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Rapid seed-to-pot screening to inform alternative growth media development for coal mine rehabilitation

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Abstract

The rehabilitation of Australian coal mines to achieve post-mining land uses (PMLUs) is constrained by a lack of suitable growth media. Coal mining rehabilitation therefore increasingly uses mined spoils to develop alternative growth media (AGM). However, successful AGM use depends on appropriate characterisation, field assessments and quality amendments. This study used a 2-stage assessment to rapidly evaluate germination rates of multiple species across varying mine-derived materials and to understand the influence of composted abattoir waste on growth media development for mine spoils and coal rejects under optimised nursery-scale conditions.

Stage 1 assessed 27 native species and one cover crop across 12 mine-derived materials sourced from BHP's Goonyella Riverside Mine, including stockpiled topsoil, various Tertiary and Permian spoils, and coal rejects, under climate-controlled germination room conditions. Stage 2 further verified 7 top-performing materials based on cover crop germination response, with the best-germinating species transplanted into 52 L pots of amended materials mixed with nitrogen- and phosphorous-rich composted abattoir waste.

Stage 1 results showed coal rejects yielded the highest germination of native tree and shrub species, while topsoil had the lowest germination, attributed to its high salinity and hard-setting properties. Coated native grass seed germinated poorly across all materials. Preliminary Stage 2 findings show compost improves AGM chemical and biological characteristics to support transplanted natives but offers minimal direct improvement to physical characteristics due to its low organic carbon content.

The 2-stage approach provides a reliable, rapid method to shortlist pioneer species and verify AGM variations for achieving suitable PMLUs. It offers a targeted approach for screening mined materials, assessing ameliorants, and investing in native species with a proven germination and establishment record.

Keywords: rehabilitation, revegetation, native seed, germination, growth media

1 Introduction

Establishing sustainable vegetation on post-mining landforms remains a persistent challenge for mine closure, particularly where rehabilitation relies on heterogeneous waste materials and limited volumes of high-quality topsoil (Tibbett 2024). In many Australian coal mining operations, final landforms are constructed from combinations of Tertiary and Permian spoils, coal rejects and/or stripped and stockpiled soil horizons. Combinations and/or amendments of these materials are then used as alternative growth media (AGM) but remain substantially different from undisturbed reference soils in their physical, chemical and biological characteristics (Tibbett 2023).

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Vegetation establishment in these varying AGMs continue to prove to be a critical bottleneck in rehabilitation, as failure during germination or seedling establishment often leads to long-term underperformance, increased rework and higher closure costs (Daws et al. 2022; Commander et al. 2020; Tiemann et al. 2022). Seed germination is highly sensitive to growth media properties, such as surface stability, moisture retention, salinity, sodicity and compaction, as well as to interactions between seed traits and substrate behaviour (Fenner & Thompson 2005). Despite this sensitivity, rehabilitation performance is commonly assessed at later stages (e.g. vegetation cover or biomass), with limited quantitative information available on the initial establishment phase that underpins longer-term outcomes.

Small-scale, climate-controlled screening assessments provide an opportunity to reduce the uncertainty of germination impacts from mine materials' characteristics early in the rehabilitation process (Johnson et al. 2023). Nursery-based germination trials under optimised conditions allow material-driven constraints on establishment to be identified rapidly and at relatively low cost, before committing to larger-scale pot trials or resource-intensive, field-scale implementation (Johnson et al. 2023). Such approaches enable rehabilitation practitioners to separate seed-related limitations from material constraints, prioritise suitable material–species-amendment combinations, and avoid the assumption that materials classified under the same geochronological or operational category will perform equivalently in rehabilitation. Findings from these smaller-scale assessments can inform medium-sized pot-scale trials that further validate material performance and plant growth responses in mine-derived materials beyond the initial germination response (Fernández-Landero et al. 2024).

To address this need for informed rehabilitation practices for faster and evidence-based decision-making, a 2-stage assessment framework was developed for BHP's Goonyella Riverside Mine to evaluate the germination performance of a cover crop (*Echinochloa esculenta*) and a native woodland seed mix in mine-derived Permian and Tertiary spoils and coal rejects for rehabilitation use. The native seed mix comprised 11 framework tree species, 7 woody understorey species and 9 perennial grasses, all endemic to the local region. A 2-stage framework was designed to generate practical evidence of plant performance in AGM within months rather than years, supporting risk-informed closure planning where access to suitable topsoil is constrained.

Stage 1 focused on germination screening under climate-controlled nursery conditions to establish whether emergence was feasible across different mine-derived materials without amendment to establish a baseline, identify potential pioneer plants species, and verify the influence of material characteristics. The plant species with the highest germination rate across the most mine materials from Stage 1 were then progressed to the Stage 2 pot-scale trial assessment. The objective of Stage 1 was to quantify variability in emergence and establishment across the varying species in mine-derived materials under controlled conditions, thereby identifying species–material combinations that warranted progression for longer-term testing.

Stage 2 built on the germination screening by progressing seven selected mine-derived materials and the best-performing plant species to a pot-scale trial. The trial evaluates how amendment with composted abattoir waste influences growth media condition and supports early plant establishment and development. As plant growth assessments are ongoing, this paper reports only preliminary trends in growth media condition and early establishment.

This paper presents a 2-stage assessment framework developed to evaluate the suitability of mine-derived materials as AGM for rehabilitation at Goonyella Riverside Mine. Specifically, the paper aims to demonstrate how rapid, climate-controlled germination screening can be used to identify material–species combinations with the greatest establishment potential, and how these results can inform subsequent pot-scale testing of compost-amended growth media. By separating early germination performance from later plant growth responses, the framework provides a practical and evidence-based approach for reducing uncertainty in material selection, prioritising rehabilitation investment, and supporting more defensible closure planning where suitable topsoil resources are limited.

2 Materials and methodology

This study applied a structured, 2-stage approach to evaluate the suitability of mine-derived materials and plant species combinations for evidence-based rehabilitation decisions.

2.1 Stage 1 – rapid germination assessment

Mine-derived materials were sourced from BMA's Goonyella Riverside Mine and represented the range of potential growth media available for rehabilitation, including stripped topsoil, Permian and Tertiary spoils, and coal rejects. In addition, a composted abattoir waste (herein referred to as 'compost') sourced from a local abattoir and processing facility in Central Queensland was included as a reference material to a establish baseline germination performance. The compost was produced via outdoor aerobic composting which combined animal-based abattoir waste, straw and local soils.

The soil-based material characteristics are shown in Table 1.

In total, 12 material types were assessed (including compost). For the purposes of germination assessments, site-sourced material was sub-sampled from large intermediate containers (Figure 1a) and a workable fines fraction (≤3 cm) was created via mechanical breakdown using a cement mixer and sieve (Figure 1b). The materials were processed only to the extent necessary to enable consistent tray-based germination testing while retaining material-specific physical, chemical and biological characteristics relevant to field establishment.

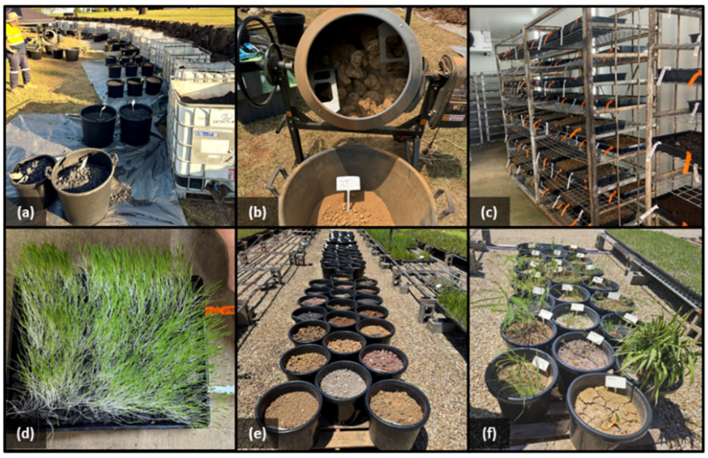

Figure 1 Experimental progress photos of (a) supplied material; (b) mechanical breakdown; (c) germination trays; (d), cover crop response in coal rejects; (e) pot trial layout; (f) preliminary plant establishment

The germination testing was conducted in a climate-controlled commercial germination room. Community seedling trays per material, per species were used to allow germination and establishment of each seed within a shared volume of material. This was done so as to provide a more field-representative interaction between seeds and material properties such as moisture distribution, surface crusting and consolidation behaviour. A temperature of 24°C and a humidity range of 20–80% was maintained in the germination room. The seedlings were lightly irrigated using a hand spray misting on a weekly basis to maintain adequate moisture without saturating the growth media (Figure 1c). Germination monitoring commenced immediately following sowing and ran for 3 months to capture second germination stages (Commander et al. 2021). Germination outcomes were classified using 3 categories to distinguish early seed response from successful establishment:

- Ungerminated – no visible evidence of germination.
- Struck (failed establishment) – evidence of initial germination (e.g. radicle emergence) without sustained emergence or root establishment.
- Germinated (established) – successful emergence above the growth media surface with visible green leaf tissue and established roots (Fenner & Thompson 2005).

Table 1 Physical, chemical, biological characteristics of germination material

Parameter	Unit	C	Re	T1	T2	T3	Ts	WPB	WPG	WPP1	WPP2	WPP3	WP	WT
Physical properties														
Dispersion Index		1	3	3	3	0	0	1	2	2	1	8	1	2
Emerson Class		7	7	2	3	6	6	6	3	2	3	2	3	3
Clay	%	32.8	10.1	49.7	56.7	35.5	59.9	34.6	35.6	46.0	50.7	36.2	36.5	60.6
Chemical condition indicators														
pH (1:5 water)	pH	8.0	9.9	8.8	8.4	8.5	7.4	8.6	9.7	8.9	9.0	9.4	9.1	8.6
EC (1:5 water)	dS/m	2.1	0.3	1.4	2.1	2.4	3.6	1.6	0.7	1.5	0.6	0.7	1.3	1.2
Sodicity/exchange chemistry														
Exchangeable calcium*	cmol(+)/kg	10.8	4.2	2.0	2.5	7.1	3.5	5.0	7.2	6.1	20.0	5.2	5.2	3.6
Exchangeable sodium*	cmol(+)/kg	5.0	3.0	14.0	18.0	10.6	18.3	8.4	5.3	11.3	4.0	6.0	9.3	12.0
Cation exchange capacity*	cmol(+)/kg	30.5	9.3	25.3	32.2	24.8	31.9	21.8	22.3	28.6	34.5	18.9	25.3	24.8
Sodium % of cations - incl. Al*	%	16.5	32.5	56.3	55.3	41.7	57.7	38.7	24.0	40.0	11.7	31.7	36.7	48.3
Plant nutrients – macronutrients														
Potassium (Colwell)	mg/kg	2,400	105	103	85	155	49	101	155	130	88	110	120	140
Nitrate nitrogen	mg/kg	417	1.4	2.4	6.4	33.3	73.3	4.9	7.5	7.5	32.7	5.1	42.3	7.6
Ammonium nitrogen	mg/kg	640	11.5	1.5	1.4	1.6	2.2	2.6	2.1	2.9	2.2	3.6	1.9	9.9
Phosphorus (Colwell)	mg/kg	746	3.5	11.0	9.1	5.3	6.7	3.1	2.6	2.6	7.2	9.0	3.7	12.1
Organic matter/carbon/biological														
Organic carbon	%	2.6	3.1	0.2	0.3	0.9	0.5	1.6	0.6	0.7	0.7	0.3	0.7	0.2
Microbial resp. (CO_2 burst)	mg/L CO_2	38.3	<5	ND	<5	ND	ND	<5	ND	<5	ND	ND	<5	ND
Active (labile) carbon	mg/kg	779	227	37.3	84.6	169	173	232	124	170	207	109	188	34.1

Note: Material codes are as follows—C: compost; Re: rejects; T1–T3: Tertiary (Sites 1–3); Ts: topsoil; WPB: weathered Permian (black); WPG: weathered Permian (grey); WPP1–WPP3: weathered Permian pink (sites 1–3); WPR: weathered Permian; WT: weathered Tertiary. ND = not detected; <5 = below laboratory detection limit. *Indicates ammonium acetate extraction for exchangeable cations and available P. Values >100 rounded to the nearest whole number to improve table readability. EC = electrical conductivity.

This classification recognises that initial germination does not necessarily equate to establishment suitable for transplanting or longer-term rehabilitation outcomes. Germination observations and results were recorded through a combination of scheduled site inspections and routine nursery monitoring. Photographic records were taken for trays exhibiting active germination (Figure 1d). The most successful species that could produce mature seedlings with established roots of sufficient size for transplant were used for the next pot trial phase.

Seeds from 27 native plant species and one cover crop species were assessed. The selected species included trees, woody understorey shrubs and perennial grasses commonly used in mined land rehabilitation for the region. Prior to sowing, seed batches were verified to determine seeds per unit mass. It was found that substantial variation was observed between batches. Therefore, verification of all species was undertaken to standardise sowing density across materials and species and to reduce uncertainty associated with chaff-rich, floret-based or highly variable seed lots.

2.2 Stage 2 – pot trial growth media development and early growth response

Stage 2 extended the germination screen into a pot-scale test of whether compost amendment could improve selected mine-derived materials for use as AGM. Seven materials, including coal rejects, and both Tertiary and weathered Permian spoil, were progressed from Stage 1 to represent the main operational material classes and a range of establishment responses.

Material selection was based on the germination response of the cover crop, which was used as a practical and functional comparator because it emerged rapidly across materials and enabled timely initiation of the pot trial phase. The cover crop was also considered relevant to rehabilitation due to its role in providing rapid ground cover for erosion control, short-term biomass production and subsequent organic matter inputs (Figure 1d). Each material was amended with compost at 0, 2 or 5% w/w and placed in 52 L pots, equivalent to approximately 0, 50 and 125 t/ha, respectively. This produced 21 treatments in total, with each material × compost rate combination treated as a separate growth media treatment (Figure 1e). Compost was incorporated through the upper 0–30 cm of the profile to reflect the amendment depth likely to be achievable during field rehabilitation. The pots were arranged in a randomised complete block design.

Seedlings established during Stage 1 were transplanted into the pot treatments to assess early establishment and growth response under controlled nursery conditions. The species with the highest germination rates were selected for transplant. Pots were irrigated daily (4 mm) to maintain plant-available moisture without saturating the growth media. This regime was not intended to simulate field rainfall, but to optimise conditions for rapid assessment of compost addition and plant growth without limiting water. The trial remains ongoing, with final plant response assessment scheduled for late September 2026; therefore, only preliminary growth media trends and early establishment observations are reported here (Figure 1f).

Growth media condition was monitored through repeated sampling of the upper 0–20 cm at approximately 3-monthly intervals. Samples were analysed by a NATA-accredited soil laboratory for particle size distribution (hydrometer), dispersion behaviour (Emerson aggregate test), slaking behaviour (slake assessment), pH (1:5 water), electrical conductivity (1:5 water), exchange chemistry (ammonium acetate extraction), available phosphorus (Olsen P), macro- and micronutrients, organic carbon, labile carbon and microbial activity (CO_2 burst). These measurements were used to assess whether compost amendment produced directional improvements in growth media condition and to support interpretation of the ongoing plant establishment responses.

3 Results and discussion

3.1 Interpretation of the staged assessment approach

The staged assessment approach was used to generate 2 complementary lines of evidence relevant to rehabilitation decision-making. Stage 1 functions as a rapid biological screen, indicating whether emergence and early establishment are feasible across contrasting mine-derived materials under consistent nursery conditions. Stage 2 then extends this screening by testing whether compost amendment produces a consistent, directional improvement in growth media condition indicators linked to establishment potential (e.g. salinity, sodicity, organic carbon and nutrient availability), providing mechanistic context for the Stage 1 responses. Coal rejects, typically regarded as a low-quality substrate, supported comparatively strong native emergence, whereas stripped local 'topsoil' performed poorly in this screening. Stage 2 investigations help assess these outcomes by monitoring salinity, sodicity and carbon status trends over time in the presence of plants, showing the positive impact of compost amendment on multiple constraints simultaneously and highlighting its limitations when severe structural issues are present.

3.2 Implications of methodology and approach

Stage 1 and Stage 2 were implemented as a pragmatic screening workflow, and the results should be interpreted accordingly. The approach is intended to inform AGM development by identifying strong and weak performers and by highlighting likely establishment constraints that warrant targeted follow-up, rather than to provide definitive estimates of field germination rates. A key methodological implication from Stage 1 was the need to verify seed lots before sowing. Seed batches ranged from relatively clean lots with consistent seeds-per-gram to chaff-rich or mixed floret material where seed numbers could not be reliably inferred from mass. Batch verification (seeds-per-gram or seeds-per-scoop) was therefore undertaken to standardise sowing density across species and materials, and notes were recorded where contamination, mixed batches or treatment-related weight changes were likely to influence interpretation (e.g. grass florets and highly chaffy eucalypt seed batches). The Stage 1 outcome classification (ungerminated, struck, germinated/established) is also important for rehabilitation interpretation. Several perennial grasses showed initial strike without sustained emergence, indicating that radicle response alone can overestimate establishment potential where roots fail to penetrate or seedlings fail soon after emergence. Recording strikes separately, therefore, increases the practical value of the screening by identifying treatments in which seedbed physical behaviour is likely to constrain establishment.

The screening approach also involves inherent limitations. Stage 1 used single trays per species–material combination (limited replication), and some responses were recorded as presence/absence or approximate counts where high-density emergence made accurate counting impractical (notably the cover crop). Stage 1 results should therefore be treated as a comparative pre-screen to prioritise combinations for replicated pot or field validation, rather than as definitive germination percentages.

Key steps for applying the approach in rehabilitation planning include:

- Verify seed lots (seeds-per-gram/scoop and contamination) before sowing to avoid confounding material effects with seed quality effects.
- Distinguish strike from established germination to better reflect rehabilitation-relevant establishment constraints.
- Use Stage 1 to prioritise combinations for replicated testing and pot/field validation, rather than to infer absolute germination percentages.
- Retain detailed nursery notes (dates, die-off, transplanting, watering regime and amounts) as timing and survivorship can be as informative as total emergence.

3.3 Stage 1 – rapid pre-screening germination assessment

Stage 1 comprised a full factorial screening of the rehabilitation seed mix across 12 materials and 28 species, resulting in 336 species–material tray entries. Across the native species, germination outcomes varied strongly by material and species group (Table 2). Coal rejects (Re) produced the broadest and most consistent native germination response, with successful emergence recorded across multiple framework tree species (including *Allocasuarina spp., Atalaya hemiglauca, Casuarina cristata, Corymbia citriodora and Eucalyptus crebra*) as well as selected understorey species (e.g. *Acacia crassa and Petalostigma pubescens*). This supports the use of coal rejects as a candidate AGM base material for early establishment, particularly where alternative substrates exhibit physical constraints that limit emergence. In contrast, the stripped topsoil (Ts) yielded comparatively few native germination responses (Table 2). While topsoil performance can be highly dependent on site and handling, this result indicates that the specific topsoil source used in this study was a poor germination substrate under the screening conditions and reinforces the need to validate topsoil condition and function before relying on it for establishment.

Tertiary and Permian materials showed mixed outcomes, with germination tending to be restricted to a small subset of species and/or to specific variants within the same material group (i.e. Permian versus Tertiary) (Table 2). The weathered Permian pink variants were notable in that WPP3 supported germination in several framework tree species (e.g. *Allocasuarina spp.*, *Atalaya hemiglauca* and *Casuarina cristata*), whereas other related treatments displayed fewer germination events. These patterns indicate that relatively subtle differences in material provenance and physical behaviour can translate into meaningful differences in emergence under otherwise standardised nursery conditions.

Perennial grasses performed poorly in Stage 1, with most treatments recording either no emergence (in the case of coated seed) or strike-only responses (uncoated seed) (Table 2). Where strikes were observed for the uncoated seed, these were not sustained through to root establishment, indicating that the limiting factor was likely not just seed activation alone but constraints associated with root establishment (e.g. inadequate root penetration, surface crusting or unstable moisture conditions). The coated grass seeds did not strike in the any mined materials. However, in nursery potting mix under high moisture conditions, germinations where successful (>80% rate). This finding is consistent with the practical difficulties often encountered in establishing coated or floret-based native grass seed lots in disturbed substrates, and reinforces the value of separating strike from successful establishment when screening AGM options. The cover crop (*Echinochloa esculenta*) germinated across all materials (Table 2), providing a functional check that nursery moisture and temperature conditions were broadly suitable for emergence. Accordingly, differences observed among native species are best attributed to material–species interactions and material-driven establishment constraints, rather than to nursery conditions alone.

When considered alongside the material condition indicators (Table 1), the Stage 1 results suggest that stronger native tree/shrub emergence tended to occur in materials with lower salinity and reduced physical constraint at the seedbed surface. Coal rejects (Re), which recorded the highest overall native germination total (15; Table 2), also exhibited the lowest electrical conductivity (EC = 0.3 dS/m) and the lowest clay content (10.1%; sandy loam), consistent with reduced osmotic stress and improved infiltration and aeration relative to clay-rich spoils. Among the spoil-derived materials, weathered Permian pink material (WPP3) recorded comparatively higher native germination (9), with similarly low EC (0.7 dS/m) and moderate clay (36.2%), whereas WPP2 produced an intermediate response (5) and had the lowest sodium percentage of cations (11.7%). In contrast, materials with very high sodicity and/or heavy texture generally yielded low native germination totals, including T1 and T2 (2 each) which had high clay contents (49.7–56.7%) and extreme sodium percentage of cations (55.3–56.3%), and Ts (3) which combined very high clay (59.9%) with the highest EC (3.6 dS/m). The comparatively stronger response observed in T3 (7) relative to T1–T2 indicates that differences in physical characteristics remain important determinants of emergence, even where materials are broadly classified within the same spoil category.

Table 2 Stage 1 germination results across 11 mine material types and compost

	Species	C	Re	T1	T2	T3	Ts	WPB	WPG	WPP1	WPP2	WPP3	WP
Framework trees	*Acacia shirleyi*	–	–	G	–	G	–	–	–	–	G	–	–
	Allocasuarina littoralis	–	G	–	–	–	–	–	–	–	–	G	–
	Allocasuarina luehmannii	–	G	–	–	G	–	G	–	–	–	G	–
	Atalaya hemiglauca	–	G	–	–	G	–	–	G	–	–	G	–
	Casuarina cristata	–	G	–	–	G	–	–	–	–	G	G	–
	Corymbia citriodora	G	G	–	–	–	G	–	–	–	–	G	–
	Eucalyptus crebra	–	G	–	–	–	–	–	–	–	–	G	–
	E. exserta	–	-	–	–	–	–	–	–	–	–	–	–
	E. melanophloia	–	G	–	–	–	–	–	–	–	–	–	–
	E. populnea	–	-	–	–	–	–	–	–	–	–	–	–
	Lysiphyllum hookeri	–	G	–	–	G	G	–	G	G	–	–	–
Woody understorey	*Acacia conferta*	–	-	–	G	–	–	–	–	–	–	–	–
	Acacia crassa	–	G	–	–	–	–	–	–	–	–	–	–
	Acacia flavescens	–	–	–	–	–	–	–	–	–	–	–	–
	Geijera parvifolia	–	–	–	–	–	–	–	–	–	–	–	–
	Grewia latifolia	–	–	–	–	–	–	G	–	–	–	–	G
	Petalostigma pubescens	–	G	–	–	–	–	–	–	–	–	–	–
	Pittosporum angustifolium	–	–	–	–	–	–	–	–	–	–	–	–
Perennial grasses	*Aristida latifolia*	–	G	–	–	S	–	–	–	–	–	S	–
	Bothriochloa bladhi	–	–	–	–	–	–	–	–	–	–	–	–

	Species	C	Re	T1	T2	T3	Ts	WPB	WPG	WPP1	WPP2	WPP3	WP
	Chloris truncata	–	–	–	–	–	–	–	–	–	–	–	–
	Cymbopogon refractus	–	G	–	–	G	–	–	–	–	G	G	–
	Cynodon dactylon	–	G	–	–	-	–	–	–	–	–	–	–
	Enteropogon acicularis	–	G	–	–	S	–	–	–	–	G	G	–
	Heteropogon contortus	–	S	–	–	S	S	S	–	–	S	S	–
	Panicum decompositum	–	–	–	–	–	–	–	S	–	–	–	–
	Themeda trianda	–	–	–	–	S	–	–	–	–	–	–	–
	Echinochloa esculenta (cover crop)	G	G	G	G	G	G	G	G	G	G	G	G
Germination total		2	15	2	2	7	3	3	3	2	5	9	2
Strike-only total		0	0	0	0	4	1	1	1	0	1	2	0

LEGEND: G = Germinated. S = Struck only (no true germination) - = No germination or strike observed. Note: Material codes are as follows—C: composted abattoir waste; Re: rejects; T1–T3: Tertiary (Sites 1–3); Ts: topsoil; WPB: Weathered Permian (black); WPG: Weathered Permian (grey); WPP1–WPP3: Weathered Permian pink (Sites 1–3); WPR: Weathered Permian; WT: Weathered Tertiary

To progress the screening outcomes into growth media development, 7 materials associated with the best cover crop germination responses were selected for the Stage 2 pot trial assessment (Re, T1, T2, T3, WPP2, WPP3 and WP; Table 2). As outlined in Section 2.2, this subset was chosen to represent the key operational material groups and the range of Stage 1 establishment responses, while remaining practical within nursery space and resource constraints. The following section therefore focuses on how compost amendment alters key growth media condition indicators across these Stage 2 materials (Figure 2), providing mechanistic context for the Stage 1 patterns and a basis for subsequent material-specific interpretation once the full pot trial dataset is available.

3.4 Stage 2 – growth media development in response to compost amendment

This section provides an overview of the impacts of compost amendment on the physical and chemical properties of growth media during Stage 2, highlighting key findings relevant to rehabilitation efforts. A subset of soil characteristics is shown in Figure 2. Results are reported as averages across all materials for each compost rate to focus on the overall amendment signal. Material-specific responses are not presented here as the pot trial is ongoing and plant response outcomes are still being compiled.

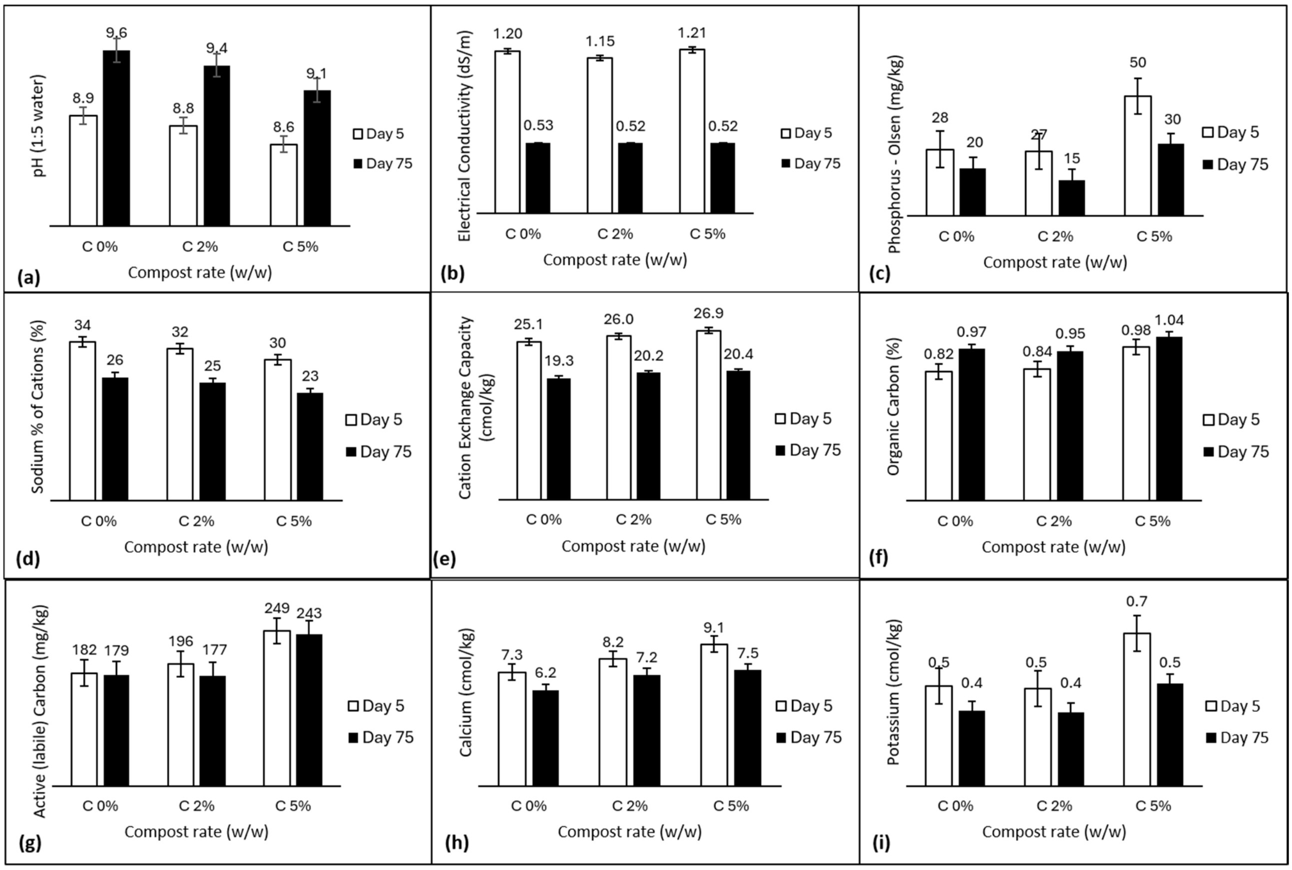

Figure 2 Stage 2 preliminary physical, chemical and biological averaged parameters with standard error bars of mine materials with varying compost rates. (a) pH; (b) Electrical conductivity; (c) Phosphorus; (d) Sodium percentage of cations; (e) Cation exchange capacity; (f) Organic carbon; (g) Active (labile) carbon; (h) Calcium; (i) Potassium

All materials assessed in Stage 2 were alkaline at baseline, with pH (1:5 water) averaged values ranging from approximately 8.6 to 9.6. Higher rates (5% w/w) of compost amendment resulted in small but statistically significant reductions in pH across most materials (Figure 2a). These reductions in pH are meaningful in alkaline systems, as they impact plant-available nutrients.

EC generally declined over the monitoring period, indicating leaching and/or stabilisation of salts (Figure 2b). Importantly, EC values were not significantly impacted by compost addition, suggesting that the application rates used do not introduce unacceptable salinity risk for AGM development.

Compost application generally resulted in an increase in plant-available phosphorus (Olsen P) across all materials as a result of compost's inherently high P levels (Figure 2c). Several materials that were severely phosphorus deficient at baseline exhibited order-of-magnitude increases following amendment, with a clear dose-response relationship (C5 > C2 > base). Although Olsen P declined slightly between sampling events, compost-amended treatments retained substantially higher P availability than unamended controls (Figure 2c). The sustained elevation of Olsen P suggests that organic phosphorus inputs from compost are less susceptible to immediate fixation, supporting their use in alkaline, clay-rich rehabilitation substrates (von Wandruszka 2006).

Exchangeable sodium results confirmed that several materials were highly sodic, exceeding 45% in some Tertiary and Permian spoils (Table 1). Compost application did not increase exchangeable sodium percentage (ESP) and resulted in measurable reductions in ESP across most materials by increasing cation exchange capacity (Figures 2d and 2e). While compost alone was insufficient to remediate severe sodicity, the observed reductions in ESP, combined with increases in organic carbon, are likely to improve aggregate stability and reduce dispersion risk (Robertson et al. 2026). This interpretation aligns with the reduction in dispersion indices observed in compost-amended treatments and provides a plausible mechanism for improved early establishment relative to unamended materials.

Organic carbon exhibited the strongest treatment response of all parameters measured, with up to 4-fold increases in degraded materials following compost application. Elevated organic carbon levels persisted between the 70-day monitoring period, indicating successful incorporation and short-term stability of added carbon (Figure 2f). The increase in labile (active) carbon further suggests enhanced microbial activity and nutrient cycling potential (Figure 1g). These improvements are particularly important in sodic and low-fertility materials, where biological function is often severely constrained. The strong response of organic carbon indicates its responsibility for improved establishment observed in amended materials and reinforces its role as a primary driver of AGM performance.

Calcium and potassium availability increased with compost addition, increasing baseline nutrient limitations across the mine materials (Figures 2h and 2i). However, low calcium-to-magnesium ratios exist in some sodic clay-dominated mine materials (Table 1), indicating that organic amendment alone is unlikely to fully resolve structural constraints, and that integrated amendment strategies (for example, gypsum combined with organic matter) may be required for long-term rehabilitation success.

3.5 Linking Stage 2 trends to Stage 1 establishment outcomes

When considered together, the Stage 1 and Stage 2 results indicate that materials supporting early germination tend to exhibit more favourable chemical condition and lower structural constraint, either inherently (e.g. coal rejects) or following amendment. Conversely, materials characterised by extreme sodicity, low organic carbon and poor aggregation were associated with limited or strike-only germination responses. The results highlight that early establishment success is governed by a combination of physical behaviour and chemical condition, rather than nutrient supply alone. Compost amendment improves multiple limiting factors simultaneously – increasing organic carbon, enhancing nutrient availability and partially mitigating sodicity – but cannot fully overcome severe structural constraints within short timeframes.

3.6 Implications for alternative growth media selection in mine closure

The integrated results demonstrate that coal rejects amended with organic compost represent a viable AGM option for early establishment, particularly where suitable topsoil is limited. More broadly, the staged assessment framework provides a practical, repeatable method for screening materials and amendments prior to field trials, reducing closure risk by identifying unsuitable substrates early. Rather than assuming material suitability based on classification or origin, the results emphasise the value of empirical, early-stage testing to inform AGM design and prioritise rehabilitation investments.

4 Conclusion

This study demonstrates the value of a staged, small-scale assessment framework for screening mine-derived materials and amendments prior to field-scale rehabilitation. Combining rapid germination screening with early growth media characterisation provides insight into both the feasibility of plant establishment and the material-driven constraints that influence early rehabilitation performance.

Stage 1 results showed that germination and early establishment responses varied markedly between materials that are often treated as broadly equivalent during closure planning. Coal rejects supported the most consistent and widespread native germination response, while stripped topsoil performed poorly, highlighting that material origin alone is an unreliable indicator of rehabilitation suitability. Perennial grass species frequently exhibited strike without sustained establishment, indicating that physical constraints within growth media can limit establishment even where initial seed activation occurs.

Stage 2 results (reported as treatment means averaged across the materials progressed to pot trials) showed that compost amendment produced consistent directional improvements in multiple growth media condition indicators relevant to early establishment. Increases in organic carbon, nutrient availability and cation exchange capacity, together with partial reductions in ESP, provide mechanistic support for improved establishment potential in amended materials. However, severe sodicity and unfavourable calcium-to-magnesium ratios persisted in some spoil-derived substrates, indicating that organic amendment alone is unlikely to fully resolve structural constraints within short timeframes and that integrated amendment strategies may be required.

When considered together, the results indicate that early rehabilitation success is governed by an interaction between material physical behaviour, chemical condition and climate conditions, rather than nutrient supply alone. The staged assessment approach used in this study provides a practical, repeatable method for identifying candidate AGM, prioritising amendment strategies and reducing uncertainty before committing to larger-scale pot or field trials. This framework supports more defensible material selection and risk-informed decision-making in mine closure planning where access to suitable topsoil is limited, and provides a clear basis for subsequent material-specific evaluation as the Stage 2 pot trial dataset is completed.

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