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Germination and Survival of Grasses and Legumes Are Enhanced on Blended Byproduct Caps Compared to Bauxite Residues

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Abstract Establishment of vegetation cover is one of the key steps in the final closure strategy for tailings storage facilities. Bauxite residues (Bayer process tailings) are highly alkaline, saline-sodic materials that make direct revegetation challenging unless the harsh chemical properties of residues are improved towards plant tolerable values. Currently, either 'cap and store' or 'in situ remediation' approaches are used to close and revegetate bauxite residue storage facilities. A new approach called 'blended byproduct capping' (blending tailings with available byproducts such as fly ash, eucalypt mulch and sewage water on-site) has been developed to avoid common drawbacks of existing closure methods. In this study, a germination assessment of two grass species (barley (*Hordeum vulgare*) and ryegrass (*Lolium multiflorum*)) and three annual legume species (lupin (*Lupinus angustifolius*), mungbean (*Vigna radiata*) and serradella (*Ornithopus sativus*)) was used to evaluate substrate suitability of the developed blended byproduct caps of different textures (bauxite residue fines, bauxite residue sand and bauxite residue fines plus 10% bauxite residue sand). Potting mix and unblended and unleached bauxite residues were used as positive and negative controls, respectively. Barley, ryegrass, mungbean and serradella had germination rates of > 80% in blended byproduct caps and potting mix, whereas lupin germination rates were ≤ 50%. Barley germinated (< 10%) on unblended residues, while lupin germinated only with bauxite residue fines (0.8%). However, plant survival in the blended byproduct caps was also poor, suggesting that capping materials require further optimisation to support vegetation efforts. The pH and Na concentrations in the blended byproduct caps remained above target values for vegetation establishment, and were the likely causes of poor plant survival. Addition of acidifying agents in future blended byproduct cap trials is recommended to improve conditions for plant growth.

Keywords Bauxite residue fines · Bauxite residue sand · Red mud · Revegetation · Alkalinity · Sodicity

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1 Introduction

Globally, around 150 million tonnes of bauxite residue are produced each year (Healy, 2022). In addition, 4 billion tonnes of bauxite residue is currently stored in bauxite residue storage areas globally (Healy, 2022). As bauxite residues (sometimes referred to as red mud) are generally highly alkaline, saline and sodic (Jones & Haynes, 2011; Santini & Banning, 2016; Taki et al., 2023, 2025), can create risks for contamination of the surrounding environment via wind/water erosion and leaching (Di Carlo et al., 2019). For example, macrophytes (e.g. *Persicaria amphibian*) growing in Kinghorn Loch Lake in the UK, contaminated by bauxite residue leachate over 30 years, had arsenic (As) concentrations that were considered extremely toxic to potential grazers (Olszewska et al., 2016). Bauxite residue has also been shown to cause a genotoxic effect in *Tradescantia* due to a higher concentration of vanadate (Mišík et al., 2014). Bauxite residues, therefore, present a key challenge for mining industries to develop and apply effective remediation strategies to prevent pollution and site contamination, and for closure of tailings storage facilities.

Surface vegetation establishment is a key milestone towards successful closure of bauxite residue storage areas (Healy, 2022). However, both physical and chemical properties of bauxite residues pose several challenges to establish vegetation. For example, bauxite residue is highly alkaline (average pH 11.3), has high salinity (average electrical conductivity (EC) 7.4 mS cm^{-1}) and is frequently sodic (exchangeable Na percentage 69%). In addition, bauxite residues are low in organic carbon (OC; < 0.3 wt %), with poor drainage and porosity associated with high bulk density (average 2.5 g cm^{-3}), and is fine-grained (particle size $2-100$ µm and average specific surface area 32.7 m^2 g^{-1}) (Gräfe & Klauber, 2011a; Gräfe et al., 2011b; Santini & Banning, 2016; Taki et al., 2023, 2025). Further, bauxite residue generally has elevated concentrations of trace elements such as As, chromium (Cr), cobalt (Co), nickel (Ni) and vanadium (V) (Burke et al., 2012; Santini et al., 2021; Taki et al., 2023, 2025). Therefore, amelioration of bauxite residue is required to establish conditions that are more favourable to establishment and persistence of plant growth.

Two main approaches are used to improve conditions in order to vegetate bauxite residue storage areas for closure: (i) 'cap and store', and (ii) 'in situ remediation' (Jones & Haynes, 2011). 'Cap and store' involves importing a plant growth medium (usually high quality topsoil) which is deposited over the untreated bauxite residue along with an impermeable layer (e.g. clay, geotextile, sand etc.). Plants are then grown in the cap layer. In situ remediation involves application of organic and inorganic amendments to remediate the bauxite residue itself, with vegetation then established directly in the remediated residue (Santini & Fey, 2013). There has been extensive study of how various amendments can improve residue properties during in situ remediation (Courtney & Mullen, 2009a; Jones et al. 2012a; Di Carlo, 2020; Phillips & Courtney, 2022). These studies have shown some successful vegetation establishment on bauxite residue. However, buying the amendments is expensive and amendments are not always available on or close to site. In addition, nutrient deficiency and metal toxicity still remained at a toxic level. Therefore, an alternative solution is required to mitigate the drawbacks of in situ remediation, vegetation establishment and closure of bauxite residue storage facilities. Previously, we showed that 'blended byproduct capping' has the potential to significantly ameliorate hostile growth conditions, especially when coupled with leaching (Taki et al., 2023, 2025). More weathered substrates are also more likely to be leached and less hostile to plant growth (Taki et al., 2023, 2025), but this remains to be tested.

Grasses and legumes are highly suitable candidates for bauxite residue revegetation due to their rapid growth, tolerance of high alkalinity, salinity and sodic conditions, and (for legumes), increased N supply via fixation (Courtney & Mullen, 2009a; Jones & Haynes, 2011). Species successfully grown in previous studies of bauxite residues to which amendments have been applied ($\pm$ weathering and leaching) are listed in Table 1. It is evident that a wide range of species and/or species mixes may be suitable for revegetation depending on the extent to which residues have been pre-treated, climate (e.g. higher versus lower rainfall), and other factors such as availability of material that can be incorporated with bauxite residues. Several ryegrass varieties have been extensively used for bauxite residue revegetation (Banning et al., 2014; Courtney et al., 2009b; Eastham

Table 1 List of grass and legume species that used for germination study in amended bauxite residues

Grasses		
Common name	**Botanical name**	**Reference**
Tall wheatgrass	*Agropyron elongatum*	Wong & Ho, 1994
Bermudagrass	*Cynodon dactylon*	Woodward et al., 2008; Khaitan et al., 2010
Yorkshire Fog	*Holcus lanatus*	Courtney & Timpson, 2005; Courtney et al., 2009b
Perennial ryegrass	*Lolium perenne*	
Wimmera ryegrass	*Lolium rigidum*	Eastham et al., 2006; Banning et al., 2014
Creeping bentgrass	*Agrostis stolonifera*	Courtney et al., 2009b
Red fescue	*Fescue rubra*	
Garden cress	*Lepidium sativum*	Finngean et al., 2018
Legumes		
Common name	**Botanical name**	**Reference**
White clover	*Trifolium repens*	Courtney et al., 2003; Courtney and Timpson (2005); Courtney et al., 2009b
Red clover	*Trifolium pratense*	
Meadow vetchling	*Lathyrus pratensis*	
Common birdsfoot trefoil	*Lotus corniculatus*	
Black medic	*Medicago lupulina*	
Bush vetch	*Vicia sepium*	

et al., 2006). Barley has been used to revegetate gold mine tailings (Mains et al., 2006). Lupin (a legume) has been used to vegetate alkaline (pH > 9) magnetite tailings; and increased nitrogen and phosphorus content in the tailings materials and assisted to establish native species (Zhong et al., 2021). In addition, mungbean (a legume) has also been reported as highly heavy metal tolerant (Rahdarian et al., 2022). We might thus expect that inclusion of legumes in early stages of management along with fast-growing grasses, may further improve growth conditions for capping materials.

In this study, we use a germination study to evaluate the efficacy of a range of blended bauxite residues as capping material to support plant growth (see Taki et al., 2023, 2025). The aims of this study were to: (a) evaluate the efficacy of three weathered and leached blended byproduct caps of different textures (bauxite residue fines, bauxite residue sand, bauxite residue fines plus 10% bauxite residue sand) as plant growth media; and (b) evaluate candidates for bauxite residue revegetation. We compared germination, growth and survival of two annual grass species (*Lolium multiflorum* and *Hordeum vulgare*) and three annual legume species (*Lupinus angustifolius, Vigna radiate* and *Ornithopus sativus*) in the blended byproduct caps. We used potting mix as a positive control, and fresh (unblended and unleached) bauxite residue as a negative control, matching residue texture to that used in each of the three blended byproduct caps. Germination and survival were expected to be higher in bauxite residue blended with byproducts than fresh bauxite residues owing to decreased alkalinity, salinity, and sodicity. We also expected that germination and survival rates of grasses would be greater than those of legumes.

2 Materials and Methods

2.1 Experimental Design

Three different types of bauxite residues: (i) bauxite residue fines (BRF); (ii) bauxite residue sand (BRS); and (iii) bauxite residue fines plus 10 wt % bauxite residue sand (BRF + BRS) were blended with three byproducts: fly ash (10 wt %), sewage water (10 wt %) and eucalypt mulch (5 wt %); and leached for 18 weeks (three wetting and three drying cycles, three weeks each) to mimic field weathering before their use in the germination trial. The characterisation of the residue materials, and effect of byproducts application and leaching were reported in Taki et al. (2025). Potting mix was used as a positive control,

and unblended and unleached bauxite residues were used as a negative control, matching residue texture to that used in each of the three blended byproduct caps. The properties of unblended unleached bauxite residues and blended and leached bauxite residues are given in Table 2 and summarised from Taki et al., (2023 & 2025), and detailed properties of potting mix are given in Table S1.

We tested the efficacy of three weathered and leached blended byproduct caps using a two-factor experiment (germination media × plant species). A total of seven germination media were used for the experiment. Three germination media were developed by combining a bauxite residues type (fine (BRF), sand (BRS), and a 90:10 mix of (BRF + BRS)) with fly ash (10 wt%), sewage water (10 wt%), and eucalypt mulch (5 wt%). These were compared with three fresh, unleached and unblended media (BRF, BRS, and BRF + BRS), as well as a commercial potting mix. Fresh (unblended and unleached) residues were included to represent baseline material conditions early in the "life" of the residues. By contrast, the blended and leached byproduct mixtures were designed to reflect residue types that are known to show improved chemical properties (Taki et al., 2025) and thus reflect a likely more practical and rehabilitation-oriented treatment.

The five grass and legume species were: (i) *Lolium multiflorum* (Ryegrass); (ii) *Hordeum vulgare* (Barley); (iii) *Lupinus angustifolius* (Lupin); (iv) *Vigna radiata* (Mungbean); and (v) *Ornithopus sativus* (Serradella). Characteristics of the selected species are described in Table S2. The experiment was set up with a randomised complete block design with four replicates per treatment, creating a total of 140 pots. Two kg of the germination media were added to pots (101 mm height by 203 mm wide).

All germination media (except potting mix) were amended with the following basal nutrients (in mg/kg soil) mixed through in liquid form before media were packed into pots and seed sown: N (33.3); P (60); K (148.5); Zn (9.9); Cu (9.9) and Mo (0.08). N was re-applied as liquid ammonium nitrate at two weeks after sowing at 16.65 mg/kg soil to the soil surface in a dilute solution. The experiment was conducted under standard glasshouse conditions at The University of Western Australia in Perth, Western Australia (31.97S, 115.82E) during March–April in 2021 with

Table 2 Properties of unblended and unleached bauxite residues, and blended and leached bauxite residues

Properties	Unblended and unleached			Blended and leached		
	BRF	BRF + BRS	BRS	BRF with byproducts	BRF + BRS with byproducts	BRS with byproducts
pH	10.7 ± 0.04	10.47 ± 0.01	10.45 ± 0.03	9.68 ± 0.05	9.69 ± 0.02	9.94 ± 0.11
EC (mS cm^{-1})	6.37 ± 0.34	6.01 ± 0.45	6.25 ± 0.04	0.53 ± 0.05	0.48 ± 0.04	0.23 ± 0.04
Al (%)	9.44 ± 0.05	8.67 ± 0.13	7.55 ± 0.03	9.08 ± 0.07	8.42 ± 0.15	7.51 ± 0.001
Ca (%)	1.15 ± 0.04	1.07 ± 0.04	0.18 ± 0.002	1.0 ± 0.01	1.02 ± 0.03	0.19 ± 0.001
Fe (%)	38.9 ± 0.28	37.5 ± 0.4	42.54 ± 0.2	36.19 ± 0.7	37.40 ± 0.4	42.5 ± 0.13
K (%)	0.04 ± 0.01	0.07 ± .001	0.04 ± 0	0.09 ± 0.001	0.08 ± 0.002	0.04 ± 0
Na (%)	2.69 ± 0.24	1.97 ± 0.09	1.44 ± 0.01	0.97 ± 0.01	0.93 ± 0.02	0.23 ± 0.005
P (%)	0.05 ± 0.00	0.05 ± .002	0.02 ± 0.001	0.05 ± 0.001	0.05 ± 0.002	0.02 ± 0.001
S (%)	0.3 ± 0.02	0.23 ± 0.01	0.08 ± 0.002	0.21 ± 0.009	0.23 ± 0.007	0.11 ± 0.001
Si (%)	4.22 ± 0.01	3.62 ± 0.16	3.66 ± 0.01	5.26 ± 0.4	5.08 ± 0.13	5.0 ± 0.02
Ti (%)	2.67 ± 0.02	2.66 ± 0.01	1.53 ± .003	2.60 ± .05	2.44 ± 0.02	1.47 ± 0.006
Cr (mg/kg)	629 ± 1.85	700 ± 4.73	1225 ± 1.8	611 ± 10.5	694 ± 7.83	1181 ± 1.94
Ni (mg/kg)	75 ± 2.06	69 ± 2.64	82 ± 2.52	78 ± 2.76	85 ± 3.08	88 ± 2.0
Mo (mg/kg)	14.83 ± 0.7	10.23 ± 0.23	8.55 ± 0.61	8.25 ± 0.17	7.97 ± 0.8	7.28 ± 0.45
V (mg/kg)	1216 ± 10.9	1136 ± 5.02	1194 ± 3.53	1093 ± 22.9	1113 ± 7.73	1175 ± 0.83
Total organic C (%)	0.41 ± 0.03	0.26 ± 0.01	0.22 ± 0.01	2.40 ± 0.04	2.35 ± 0.04	2.15 ± 0.02
Total N (%)	0.03 ± 0.00	0.03 ± 0	0.02 ± 0	0.04 ± 0	0.04 ± 0	0.03 ± 0

an average day length of 12 h and an average day/night temperature of 22.3/16 °C. Thirty seeds were sown per pot. Seeds were pre-treated with 1% sodium hypochlorite (NaOCl) and 0.01 mM calcium chloride ($CaCl_2$) as fungicides, and to break dormancy.

2.2 Assessment of Germination and Survival Rates

Seed germination was recorded daily. Protruded visible cotyledon(s) were considered as germinated. Germination percentage was calculated following the equation below:

$$Germination\ rate\ (\%) = \frac{number\ of\ seeds\ germinated\ in\ each\ pot}{total\ number\ of\ seeds\ sown\ in\ each\ pot} \times 100$$

Seedlings continued to count as 'germinated' until they died. Plants were considered dead when no green leaves remained in shoots and all leaves and stems were brown in colour. Survival rate was calculated following the equation below:

$$Survival\ rate\ (\%) = \frac{number\ of\ survived\ seedlings}{maximum\ number\ of\ germinated\ seedlings} \times 100$$

Time to first emergence was the day when protruded visible cotyledon(s) were first observed in each species after sowing. Time to maximum emergence was the day when all/maximum number of seeds germinated and later none of the seeds germinated until terminating the experiment.

2.3 Data Analysis

Data were analysed using R version 4.2.1 (R Core Team, 2022). Generalized linear modelling (GLM) was performed using *lme4* package version 1.1—30 (Bates et al., 2022) to identify differences in plant responses (germination, survival, time to first emergence and time to maximum emergence) to different growth media (blended byproduct caps). The experiment followed a randomized complete block design, with Replication treated as the blocking factor. The block effect (Rep) was initially tested by fitting models with and without Rep. As the block effect was not statistically significant and did not improve model fit, it was excluded from the final GLMs. GLMs for germination and survival followed a binomial error distribution (logit) whereas time to first emergence and time to maximum emergence followed a Gaussian error distribution (identical). Relationships of plant response variables to soil chemical properties (pH, EC, Al, Ca and Na concentration, and CEC) were tested by Spearman correlation coefficients using *psych* package version 2.2.5 in R (Revelle, 2022).

3 Results

3.1 Germination Rates

Blending bauxite residue with byproducts, followed by weathering and leaching, significantly increased germination rates of all five species, compared to fresh (unblended and unleached) BRF, BRS and BRF + BRS (Fig. 1 & Table 3). Both grass species, ryegrass (*L. multiflorum*) and barley (*H. vulgare*) had germination rates > 93% in BRF, BRS and BRF + BRS blended with byproducts, and > 99% in potting mix. There were no significant differences in germination rates among ryegrass, barley, serradella (*O. sativus*) or mungbean (*V. radiata*) within any of the blended byproduct caps. Lupin (*L. angustifolius*) fared poorly in blended byproduct caps, with significantly lower germination rates than all other species (41—51%), despite germinating well in potting mix (~ 92%; not significantly different to any other species). Germination rates in blended byproduct caps were not significantly different from those in potting mix (positive control) for any species except lupin. Among the legume species, mungbean (*V. radiata*) and serradella (*O. sativus*) were most successful, with germination rates > 84% in both blended byproduct caps and potting mix. In contrast, in fresh BRF, BRS and BRF + BRS, ryegrass, serradella and mungbean completely failed to germinate, and lupin (1%) and barley (2.5—9.2%) germination rates were very low.

Very low germination rates in the fresh bauxite residues (BRF, BRS and BRF + BRS) demonstrated that these materials were unsuitable for germination without modification. Significant negative correlations between germination and H_3O^+ (r = 0.51), EC (r = —0.81) and Na (r = —0.79) suggests that these are the main properties that severely inhibited germination in fresh bauxite residues (Table 4).

3.2 Survival Rates

Despite strong germination, survival rates of all species in BRF, BRS and BRF + BRS blended with byproducts

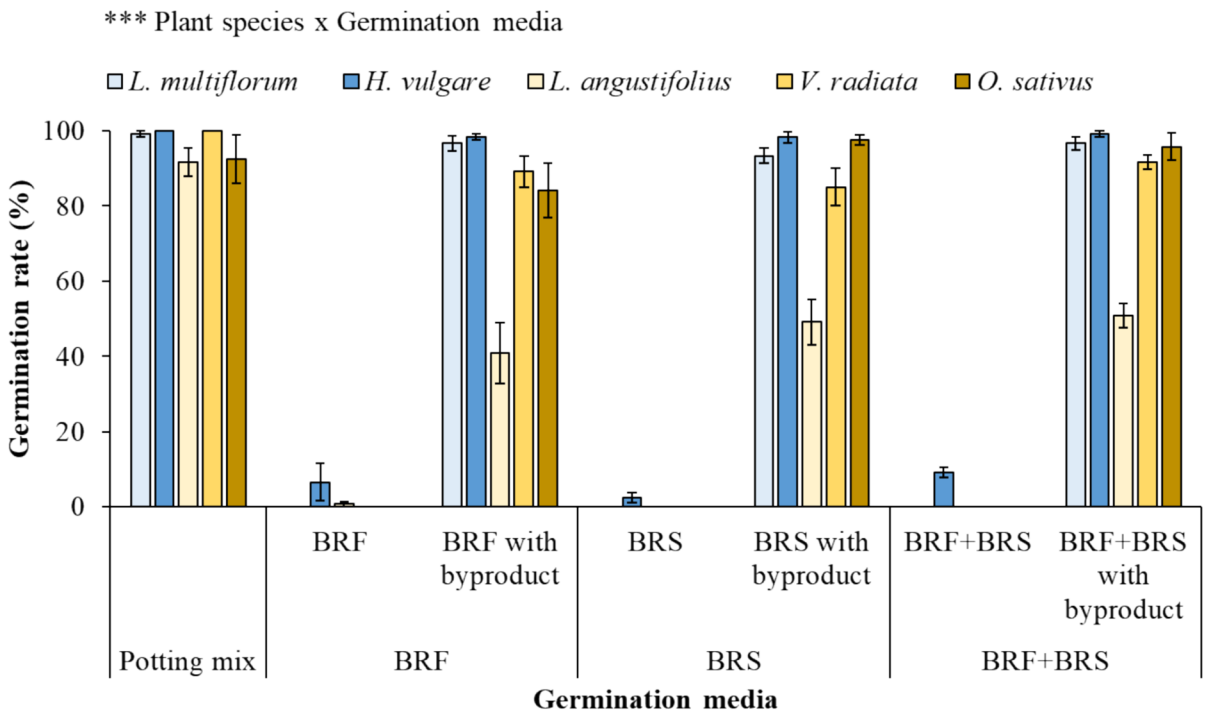


Fig. 1 Germination rate (%) of five plant species in different germination media: potting mix, bauxite residue fines (BRF, with and without byproduct), bauxite residue sands (BRS, with and without byproduct) and bauxite residue fines + bauxite residue sands (BRF + BRS, with and without byproduct). Binomial generalized linear models with a logit link were fitted using the number of germinated vs. non-germinated seeds as the response to test interactions between plant species and germination media. Data were presented as germination rate (%) calculated as the proportion of seeds germinated per pot. Bars represent estimated marginal means (± SE) back-transformed to percentages from the fitted model. There was significant interaction ($P \leq 0.001$) between germination media and plant species for germination rate. Details of the statistical analysis of different measured parameters are given in Table 3

were significantly lower than those in potting mix (Fig. 2 & Table 3). The only exception was ryegrass grown in BRS blended with byproducts (82% survival), which showed statistically equivalent survival rates to that of ryegrass in potting mix (100% survival). In potting mix, survival rates for all five species were 100%.

In contrast, none of the plants that germinated in the fresh residues survived. In the blended byproduct caps, ryegrass had a significantly higher survival rate (52.9—82.8%) than lupin (0—1.6%), mungbean (0—17%) or serradella (7.5—12.5%), and barley was intermediate (24—53%). For both ryegrass and barley, BRS blended with byproducts produced a significantly higher survival rate (ryegrass: 83%; barley: 53%) than BRF blended with byproducts (ryegrass: 53%; barley: 24%), and BRF + BRS blended with byproducts in the case of ryegrass (55%). The texture of the blended byproducts cap had no statistically significant effect on survival of any species. Correlation with survival and H_3O^+ (r = —0.80), EC (r = —0.83) and Na (r = —0.82) were significantly negative (Table 4).

3.3 Time to First Emergence and Maximum Germination

Fresh BRF + BRS significantly delayed emergence for barley, taking three days longer to achieve first emergence compared to a potting mix (Fig. 3 & Table 3). There were no significant differences in time to first emergence for any other combination of residue/growth medium type, or species.

No significant differences were observed in time to maximum germination among any combinations of residue/growth medium type, or species, other than serradella in potting mix (Fig. 4 & Table 3). Serradella took a significantly longer time (10 days) compared

Table 3 Main effect and significant interactions in Generalized linear models (GLMs) for plant species and germination media: (a) germination; (b) survival; (c) time to emergence, and (d) time to maximum emergence showing degrees of freedom (DF), deviance and *P* values

Variable	DF	Deviance	*P* value
(a) Germination			
Plant species	4	7163.55	≤0.001
Germination media	6	241.55	≤0.001
Plant species x Germination media	24	288.99	≤0.001
(b) Survival			
Plant species	4	151243.62	≤0.001
Germination media	6	14326.52	≤0.001
Plant species x Germination media	24	22484.01	≤0.001
(c) Time to first emergence			
Plant species	4	101.67	≤0.001
Germination media	6	52.9714	≤0.001
Plant species x Germination media	24	138.32	≤0.001
(d) Time to maximum emergence			
Plant species	4	1098.34	≤0.001
Germination media	6	65.88	≤0.001
Plant species x Germination media	24	268.01	≤0.001

to mungbean in potting mix (4.75 days), lupin in BRS with byproducts (5 days), and barley in both BRS with byproducts (3.75 days) and BRS + BRF (4.75 days).

4 Discussion

4.1 Plant Germination Improved on Blended Byproducts

Germination and survival assessment is commonly used and widely accepted for evaluating the performance and potential phytotoxicity of various growth media (Fourrier et al., 2021; Jones et al., 2012b; Sarathchandra et al., 2022). Here, germination and survival testing were used to assess the performance of developed blended byproduct capping materials as plant growth media (Taki et al., 2025). High germination rates observed in byproduct caps (BRF, BRS and BRF + BRS blended with byproducts), comparable to those of potting mix, and significantly higher than in fresh residues, demonstrated that these capping materials were appropriate media for germination of all five species (Fig. 1). Blending with byproducts, and leaching and weathering of the blended materials, created a soil-like material for germination.

Low germination rates in fresh bauxite residues are likely due to high alkalinity, salinity and sodicity (Taki et al., 2025). This supports other previous findings that observed low seedling emergence in fresh bauxite residues (Courtney & Mullen, 2009a; Di Carlo et al., 2020; Wong & Ho, 1993). In a high pH environment, ion imbalance occurs in the seeds which directly affects the absorption of minerals, in turn resulting in structural decomposition and death of seeds (Zhang & Mu, 2010). Under saline conditions, seeds are prevented from taking up inorganic ions due to low water potential, which are essential to accelerate the germination process (Debez et al., 2004; Guo et al., 2010; Zhang et al., 2008). A study by Wang et al. (2022) reported that seed germination is severely inhibited by alkaline salts (e.g. Na_2CO_3) compared to neutral salt (e.g. NaCl). This study also reported that seed germination was not only affected by pH alone, but also by the interaction between pH and salts. As bauxite residue has higher alkaline salts concentration (e.g. NaOH, Na_2CO_3) and high pH; therefore, lower seed germination was observed in this study (Fig. 1). This effect is also reflected in time to first germination and maximum germination (Figs. 3 and 4).

Table 4 Correlation values (Spearman's r at significant $P \leq 0.05$) for different germination indexes with growth media's selected chemical properties. Note: *, $P \leq 0.05$; **, $P \leq 0.01$; ***, $P \leq 0.001$

Germination index	H_3O^+	EC	Al	Ca	Na	CEC
Germination	0.53**	- 0.81***	- 0.25	- 0.05	- 0.79***	- 0.07
Survival	0.80***	- 0.83***	- 0.29	- 0.08	- 0.82***	- 0.11
Time to first emergence	0.27	- 0.52**	- 0.21	- 0.10	- 0.52*	- 0.09
Time to maximum emergence	0.51**	- 0.72***	- 0.12	0.06	- 0.71***	0.02

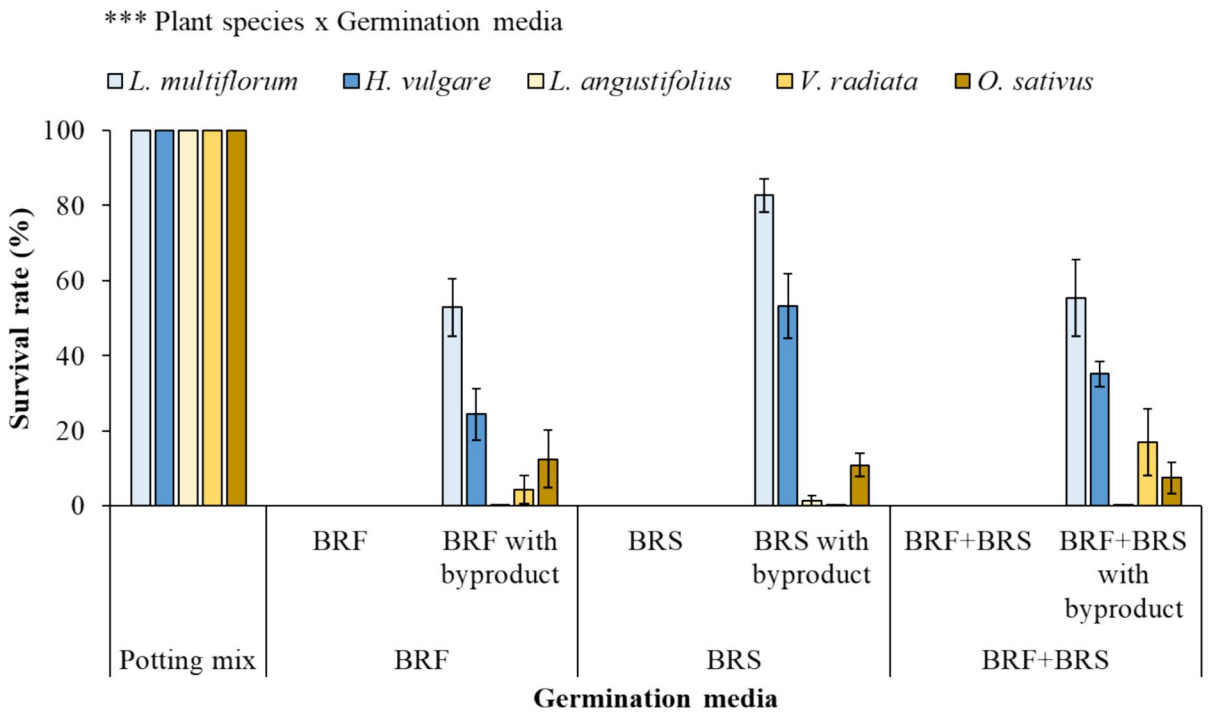


Fig. 2 Survival rate (%) of five plant species in germination media: potting mix, bauxite residue fines (BRF, with and without byproduct), bauxite residue sands (BRS, with and without byproduct) and bauxite residue fines + bauxite residue sands (BRF + BRS, with and without byproduct). Binomial generalized linear models with a logit link were fitted using the number of survived plants vs. dead plants as the response to test interactions between plant species and germination media. Data were presented as survival rate (%) calculated as the proportion of survived plants per pot. Bars represent estimated marginal means (± SE) back-transformed to percentages from the fitted model. There was significant interaction ($P \leq 0.001$) between germination media and plant species for survival rate. Details of the statistical analysis of different measured parameters are given in Table 3

4.2 High Alkalinity and Sodicity Caused Plant Death after Germination in the Capping Materials

In this study, a low concentration of plant available nutrients was observed in the blended byproduct caps (Taki et al., 2025), which is very common in bauxite residue. Nutrient solution was applied prior to seeding to mitigate nutrient deficiencies. However, despite sufficient concentrations of nutrients being present in the growth media, imbalances and deficiencies can still be caused by the interference of high alkalinity, salinity and sodicity as outlined above (Table 4). Salinity in the blended byproduct caps was below the target level (< 2 mS cm^{-1}; Taki et al., 2025). Therefore, it is unlikely that salinity affected survival, although a negative correlation was observed. The negative correlation with EC may be due to comparisons made with fresh residues.

Vegetation establishment on fresh bauxite residues is severely limited by the residue's chemical and physical properties (Fourrier et al., 2021; Santini & Fey, 2013). At high pH, high concentrations of alkaline anions such as OH^-, CO_3^{2-}, HCO_3^- and $Al(OH)_4^-$ present in the bauxite residue, have phytotoxic effects. As a result, shoot growth (due to lack of cytokinin export), root growth, root respiration, and root pressure driven solute export to the xylem (Gupta & Abrol, 1990) are all limited, and can ultimately result in plant death.

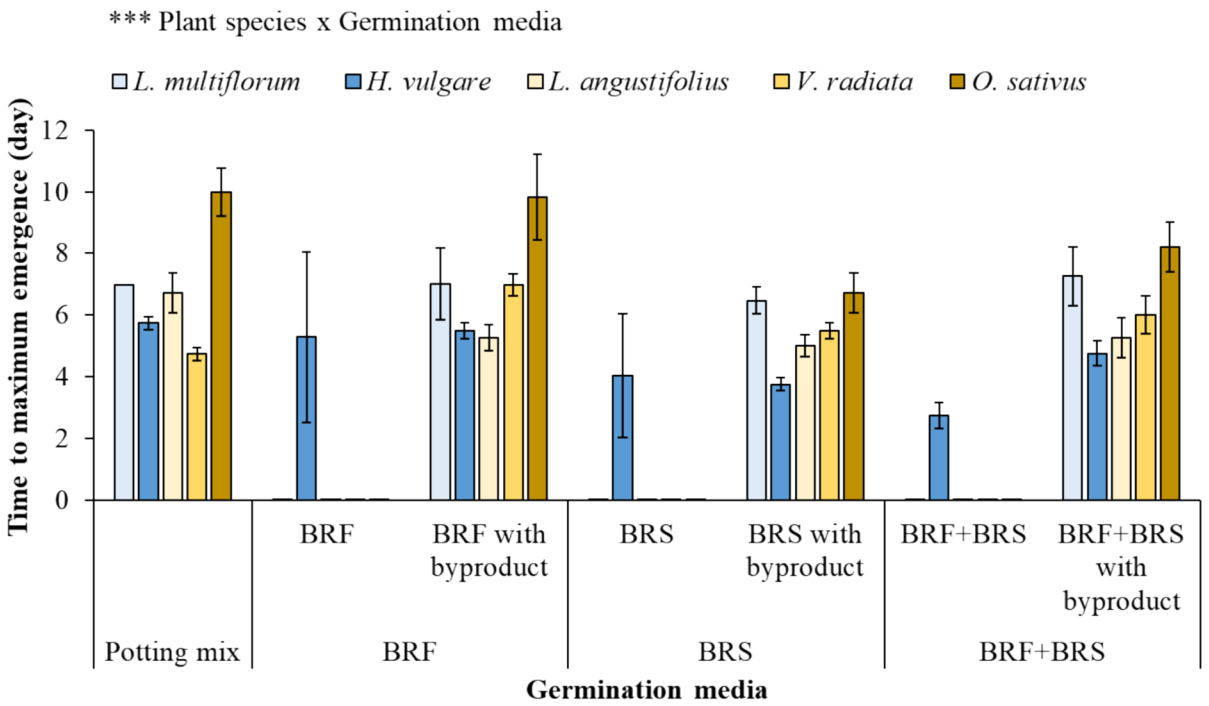


Fig. 3 Time to first emergence (day) of five plant species in germination media: potting mix, bauxite residue fines (BRF, with and without byproduct), bauxite residue sands (BRS, with and without byproduct) and bauxite residue fines + bauxite residue sands (BRF + BRS, with and without byproduct). Generalized linear modelling (GLM) was performed to test interactions between plant species and germination media. Bars are means of ± standard error (n = 4). There was significant interaction ($P \leq 0.001$) between germination media and plant species for time to first emergence. Details of the statistical analysis of different measured parameters are given in Table 3

Salinity stress can also inhibit plant survival through ionic toxicity and osmotic stress (Marschner, 2012). Under high rhizosphere osmotic pressure, an excessive amount of salts can be taken up by plants, decreasing photosynthesis and stomatal conductance. Salt accumulation can affect the stomatal (main structure for gas exchange control) openings, and their size and density, which reduces photosynthesis (CO_2 uptake) and transpiration in plants. When the rate of photosynthesis decreases, plants increase the production of toxic reactive oxygen species (ROS; e.g. H_2O_2) (Fadzilla et al., 1997; Mittler, 2002; Moran et al., 1994), and enzymatic antioxidant activities such as catalase and superoxide dismutase, which are responsible for ensuring a balance between formation and removal of ROS (Hanin et al., 2016). An imbalance of ROS under low photosynthesis conditions causes plant cell death and accelerates overall plant death. Elevated concentrations of exchangeable Na in the blended byproduct caps may have inhibited Ca^{2+} uptake, resulting in plant Ca deficiency. This can subsequently cause low plant membrane permeability which limits uptake of plant macro and micro nutrients (e.g. K, Zn, Cu, Mn; Jones & Haynes, 2011). In this study, higher plant death was observed in the blended byproduct caps (Fig. 2), this may be due to the stress of alkalinity and sodicity or their combined effects.

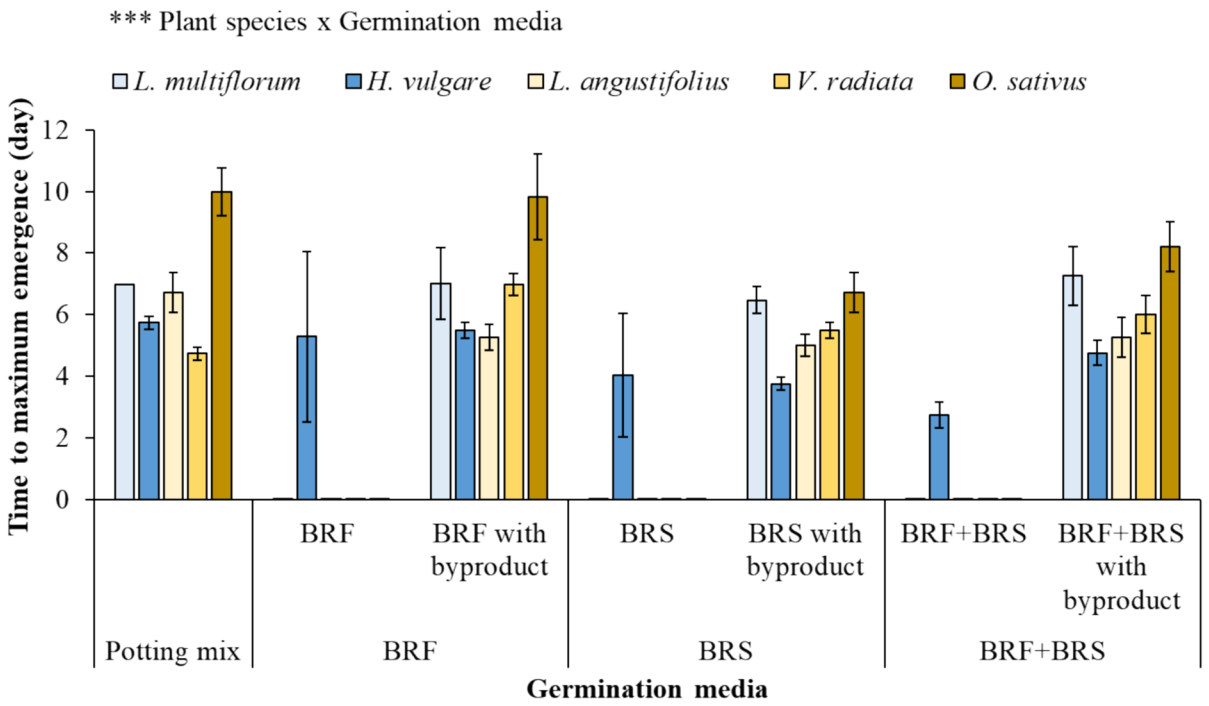


Fig. 4 Time to maximum emergence (day) of five plant species in germination media: potting mix, bauxite residue fines (BRF, with and without byproduct), bauxite residue sands (BRS, with and without byproduct), and bauxite residue fines + bauxite residue sands (BRF + BRS, with and without byproduct). Generalized linear modelling (GLM) was performed to test interactions between plant species and germination media. Bars are means of four replicates ± standard error. There was significant interaction ($P \leq 0.001$) between germination media and plant species for time to maximum emergence. Details of the statistical analysis of different measured parameters are given in Table 3

5 Conclusions

Blended byproduct caps were suitable for grass (ryegrass and barley) and legume (mungbean and serradella) species germination; however, the materials remained hostile to plant survival. High pH and Na concentrations were the main chemical properties that likely caused plant death. Ryegrass (*L. multiflorum*) and barley (*H. vulgare*) showed better survival performance than other species, suggesting that these grasses have some characteristics to survive in harsh conditions. Overall, further improvements are suggested to improve blended byproduct cap properties for successful establishment of a vegetation cover when used as cover materials during tailings storage facility closure. Decreasing pH and sodicity should be the immediate focus of these further works, and may include approaches such as further leaching and weathering, and addition of more or other byproduct materials to acidify and desodiate the blended byproduct cap media.

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Declarations

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