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Selective ion exchange recovery for enabling passive wetland treatment of bauxite processing residue leachates

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Abstract

Bauxite residue disposal can give rise to alkaline leachate that requires long-term treatment. Results are presented trialling a mesocosm-scale system integrating selective metal(loid) recovery with passive treatment technologies for application to high pH bauxite processing residue leachates. This system, combining ion exchange resin adsorbents for targeted removal of potentially ecotoxic metal(loid)s (e.g. vanadium [V], arsenic [As]) with aerobic wetland polishing beds, aims to treat alkaline leachates to meet effluent targets with reduced energy and chemical demands compared to conventional acid dosing and high-density sludge processes.

Commercially available ion exchange resins were tested for their ability to selectively remove metal(loid)s from bauxite processing residue leachates sourced from a legacy disposal area in Western Europe. Results indicated fast and efficient removal of V (88%) and As (93%) from solution, with removal efficiency remaining high after repeated treatment cycles (V:85%, As:75% after 11 cycles). Recovery efficiency during resin elution using sodium hydroxide (NaOH) remained above 90% after repeated cycles for both target metal(loid)s, indicating effective re-use of adsorbent materials.

Aerobic wetland mesocosms containing common reeds (Phragmites australis) were assessed for their suitability as a final polishing step for leachates post-ion exchange treatment. Bauxite residue leachates of varying ionic strength were used as influent, with effluent water quality monitored over a period of >100 days to determine treatment efficiency. Wetland mesocosms were effective in buffering effluent pH to within environmentally acceptable limits (pH <9) under all leachate scenarios, and wetland soils inhibited residual aqueous metal(loid) content, with efficient removal efficiencies for V (up to ~94%), As (up to ~48%) and aluminium (up to ~87%).

Keywords: *red mud, resource recovery, critical elements, wetland, valorisation, nature-based solutions*

1 Introduction

In excess of 120 Mt of bauxite processing residue, the high-volume byproduct of alumina refining, are produced globally each year. This residue, sometimes called red mud, is highly alkaline and sodic, and poses challenges for long-term rehabilitation (Li et al. 2024). Depending on the disposal setting, bauxite residue disposal areas (BRDAs) can generate highly alkaline (pH 13) leachate, which can be enriched in a range of oxyanionic elements that can be considered regulatory challenges, and in some cases, elements with resource recovery value (Mayes et al. 2011). Such leachates can be long-lived (i.e. multi-decadal) depending on the residue disposal volume, rainfall regime and management. As such, remedial options need to be

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sustained over long periods of time. The conventional approach to managing such waters typically involves direct acid (usually sulphuric) dosing (Gomes et al. 2018; Williams et al. 2023) to neutralise leachate and precipitate many of the more mobile elements. Residual sludges are thickened and usually disposed of in landfill. Other options for remediation of alkaline waters are at lower levels of technology readiness but can include direct dosing with carbon dioxide. This is particularly applicable for Ca^{2+}-rich leachates where carbonate precipitation subsequently drives down pH (Gomes et al. 2018; Hall 2008). Whilst we are not aware of such approaches being actively deployed for bauxite processing residue leachates, encouraging CO_2 ingress into residue (via amphirolls) or leachate can adjust pH, at least in the short-term, and lead to metal precipitation, particularly when in the presence of gypsum (Renforth et al. 2012). A more recent development for addressing alkaline leachates from BRDAs is the deployment of wetland-based systems where a combination of factors can encourage buffering of high pH waters. These include: (1) a high specific surface area of wetland substrate and emergent vegetation prompting precipitation reactions that lower pH; (2) high partial pressures of CO_2 in wetland waters and substrate, which encourages buffering; and (3) buffering by organic matter/organic acids exuded from wetland plants (Mayes et al. 2009; O'Connor & Courtney 2020). Laboratory pot trials and field pilots have demonstrated the sustained (>7 years) effectiveness of surface flow wetlands for treating post-closure (typically pH 10.5–11.5) bauxite residue leachate (Higgins et al. 2016, 2017; O'Connor & Courtney 2020).

Value recovery from bauxite residue has grown in research intensity in the last 15 years. Most of this interest focuses on the solid phase recovery of rare earth elements and scandium, however, there has been a growing research base in assessing metal(loid) recovery from leachates also. The driver of the latter has typically been environmental regulation and the removal of problematic elements such as arsenic (As) and vanadium (V), and concerns about potential uptake of these by plants in treatment systems (e.g. arsenate and vanadate ions can follow plant phosphate uptake mechanisms [Olsewenska et al. 2016]). Many tested recovery methods for V from secondary sources are based on ion exchange (Huang et al. 2010; Keränen et al. 2013; Li et al. 2013; Nguyen & Lee 2013; Zeng et al. 2009; Zhao et al. 2010), solvent extraction (Barik et al. 2014; Kim et al. 2014) and bioleaching (Mirazimi et al. 2015). Although ion exchange resins have been used previously for V recovery or removal, limited data exist on feed solutions with a pH higher than 10 (Huang et al. 2010), and only a limited number of studies are with bauxite residue leachate. These studies on bauxite residue leachate (Gomes et al. 2017) demonstrated the potential recovery of V from alkaline leachate with some selectivity and scope for recovery of V from eluents and effective re-use of resins (at least 20 cycles). However, as with many laboratory-based studies, this work used synthetic leachate with spiked concentrations of target elements, which aids modelling of the effectiveness of recovery technologies but may not accurately reflect likely deployment conditions at BRDA facilities.

The aim of this study is to show integration of selective metal(loid) recovery with leachate buffering in laboratory-scale systems using real-world BRDA leachates. Specific objectives include: (a) assessing the efficacy of anion exchange resins in selective recovery of target elements from BRDA leachate; and (b) assessing the effectiveness of mesocosm wetland systems in buffering alkaline BRDA leachate.

2 Methods

2.1 Experimental materials

All experimental work used leachate collected from a closed BRDA in Western Europe. The disposal area has a leachate collection and treatment system (based on acid dosing) that has been in operation since the refinery closure early in the 20th century. Bulk leachate samples were collected from the leachate collection system in October 2023 and June 2024 and stored in bulk HDPE containers with low headspace at 4°C until experimental use (maximum storage period ~6 months). Where dilution was required, diluted leachates were used immediately.

2.2 Selective recovery using anion exchange

Laboratory screening of the ion exchange resin metal(loid) recovery focused on two commercially available resins – Purolite A400 (strongly basic resin) and Puromet MTS9100 (amidoxime resin) – that have shown promise for selective metal(loid) removal at highly alkaline conditions in previous studies. Both resins (or those with equivalent functional groups) have documented selectivity towards V, with amidoxime resins also having the potential to selectively target gallium (Ga) in the presence of high Al concentrations at high pH (Gomes et al. 2016; Zheng et al. 2021).

Initial experimentation focused on batch trials varying the resin-to-liquid ratio to assess resin capacities. This was done using undiluted field leachate samples. Resins were preconditioned to their hydroxide form through contact with an excess volume of 5% sodium hydroxide (NaOH) solution for 24 hours and then rinsed thoroughly with deionised water prior to use to remove residual NaOH. Batches of resin were then contacted with leachates at varying solid-to-liquid ratios (0.6, 1.3, 2.7, 5.3 and 13.3 mL of resin per 100 mL of leachate), as equivalent to Gomes et al. (2016). These mixtures were agitated for 24 hours to allow equilibration before supernatants were sampled for subsequent inductively coupled plasma optical emission spectrometry (ICP-OES) or mass spectrometry (ICP-MS), and ion chromatography (IC) analysis. All experimental conditions were repeated in triplicate. To discern adsorption kinetics, 10 mL of resin was added to 500 mL of each leachate, agitated on a magnetic stirrer, and sampled at time intervals of 1, 2, 3, 4, 5, 10, 15, 20, 30, 60 and 120 minutes. Mathematical modelling of isotherm adsorption curves was performed to determine overall loading capacities for each resin under each leachate scenario, and to provide a better understanding of how changing doses impacts overall resin performance.

To assess the re-usability of resins, 5 mL of each resin (hydrated and preconditioned to its hydroxide ion form using 5% NaOH) were separately contacted with 100 mL of October 2023 BRDA leachate in triplicate (the "loading" phase). These mixtures were placed on an orbital shaker for 24 hours, after which the supernatant solutions were sampled for ICP analysis. The treated BRDA leachate was then drained off the resins and replaced with 100 mL of 5% NaOH solution (the "elution" phase) and placed back on the orbital shaker for a further 24 hours, then subjected to the same sampling and analytical procedures as batch and kinetic trials. The resins were then drained again and rinsed with deionised water to remove residual NaOH. This constituted one complete "cycle" and the process was repeated consecutively over 11 cycles using the same 5 mL batch of resin.

2.3 Buffering experiments using wetland mesocosms

Triplicate wetland mesocosms were constructed in ~5 L HDPE containers consisting of a ~30 mm layer of washed granite gravel overtopped with ~120 mm of peat-free garden compost, into which three stands of common reed (*Phragmites australis*) were planted (Figure 1). These were then saturated using tap water so that a small layer of standing water was visible above the height of the compost. The effective bed volume was calculated during saturation and across the three replicate systems was an average of 1.3 L (standard deviation 0.03). The mesocosms were situated within a controlled environment laboratory at a temperature of 21°C, beneath growth lamps on a 12-hour daily photocycle (08:00–20:00). During acclimation these were kept saturated through regular watering (with tap water) and liquid nutrient additions in early stages. Acclimation was evidenced by plant growth, leaf condition and photosynthesis measurements.

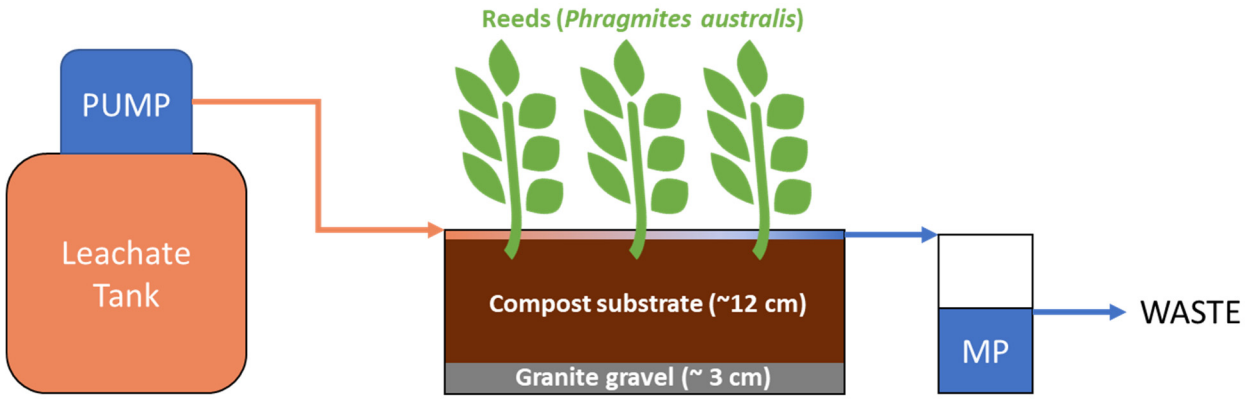

Figure 1 Schematic of wetland mesocosm showing experimental set-up and relative thickness of constituent layers within the reed bed. MP = monitoring point for sample collection

Leachate was introduced to the mesocosms after acclimation at flow rates giving an approximate residence time of 24 hours in each wetland cell. This was estimated based on measured bed volumes and calculated flow rates (measured three times a day). This residence time is similar to those documented at successful pilot systems treating BRDA leachate (O'Connor & Courtney 2020). The initial leachate introduced to the wetland was intended to be as close in composition to the leachate used by O'Connor & Courtney (2020), with a relatively low ionic strength and pH in the region of 10–11. To achieve these conditions, field leachate samples were diluted with deionised water to achieve this matrix, with the aim of gradually introducing more concentrated leachates to the wetland in successive experimental phases to test system treatment limits. Routine (typically 2–3 times weekly) influent and effluent samples were taken from the mesocosms throughout a 120-day trial to assess major physico-chemical parameters (pH, electrical conductivity [EC], oxidation-reduction potential [ORP], total dissolved solids and temperature) using a Myron Ultrameter. Selected samples were also analysed for major and minor elemental content (ICP-MS and ICP-OES) to assess metal(loid) uptake in the mesocosms. Data from the wetland mesocosms were compared against a control treatment consisting of a container of granite gravel only (i.e. no compost substrate or reeds) with the same dimensions and residence time of the wetland treatments. During the trial, influent leachate chemistry was adjusted to raise the pH and ionic strength from initial treatments and test the limits of effective pH buffering. Details on leachate quality are given in Section 3.

3 Results

3.1 Physico-chemical composition of bauxite residue disposal area leachates

The concentrations of key elements within collected BRDA leachates and published data of other leachates are provided in Table 1. Leachate samples collected in October 2023 showed typically high pH and EC expected of bauxite residue leachate, within typical ranges for BRDA leachate data published elsewhere (Table 1). Elemental analysis confirmed that these leachates were relatively enriched with As, Ga and V compared with typical post-closure leachates (O'Connor & Courtney 2020; Czop et al. 2011). Composition was broadly similar to Hungarian bauxite processing residue leachates (Mayes et al. 2011), albeit with lower aluminium (Al), iron (Fe) and molybdenum (Mo) concentrations. Analysis of the physico-chemical parameters of the leachate collected in June 2024 revealed a much lower pH (10.59) and EC (2.72 mS/cm) when compared with leachates from the same site collected in October 2023.

Table 1 Physico-chemical characteristics and elemental composition of collected bauxite residue disposal areas (BRDA) leachates (October 2023 and June 2024) and published composition data of other BRDA leachates (ORP = oxidation reduction potential; EC = electrical conductivity, N/A = not applicable, ND = no data)

Determinand	BRDA leachate October 2023	BRDA leachate June 2024	Hungary (Site K1; Mayes et al. 2011)	Modelled closure BRDA leachate (O'Connor & Courtney 2020)	Gorka pit lake (Czop et al. 2011)
pH	12.77	10.59	13.06	11.23	11.7–13.4
Temp. (°C)	21.8	25.1	3.6	N/A	9
ORP (mV)	–82	267	23	N/A	N/A
EC (mS/cm)	13.73	2.72	16.3	0.48	15–45
As (mg/L)	4.9–5.1	0.22–0.23	3.9	0.02–0.07	0.01–2.4
Al (mg/L)	90–92	0.42–0.45	1,230	4–40	19–27
Fe (mg/L)	0.25–0.26	0.071–0.074	10.2	ND	ND
Ga (mg/L)	2.3–2.4	0.041–0.042	2.3	ND	0.001–0.015
V (mg/L)	5.4–5.6	0.18–0.19	6.4	0.02–0.04	0.3–1.3

3.2 Selective recovery of critical elements from residue leachate

Isotherm experiments revealed that both resins were able to remove V to a high efficiency (maximum ~85%), with Purolite MTS9100 being slightly more effective at lower dosages (Figure 2). Promisingly, both resins also displayed a similar low affinity towards Al removal (<25 %), indicating that Al, a common fouling agent of resins, is unlikely to interfere with performance under these conditions. Selectivity was observed for As by Purolite A400, achieving high removal at the highest resin dose (>90%). Kinetics experiments (not presented) indicated fast V and As adsorption by Purolite A400, with maximum removal achieved within 30 minutes of contact time. Purolite MTS9100 exhibited very high selectivity towards Ga, even at low dosages, with removal ranging from 70–100% (Figure 2), albeit at a slower rate (120 minutes to reach maximum removal).

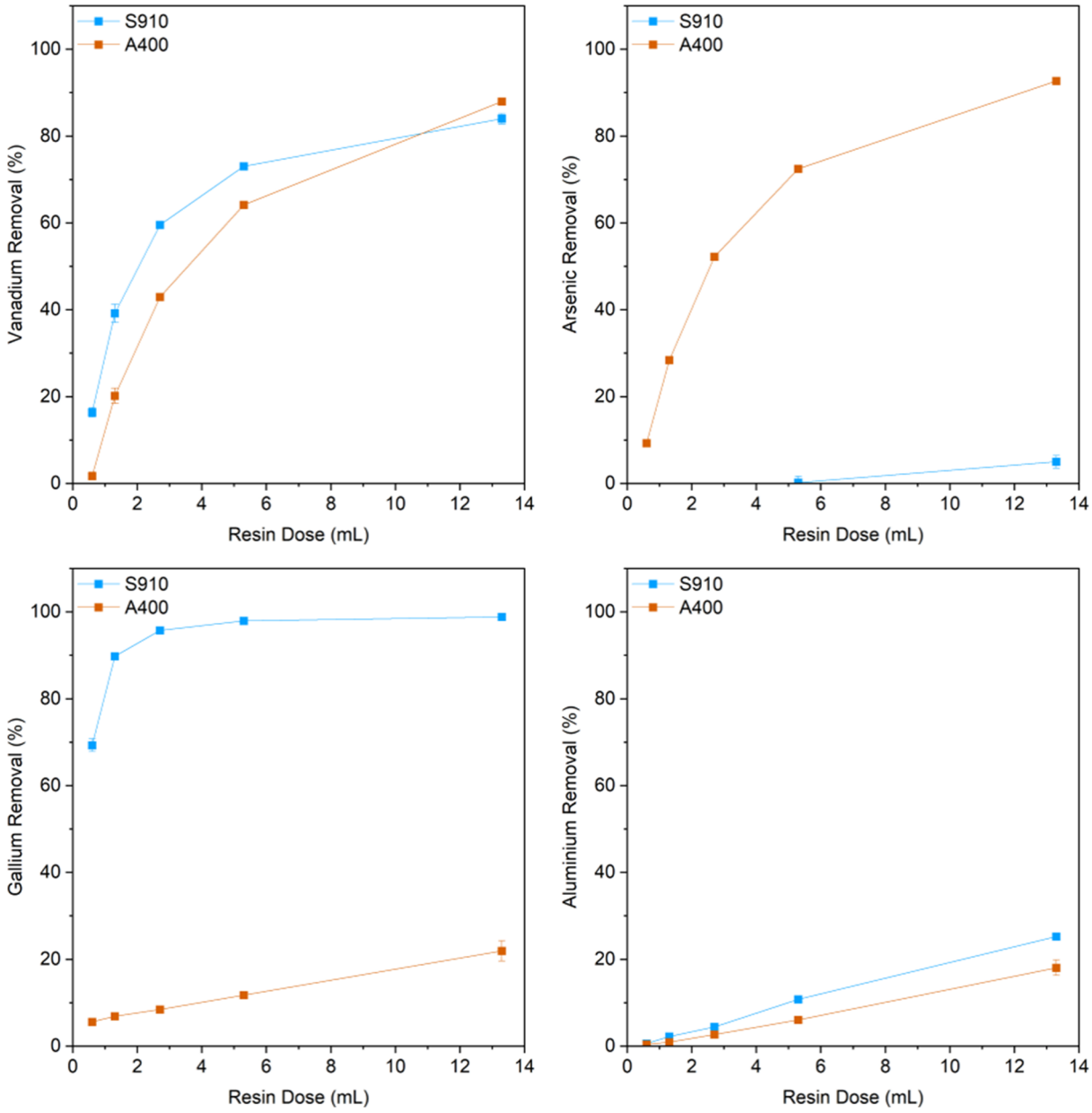

Figure 2 Comparative removal (%) of vanadium, arsenic, aluminium and gallium from bauxite residue disposal area leachates by Puromet MTS9100 (S910) and Purolite A400, as a function of resin dose (mL)

Mathematical modelling of isotherm adsorption curves was performed to determine overall loading capacities for each resin under each leachate scenario and to provide better understanding of how changing the dose impacts overall resin performance. For Puromet MTS9100, this modelling focused on V and Ga adsorption, given the relatively high removal of these metals by Puromet MTS9100 (Figure 2). The Langmuir adsorption model was used to assess the nonlinear relationship between equilibrium metal concentration (mg/L) and mass adsorbed to the resin (mg/g resin). For Puromet MTS9100, a theoretical maximum loading capacity (Q_{max}) of 1.23 mg V/g resin was determined with a good model fit (R^2 = 0.93; Figure 3, Table 2). For Ga, a maximum theoretical loading capacity of 1.59 mg Ga/g resin was determined (R^2 = 0.99).

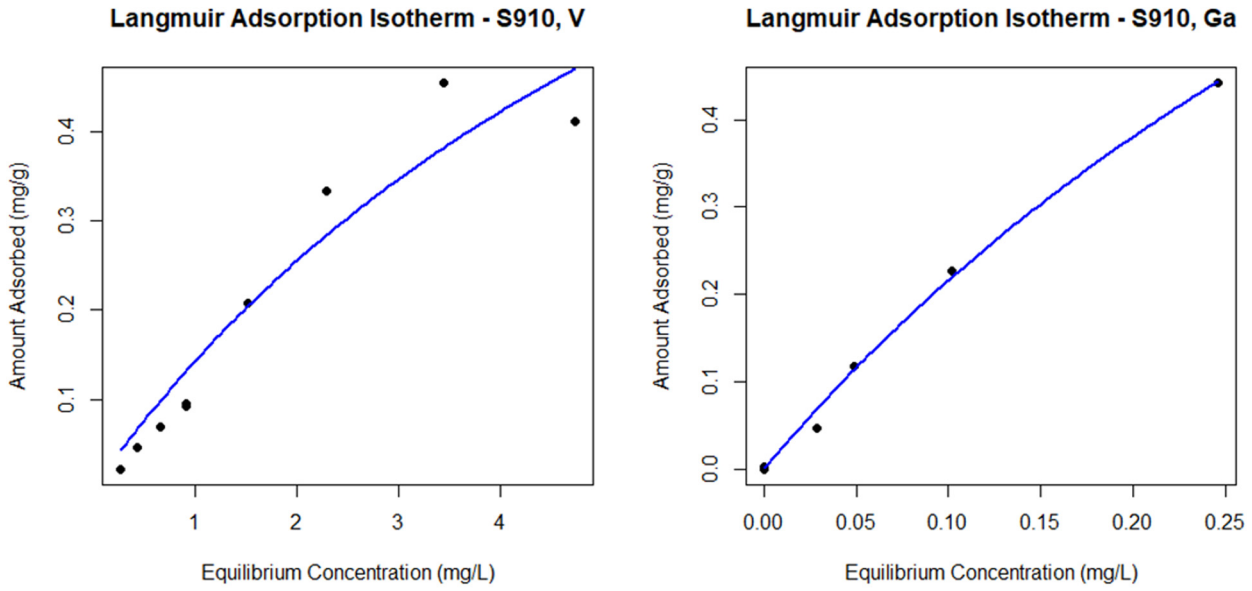

Figure 3 Modelling of vanadium and gallium adsorption by Puromet MTS9100 resin using the Langmuir adsorption model

For Purolite A400, isotherm modelling focused on the removal of V and As given the relative selectivity towards these ions displayed in Figure 2. In this instance, theoretical maximum adsorption capacities were lower than for Puromet MTS9100, with a modelled Q_{max} of 0.24 mg/g for V (R^2 = 0.95), and 0.39 mg/g for As (R^2 = 0.96) (Figure 4, Table 2).

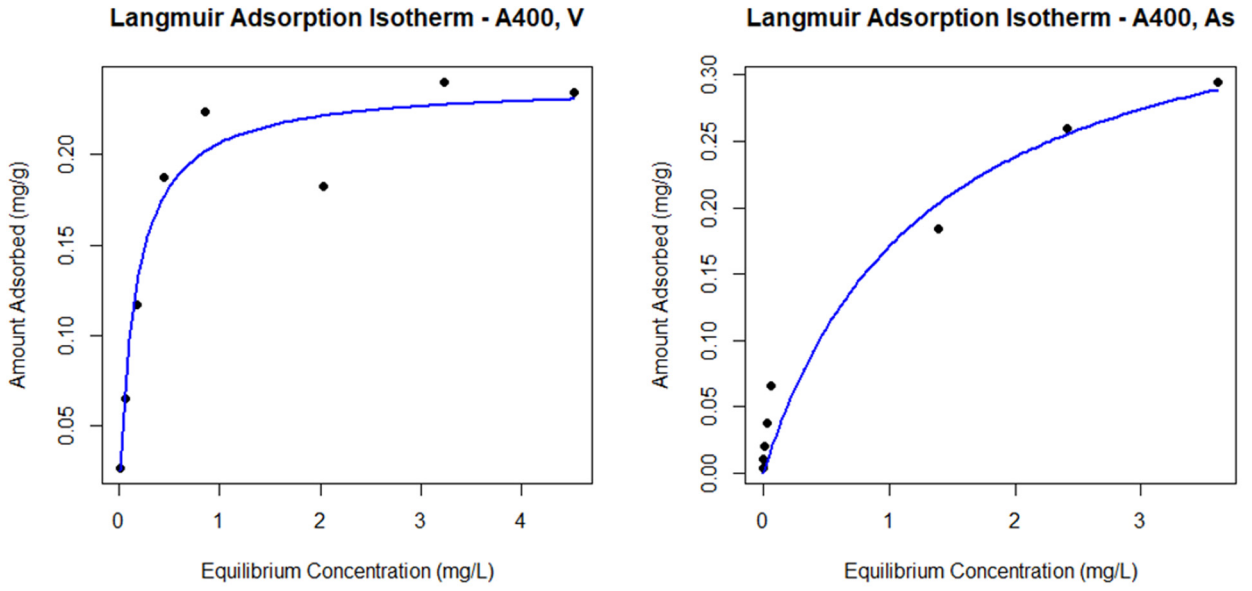

Figure 4 Modelling of vanadium and arsenic by Purolite A400 resin using the Langmuir adsorption model

Table 2 Output of Langmuir isotherm modelling for vanadium (V) and gallium (Ga) adsorption by Puromet MTS9100 (S910) and V and arsenic (As) adsorption by Purolite A400

Determinand	Langmuir constants		R^2
	Q_{max} (mg/g)	K_L (L/mg)	
V (S910)	1.23	7.64	0.93
Ga (S910)	1.59	0.63	0.99
V (A400)	0.24	0.156	0.95
As (A400)	0.39	1.29	0.96

Both resins were tested for their re-usability via repeated cycles of loading and elution. For Puromet MTS9100, effective metal removal was observed over the entire duration of the 11 cycles (Figure 5), with V and Ga removal remaining above 70% for the entire phase of the experiment. For V, the removal efficiency increased in each subsequent cycle, rising from 70 to 85% by loading cycle 11. For Purolite A400, removal of V and As remained consistent across the 11 cycles, with minimal decline (approximately 0.3% per loading cycle) in the removal percentage with each subsequent cycle, which is highly promising for long-term re-use of adsorbent beds in engineered treatment systems.

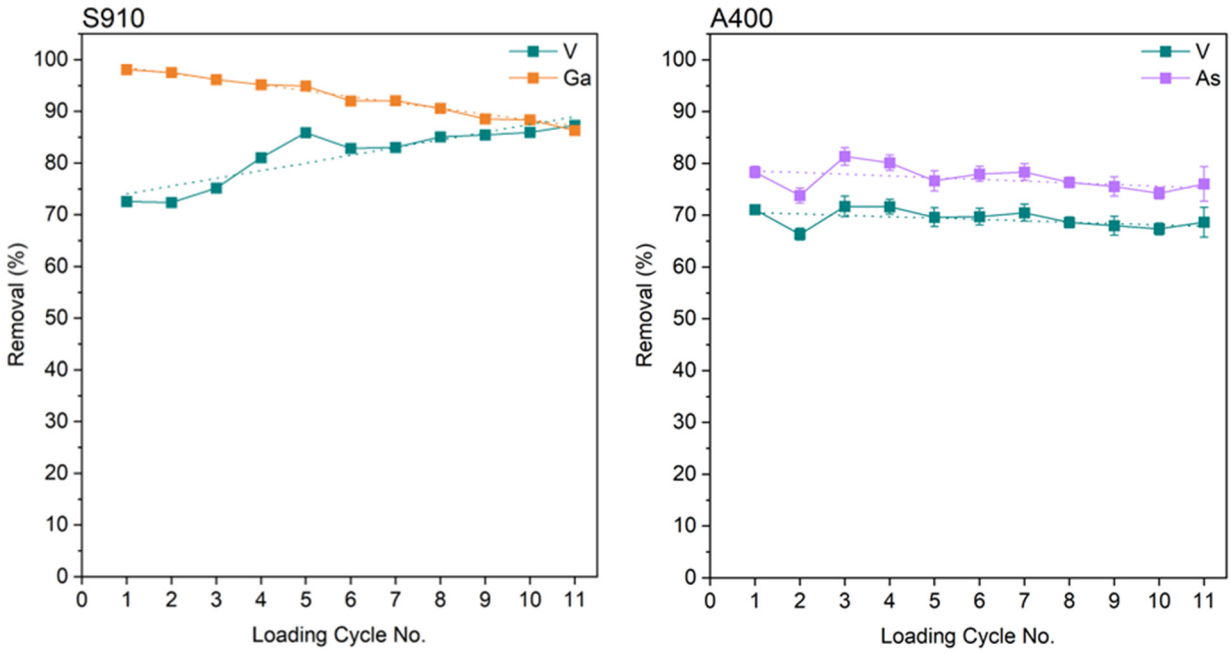

Figure 5 Calculated removal efficiency (%) of vanadium, arsenic and gallium by Puromet MTS9100 and Purolite A400 over 11 consecutive loading and elution cycles. Linear modelling is represented by dashed lines

3.3 Buffering of bauxite residue leachate in wetlands

The wetland mesocosms have been monitored under different leachate loading scenarios, progressively moving to higher pH and ionic strength after initial acclimation. For all leachate scenarios, the median input pH was between 10–11 (Figure 6). The control treatment bed, consisting only of a granite gravel substrate, offered slight pH reduction in all scenarios, but typically no lower than pH 9.5, and median pH was consistently above the target threshold of nine. Effluents from treatment beds A, B, and C were generally consistent between pH 8–9 (i.e. meeting likely discharge consent thresholds in most jurisdictions of pH <9),

even under later high ionic strength leachate conditions. A trend was observed in more recent measurements (October 2023 [diluted] leachates) towards higher effluent pH for all beds, with occasional breaches of the pH 9 target from bed A in the latest treatment scenario. The ECs of wetland mesocosm effluents (Figure 7) were generally higher than influent measurements except for the first application of June 2024 leachates, where effluent EC was typically lower. This is likely due to the flushing of soluble components from the compost substrate during the initial diluted June 2024 leachate phase, which had stabilised by the time neat June 2024 leachate was introduced, and from evapotranspiration losses from the wetlands at this small laboratory scale, which effectively concentrate effluent waters in relatively long residence time conditions (24 hours). ORP measurements (not presented) all indicated that the wetland mesocosms operated as aerobic systems (95% of effluent data between +180 and +320 mV; n = 467).

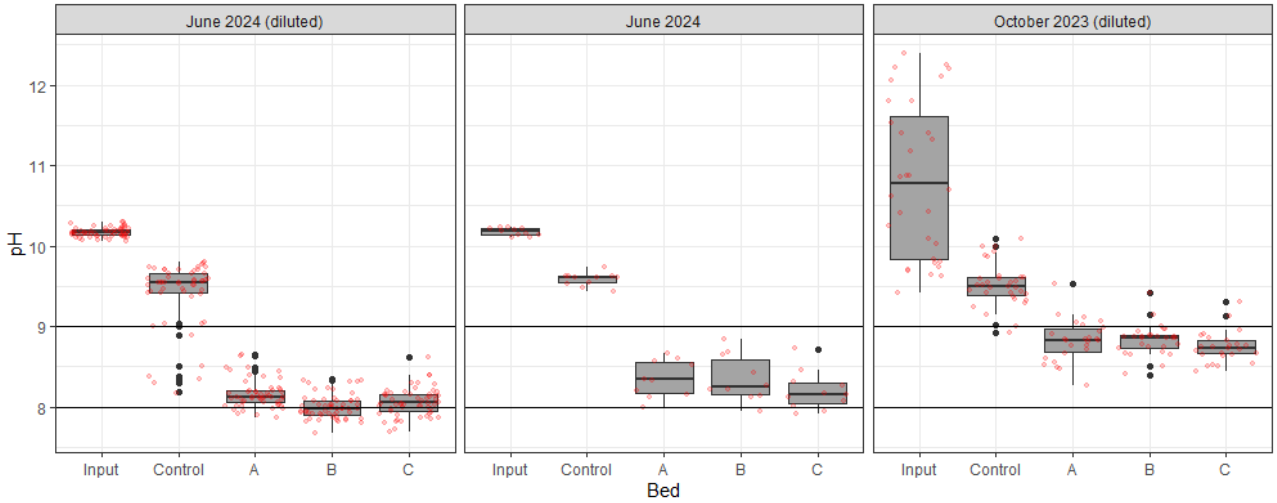

Figure 6 Monitored influent and effluent pH from control and treatment beds (A, B, C) under different leachate scenarios. Horizontal lines represent likely discharge thresholds of pH 8–9 in most jurisdictions

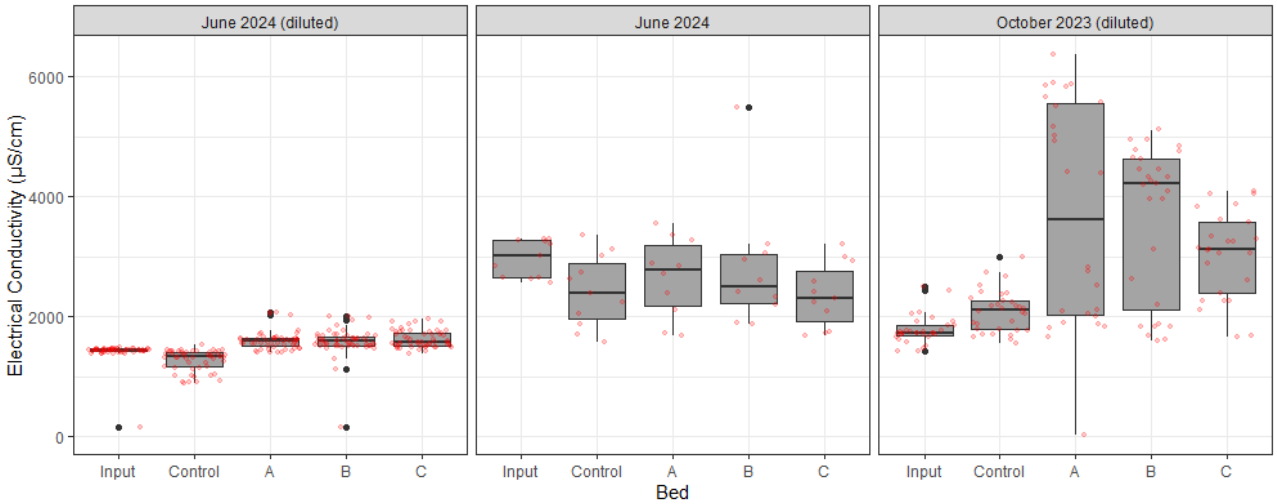

Figure 7 Monitored influent and effluent electrical conductivity (µS/cm) from control and treatment beds (A, B, C) under different leachate scenarios

It was observed that wetlands effectively removed metal(loid)s of concern from leachates, even when treating higher concentration October 2023 leachates (V: 90–94% removal, As: 47–48% removal; Table 3). Control beds could not remove any of these metals from the solution, but they did show modest Ga removal (albeit at roughly half the rate of wetland systems; Table 3). Wetland beds were also effective for residual Al

removal (46–87% removal), which is promising for final system implementation as the preceding ion exchange processes do not target Al (Figure 2).

Table 3 Selected mean metal removal (%) from wetland treatment and control beds, separated based on input leachate. Standard deviation provided in brackets (n = 10)

Leachate	System	Vanadium (%)	Gallium (%)	Arsenic (%)	Aluminium (%)
June 2024	Wetland	94.2 (3.8)	98.6 (1.8)	47.7 (19.1)	46.4 (12.2)
October 2023	Wetland	90.4 (6.4)	98.2 (0.3)	46.9 (34.1)	86.6 (5.0)
June 2024	Control	0.0	49.9 (11.3)	0.0	15.8 (23.8)
October 2023	Control	0.0	54.3 (17.8)	0.0	84.3 (5.1)

4 Discussion

4.1 Anion exchange resin for selective metal(loid) removal

Commercial resins showed promise in high percentages of influent V removal and selective As/Ga recovery (Figure 2). For each resin, modelled maximum loading capacities were lower than initially anticipated during project inception and when compared against equivalent values (e.g. for Purolite A400) in Gomes et al. (2016). However, it is important to note that this is the first report of the use of such resins for actual BRDA leachates in ion exchange isotherm experiments, with previous attempts using either synthetic V solutions or artificially spiked leachate samples to increase the concentrations of V to conditions not encountered in field conditions (e.g. Table 1; Mayes et al. 2011, Czop et al. 2011). The BRDA leachates assessed displayed metal(loid) concentrations towards the high end of values reported in the international literature (Table 1) and so are most representative of real-world use cases. The overall selectivity behaviour observed is promising for developing selective removal technologies. Puromet MTS9100 displays a high degree of selectivity towards Ga and V, which are both target elements given their high economic value, leaving Purolite A400 as a candidate for targeting problematic As concentrations in residual leachates, or also for V recovery should a single resin be employed. Also promising for Purolite A400 was the rapid rate of adsorption (~30 minutes), and the scope for repeated loading and elution cycling with limited effect on the overall V and As removal efficiency per cycle (Figure 5), a characteristic shared by Puromet MTS9100 for V and Ga extraction (Figure 5). The feasibility of re-using resins over multiple treatment cycles is critical when considering their application in an engineered treatment system, helping to improve the economic feasibility of water treatment during techno-economic analyses through reduced requirement to replace adsorbent materials.

4.2 Buffering of bauxite residue disposal area leachate in wetlands

The use of wetlands to lower the pH of alkaline leachates has previously been demonstrated for steel slag waters (Gomes et al. 2019; Mayes et al. 2009) and for post-closure BRDA waters (Higgins et al. 2016, 2017; O'Connor & Courtney 2020). The mesocosm approach here was intended to assess the limits of wetlands for addressing BRDA leachate. As such, the experimental approach began with low ionic strength and lower pH diluted BRDA (similar in composition to O'Connor & Courtney 2020), but with less dilution over time. The mesocosms have performed well to date, with a residence time of 1–4 days, an influent pH of up to ~11.5 and EC of 3 mS/cm^2, which is more concentrated than documented influent leachate in successful field pilots (O'Connor & Courtney 2020).

With every change in influent composition there was usually an immediate uplift in effluent pH, which dropped over subsequent weeks. This may reflect the adjustment of microbial communities in the mesocosms to the new conditions (higher alkalinity and salinity) given the importance of aerobic microbial communities in buffering alkaline waters through respiration (Mayes et al. 2009). Such a process is quite different to what is observed in many wetland treatment settings when there is often a "honeymoon phase"

of effective treatment, followed by deterioration – typically when sorption of metals or nutrients is key to treatment targets (e.g. PIRAMID Consortium 2003). Experimentation is ongoing with the mesocosms to establish the upper limits of influent concentration at which there is no longer effective pH buffering <9. With the current performance data there is still a gap between the diluted leachate that is being buffered (Figure 6) and the higher end of documented BRDA leachate composition (e.g. Table 1). As such, it is likely that some pH adjustment (e.g. partial acid dosing, use of balancing water) would be required for wetlands to be an effective part of a passive BRDA leachate treatment train.

There were encouraging signs for residual metal(loid) removal in the wetland mesocosms. All target elements of interest were removed at much higher rates than the control treatments (Table 3). Previous studies have shown similar residual metal(loid) removal in BRDA treatment wetlands (Higgins et al. 2016). V removal is well-documented in organic-rich wetland substrates (via complexation), and higher organic contents of wetland substrates are usually correlated with greater removal (Hudson et al. 2024). Arsenic removal is usually controlled by sorption to mineral (particularly Fe-) particles in wetland systems (PIRAMID Consortium 2003). Future leaching tests on substrates and plant tissues will help offer some indication of removal mechanisms and ongoing work is assessing the potential plant uptake of these.

4.3 Research needs and upscaling

The data presented provide advances in potential options for addressing BRDA leachates, with effective recovery of both elements of value (e.g. Ga, V) and those of regulatory concern (Al, As, V), with commercial ion exchange resins on real BRDA leachate samples for the first time. The wetland mesocosm data also potentially broadens the envelope for influent BRDA leachate quality that can be treated with wetlands. However, there are still significant developments that are required to move from laboratory to field-based demonstration.

4.3.1 Anion exchange resin deployment

Whilst the data presented here show effective removal and recovery of target elements in short residence time for complex, real-world BRDA leachates, deployment configuration needs consideration and evaluation. This could involve the use of resins in rotating bed reactors in preliminary leachate settlement ponds to further increase ion exchange reaction kinetics (Larsson et al. 2017). Evaluation of the effectiveness of leachate contact in such systems is needed for sizing pilot systems. The potential for re-use of resins needs further evaluation beyond the 11 cycles demonstrated here, as the longevity of resin performance would be a key element of future techno-economic assessments.

4.3.2 Limits of wetland deployment

Data presented here show effective buffering of diluted October 2023 BRDA leachate and undiluted June 2024 BRDA leachate from our study site. Establishing the limits of wetland treatment based on influent concentration, residence time and seasonal factors (e.g. low temperature performance) are key research priorities. This is crucial for assessing pre-treatment requirements (e.g. partial acid dosing, carbon addition) and associated costs that may be required for full-scale wetland deployment. Microbial analyses of wetland substrates would also be useful to highlight tolerant alkaliphile communities that could potentially be used as inocula at new sites. A broader review of BRDA leachate quality across multiple sites, and the long-term evolution of BRDA leachate quality, would also help to highlight where and when wetland treatment could be most suitable in BRDA post-closure settings.

4.3.3 Techno-economic assessment and lifecycle assessment

Laboratory data and subsequent pilot data are crucial for constraining techno-economic assessment and lifecycle assessment models that are required to compare treatment alternatives such as metal(loid) recovery and wetland use against established treatment options such as acid dosing (e.g. Gomes et al. 2018). Such comparisons should comprise multi-decadal timeframes, given the potential longevity of leachate generation.

5 Conclusion

This study aimed to assess the effectiveness of selective metal(loid) recovery from BRDA leachates with anion exchange resins alongside the pH buffering capabilities of wetlands in laboratory mesocosms. Data showed the potential for commercially available ion exchange products to successfully and selectively remove vanadium (88%), arsenic (93%) and gallium (95%) from field BRDA, with effective recovery of metal(loid)s from loaded resins achieved via elution over repeated treatment cycles. Buffering of BRDA leachate showed wetlands were consistently effective in lowering pH below typical regulatory limits (<9) for influent leachate with pH >10.6 and EC >3 mS/cm^2. Wetland soils were also effective in reducing residual metal(loid) concentrations (V up to ~94%, As up to ~48% and Al up to ~87%). Further research testing deployment configuration for resin-based recovery systems in rotating beds, alongside additional stress testing of wetland systems under higher ionic strength influent leachate composition, would help develop and constrain system design for field pilots, as would exploration of alternative wetland operational conditions (e.g. flow rate, geometry). Such systems could provide economic and environmental benefits over conventional BRDA leachate treatment options that require refined chemicals and higher energy inputs.

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