DeCamps, 1997). The monitoring plan must distinguish between a temporary transient and a failed remedy. A small early-time pulse does not necessarily invalidate the approach if the longer-term trend is toward lower lability and lower leachability. This is why time-resolved monitoring is important.

Where the method fits best, and where it does not

The framework is most defensible where cationic metals are concentrated in shallow soil, the soil is mildly to moderately acidic, and the remedial objective is risk reduction in place rather than complete mass removal. Typical use cases include shallow Pb-impacted brownfields, urban fill, municipal parcels awaiting reuse, legacy agricultural sites, and mine- or smelter-impacted surface soils where the contamination is laterally extensive but largely confined to the upper horizon (Berman et al., 2022; Hou et al., 2023).

The method is less suitable as a stand-alone remedy where oxyanion-forming metalloids dominate, where PFAS or chlorinated solvents are the primary drivers, where contamination resides chiefly in a deep dissolved plume, or where the soil is already strongly alkaline. In those settings, remineralization may still be useful as one component of a broader remedy, but it should not be treated as a universal substitute for contaminant-specific treatment (Christ et al., 1999; Davidson, 2013).

Communication is part of applicability. Practitioners should describe the remedy in time- and compartment-explicit terms: what happens in the treated soil, what could happen temporarily in porewater, and what metrics define success for the site decision. That framing is especially important when early-time geochemical adjustment is expected (Alloway, 2012).

Deployment value and co-benefits

For remediation practitioners, the value proposition is not just chemistry. The method can reduce excavation and hauling volumes, use locally available quarry fines, and improve the treated soil’s buffering capacity and revegetation potential. In post-remedy land uses that require vegetation or restored soil function, the same processes that immobilize metals can also improve pH and Ca availability and support healthier surface soil (Beerling et al., 2024; Goulding, 2016). When sourced from local aggregate operations, silicate fines may also offer supply-chain advantages relative to specialty amendments (Bakken et al., 2000; Dahlin et al., 2015).

Carbon sequestration can be a co-benefit, but it should remain secondary in remediation design. The primary objective is reduction of metal lability and leachability. If a project also produces incidental inorganic carbon removal or soil health improvement, those benefits are additive rather than determinative (Beerling et al., 2024; Beerling et al., 2020). That framing is important for regulators and landowners alike: this is first and foremost a risk-reduction method, not a carbon-credit strategy.

Limitations and research needs

This paper presents a field-executable method, not a claim of universal performance. The framework is grounded in real watershed observations and established geochemistry, but contaminated-site pilots are still needed to calibrate blend design against regulatory endpoints under the heterogeneity of actual brownfields. Future work should prioritize side-by-side trials against lime-only and excavation-plus-polishing workflows, durability monitoring over one to two years or longer, and bench-to-field decision tools that tie feedstock mineralogy to TCLP/SPLP and extractable-metal response (Campbell et al., 2023; Clarkson et al., 2024; Power et al., 2025).

More work is also needed on co-contaminant management, particularly for metalloids and PFAS, and on how to communicate temporary early mobilization without undermining confidence in longer-term stabilization. Even so, enough is already known to move from concept to disciplined field application. The chemistry is not speculative, the materials are widely available, and the verification tools are familiar to the remediation community.

Conclusions

Enhanced rock weathering can be repurposed from carbon removal into a practical remineralization method for stabilizing cationic metals in shallow soils. The key is not the generic use of rock dust, but the deliberate control of geochemistry through screened low-Ni, Fe–Al-rich silicate fines, optional carbonate blending, hotspot targeting, and verification against remediation endpoints. Conceptually, the method works by accelerating soil aging: it neutralizes acidity, increases negative surface charge, reoccupies exchange sites with base cations, and promotes mineral conditions that favor sorption and long-term reduction in lability.

Practically, it is best viewed as a field-executable, site-specific system that can complement or sometimes reduce reliance on excavation, particularly for shallow brownfield soils where cationic metals are the major constraint on reuse. The most defensible implementation pathway is straightforward: screen the site, screen the feedstock, bench-test the blend, place the amendment where the contamination lives, stabilize the surface, and verify response with both outcome metrics and mechanistic indicators. When done that way, ERW-derived remineralization is not merely another soil amendment. It becomes a credible remediation strategy.

Table 1. Practical design checklist for carbonate–silicate remineralization on brownfield and related contaminated sites.

Design step	Key questions and measurements	Practical output
Site/AOC delineation and depth target	Where are the metals concentrated? What are baseline pH, exchangeable acidity, and relevant extractable-metal metrics? What are the exposure pathways and intended land use?	Define treatment polygons, depth of concern, and primary performance endpoints.
Contraindications and co-contaminants	Are As/Se, PFAS, chlorinated solvents, mixed organics, or deep dissolved plumes likely to control remedy selection?	Exclude incompatible areas, segment AOCs, or plan co-amendments and alternate remedies.
Feedstock selection and QC	What is the feedstock geology, total metal burden, mineralogy, particle-size distribution, dustiness, and batch consistency? Is asbestos absent?	Approve or reject the source and define handling controls and source-specific QC.
Bench testing and blend design	What dose and carbonate fraction achieve the desired pH trajectory, extractable-metal response, and TCLP/SPLP performance?	Select blend ratio, application rate, and monitoring plan.
Placement and field execution	Will the site use top-dressing, shallow incorporation, or ex situ mixing? Where are the acidic or labile hotspots? What equipment and dust controls are available?	Finalize construction sequence, hotspot map, staging plan, and cover strategy.
Verification and adaptive management	Which metrics support signoff: leachability, extractable metals, pH, exchangeable Al, Ca:Al, and/or receiving-zone water chemistry?	Issue a verification package and define triggers for supplemental application or follow-up monitoring.

Table 2. Suggested feedstock screening and selection criteria.

Parameter	**Why it matters**	**Practical screening**	**Caution flags**
Bulk metal content	Prevents the amendment from creating a new liability.	Total metals plus feedstock leach tests where relevant.	Elevated Ni/Cr or metalloids without site-specific justification.
Mineralogy	Controls dissolution rate, scavenging potential, and acid-generation risk.	Supplier geology, petrography, XRD, or equivalent review.	Ultramafic, olivine/spinel-rich, or sulfide-bearing materials.
Fe–Al richness	Supports secondary phases and reactive sorption sites.	Prefer Fe–Al-rich mafic Ca–Mg silicate fines.	Very low Fe–Al relative to Mg-rich phases.
Particle size and dustiness	Balances reactivity against field handling and worker protection.	PSD, moisture, and dust-control plan.	Extremely fine powder with no dust-management strategy.
Batch consistency	Reduces variability in pH trajectory and metal response.	Sample each source lot or stockpile interval.	Mixed quarry wastes with no lot-based QC.
Asbestos and fibrous phases	Worker and public safety.	Asbestos screen appropriate to jurisdiction.	Positive screen or uncertain mineral fiber content.

Table 3. Verification package aligned with common remediation decisions.

Decision context	**Core metrics**	**Supporting metrics**	**Typical timing**
Reduce lability for reuse	Extractable target metals, soil pH, exchangeable acidity, exchangeable Al, Ca:Al	Vegetative cover, dust and erosion observations	Baseline; 1–3 months; 6–12 months; then as needed
Reduce leachability / support classification change	TCLP and/or SPLP	Extractable metals and soil pH	Baseline and post-treatment after chemical equilibration
Hydrologically connected stewardship	Alkalinity, Ca, dissolved Al, selected metals in lysimeters/drains/shallow groundwater	Rainfall or snowmelt context; field observations	Seasonal and event-based where relevant
Adaptive management	Hotspot resampling and spatial variability review	Field construction notes and cover performance	At each review point and before any supplemental application

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Conflict of Interest Statement

The author is the founder of BareFoote Metals, Inc. and has filed a provisional patent through Yale Ventures related to the methods described. No current financial relationships related to this work exist.

Data availability Statement

This manuscript is a methods-focused synthesis and does not present new datasets. It draws on previously published and cited studies for which data availability is described in the original sources.

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