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Comparative performance of Bauxsol™ and lime in acid mine drainage prevention from reactive waste rock for sustainable mine closure: a Canadian case study

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Abstract

Effective mine closure strategies are essential for ensuring geochemical stability of mine wastes and minimising their environmental risks. This study investigates the potential of Australian Bauxsol™ (Bauxsol) technology adapted to bauxite residues derived from the Vaudreuil Canadian refinery (Rio Tinto Aluminium and Lithium) as a sustainable alternative to lime for acid mine drainage (AMD) neutralisation and metal immobilisation for flooded waste rocks in open pits. Thirteen stabilisations tests were conducted in batch mode using 100 g of AMD-generating waste rocks and 150 mL of deionised water under controlled laboratory conditions (150 rpm on a rotary shaker), with varying amendment ratios (5 to 15% w/w Bauxsol or lime) and reaction times (4 to 24 hours). The results showed that Bauxsol increased pH progressively from 2.9 (control) to 6.7 (15%) after 24 hours. At a 15% Bauxsol amendment ratio, contaminants mobility decreased by more than 99% for Al, Fe, Zn and Cu, and reached 97% for Cd and Cr, and 95% for Ni and Co, while maintaining moderate alkalinity. Metals immobilisation efficiencies were positively correlated with amendment dosage, likely through hydroxide co-precipitation and sorption onto ferric oxides. In contrast, lime amendment induced high pH (> 12), raising concerns about effluent ecotoxicity and the stability of secondary minerals. However, Bauxsol amendment released Na (2,895 mg L^{-1}), K (83 mg L^{-1}), Ca (510 mg L^{-1}) and Mg (320 mg L^{-1}), increasing electrical conductivity to 12.5 mS cm^{-1}, while lime amendment released less Na (160 mg L^{-1}) and K (79 mg L^{-1}) but more Ca (920 mg L^{-1}), resulting in a lower increase in electrical conductivity (7.4 mS cm^{-1}). Thermodynamic modelling will provide an additional insight into the geochemical mechanisms involved. These findings highlight the potential of Bauxsol as a promising alternative to lime to prevent AMD generation from reactive waste rocks, supporting circular economy by valorising industrial residues.

Keywords: *mine closure, acid mine drainage, Bauxsol, lime, metal immobilisation, circular economy, flooded open pits*

1 Introduction

The closure of mine sites requires the implementation of sustainable strategies to ensure the geochemical stability of deposited mine waste as well as to limit long-term environmental risks. In many contexts, sulphide waste rock exposed to atmospheric conditions can generate acid mine drainage (AMD); a phenomenon that is particularly problematic during the restoration phase as it promotes water acidification and the release of dissolved metal(loid)s. From a mine restoration perspective, the addition of alkaline amendment is a commonly used approach to neutralise acidity and decrease the mobility of metal(loid)s. Lime remains a traditional choice due to its high reactivity but its use can result in extreme geochemical conditions or the rapid precipitation of secondary phases that can be unstable under saturated conditions (Dheilly et al. 2002).

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These limitations have prompted the exploration of alternative materials that are more compatible with restoration requirements. Among these alternatives, neutralised and treated bauxite residues, marketed under the name Bauxsol™, are of significant relevance because they are enriched in ferric and aluminous oxides, conferring a significant capacity for sorption and co-precipitation of metal(loid)s (Clark et al. 2004).

These Fe_2O_3 and Al_2O_3 enriched residual materials have been widely applied in Australia, where they have showed a satisfactory ability to neutralise acidic environments and immobilise different metals in various mining contexts. For example, Bauxsol has been successfully used for in situ treatment of contaminated surface water and soils (Despland 2014), passive treatment of contaminated mine drainage, and the direct amendment of tailings and waste rock to limit the production of AMD (Ardau et al. 2013). To date, only one investigation conducted in Quebec, Canada, has explored the use of Bauxsol, specifically an Australian formulation, within a permeable reactive barrier for mine drainage treatment (Lapointe et al. 2006). As part of ongoing efforts to develop locally adapted solutions for mine site rehabilitation and closure, a Quebec variant of Bauxsol (Canadian Bauxsol™) was first produced in June 2024 using bauxite tailings from Rio Tinto's (RTAL) refinery, in collaboration with Virotec. This development represents an important step forward. No other study has ever evaluated a Bauxsol produced locally, nor assessed its performance on acid-generating waste rock under controlled conditions. In addition, its regulatory status is still undefined in Quebec, and Canada reinforces the need for rigorous scientific validation prior to any operational deployment. Unlike in Australia, Bauxsol is recognised as a commercial manufactured product that facilitates its deployment. This situation raises several questions about the chemical and mineralogical composition, as well as the environmental stability, of Quebec Bauxsol, making it necessary to carry out an in-depth characterisation to evaluate its long-term geochemical behaviour and potential to be used as amendment in mine site restoration. Within this framework, Bauxsol is of particular interest as it aligns with circular economy principles by recovering bauxite residues to reintroduce them as an environmental amendment.

In this context, the present study aims to comparatively evaluate the behaviour of Quebec Bauxsol, mixed with lime as amendment to decrease the generation of AMD from sulphide-rich waste rocks, using batch tests conducted under controlled conditions.

2 Methodology

2.1 Physico-chemical and mineralogical characterisation of waste rocks and Bauxsol

Partially altered and already acid-generating waste rocks were sampled on an active gold mine site to better reproduce the geochemical behaviour of sulphide-rich waste rocks exposed to atmospheric conditions prior to mine site restoration. Before their detailed characterisation, waste rocks samples were sieved to a diameter of less than 4 mm to have the same diameter as the Bauxsol and therefore ensure the homogeneity of the materials tested. A detailed physico-chemical, mineralogical and microbiological characterisation of both Bauxsol and waste rocks samples was performed to better understand their behaviour during geochemical experiments to prevent AMD generation from waste rocks. The specific surface area was measured using the Brunauer–Emmett–Teller (BET) method (Jaroniec et al. 1998) , which is based on nitrogen adsorption at low temperatures. This technique makes it possible to determine the amount of gas adsorbed to the material and to deduce the accessible developed surface, assuming the formation of a monomolecular layer (Irwansyah et al. 2022). It thus provides a reliable estimate of the reactive surface of the material, which is essential for understanding its behaviour in pH buffering tests. Regarding the geochemical characterisation, the chemical composition of the mine waste rock and Bauxsol was determined in the laboratory. Solid samples were subjected to multi-acid digestion (nitric, HNO_3; perchloric, $HClO_4$; hydrofluoric, HF; and hydrochloric, HCl acids) in a microwave oven before being analysed by inductively coupled plasma atomic emission spectrometry (ICP-AES). The samples were also analysed by X-ray fluorescence to determine the relative percentages of oxides for major elements. Subsequently, the concentrations of sulphur and carbon were determined using an induction furnace. This technique relies on the complete combustion of the sample in a stream of pure oxygen, resulting in the oxidation of sulphur to SO_2 and carbon to CO_2. The gases produced are then quantified by infrared absorption, allowing a precise measurement of the total carbon and sulphur

contents, including sulphides. The third phase is the initial mineralogical characterisation. The samples were prepared in the form of polished epoxy resin pellets and analysed by XRD and scanning electron microscopy. An automated QEMSCAN-type analysis was also performed, allowing identification of the mineral phases and their potential role in the generation or neutralisation of acidity.

2.2 Evaluation of the performance of Bauxsol and lime to decrease acid mine drainage generation from waste rock samples

A series of 13 geochemical experiments was carried out under controlled laboratory conditions to determine the efficiency of Bauxsol for use as a replacement to lime in limiting the generation of AMD from reactive waste rock samples. To do so, 100 g of waste rock was mixed with different ratios (0, 5, 8, 10, 12 and 15% w/w) of amendments (Bauxsol and lime) and immersed in 150 mL of deionised water in 250 mL beakers. The mixtures were then placed on a stirring table, with constant stirring at 150 rpm (Figure 1) for different reaction times (4, 8 and 24 h). This method was chosen preferentially over the magnetic bar stirring method to avoid the risk of breaking the waste rock particles so as not to generate fresh contact surfaces and subsequently release metal(loid)s and additional acidity. The different timescales were chosen based on the responsiveness of Bauxsol and its effectiveness experienced during previous experiments. The mixtures were then vacuum filtered (particle size: 0.45 µm) to separately collect the solid and liquid samples for further characterisation.

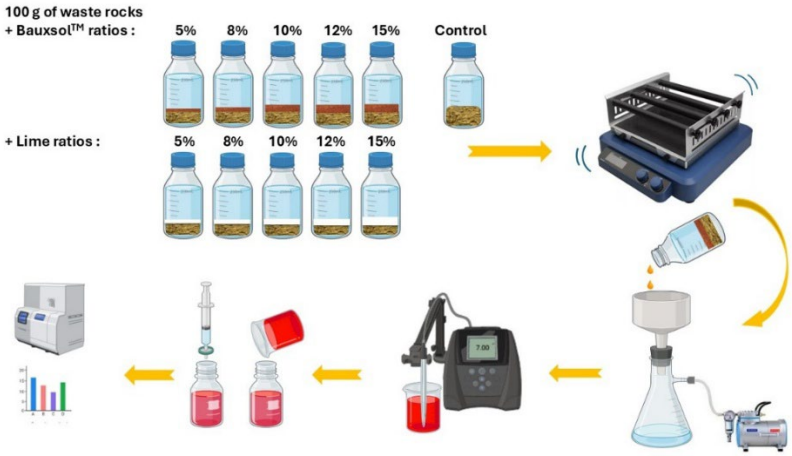

Figure 1 Experimental set-up used for batch tests with Bauxsol and lime amendments

The pH, electrical Conductivity (EC) and redox potential (Eh) of the water recovered after solid-liquid separation were measured using specific probes. After recording the parameter measurements, half of the liquid samples were poured into polyethylene bottles for chemical analysis using an ICP-AES (for the determination of dissolved metal(loid)s' content) and the remainder were filtered into bottles at < 0.45 µm for ion chromatography analysis (for the determination of sulphate, thiosulphate, fluoride and chloride contents). Leachates extracted from kinetic tests were collected, filtered to 0.45 µm and acidified prior to analysis.

3 Results and discussion

3.1 Waste rocks and Bauxsol characterisation

3.1.1 Physico-chemical characteristics

The Bauxsol sample is characterised by homogeneous particle size centered around millimetric particles (4 mm). This narrow distribution reflects a stable dispersion of the particles. The specific surface area is high, approximately 22 m^2g^{-1}, confirming a fine texture and a developed porosity. These characteristics enhance the material's effectiveness for metal(loid)s and anions retention, which is a major asset for environmental applications.

3.1.2 Mineralogical characterisation

From a mineralogical standpoint, the Bauxsol is characterised by a mineral assemblage dominated by an extremely fine-grained and complex phase, described as a mixed phase accounting for 78.33% of the sample (Figure 2a), identified by QEMSCAN analysis. Even at an analytical resolution of 1 µm this phase remains indistinguishable, indicating a very finely cemented and chemically heterogeneous matrix. Added to this dominant matrix are approximately 13.51% of secondary iron oxides (Figure 2b), occurring both as massive aggregates and disseminated within the cemented phase. These oxides display variable compositions enriched in Fe (up to 87% Fe^{O}) and incorporate a range of trace elements, reflecting their secondary and remobilised nature. Energy-dispersive X-ray spectroscopy (EDS) analyses of the associated aggregates reveal a pronounced enrichment in Al-Si-Na, suggesting a signature inherited from the Bayer process, with Na most likely associated with the caustic soda used during alumina production. The average composition of this phase notably includes Na_2O (7.15%), Al_2O_3 (22–24%) and SiO_2 (31%), with subordinate CaO and SO_3 contents, confirming the presence of a poorly crystallised sodic aluminosilicate assemblage. The mineralogical results also suggest the possible presence of Ca-bearing phases of the portlandite type; however, these are described as being completely masked by their very small size and signal mixing, rendering any formal identification particularly challenging (Figure 2c). A major distinguishing feature of the Bauxsol is the abundant presence of halite (4.23%) (Figure 2d), identified by QEMSCAN as a secondary post-polishing phase developing in positive relief on the surface of the polished pellet. This behaviour is consistent with a matrix excessively enriched in salts, with Na and Cl having been mobilized upon contact with water. Minor phases such as quartz (1.40%), diaspore (0.96%), clays (0.43%) and Ti oxides (rutile and ilmenite, < 0.6% combined) identified by QEMSCAN complete the assemblage, confirming a mineralogy largely dominated by fine-grained, hydrated and chemically reactive secondary phases.

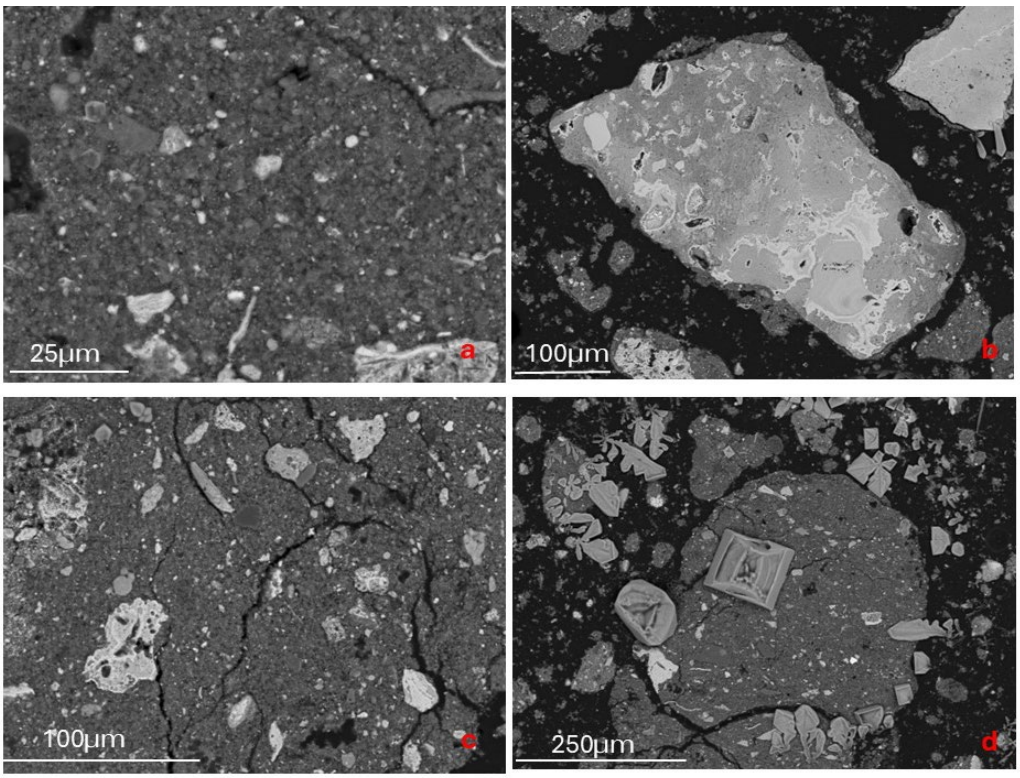

Figure 2 Representative mineralogical features of Bauxsol (Backscattered Electron (BSE)-energy-dispersive X-ray spectroscopy/QUEMSCAN analysis)

The waste rocks exhibit a mineralogy strongly marked by alteration, with more than 50% of the polished section composed of amorphous secondary iron oxides and altered sulphides, as demonstrated by QEMSCAN mapping and supported by EDS point analyses. The pronounced variability in Fe-S-O contents from one grain

to another indicates a high degree of chemical heterogeneity and suggests that these altered phases could be subdivided into more than 10 distinct mineralogical groups. Quantitatively, altered iron oxides account for approximately 36.9% (Figure 3a), while oxidised pyrite reaches 12.2% (Figure 3b), illustrating a continuous textural and chemical gradation from relatively fresh sulphides (Figure 3c) to strongly altered oxyhydroxides or sulphates.

Elemental compositions of these phases show significant Fe enrichment (up to 58% Fe in altered S-bearing phases) (Figure 3d) accompanied by S and SO_3, confirming advanced oxidation processes and the formation of reactive secondary phases such as jarosite (although minor, 0.01%).

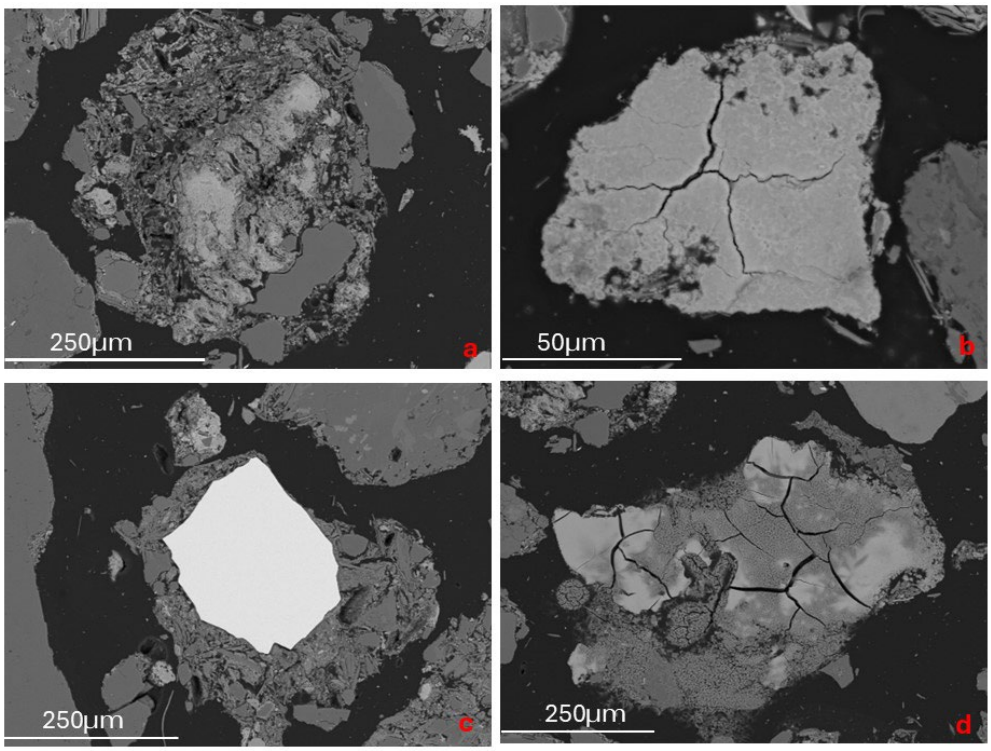

Figure 3 Representative mineralogical features of acid-generating mine waste rocks (BSE-energy-dispersive X-ray spectroscopy/QEMSCAN analysis)

The silicate fraction nevertheless remains significant, being dominated by quartz (23.3%) and mixed feldspars (14.7%), with additional contributions from plagioclase (oligoclase: 4.84%, albite: 1.49%) and phyllosilicates such as muscovite (3.32%), paragonite (0.25%), chamosite (0,2) and biotite (0.1%). These phases define an overall aluminosilicate framework for the waste rock, albeit one profoundly modified by sulphide-driven alteration. Secondary occurrences of gypsum (0.81%), apatite, epidote and amphiboles indicate the redistribution of elements (Ca, S, P) during alteration processes. Finally, a non-negligible proportion of the observed phases corresponds to amorphous assemblages enriched in Mg, Al, Si, P, S, Cl, Mn and Ti, detected through combined QUEMSCAN and EDS signals and described as geochemical ‘trash bins’, highlighting the considerable mineralogical complexity and potential reactivity of the tailings in the context of neutralisation tests.

3.1.3 Waste rock and Bauxsol sulphur and carbon content

Mine waste rocks are characterised by a very low total C content (0.03 wt%) combined with a high total S content (2.7 wt%), resulting in an extremely high S/C ratio that is typical of strongly acid-generating materials. This geochemical signature is corroborated by a very high acid potential (AP), estimated at 84.37 kg $CaCO_3$/t of waste rock, whereas the neutralisation potential (NP) remains very low (2.5 kg $CaCO_3$/t). Consequently, the net neutralisation potential (NNP = NP - AP) is strongly negative (NNP= −81.9 kg $CaCO_3$/t), classifying

these waste rocks as potentially to highly acid-generating according to classical AMD prediction criteria (NNP < -20 kg $CaCO_3$/t). These materials exhibit virtually no intrinsic buffering capacity and are therefore prone to generating substantial net acidity upon sulphide oxidation, highlighting the need for alkaline amendments to mitigate system acidification. In contrast, Bauxsol displays a higher total C content (0.30 wt%) and a low total S content (0.26 wt%), resulting in a low S/C ratio and a limited potential for acidity generation. Its AP is moderate (8.125 kg $CaCO_3$/t) while its NP reaches 25 kg $CaCO_3$/t, yielding a distinctly positive NNP (16.9 kg $CaCO_3$/t). According to established classification schemes, this positive acid-base balance allows Bauxsol to be classified as a non-acid-generating material, with an excess neutralisation capacity. Besides, mineralogical data indicate that in Bauxsol, sulphur is exclusively detected as oxidised sulphur (SO4), with no evidence of sulphide minerals, indicating that sulphur seems to be predominantly present as sulphate species that do not generate acidity through oxidation. Consequently, the AP calculated from total sulphur for Bauxsol should be regarded as conservative and likely overestimates its effective acid-generating capacity. In contrast, sulphur in mine waste rocks is largely hosted in sulphide minerals, mainly pyrite, together with secondary sulphur-bearing oxidation products, which directly explains their very high AP and strongly negative NNP.

3.2 Evaluation of the performance of Bauxsol and lime to decrease acid mine drainage generation from waste rock samples

3.2.1 Evolution of pH/redox potential/electrical conductivity/physico-chemical parameters

The results of the batch experiments show a gradual improvement in the physico-chemical parameters of the leachate with the addition of Bauxsol and lime (Figure 4). The control, without any amendment, remained very acidic, with a pH of 2.93 after 4 h which dropped to 2.5 after 8 and 24 h, confirming the potential of waste rocks to produce large amounts of acidity without the addition of neutralising materials.

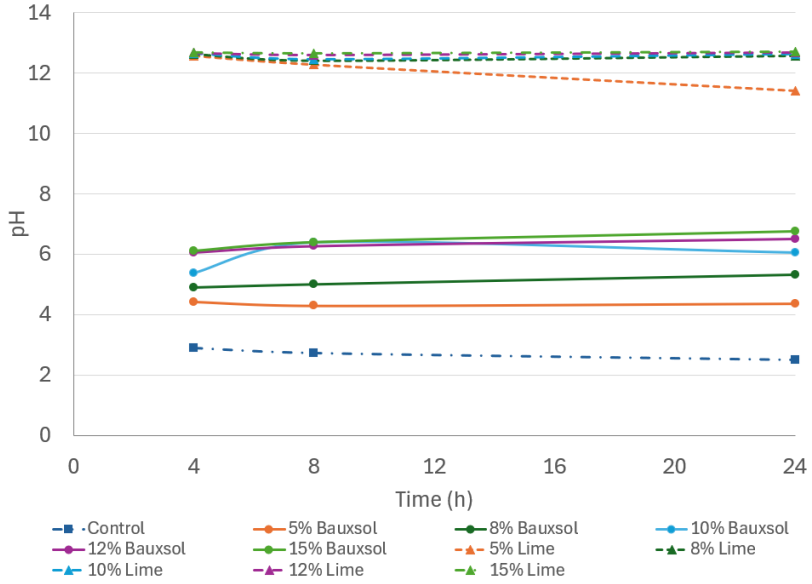

Figure 4 Evolution of pH as a function of time and as a function of the added amendments' ratios using Bauxsol (solid line) or lime (dashed line)

The addition of Bauxsol results in a gradual increase in pH depending on the ratio and contact time. For 5%, the pH slowly increases to 4.30–4.43, reflecting partial neutralisation over time, which mainly occurs within the first 4 hours. At 8% the values reach 4.9–5.31 depending on the duration, indicating a notable improvement when increasing the proportion of Bauxsol in the mixture. This trend continues with a 10% addition of Bauxsol, where the pH increases from 5.39 after 4 h to 6.05 after 24 h. Similar trends were observed for the mixtures composed of 12 and 15% of Bauxsol ,with slight increase in final pH observed when increasing the proportion of Bauxsol. This trend can be explained by the presence of oxides such as hematite (Fe_2O_3), goethite [FeO(OH)], gibbsite [$Al(OH)_3$] and boehmite [AlO(OH)], which are known for their high

buffering capacity and ability to bind metal(loid)s by adsorption or co-precipitation, in the Bauxsol. These results show that the effectiveness of Bauxsol is directly dependent on the ratio applied and the contact time. Intermediate ratios, such as 12%, offer an interesting neutralisation efficiency, while 15% amendments lead to near-neutral conditions, which are optimal for decreasing the solubility of most of leachable metal(loid)s (Figure 4). In comparison, lime induces an immediate and very high increase in pH, reaching values above 12 from the first ratios (Figure 4). For the mixture composed of 5% lime, the final pH varies between 11.4 and 12.5 depending on the retention time. A slight increase in final pH values has been observed as the proportion of lime in the mixture increases from 8 to 15%, reaching a plateau around 12.6–12.7. These results confirm that lime significantly increases pH and alkalinity, which could decrease the mobility of metal(loid)s through co-precipitation as hydroxides and sorption mechanisms, even if some Fe and Al can be released as $Fe(OH)_4^-$ and $Al(OH)_4^-$ at such high final pH. Although lime is effective in neutralising acidity, the amounts used must be rigorously determined to restrict pH increases below 9.0 and therefore avoid the need to inject some CO_2 to decrease the final pH and meet the Directive 019 criteria (local regulatory criteria [MELCCFP 2026]).

Regarding the evolution of the redox potential (Eh), the results indicate that the addition of Bauxsol or lime leads to a gradual decrease as the contact time increases (Figure 5). The control shows high values, with 822.2 mV after 4 h, reflecting a strongly oxidising environment favourable to the oxidation of sulphides and the release of ferric iron (Fe^{3+}) in solution. For Bauxsol experiments it can be noticed that the increase of the proportion of Bauxsol used in the mixture leads to a decrease of Eh values as the retention time increases (Figure 5). After amendment with 5%, a major decrease of Eh values is observed, going from 657.3 mV after 4 h to 594.6 mV after 24 h. The highest ratio (15% of Bauxsol) shows the lowest Eh values (529.3 mV at 4 h versus 431.8 mV at 24 h), highlighting a possible limitation of the oxidation reactions responsible for acid generation and metal(loid)s release as the proportion of Bauxsol added increases, contributing to the chemical stabilisation of the waste rock. This phenomenon may be linked to the progressive formation of iron oxyhydroxides [$Fe(OH)_3$] at a pH close to neutrality, which helps to immobilise the products of sulphide oxidation. For the oxidation-reduction potential (Eh) of waste rocks amended with lime, the behaviour is different (Figure 5). The Eh drops sharply, from 166.4 mV after 4 h for 5% to about 141.9 mV at 24 h for 15%, reflecting a highly reducing environment. This rapid reduction, from 822.2mV to 166.4mV, effectively limits sulphide oxidation, but combined with a pH above 12 it can promote the precipitation of secondary minerals, favouring the immobilisation of dissolved metals (Mn, Zn, Ni).

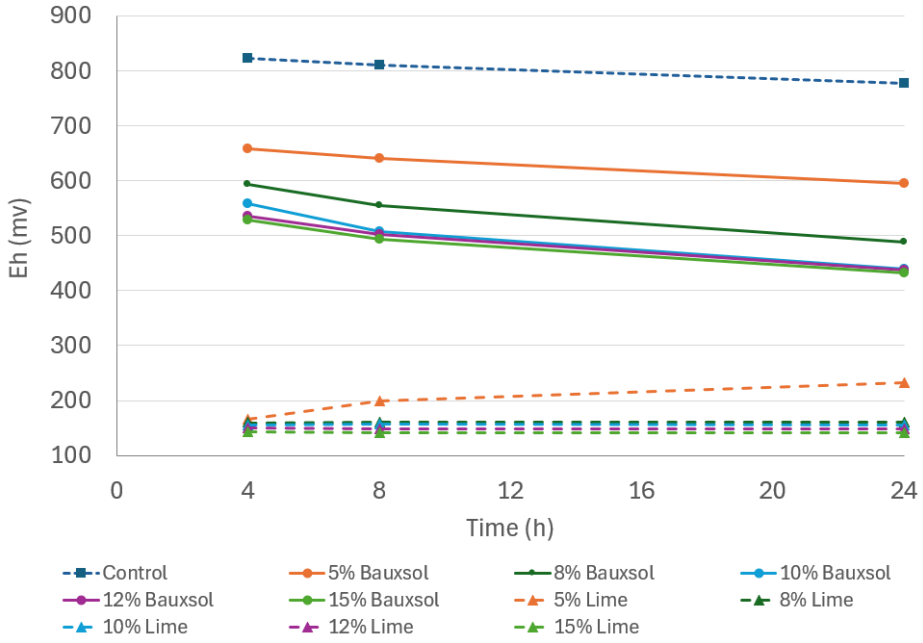

Figure 5 Evolution of the oxidation-reduction potential (Eh) as a function of time and of the ratios of the added Bauxsol (solid line) or lime (dashed line)

Regarding electrical conductivity, the values increase with the Bauxsol ratio, from 7.25 mS/cm for 5% to 12.54 mS/cm for 15% (Figure 6). This increase reflects the release of ions in solution, possibly related to cationic exchanges and the partial dissolution of the soluble phases of Bauxsol. Indeed, the presence of NaCl in this amendment, as well as the reagents used for its neutralisation (i.e. $CaCl_2$, $MgCl_2$), can explain the increase in EC observed as the proportion of Bauxsol used increases. While this increase does not compromise the capacity of Bauxsol to neutralise the acidity released from waste rocks, it highlights the need to carefully select the amount of Bauxsol to be added as amendment to avoid potential adverse impacts on water quality due to residual salinity and associated toxicity. In the long term, this salinity could influence the mobility of the elements and structure of soils, which requires careful management of the applied rates.

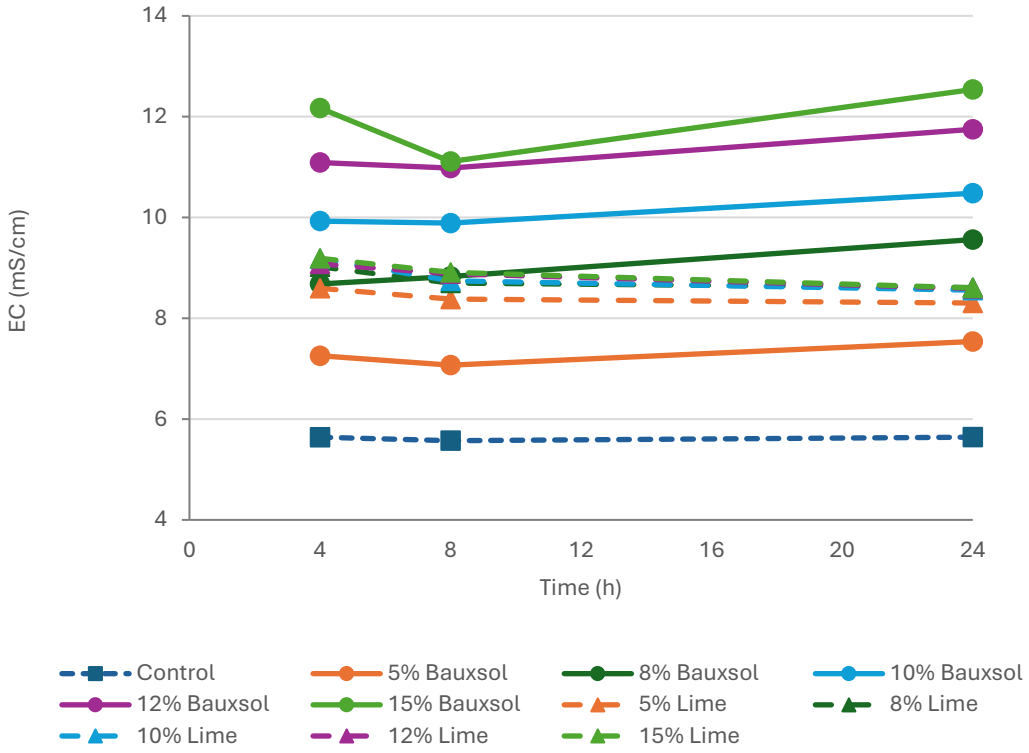

Figure 6 Evolution of the electrical conductivity (EC) as a function of time and of the ratios of the added Bauxsol (solid line) or lime (dashed line)

The high and relatively stable EC (8.3 to 9.2 mS/cm) obtained after the addition of different proportions of lime reflects a high ionic concentration in the solution (Figure 6). This phenomenon is explained by the rapid and complete dissolution of the hydrated lime used [$Ca(OH)_2$]. This highly soluble neutralising agent releases Ca^{2+} and OH^- ions in large quantities, which simultaneously increases the EC and pH (> 12). The presence of excess hydroxide ions gives the medium a very high alkalinity, which is likely to promote the precipitation of metals in the form of hydroxides [i.e. $Al(OH)_3$, $Fe(OH)_3$, $Mn(OH)_2$)] which could contribute to their immobilisation.

In summary, Bauxsol ensures a gradual decrease in Eh and controlled neutralisation, while lime induces extreme conditions (high pH and low Eh). On the other hand, these 2 amendments also lead to an important increase in EC, which is an indicator of a high ionic concentration in the leachate.

3.2.2 Chemical analyses of dissolved metal(loid)s

A major decrease in metal(loid)s concentrations is observed for most of the metal(loid)s after the addition of Bauxsol (Table 1), indicating that the immobilisation of these contaminants may occur through co-precipitation and sorption mechanisms activated by the mineralogical and chemical properties of Bauxsol.

Table 1 Concentrations of metal(loid)s (mg L^{-1}) in solutions as a function of Bauxsol amendment and lime ratios

Elements (mg L-1)	Control	5% Bauxsol	8% Bauxsol	10% Bauxsol	12% Bauxsol	15% Bauxsol	5% Lime	8% Lime	10% Lime	12% Lime	15% Lime
Al	190	85	0.61	0.12	0.09	0.058	0.96	0.071	0.11	0.1	0.03
As	0.08	0	0	0.001	0.001	0	0.0064	0.0070	0.0060	0.0060	0.0055
Cd	0.05	0.03	0.008	0.003	0.001	0.001	0.0010	0.0010	0.0010	0.0010	0.0010
Ca	580	510	500	620	500	510	590	1,100	1,100	1,000	920
Cr	0.23	0.005	0.005	0.005	0.005	0.005	0.019	0.0052	0.0065	0.0068	0.0082
Co	0.35	0.23	0.10	0.038	0.02	0.02	0.020	0.020	0.020	0.020	0.020
Cu	4.90	0.19	0.057	0.014	0.025	0.017	0.15	0.15	0.15	0.15	0.18
Fe	790	0.49	0.10	0.10	0.10	0.10	0.1	0.1	0.1	0.1	0.1
Mg	74	230	270	360	290	320	1.7	0.20	0.20	0.20	0.20
Mn	8.20	6.30	4.10	2.60	0.70	0.32	0.0030	0.0030	0.0030	0.0030	0.0030
Ni	0.28	0.22	0.14	0.09	0.028	0.014	0.010	0.010	0.010	0.010	0.010
Pb	0.01	0.003	0.001	0.002	0.002	0.001	0.0010	0.0010	0.0010	0.0010	0.0010
K	1.50	10	9.90	11	8.30	11	99	74	77	72	79
Na	9.30	1,200	1,800	2,700	2,600	3,000	230	180	170	150	160
Zn	9.40	4.40	0.54	0.11	0.021	0.031	0.0055	0.0050	0.0050	0.013	0.012

For some elements, the immobilisation efficiencies (Table 2) seem to be slightly dependent on the proportion of Bauxsol used in the mixture, with low increases (< 10%) in removal efficiencies observed with the increase of Bauxsol. For example, dissolved iron is efficiently removed (up to 99.93%) even with a low proportion of Bauxsol (5%), which might be explained by its precipitation as hydroxides and which is favoured by the rise in pH (Kang et al. 2016). These reactions are favoured by the partial dissolution of hydroxylated phases such as gibbsite [$Al(OH)_3$] and boehmite [AlO(OH)], as well as by ferric oxyhydroxides (hematite, goethite) contained in the mineralogical composition of Bauxsol, which provides reactive surfaces for metal(loid)s fixation. Ferric oxides such as goethite (FeOOH) and hematite (Fe_2O_3) exhibit slower dissolution kinetics (10^{-11} to 10^{-13} $mol.m^{-2}.s^{-1}$ for goethite and 10^{-14} to 10^{-16} $mol.m^{-2}.s^{-1}$ for hematite) (Bruno et al. 1991), but provide stable reactive surfaces for the sorption of metal(loid)s. Indeed, it can be noticed that the concentration of As is decreased by 99.0–99.6%, which can be explained by its affinity for Fe-oxyhydroxides via inner-sphere complexes (Naja & Volesky 2011), where the As(+V) ion shares hydroxyl ligands with the surface, forming strong covalent bonds (Gauthier et al. 2024). This complex, characterised by the absence of interposed water molecules, confers high thermodynamic stability and resistance to desorption (Belaid & Kacha 2011). Chromium follows the same immobilisation mechanism through its sorption onto Fe- and Al-oxyhydroxides (such as goethite; hematite; ferrihydrite). Lead immobilisation (65.6–88.9%) seems to be associated with strong adsorption onto Fe- and Al-oxyhydroxides, as well as its co-precipitation as secondary minerals such as cerussite ($PbCO_3$) and plumbojarosite ($PbFe_6(SO_4)_4(OH)_{12}$) (Burton et al. 2022), which reinforces its long-term immobilisation.

Table 2 Removal efficiencies (%) of metal(loid)s based on added Bauxsol and lime ratios

	Bauxsol					Lime				
Element	**5%**	**8%**	**10%**	**12%**	**15%**	**5%**	**8%**	**10%**	**12%**	**15%**
Al	55.26	99.68	99.94	99.95	99.97	99.49	99.96	99.94	99.95	99.98
As	99.63	99.63	99.24	99	99.45	92.00	91.25	92.5	92.5	93.13
Cd	44.68	84.04	94.26	97.87	97.87	97.87	97.87	97.87	97.87	97.87
Ca	12.07	13.79	−6.9	13.79	12.07	−1.72	−89.66	−89.66	−72.41	−58.62
Cr	97.83	97.83	97.83	97.83	97.83	91.74	97.74	97.17	97.04	96.43
Co	34.29	71.43	89.14	94.29	94.29	94.29	94.29	94.29	94.29	94.29
Cu	96.12	98.84	99.71	99.49	99.65	96.94	96.94	96.94	96.94	96.33
Fe	99.94	99.99	99.99	99.99	99.99	99.99	99.99	99.99	99.99	99.99
Mg	−211	−265	−386	−292	−332	97.70	99.73	99.73	99.73	99.73
Mn	23.17	50.00	68.29	91.46	96.10	99.96	99.96	99.96	99.96	99.96
Ni	21.43	50.00	67.86	90.00	95.00	96.43	96.43	96.43	96.43	96.43
Pb	65.56	88.89	83.33	81.11	88.89	88.37	88.37	88.37	88.37	88.37
K	−567	−560	−633	−453	−633	−6,500	−4,833	−5,033	−4,700	−5,167
Na	−12.803	−19.255	−28.932	−27.857	−32.158	−2.373	−1.835	−1.728	−1.513	−1.620
Zn	53.19	94.26	98.83	99.78	99.67	99.94	99.95	99.95	99.86	99.87

Conversely, for some elements such as Al, Ni, Cd, Co, and Zn, the proportion of Bauxsol used in the mixture seems to influence the immobilisation efficiencies. Indeed, dissolved Al, initially leached from waste rocks at 190 mg/L, has been efficiently immobilised with the addition of Bauxsol as amendment, with efficiencies reaching 55.26% at 5% Bauxsol and 99.97% at 15% Bauxsol (Table2). This rapid immobilisation of Al is favoured by its presence as gibbsite ($Al(OH)_3$), which is a highly reactive mineral identified in Bauxsol whose dissolution rates in an acidic medium (pH between 2 and 4) are of the order of 10^{-6} to 10^{-7} $mol.m^{-2}.s^{-1}$ and remain measurable (10^{-9} $mol.m^{-2}.s^{-1}$) at pH between 5 and 6 (Bénézeth et al. 2008). The boehmite (AlOOH) also contributes to Al fixation with typical dissolution rates 10 to 100 times lower (10^{-8} to 10^{-10} $mol.m^{-2}.s^{-1}$) (Bénézeth et al. 2008). Ni and Zn exhibit slower immobilisation kinetics and less robust fixation as they mostly adsorb as outer-sphere complexes, where the ion retains its hydration envelope and interacts with the surface through electrostatic forces. These weaker and reversible complexes are sensitive to ionic strength, and competition with Na^+ and Ca^{2+} for sorption sites seems to occur, explaining the observed dependence on Ni and Zn removal with Bauxsol dosing and contact time.

Notably, Zn and Ni removal efficiencies increase from 53.2 and 21.4%, respectively, at 5% addition of Bauxsol to 99.7 and 95%, respectively, at 15%; indicating a dependence of their immobilisation efficiencies towards the availability of reactive sites and the progressive saturation of the precipitating phases. The low immobilisation of Co (34.3%) after the addition of 5% Bauxsol suggests a limited capacity of this amendment for this metal. This low affinity can be explained by the presence of Fe mainly crystallised in the form of hematite, which binds Co more weakly, unlike amorphous Fe- and Mn-oxides which have a high affinity for this metal (Cornell & Giovanoli 1989). However, the increase in the Bauxsol ratio strongly improves its retention, reaching up to 94.8% immobilisation efficiencies with 15% Bauxsol; likely due to the precipitation of Co in the form of $Co(OH)_2$ induced by the increase in pH (Lin et al. 2002).

However, the chemical composition of Bauxsol also explains some side effects. Indeed, the presence of Na_2O (4.22%) and NaCl (2.4%) in this amendment leads to a major release of Na in the different leachates which is proportional to the amount of Bauxsol used. The immobilisation efficiencies are expressed as negative values in Table 2, with values ranging from −12,803% at 5% addition of Bauxsol to −32,158% at 15%, which greatly increases EC and might pose a high risk of salinisation. Potassium follows the same trend with immobilisation efficiencies ranging from −566% (at 5% amendment) to −633% (at 15% amendment). Calcium and magnesium were also released from the alkaline phases (CaO at 2.06%, MgO at 0.95%), indicating potential ion exchange mechanisms occurring during the sorption of metal(loid)s and partial dissolution of primary minerals initially present in Bauxsol under near-neutral conditions. These phenomena, although secondary to neutralisation, must be monitored to avoid degradation of the water quality of the final effluent.

In summary, the high specific surface area (22 m^2/g) and the high sorption capacity of Bauxsol promote the formation of stable surface complexes and the co-precipitation of metal(loid)s. The growth of ferric coatings follows a 2-stage process with an initial phase of highly porous colloidal deposition. This provides a limited barrier to diffusion, followed by progressive densification by precipitation in the pores, which reduces permeability and generates increased stability. In the same context, contaminant sorption appears to be strongly controlled by the initial pH of the solution, as widely reported in the literature (Neculita & Rosa 2019). pH is a key parameter influencing multiple geochemical processes, including speciation, complexation reactions and sorption-desorption processes. Although pH and redox conditions are interrelated, pH does not directly govern the redox behaviour of chemical species. In particular, the sorption of cationic species generally increases with increasing pH, reflecting enhanced surface charge interactions and metal retention under less acidic conditions.

As far as lime is concerned, after its application the concentrations of potentially problematic metal(loid)s drop drastically for most of them. These high immobilisation efficiencies can be explained by the fundamental role of hydrated lime [$Ca(OH)_2$], which neutralises the acidity of waste rock by consuming hydrogen ions (H^+) and leads to a rapid rise in pH. This chemical change decreases the solubility of most metal(loid)s and promotes their precipitation in the form of hydroxides or carbonates. As observed for Bauxsol, the immobilisation of Al is highly efficient, reaching up to 99.5–99.9, which corresponds to a quasi-total removal.

In an acidic environment Al^{3+} is very mobile, while at pH > 6 it precipitates in the form of amorphous $Al(OH)_3$ (Cravotta 2008), which may explain the high removal efficiencies (Table2). Iron exhibits high immobilisation efficiency, primarily due to the rapid increase in pH induced by lime addition, which promotes the precipitation of Fe(III) hydroxides under alkaline and oxidising conditions. These phases, often amorphous or poorly crystalline, possess a high sorption capacity and play a key role in the retention of trace metal(loid)s.

However, the stability of these ferric hydroxides strongly depends on the long-term evolution of redox conditions. Under reducing conditions, Fe(III) may be reduced to Fe(II), leading to the dissolution of these hydroxides and the subsequent release of iron and associated metal(loid)s into solution. In such environments, iron may instead be stabilised as Fe(II), potentially forming $Fe(OH)_2$, although this phase generally exhibits limited stability and remains highly dependent on the Eh–pH conditions of the system.

Trace metals are also strongly removed through 2 mechanisms: direct precipitation as hydroxides and sorption to newly formed Fe- and Al-hydroxides. Chromium, present at 0.23 mg/L in the control, fell to 0.019 mg/L at 5% and remained below 0.002 mg/L at 15%. Lime promotes the reduction of Cr(VI+) to the less mobile Cr(III+), which precipitates as $Cr(OH)_3(s)$ from pH above 6 (Zhang et al. 2024). Cadmium goes from 0.047 mg/L to < 0.001 mg/L at 5% and becomes almost undetectable at 15%, indicating its precipitation as $Cd(OH)_2$ at pH > 8, but it can resolubilise if the pH drops later. The concentration of arsenic, initially leached at 0.097 mg/L, is decreased to 0.0076 mg/L at 5%, and to 0.0066 mg/L at 15%, indicating a high immobilisation but slightly lower than that observed for Bauxsol (Table 2). Nickel, present at 0.28 mg/L in the control, drops to < 0.01 mg/L at 5% amendment and remains at this level for all assays, which is explained by its precipitation as $Ni(OH)_2$ and sorption on $Fe(OH)_3$. The concentration of Zn decreases from 9.4 to 0.006 mg/L (at 5% amendment) and to 0.012 mg/L (at 15% amendment). For Mn, its concentration drops from 7.4 to 0.003 mg/L at 5%, and Pb goes from 0.033 to 0.004 mg/L (88.37%) thanks to the precipitation of $Pb(OH)_2$ and sorption to the newly formed Fe- and Al-hydroxides.

Unlike Bauxsol, lime is distinguished by a much more controlled chemical behaviour regarding alkalis. It mainly releases Ca accompanied by low amounts of Na (from −1,620 to −2,373 %) and K (from −5,166 to −6,500%) (Table 2), confirming a limited release despite the increase in the dose of lime. Calcium, on the other hand, shows a much more marked increase. The negative values of −1.72 to −89.66% reflect an enrichment of the solution consistent with the increase in measured concentrations, from 570 mg/L in the control to about 1,100 mg/L for 8% lime. This increase is the result of the dissolution of hydrated lime ($Ca(OH)_2$) and the establishment of an equilibrium with the carbonates in solution.

4 Conclusion

This work provides a comparative evaluation of Canadian Bauxsol™ and lime as amendments for limiting acid mine drainage generation from sulphide-rich waste rocks. Emphasis was placed on how amendment dosage affects solution chemistry (pH, redox potential and EC) and metal(loid) retention in leachates, with the objective of identifying effective treatment ranges and clarifying the mechanisms governing contaminant immobilisation. The results of the batch tests demonstrate that Canadian Bauxsol can be a high-performance and sustainable alternative to lime for the neutralisation of acid-generating waste rock. Unlike lime, which induces extreme conditions (pH > 12) that are likely to compromise the geochemical stability of the effluents, Bauxsol allows the pH to rise gradually to values close to neutral, favouring the controlled formation of stable iron and aluminium oxides and hydroxides. The decrease in the redox potential observed also confirms an attenuation of the oxidative processes responsible for acid generation. From a chemical point of view, Bauxsol has a very high capacity to immobilise the main metals (Al, Fe, Zn, Cu, Cd, Co, Mn, Ni), with efficiencies exceeding 95% for amendment ratios of 10 to 15%. This performance can be explained by the combination of surface mechanisms (adsorption, complexation) and co-precipitation within the Fe- and Al-oxyhydroxides. Although the amendment induces a greater release of sodium and potassium ions, related to its mineralogy and the manufacturing process, the evolution of the physico-chemical parameters shows that neutralisation and the decrease of the metal(loid)s' mobility remain much more stable and controlled than those obtained with lime. Canadian Bauxsol appears to be a promising mineral amendment for the

stabilisation of mine waste, particularly in the context of mine closures where the sustainability of solutions and the limitation of secondary impacts are essential. Its industrial origin and local availability also reinforce its relevance to a circular economy framework. The use of Bauxsol, derived from industrial residues, supports a circular economy approach by promoting the valorisation of waste materials instead of relying on conventional raw reagents. This strategy contributes to reducing environmental footprints while enhancing resource efficiency in mine water treatment applications.

The long-term performance of the treatment may involve several potential limitations that warrant further investigation. In particular, under saturated or reducing conditions, iron hydroxides may undergo reductive dissolution, leading to the possible remobilisation of iron and associated sorbed metal(loid)s. In addition, although alkaline amendments initially ensure effective neutralisation, the presence of sulphide-bearing waste rock implies a significant acid-generating potential that may be progressively released over time, especially under oxidising conditions. The eventual depletion of the neutralising capacity could result in a decrease in pH, destabilisation of Fe and Al-oxyhydroxides, and the subsequent release of previously immobilised elements. These processes represent potential long-term risks that should be carefully evaluated.

Additional work, including thermodynamic modelling and tests under dynamic or longer-term conditions, will refine the understanding of the mechanisms involved and optimise the use of Bauxsol in the field.

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