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Recent developments in the science and technology of in situ solvent leaching of tailings for reprocessing, rehabilitation and closure

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Abstract

Tailings storage facilities pose environmental hazards and their failure can cause contaminated materials to be released, affecting people and ecosystems. Conversely, tailings are significant resources of unrecovered metals, especially in older facilities produced using less efficient mineral processing. The already finely ground material makes remining and reprocessing of tailings appealing, but challenges include the risk of damaging the structural integrity of the tailings, handling costs, and the potential for release of contaminants. Here we examine in situ solvent leaching as a potential alternative to conventional excavation due to some recent developments in the underpinning science and technology.

An overall successful, economic and safe in situ process requires four key components:

- *A solvent that is effective, safe and cheap.*
- *Fluid flow should be feasible, can be monitored and ideally controlled, and solvent and metals can be recovered.*
- *It should have neutral or, ideally, positive impacts on the ecosystem, including microbiota, flora and sustainable land use pathways.*
- *The necessary social licence to operate must be obtained, especially locally.*

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These components are illustrated through a case study on a Cu-rich tailings facility in the Philippines. This demonstrates how solvent design involves assessing not just efficiency, but also environmental safety including the impacts on the microbiota and plant growth of solvent treatment. Near-continuous electrical resistivity tomography (ERT) monitoring is shown to be able to image solvent flow and reaction, while electrokinetics is being developed to enhance leaching, direct flow and recover metals. Field demonstration of solvent leaching and ERT monitoring is achieved through ~1 m^3 instrumented mesocosm experiments based on the tailings and open to the natural environment. Social licence to operate is being developed through long-term engagement with local stakeholders to understand needs and aspirations.

Keywords: *in situ leaching, tailings reprocessing, novel solvents, lixiviant, solvent flow, geoelectrical monitoring, electrokinetics, ecosystem development, mesocosms, social licence*

1 Introduction

1.1 Tailings: challenges versus opportunities

Tailings – the finely ground waste product remaining after extraction of valuable mineral or metals from mined ore – present a variety of challenges during and after mine operation. They may contain reactive sulphide minerals which, if poorly managed, may generate acid mine drainage (AMD). Toxic metals in tailings may cause contamination via dust (Csavina et al. 2012) or be mobilised by AMD that could enter groundwater or rivers (Lindsay et al. 2015). Tailings are often low in nutrients and/or toxic to the development of ecosystems (Macdonald et al. 2017) and are thus often slow to re-vegetate, and hence become amenable to new productive land use. Finally, catastrophic failures of tailings storage facilities (TSF) are all too common and cause loss of life, environmental contamination, considerable economic losses, damage to the reputation of the mining industry and erosion of public trust (Franks et al. 2021).

In contrast, tailings may present several opportunities. Tailings often contain residual metals that were not possible, or not economic, to recover in the past when the ore was processed. With modern more efficient processing technology it may be possible to economically recover more metal – perhaps including by-products that were discarded as uneconomic in the past, but which are now regarded as sought after critical technology metals. Crushing and grinding ores for processing is highly energy intensive (consuming ~1.8% of global energy; Napier-Munn 2015) but tailings may be amenable to reprocessing with little or no additional grinding, and consequent low energy consumption, providing environmental credits to the metals produced. Given the large volumes of tailings globally, they represent a substantial potential resource that could be exploited that would reduce the need for new primary mining. Furthermore, reprocessing may reduce the content of toxic metals and sulphides in the tailings and thereby reduce contaminant pathways and provide landscapes more amenable to the development of vegetation and ultimately new productive land for food, fibre or amenity use. Since water saturation and overtopping is a prime cause of TSF failure (Lyu et al. 2019), development of deeply rooting plants serves to stabilise tailings by increasing structural binding and through promoting dewatering (Mendez & Maier 2008). Overall, reprocessing and remediation may add value and reduce the ongoing environmental and social liabilities for those responsible for legacy tailings post-closure.

This paper explores the challenges and some new developments for tailings reprocessing, focusing on the potential for in situ leaching to provide a viable approach for some types of tailings. This is done using examples for Cu-rich tailings from the Philex Mining Corporation (PMC) Padcal Mine (Benguet Province, Philippines), that are the focus of our current research via the Philippines Remediation of Mine Tailings (PROMT) project (2021–2025). The Philippines has been heavily mined over the last century, creating extensive legacy mine tailings which have often had detrimental impacts on the environment (Domingo et al. 2024). There is tension between the need for expansion of mining for economic growth and the need to protect the exceptional biodiversity, as such the Philippines represents a frontier area for the development of more sustainable mining practices across the tropics (Domingo et al. 2024).

1.2 Where is the financial opportunity?

Reprocessing of tailings and other mine wastes is not new – it has been occurring since mining began – with each new approach or technology potentially enabling further economic value to be extracted. Nevertheless a large proportion of tailings remain unprocessed. Although, as noted in Section 1.1, other benefits can be accrued to multiple stakeholders through reprocessing, typically the primary driver to reprocess defaults to recovering value from metals, simply because it is difficult to quantitatively factor in the other benefits. Assessment of the global resource is fraught with difficulty but, given the large volumes of tailings, vast figures are often quoted. For example, The Intelligent Miner blog (Leonida 2022) describes 280 billion tonnes of tailings worldwide with an estimated value of contained precious, critical and strategic metals thought to exceed USD 3.4 trillion. Driven by such figures, together with the predictions of large increases in metal demand for industrialisation and the green transition (IEA 2021), there is a growing interest from a range of companies in carrying out more widespread tailings reprocessing such as Century Zinc (Sibanye-Stillwater 2024) and Regeneration (Resolve 2024).

Given that mineral processing efficiency has improved with time it should be no surprise that older tailings will tend to contain the highest metal value per tonne. For example, at the PMC Padcal Mine, tailings deposited from 1971 to the present show a trend in decreasing Cu grade from an estimated 0.3% in TSF1 through to 0.04% in the modern tailings in TSF3 (Figure 1). Notably the grade of the oldest tailings in TSF1 may be higher than the grade for the resource currently being mined. On the other hand, the modern tailings in TSF3 are barely enriched in Cu (~15x) compared to average crustal values. It should be stressed that these figures are estimates only from sparse sampling and not code-compliant resources, nevertheless they suggest TSF1 could contain ~0.25 Mt Cu, worth ~USD 2480 M – *if* it could be economically extracted. In general, modern tailings are unlikely to be prospective and the best opportunities are in older legacy tailings and other mine wastes. These though may have smaller volumes and be less homogeneous so there may be a sweet spot point somewhere in between, depending on the approach used. Of importance for whether reprocessing could be economic, is the unit value of contained metal per tonne of tailings. At current Cu prices (July 2024) in the PMC tailings, these range from 4 to 29 USD/t. These figures give an absolute upper limit to the cost of reprocessing for it just to break-even – for profitability the unit processing cost would need to be significantly less. For comparison the Padcal mine production costs were ~USD 15/t in 2022 (PMC 2022) – reprocessing must therefore be done very cheaply.

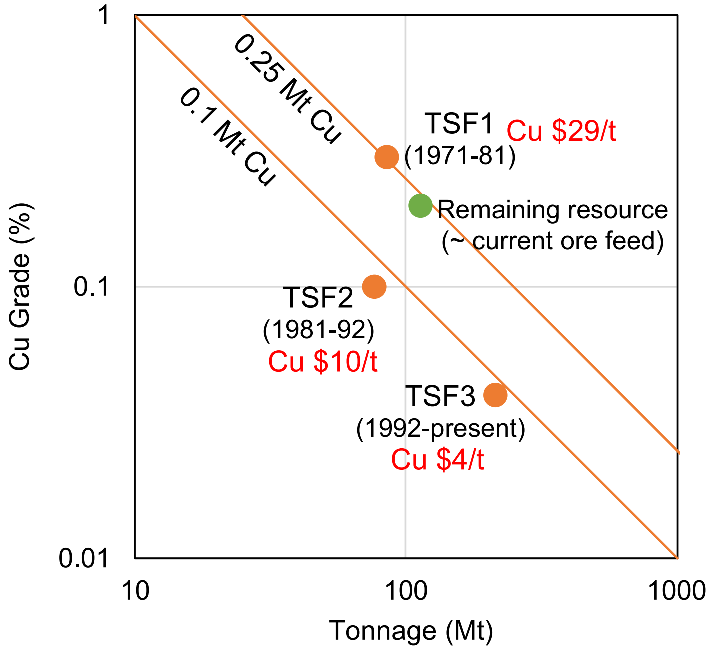

Figure 1 Grade-tonnage plot for estimated endowment of Cu in the three tailings storage facilities (TSF) at the Padcal Mine, Philippines (Philex Mining Corp.), including unit value of contained Cu in red. Tonnage data: PMC (2021), grades PMC (2021)

2 Remining versus in situ leaching for reprocessing of tailings

Currently tailings reprocessing operations involve remining the tailings, i.e. excavating them to process ex situ in a plant. Here tailings may be beneficiated by physical separation processes such as gravity, magnetic or flotation concentration to produce a concentrate for sale and/or may undergo hydrometallurgical processing such as cyanidation to recover gold. Typically, this will require some finer regrinding of the tailings since the reason that more of the target metal was not recovered in the first place is usually that its minerals were not sufficiently well liberated from the gangue for them be extracted when initially processed. New, more advanced processing techniques may also be available compared to when the tailings were first produced. During the mine life remined tailings can be reprocessed through the existing infrastructure. For example, at the operating PMC Padcal Mine ~300 t of tailings from TSF1 were reprocessed daily in the period of 2020–2024 through the existing mill. One challenge for reprocessing through an operating plant set up to deal with primary ore can be that the tailings mineralogy may have been modified since deposition. This is particularly the case in older sulphide-rich tailings, that have not been stored in a water-saturated oxygen deficient storage facility. The sulphide minerals oxidise and form diverse secondary mineral assemblages (Boulet & Larocque 1998; Lindsay et al. 2015) which means that the tailings may behave differently in the processing plant and, at the extreme, may not be able to be processed.

If the mine has closed and the processing facility has been decommissioned, then reprocessing would require either installing a new plant, bringing in a temporary mobile processing plant or trucking tailings to the nearest processor, all of which would incur significant additional cost that could render reprocessing unviable. Another cost consideration is the handling to excavate and transport to the processing plant. In a large mine, economies of scale through infrastructure such as conveyor belts keeps these costs down, but small-scale remining with truck and shovel has considerably higher unit costs which can be unaffordable. Use of hydraulic mining with high pressure monitors to produce a pumpable slurry can be more efficient and is used in South Africa for gold tailings and at Century Zinc (Sibanye-Stillwater 2024). However, unless backfilling is taking place while excavating, remining of tailings means that additional space needs to be found for the second-generation tailings from processing, which may be a problem in some settings. A final consideration with remining should be that it is critical that these operations do not risk destabilising the tailings storage facility since the potential consequences here are grave. Due care should therefore always be taken of geotechnical properties and modelling of stability.

We propose that a potential alternative to conventional remining of tailings could be in situ leaching (ISL). The approach would be to introduce a solvent (aka lixiviant) into the pore space of a volume of tailings where it selectively leaches out target metals which are then recovered from the collected pregnant solution. In fact, this process is already used to mine U (IAEA 2016), has been used for Cu (Seredkin et al. 2016) and a similar process is employed to recover Cu by heap leaching in which crushed amenable ore is leached on engineered pads (Dreier 2020). Knowledge transfer from these fields will be important. Tailings are generally porous and have moderate hydraulic conductivity (~10^{-6} – 10^{-7} m/s) (Aubertin et al. 1996; Lindsay et al. 2015) so that fluids could feasibly be passed through them in realistic timescales. Advantages of an ISL approach would include: no handling costs since the tailings remain in place, avoidance of dust emissions, only a small process plant required, and no additional space for secondary tailings needed. As a result, CapEx costs are likely to be lower compared to a new ex situ processing plant (Seredkin et al. 2016). Of course, ISL will only be feasible if the target minerals are amenable to leaching – poorly soluble minerals such as cassiterite will always likely need to be remined and physically concentrated. Conversely, tailings that have had their mineralogy modified post-deposition by oxidation, perhaps over decades, may actually be more amenable to ISL than their freshly deposited equivalents. The diverse nature of tailings in terms of their primary deposit, mineralogy, age and environment means that a one-size-fits-all approach to ISL will not be successful. In detail, no two tailings volumes will be the same. Instead, each tailings project will need detailed evaluation of a range of factors to be able to provide an overall assessment as to whether ISL would be viable in a specific situation and to design the ISL process.

3 Considerations and characterisation needed for an in situ leaching process

The characteristics that would need to be understood to assess viability and design an ISL process for a volume of tailings relate to three somewhat inter-dependent categories of solvent leaching, fluid flow and monitoring, and the ecosystem. These are summarised in Table 1 and discussed in the following sections.

Table 1 Characterisation needed for in situ leaching

Solvent leaching	Fluid flow and monitoring	Ecosystem
Geometallurgy	**Hydrology**	**Abiotic**
Resource grade/tonnage	Rainfall	Potentially toxic elements
Tailings geometry	Evapotranspiration	Nutrient availability and nutrient limiting factors
Mineralogy	Hydraulic conductivity	
Mineral liberation	Porosity	**Biotic**
Spatial variation	Anisotropy and spatial variation	Current baseline
Solvent	Tailings geometry and design	(micro and macrobiota)
Efficiency	**Petrophysical properties**	Interactions with solvent and leached metals
Specificity	Grain size distribution	
Cost efficient/recyclable	Electrical resistivity	Native climax ecosystem
Degradation	Chargeability	Desired end-use and ecosystem services
Ecotoxicity	Shear strength	
Nutrient contribution		
Nutrient liberation		

3.1 Solvent leaching

The first considerations for solvent leaching are standard geometallurgical investigations that would be required in any case for ex situ processing. Consideration of the overall grade and tonnage of the potential resource define its metal content, potential value and overall economics. The mineralogy, of both the ore and gangue minerals, will guide assessment of the amenability to solvent leaching. However, liberation analysis of the target minerals and assessment of their enclosing grains (and whether they are leachable) will control what proportion of the target minerals will be practically leachable. For example, if 60% of the copper phase is enclosed in unleachable quartz then only 40% is practically leachable. Ultimately test leaches are required to confirm the leachable proportion of the target metal, which feeds into the resource model. Geometallurgy also considers the spatial variation of grade, mineralogy and liberation across the tailings volume and feeds back into the economic assessment and decisions regarding which parts might be viably mined by leaching. Where leaching to remove an ecotoxic element for tailings decontamination is the primary or subsidiary aim then all the above factors apply for this element as well.

For solvent selection, clearly the solvent must leach target metals to high efficiency, but it must be specific enough that other elements are not leached in excessive amounts since they would need separation from solution and disposal. The solvent must be cost-effective, which is controlled by not just the price for the solvent but also the ability for the solvent to be recycled, as well as solvent loss due to not being recaptured or degradation. Furthermore, solvent components should be readily available in sufficient quantities. A variety of standard techniques such as electrowinning or ion-exchange are available for metal recovery from pregnant solutions making this step relatively low-risk.

The risks of leakage of solvent, perhaps bearing metal, must be evaluated and solvents should be benign in the environment and be readily degraded. In addition, a solvent should also meet the test of public acceptance. For example, while cyanide is used widely in the mining industry for leaching gold in controlled conditions, the public is already resistant to its use and would be unlikely to accept its unconstrained use in tailings facilities.

Ideally, the residual solvent, or its breakdown products, might contribute organic carbon and/or nutrients to the tailings and so help promote ecosystem development. In addition, solvent treatment could aid in liberation of nutrients from tailings minerals making them bio-available for microbes and plants.

3.2 Fluid flow and monitoring

A good understanding of tailings hydrology will be critical to successful ISL. Fluid flow is governed by hydraulic conductivity – this may be both spatially variable, and anisotropic, depending on the tailings architecture. Storage capacity of solvent will depend on porosity and saturation, which will also vary spatially. The design of the tailings impoundment will be relevant to the hydrology and therefore designing a leach system, since modern TSF are generally lined with geomembranes which should constrain the solvent, whereas older TSF can be unlined, or the geomembrane may have failed. If the TSF is open to bedrock, then the hydraulic conductivity of the bedrock would also be important. Modern tailings facilities tend to be designed to remain saturated to limit oxygen ingress, whereas older tailings may be variably undersaturated in parts and water flow may already be occurring. Being typically open at the surface means that the rainfall onto tailings and its variation such as seasonality need to be known as this will impact on fluid flow and dilution.

Petrophysical properties such as grain size distribution and electrical resistivity link tailings properties to monitoring techniques described in Section 5. Shear strength relates to overall TSF stability and any changes with leaching should be investigated to ensure that tailings are not destabilised through leaching.

3.3 Ecosystem

The tailings may contain metals that are toxic to plants and microbes, so it is important to measure the concentrations of all potentially toxic metals and to determine their behaviour during leaching. Tailings are typically depleted in essential plant nutrients (e.g. Macdonald et al. 2017) so that the ecosystem may be currently limited by nutrient availability. Therefore, designing solvents that can provide nutrients (Section 3.1) may accelerate ecosystem development post leaching.

Understanding the current baseline of the tailings in terms of the existing micro and macrobiota is essential for understanding how solvent leaching and the release of metals may perturb this. Although many tailings appear lifeless, they can be well colonised by a diverse microbiota and some, especially in tropical environments, may already be well vegetated through human interventions or spontaneous colonisation. The activity of plants and microorganisms may contribute to remediation of residual solvents, and microbes in particular can use many as substrates (Martin et al. 2016). Knowledge of the native climax ecosystem in the area can help inform what the end stage of colonisation could be and how far colonisation has proceeded toward the end point. Similarly, the desired final land use of the tailings and anticipated ecosystem services should be a consideration in the ISL design.

4 Designing novel solvents for in situ leaching

Hydrometallurgical leaching of ores and concentrates has traditionally relied on a limited set of solvents to extract target metals, such as cyanide for gold and sulfuric acid for copper. These solvents can lack metal selectivity and within a tailings storage facility have the potential for release of toxic and/or acid metal-bearing leachates to the environment, creating challenges in meeting regulatory and public approval. Recently, a greater diversity of more sustainable solvents for extractive metallurgy has been developed through adoption of green chemistry principles (Anastas & Warner 1998), in particular green solvents that avoid toxic or environmentally deleterious components, are biodegradable, and show enhanced metal selectivity. Solvometallurgy – the use of non-aqueous or low water solvents – is an emerging branch of extractive metallurgy that, when coupled with green chemistry principles, enables the design of solvents particularly suitable for treatment of ores and tailings and which are also amenable to bioremediation (Binnemans & Jones

2017). Some deep eutectic solvents (DES), specifically type III DES (Smith et al. 2014), may be suited to solvometallurgical leaching of tailings through a range of benefits including low volatility, tuneable to give high target metal selectivity, relatively low cost and low ecotoxicity. These have been demonstrated to be capable of leaching a wide range of minerals including sulphides and oxides (Jenkin et al. 2016; Pateli et al. 2020). In addition, previous work has shown that aqueous solutions of certain organic acids, such as citric and methanesulfonic acid, perform similarly to strong mineral acids for leaching Cu and As from tailings, due to their capability for metal chelation (Crane & Sapsford 2018). Such 'novel' solvents are a highly active area of research with new formulations and applications being published on an almost daily basis.

To design a solvent to leach Cu from PMC TSF1 tailings, we first considered whether DES might be suitable. Although DES retain functionality with some dilution, the high-rainfall tropical climate meant that dilution and loss of these non-aqueous solvents could be a particular challenge. Furthermore, in initial scoping work some standard DES formulations performed less well than other solvents and, at high concentrations, were phytotoxic (De Oliveira et al. 2024). Therefore, we focused on developing suitable aqueous solvents by first examining the range of possible environmentally benign components that could also act as plant nutrients and then by considering their actions in a solvent (Figure 2). Initial standard batch-leach tests suggested that the redox agents did not increase Cu leaching and the search then focused on the overlap between bond-breakers, pH adjusters and metal complexing agents. Combinations involving binary and ternary mixtures were tested, as often the combined actions of different components can cause enhanced leaching. However, in the case of the PMC TSF1 material, solutions of simple common organic acids such as malic and citric acid were found to be the most effective for leaching Cu under batch test conditions, with Fe, the other major element leached, relatively suppressed in comparison (Figure 3). These organic acids have the advantage that they are easily accepted by the public since they are common additives in soft drinks, foodstuffs, soaps and cosmetics. This use also means that they are easily available cheaply in large quantities. While further optimisation of solvents may well be possible for these tailings, citric acid was taken forward for use in field trials.

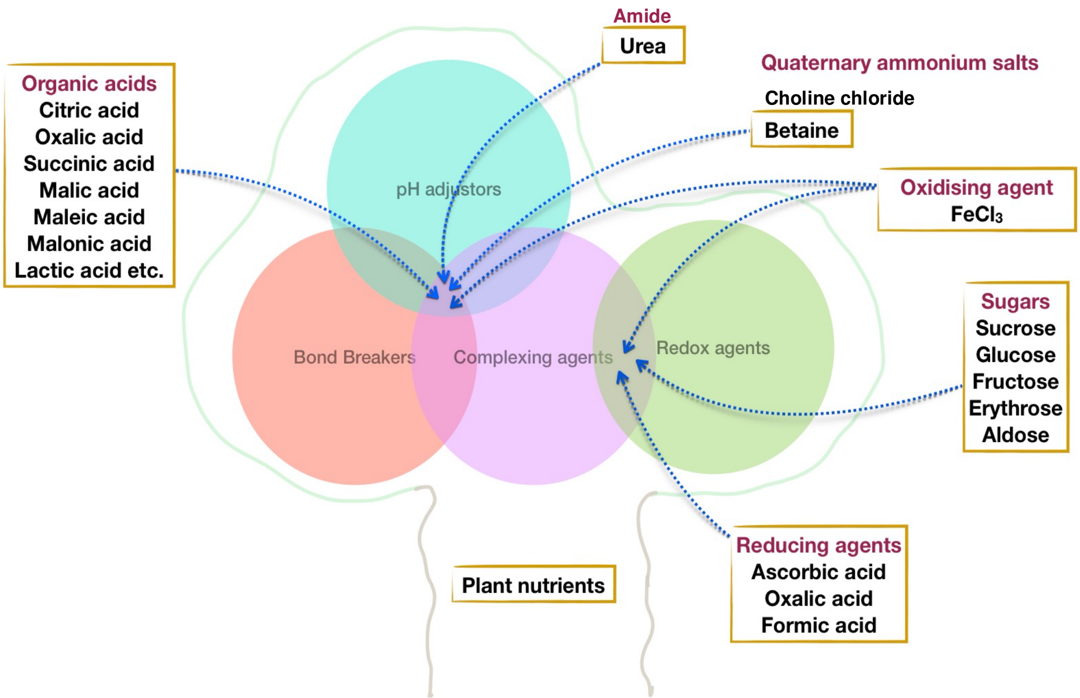

Figure 2 Possible components for environmentally-benign aqueous solvents for tailings leaching and their main actions

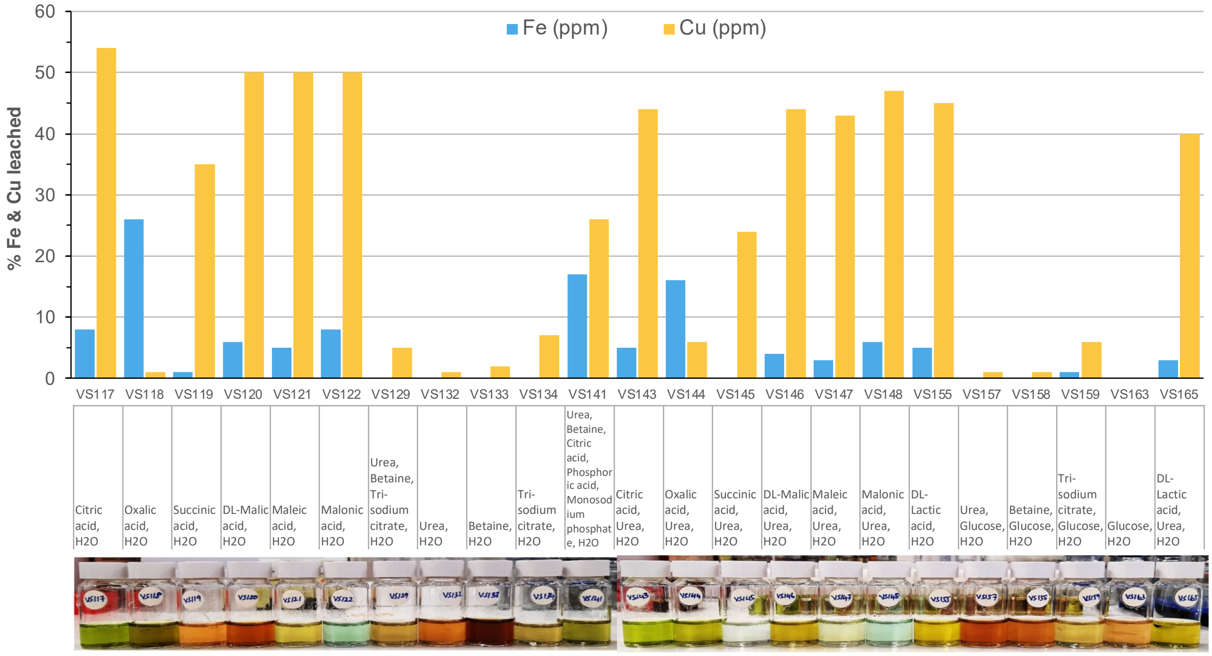

Figure 3 Results panel showing the solution formed in some batch-leach tests and the proportion of Fe and Cu leached from TSF1 tailings

5 Monitoring and control for in situ leaching

Geoelectrical approaches, including electrical resistivity tomography (ERT) and induced polarisation, are commonly applied in the minerals industry for exploration at the regional/orebody scale – but the use of geophysical monitoring for tailings is an emerging area of science (Dimech et al. 2022). Geoelectrical monitoring approaches are being developed for other relevant environmental and engineering applications, including heap leaching (Rucker et al. 2009) and contaminant transport (Kuras et al. 2016) and have great potential for application to tailings. Resistivity is sensitive to processes in the near surface (Loke et al. 2013) such as moisture content (relevant to tailings stability and rooting zone processes), pore fluid composition (e.g. solvents versus groundwater), weathering (mineralogical change), consolidation and mineral precipitation processes (changing porosity). The ability of ERT to monitor changes in moisture content or pore fluid composition (in saturated conditions) in 4D enables the tracking of fluid movement, potential infiltration fronts, and preferential flow pathways. Characterisation and monitoring on tailings to date is often based on point sampling only. However, due to the marked heterogeneity and anisotropy (layering) of tailings, this sampling has limited capability to capture complex hydrodynamic processes and flow paths. The development of geoelectrical monitoring has been greatly aided by recent advances in instrumentation, which now permit high-spatiotemporal resolution monitoring by fixed in situ sensors with telemetric control and data retrieval. The PRIME (PRoactive Infrastructure Monitoring and Evaluation) system that we are employing to monitor the tailings and experimental setups at PMC TSF1 is currently world-leading as a low-cost geoelectrical measurement and information delivery system (Holmes et al. 2020). Petrophysical property relationships obtained through laboratory experiments allow translation of the measured geophysical properties into hydrological or geotechnical properties e.g. resistivity to volumetric moisture content (Merritt et al. 2016).

At TSF1 we are employing the PRIME system for daily monitoring of electrical properties along ~120 m arrays that run along two tailings benches and across the dam separating the benches. This will enable us to better understand the larger scale hydrology in the tailings through the seasonal changes in saturation. Coupling geophysical inversion with hydrological modelling calibrated by sampling data can improve the estimation of TSF properties (e.g. hydraulic conductivity), which in turn allows improved understanding and planning of an in situ leach process.

In addition, we are using PRIME to monitor controlled experiments in instrumented mesocosms. Mesocosms are outdoor experimental systems in the natural environment that examine a constrained volume of tailings under semi-controlled conditions and so bridge between lab-experiments and field trials. Demonstrating experiments beyond the lab is an essential step in the scale-up of a process and enables exploration of phenomena that might only be observable at scale, such as changes in fluid flow with solvent interaction, and environmental influences that are not reproducible in the laboratory (from seasonal changes to typhoons). Both industry and government give much more credence to these larger scale experiments which can then help accelerate adoption. At PMC we have built four instrumented mesocosms at TSF1 (Figure 4) in clean IBCs (intermediate bulk containers) that have had the tops removed so that they are open to the weather. Constructed in April 2023, these each contain ~0.88 m^3 of excavated TSF1 tailings recompacted to the same density as measured on the tailings in situ (~1.6 g/cm^3) giving a mass of ~1.4 t. ERT electrodes and moisture sensors are arranged in vertical arrays to image a central volume away from edge effects (Figure 4b). Effluent is collected in a drainage layer separated by a geotextile membrane and passes over an electrical conductivity (EC) sensor for continuous measurement of dissolved load before collection. IBC1 is retained as a control and is simply untreated tailings open to the weather. The other three IBCs have been used for manipulative experiments to investigate leaching behaviour and whether this can be imaged with the ERT sensors. In these experiments citric acid at various concentrations has been added in specific geometries and volumes for set timescales. This is then followed by a washout phase where water is added either artificially and/or by natural rainfall. The effluent leachate is collected in batches on which EC and pH are measured and it is subsampled for geochemical analysis. ERT data are collected daily and more frequently during experiments; EC and moisture data are collected at 20-minute intervals.

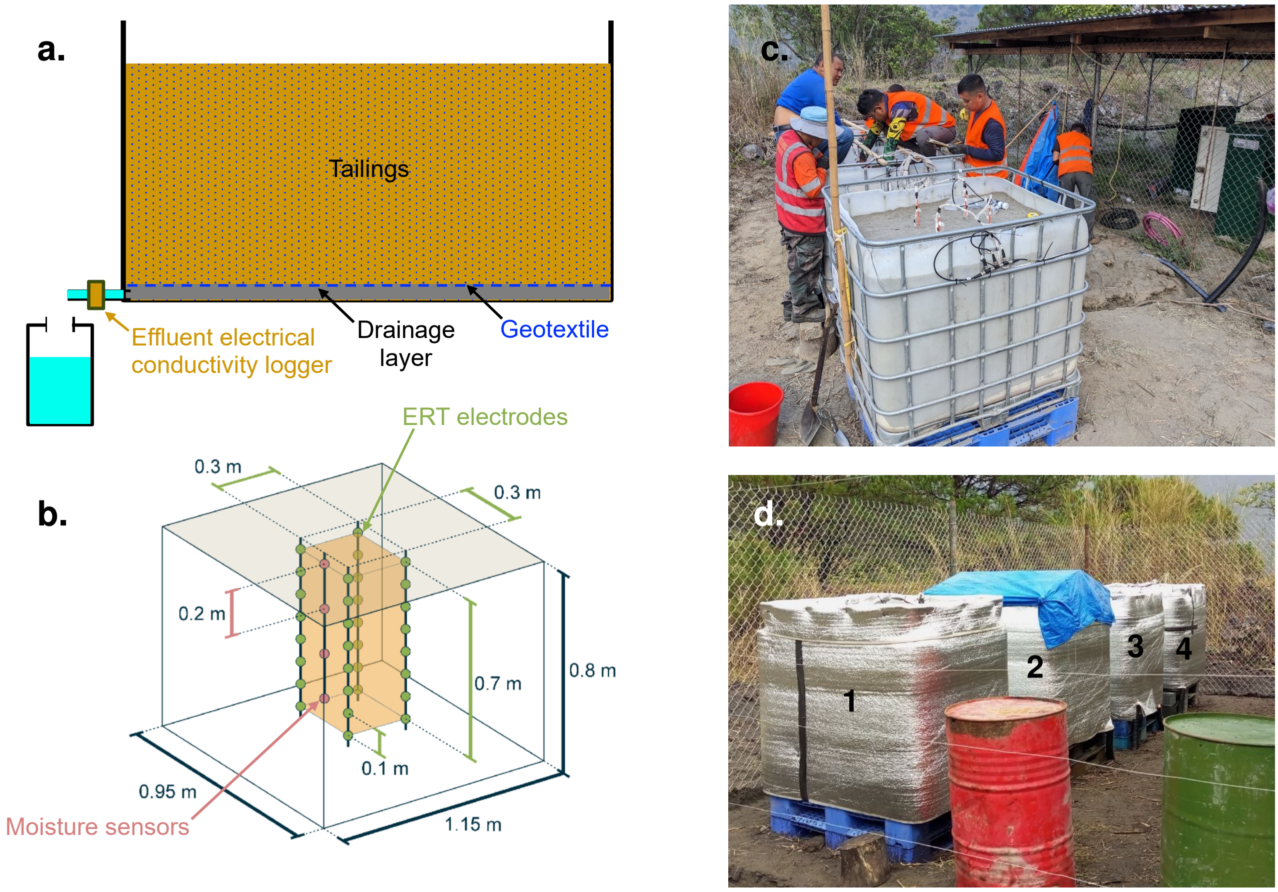

Figure 4 Instrumented mesocosms at PMC TSF1. (a) Cross-section showing drainage layer and monitoring of effluent electrical conductivity; (b) Internal design of electrical resistivity tomography (ERT) electrodes and moisture sensors; (c) Mesocosms are built from topless IBC containers shown here during construction; (d) The final four mesocosms at TSF1; the insulation is to damp heating by direct sun; IBC2 is covered here to exclude rainwater during an experiment

To date in PROMT it has been possible to demonstrate that ERT can image differences in moisture content, the leaching of tailings by the solvent with time, and the difference between water and citric acid (since the latter is more ionised and so has higher EC). For example, Figure 5 is the image resulting from inversion of ERT data for an experiment in IBC2. In the experiment the IBC was saturated with citric acid, which was left to react for a number of days. The image shows a time slice during the subsequent washout phase when water had been added to the top, but reacted Cu-rich solvent was still being measured at the outlet. The imaging results clearly show a change in resistivity (especially pronounced in Figure 5b) that can be interpreted as the boundary between porewater at the top, with higher resistivity than citric acid, and reacted solvent at the bottom with lower resistivity than the initial citric acid. These results demonstrate the potential to use ERT at scale to monitor the movement of solvent and its reaction in a tailings facility and so control the ISL process through for example adjusting the head gradient.

Another technique that is being investigated in PROMT in relation to ISL of tailings is electrokinetics (EK). This employs an electric field to induce movement of the solvent and leached target metal ions via electromigration and electroosmosis (Figure 6a). These processes are known to be less susceptible to physical heterogeneities within soils and sediments than advection-dominated systems where there is limited flow across low hydraulic conductivity boundaries. Under EK such physical heterogeneity is less inhibiting because the electric field is not directly affected by hydraulic conductivity (Gill et al. 2016). EK is a relatively mature technology that has found commercial application in the wastewater treatment and contaminated land remediation industries (Agnew et al. 2011). However, research into its potential combination with in situ leaching for the recovery of metals from the solid phase, remains in its infancy (Martens et al. 2021). EK may be useful in ISL for accelerating leaching, for enabling access of solvent to materials where hydraulic conductivities are too low to be feasible by hydraulically driven flow alone, and by providing a process to capture target metals as a solid product by electroreduction onto the cathode. In addition, EK could be employed at the boundaries of the ISL system where it might be used to help avoid escape of solvent and contaminants where this is not possible by hydraulic pumping alone. To test the application of EK on tailings in PROMT we have developed both lab-based experiments and field mesocosms in IBCs similar to those described earlier. These mesocosms are both for EK alone (Figure 6b) and to test combined EK and ERT to show how we might image EK induced changes as they occur.

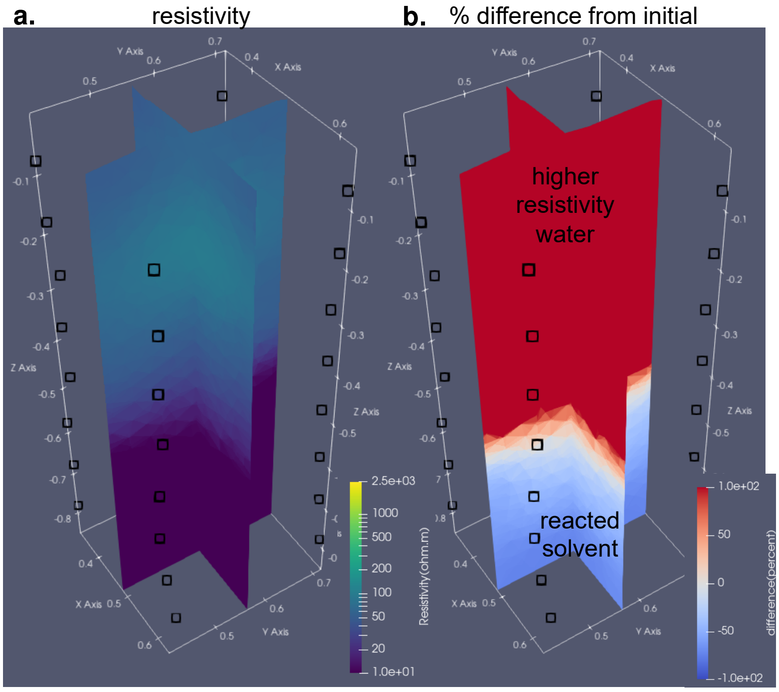

Figure 5 Model derived from inversion of ERT data collected in IBC2 on the 27 May 2023. (a) Resistivity in ohm-metre; (b) Difference in resistivity (%) from the homogeneous initial state when tailings were first saturated with solvent

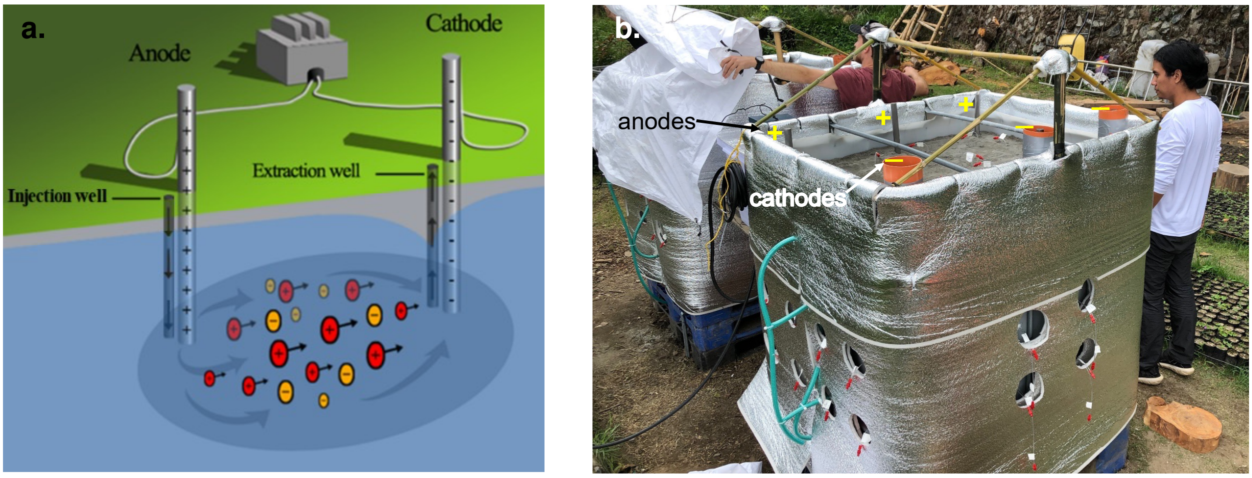

Figure 6 (a) Simple 2D representation of electrokinetics; (b) Field mesocosms for electrokinetics experiments containing PMC TSF1 tailings

6 Ecosystem development and in situ leaching

The establishment of plants and concomitant incipient soil development tends to correlate with increasing soil biodiversity and function (Luo et al. 2020). The geochemical and physical characteristics of mine tailings have been shown to affect microbial community structure (Chung et al. 2019). At PMC TSF1 a diverse microbial community has been identified, with the diversity and the range of metabolic pathways increasing with plant diversity (Lazaro et al. 2024). This provides a baseline against which the effect of perturbations caused by ISL can be measured. Work is currently underway to assess how the microbial community responds to citric acid treatment and initial results suggest that there will be some slow partial degradation of the citric acid by microbial activity. Degradation will need to be accounted for in ISL design, but also enables a pathway for removal of residual solvent and amelioration of acidic pH.

As part of solvent selection and design refinement (Section 4), we are scoping the effect of residual solvents on plant growth, which may be positive – through nutrient provision or release from the tailings – or negative – through phytotoxicity. De Oliveira et al. (2024) examine the effect of various DES at different concentrations. They show a complex picture with both positive effects through nutrient release, and negative effects due to phytotoxicity, being widely variable depending on DES formulation, concentration and exposure. Further research is warranted. Initial work assessing the effects of organic acids on plant growth shows detrimental effects at high concentrations but neutral or positive effects at low concentrations (Figure 7). Such effects would need to be incorporated into ISL design. If desired, it may be possible to preserve plants on already vegetated tailings by only leaching below root depth. Since the aim is to recapture as much solvent as possible for metal recovery, and residual solvent can then be diluted, either artificially or naturally, it would seem that, with suitable design, low residual concentrations of solvents could be achieved that are not only within the environmental envelope for plants to grow (Spain & Tibbett 2011) but are also beneficial to plant growth and overall ecosystem development.

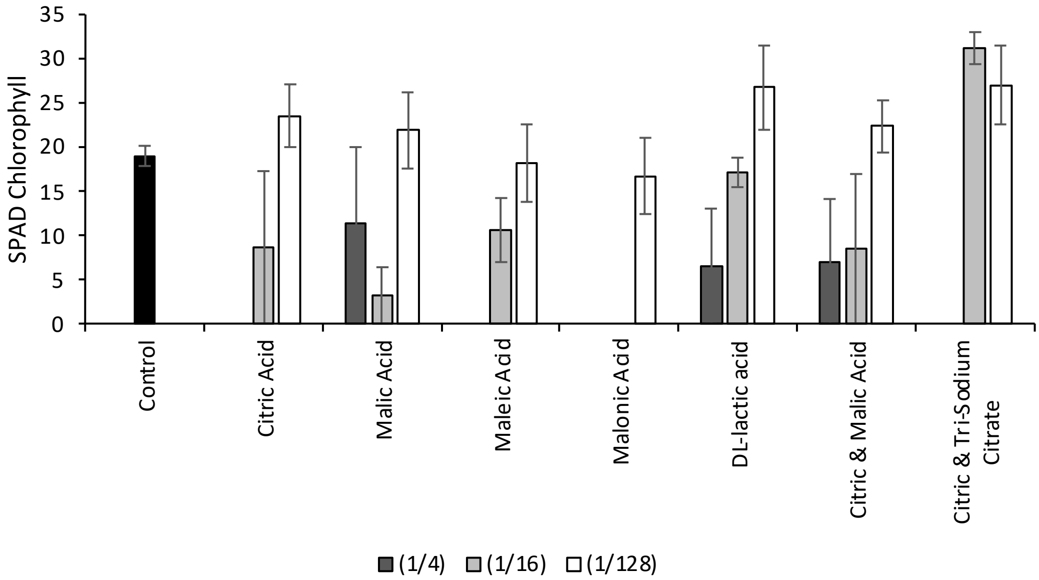

Figure 7 Plant chlorophyll (*Brassica napus*) as a measure of plant health in tailings treated with 1 M organic acids at different dilutions with water. Data shown are 10 days after planting into treated tailings

7 Obtaining the social licence for in situ leaching

Developments in new science and technology count for little if they are not adopted, and a key challenge here is ensuring that the entire range of relevant stakeholders, from government regulators through to local communities, give the necessary permissions. There are a multitude of examples of new initiatives in mining not progressing because of poor stakeholder relations, in particular with local communities. Therefore, a key pillar of the PROMT project is to ensure that from the outset local stakeholders are not only kept in touch with developments through the project but are consulted on their needs and aspirations for new developments in a collaborative manner. The PMC Padcal Mine supports a community of 2,000 employees, is located on the ancestral domains of the Igorot tribes, and royalties are paid for land rights (Pan et al. 2024). The mine is nearing closure, but although this was originally planned for 2011, the date has repeatedly been put back and is now set to 2027 (PMC 2022). The threat of closure makes the possibility of new developments a vital but sensitive subject since expectations needs to be managed.

The most prominent stakeholders were identified and have been engaged in a series of workshops. Details of the first workshop are reported by Pan et al. (2024) who uses the ecosystem services framework (DeLorme et al. 2021) as a narrative for engagement. Other techniques such as participatory mapping (Chambers 2006) are also being used to help understand the relative importance of different local features and amenities to the local population (Figure 8) (Quierrez 2023). The stakeholders have raised questions about issues such as groundwater integrity relating to ISL, enabling the research team to address those concerns early on. Overall participants were optimistic about restoration potential. This approach provides a roadmap for good practice in community engagement for mine closure elsewhere.

Figure 8 Example of participatory map through which the community identify natural, economic, and social resources of importance to them related to the PMC Padcal Mine (Quierrez 2023)

8 Conclusion

Older tailings will generally be more prospective in terms of grade than more recently deposited tailings. In situ leaching may provide an alternative to conventional remining of tailings. We suggest that an overall successful, economic and safe in situ process requires four key components:

- A solvent that is effective, safe and cheap.
- Fluid flow should be feasible, can be monitored and ideally controlled, and solvent and metals can be recovered.
- It should have neutral or, ideally, positive impacts on the ecosystem, including microbiota, flora and sustainable land use pathways.
- The necessary social licence to operate must be obtained, especially locally.

New science and technologies that facilitate in situ leaching include: the use of novel solvents, such as organic acids; the use of geoelectrical methods to monitor and control fluid movement and the leaching process; and a more holistic understanding of tailings ecosystems and the effects of novel solvents. Coupled with effective and collaborative stakeholder engagement to obtain the social licence to operate, these developments pave the way to successful implementation of in situ leaching. Although this approach will require determining a wider range of characteristics of the tailings to be able to assess viability and design a ISL process, the potential rewards are large. In situ leaching can provide metals without the need for primary mining while also remediating legacy mine tailings.

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