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# An approach to creating alternative growth media for the revegetation of mines

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## Abstract

*Successful mine closure commonly depends on the establishment of vegetation that is sustainable, resilient and aligned with the intended post-mining land use (PMLU). While topsoil overlaying benign spoil is the preferred growth medium for rehabilitation, many mine sites face a combination of hostile spoil and topsoil deficits, with available topsoil volumes insufficient to meet rehabilitation demands. Where spoil is hostile and topsoil is limiting, alternative growth media must be manufactured from subsoil and spoil materials that typically exhibit one or more constraints to vegetation establishment. Soil is a composite of chemical, physical and biological properties and the focus should be on its functions that support plant growth and ecosystem services, rather than soil composition. This paper presents a practical, site-specific 5-stage framework for developing alternative growth media:*

1. *defining the target PMLU and associated soil quality requirements*
2. *identifying and characterising the physico-chemical properties of available growth media resources*
3. *developing strategies to ameliorate growth media constraints*
4. *trialling amelioration strategies*
5. *monitoring vegetation performance and growth media physico-chemical properties over time.*

*Drawing on the broader literature concerning soil fertility dynamics in Australian mine rehabilitation, the framework addresses common limiting characteristics of subsoil and spoil materials with reference to both grazing and native woodland PMLUs. A key principle is that growth media must not present hostile conditions to plant growth but have erosional stability, or it must be ameliorated to remove such conditions prior to placement. The paper further argues that rehabilitation trajectories, rather than point-in-time comparisons with reference ecosystems, represent the most meaningful basis for evaluating rehabilitation progress and compliance criteria.*

**Keywords:** *post-mining land use, soil constraints, soil amelioration strategies, mine rehabilitation*

# 1 Introduction

Mining in Australia disturbs vast areas of land that require rehabilitation at the conclusion of operations. Regulatory frameworks in Queensland mandate progressive rehabilitation and post-closure monitoring, and there is increasing expectation that rehabilitation demonstrates a return of ecological function rather than merely vegetative cover. (Banning et al. 2011 ).

Central to ecological function is soil fertility: the capacity of a soil to supply water and nutrients, support microbial communities, maintain physical structure and sustain plant productivity (Bradshaw 1997; Karlen et al. 1997). Mine operations disrupt soil fertility through stripping and stockpiling of topsoil, mixing of soil

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layers, compaction by heavy machinery and exposure of subsoil or spoil materials with hostile physical or chemical properties (Sheoran et al. 2010; Wehr et al. 2026) . Restoring the fertility of these disturbed soils requires identification and amelioration of constraints affecting erosional stability and plant growth.

A critical practical challenge is the frequent lack of available topsoil to achieve mine rehabilitation. In undisturbed Queensland landscapes, the topsoil (A-horizon) may range from a few centimetres to over a metre in thickness. As the soil layer with the greatest biological activity, seed bank and organic matter accumulation, it is critical for effective rehabilitation at mines. However, available topsoil volumes are commonly insufficient relative to the rehabilitation task; therefore the use of subsoil and spoil materials as bulk components of a manufactured growth medium is required (daSilva et al. 2024; Wehr et al. 2026) These materials generally have a low organic carbon content and reduced biological activity, and may exhibit one or more chemical or physical constraints including salinity, sodicity, extremes of pH or structural instability.

This paper presents a structured 5-stage framework for creating alternative growth media from available mine materials, developed in collaboration with the Office of the Queensland Mine Rehabilitation Commissioner. The framework draws on the peer-reviewed literature on Australian mine rehabilitation and soil fertility as summarised in daSilva et al. (2024) and Wehr et al. (2026). The framework is intended to reduce uncertainty, improve rehabilitation performance and increase confidence in achieving sustainable closure outcomes across a range of post-mining land uses (PMLUs).

The proposed framework is based on the premise that the manufactured growth media should replicate the functions of natural soil, not necessarily reproduce its exact composition or structure. Soil is a composite of chemical, physical and biological properties that support plant growth and ecosystem services (Brady & Weil 2008). Plants will grow in completely inert synthetic media (e.g. sand, rockwool, nutrient solutions) if sufficient air, water, nutrients and sunlight are available (Handreck & Black 2010). In the mine rehabilitation context, the main roles of a growth medium are the anchorage of plants, supply of water and nutrients, and provision of habitat for soil organisms. Any manufactured medium that fulfils these functions over the long-term is, in principle, suitable.

This focus on soil function has important implications for target-setting. It is unrealistic to expect a manufactured growth medium to have identical physical properties to the reference (undisturbed) soil. Soil texture, structure and depth will inevitably differ between replaced topsoil or manufactured spoil covers and reference-site soil profiles, and water relations in the manufactured medium will correspondingly differ. Reference or analogue sites are most appropriately used to estimate the end point of vegetation composition and soil fertility under steady state conditions, not as point-in-time compliance targets for rehabilitation sites developing from a point of maximum disturbance (Figure 1).

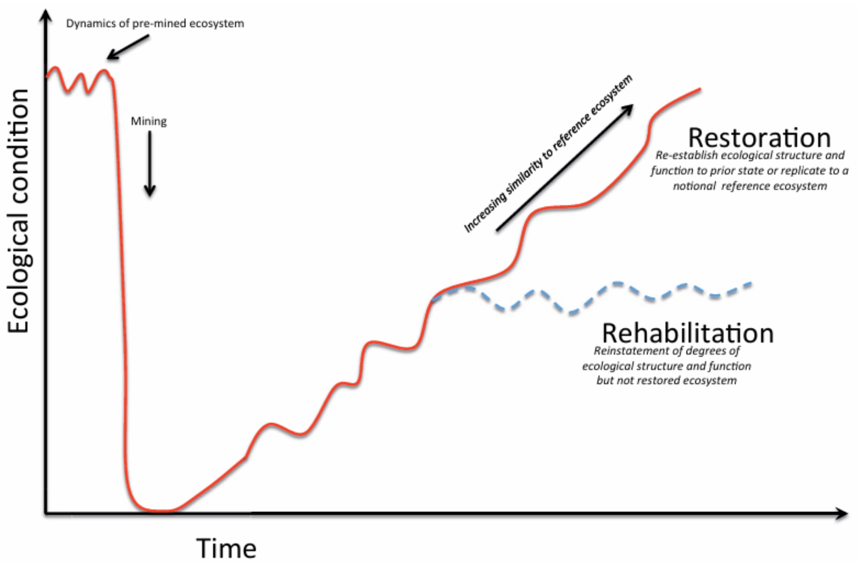



**Figure 1 Hypothetical ecosystem development over time (Commonwealth of Australia 2016)**

Compliance frameworks that require rapid attainment of reference-site soil conditions are difficult to achieve, especially since Australian native ecosystems require decades to reach a quasi-steady state (Harries et al. 2024).

A more appropriate basis for evaluation of rehabilitation success should be its trajectory: is the manufactured growth medium developing in a direction consistent with achieving the target PMLU? Initially, the growth medium will be low in soil organic carbon (SOC), organic nitrogen and organic phosphorus (Figure 2). The main nutrients are often added as fertiliser or mulch. Organic matter is rapidly broken down, and fertiliser can be lost due to volatilisation and leaching, resulting in a decrease in availability over time. As vegetation develops, the nutrients are increasingly held in the biomass and SOC as organic nitrogen (N) and organic phosphorus (P) forms. As SOC builds up in soil, so does organic N and organic P, and the soil nutrients will eventually reach a steady state after a long period of time (possibly decades). Hence, the aim should be to rapidly 'transfer' the added nutrients into vegetation (i.e. convert inorganic nutrients to organic nutrients) to minimise losses (Ribeiro et al. 2025).

The steady state content of SOC (and thus organic N and P) is determined by clay content, microbial activity, temperature, rainfall, and the quantity and quality of organic inputs (Mitchell et al. 2021; Xu et al. 2024). A manufactured growth medium derived from spoil with a different mineralogy may be inherently incapable of accumulating SOC to the levels found at reference with different mineralogy, regardless of the management applied. Furthermore, in any soil, SOC will fluctuate with the seasons and moisture conditions (Mitchell et al. 2021). Establishing realistic SOC targets that account for the textural properties of the available materials is therefore essential to avoid unattainable compliance criteria. Similarly, the depth of effective rooting at rehabilitated mine sites is often defined by the occurrence of a hostile layer (such as a saline or sodic horizon, or a compacted layer) that limits root penetration, whereas at reference sites, effective rooting depth may be constrained only by water availability or rock.

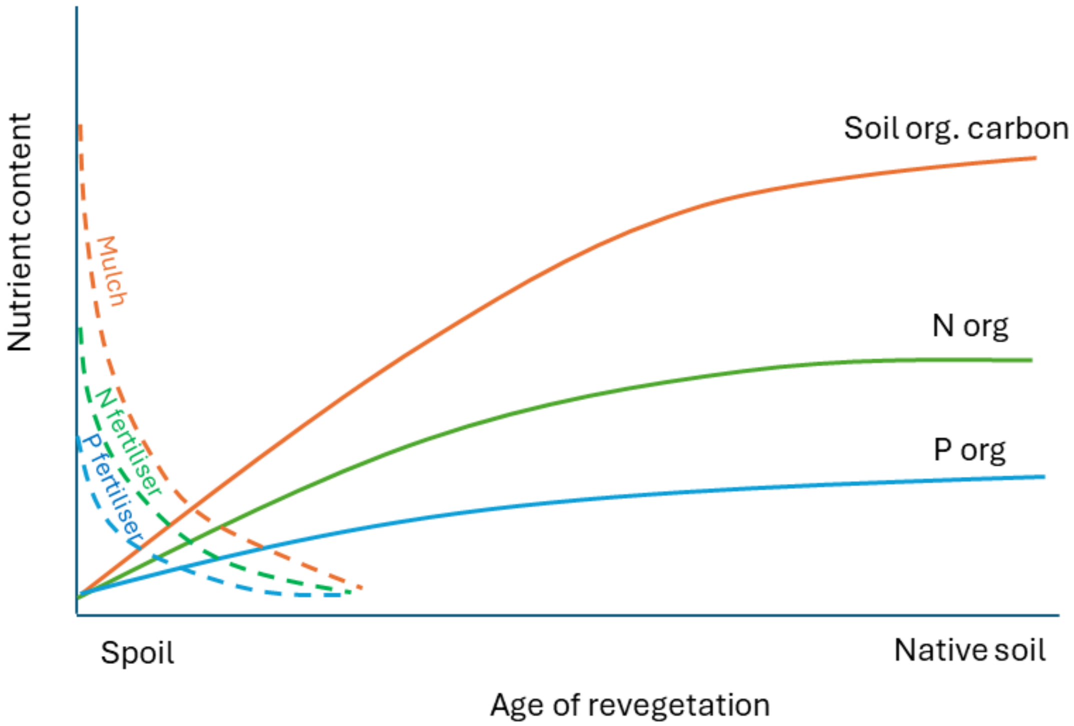



**Figure 2 Hypothetical changes in soil nutrients over time. Spoil is initially low in organic carbon, and organic nutrients such nitrogen (N org) and phosphorus (P org), and most fertility is added as organic matter (e.g. mulch) or fertiliser. The added organic matter and fertiliser N and P are rapidly converted into organic forms as vegetation develops and builds soil organic carbon**

# 2 Stage 1: defining the target post-mining land use and associated soil quality requirements

The first stage of the framework requires definition of the intended post-mining land use as this determines subsequent decisions regarding growth media design, amelioration and monitoring. Here we focus on 2 common PMLUs:

- grazing land (native and/or exotic pasture species)
- native vegetation woodland.

These 2 land uses have fundamentally different requirements from a growth medium, particularly in relation to nutrient levels, pH tolerance and the role of biological inoculants.

## 2.1 Grazing land use

Grazing pasture establishment offers the benefit of relatively rapid vegetation cover (typically 1–3 years), which reduces erosion risk during the early rehabilitation phase. Dense groundcover (generally > 70% cover) is effective for erosion control on slopes (International Erosion Control Association (Australasia) 2025), though in low rainfall areas vegetation density is limited by water availability. A key advantage of pasture-based PMLUs is that legumes can be incorporated into species mixes to provide biological nitrogen fixation, improving soil nitrogen status over time (Skousen & Zipper 2018). However, legumes have higher nutrient requirements than grasses, particularly for phosphorus (P) and sulphur (S), and P starter fertiliser is required to ensure nodulation and N fixation by legumes (Tekulu et al. 2020; McLaughlan et al. 2023).

Two exotic grass species with exceptional tolerance of variable soil conditions, Rhodes grass (*Chloris gayana*) and Signal grass (*Urochloa decumbens*), are commonly used in Queensland mine revegetation and can tolerate a range of pH, salinity, drought and clay content conditions (Wehr et al. 2026). For pasture PMLUs, soil phosphorus measured with the Colwell method should exceed 10 mg/kg to ensure adequate pasture growth and quality (Weaver et al. 2024), and total N should exceed 0.15% or nitrate N should be maintained above 10 mg/kg (Meat and Livestock Australia 2024). This requirement is essentially determined by the need to produce high-quality fodder for grazing animals.

Production systems also differ fundamentally from native woodlands in their requirement for nutrient replenishment. In pastures, nutrients are exported in harvested biomass (through grazing) and require ongoing fertiliser inputs to sustain productivity. This is in contrast to native woodland systems, where nutrient cycling through decomposition of litter and below-ground biomass is central to long-term fertility maintenance (Mulligan et al. 1999). The manufactured growth medium for a grazing PMLU must therefore be designed to support repeated nutrient additions and sustainable grazing management practices, whereas the native woodland growth medium should, over time, develop towards a more closed (internal) nutrient cycle.

## 2.2 Native vegetation (woodland) post-mining land use

Native vegetation is more complex to establish and manage than pasture but ultimately delivers greater ecological value in terms of biodiversity, carbon sequestration and ecosystem function. Species selection for rehabilitated mine sites should be based on the species palette, life forms and stem densities found at analogue sites within the same regional ecosystem (Wehr et al. 2026). Successional attributes of the species selected for initial establishment should also be taken into account. Where full native ecosystem recreation is not feasible, hybrid or novel ecosystems may be appropriate; hybrid ecosystems incorporate key ecosystem functions and attributes of native ecosystems but are better adapted to post-mining soil conditions (Spain et al. 2023).

Native vegetation in Australia has often evolved on nutrient-poor soils, particularly in relation to P. Adding high rates of P fertiliser (> 25 kg P/ha) to native vegetation rehabilitation can drive dense groundcover and *Acacia*-dominated communities that exclude slower-growing successional species (Burger et al. 2010; Daws

2022; daSilva et al. 2024). Site-specific fertiliser rates should therefore be established through consideration of species requirements and validation through field trials, investigating both rate and deep placement effects, before large-scale application (Ruthrof et al. 2013; Kwak et al. 2018). For native woodland PMLUs, Colwell P levels in the growth medium of 5 mg/kg are a reasonable target consistent with values at analogue sites (Wehr et al. 2026).

Defining target soil conditions for a native vegetation PMLU generally requires reference to undisturbed analogue sites. For Queensland, analogue sites may be characterised using the Soil and Land Information Land Suitability database, Land Resource manuals, the Queensland Globe Biota layer, regional ecosystem descriptions (Neldner et al. 2023) and direct field sampling of adjacent undisturbed sites (Wehr et al. 2026). It is important to recognise that the soil depth required to support native woodland may differ from what is achievable at a rehabilitated mine site. In reference woodland, effective rooting depth is commonly defined by water availability or rock, whereas in rehabilitated sites it may be constrained by the presence of hostile spoil layers at depth or compaction, requiring careful planning of spoil profile construction and amelioration.

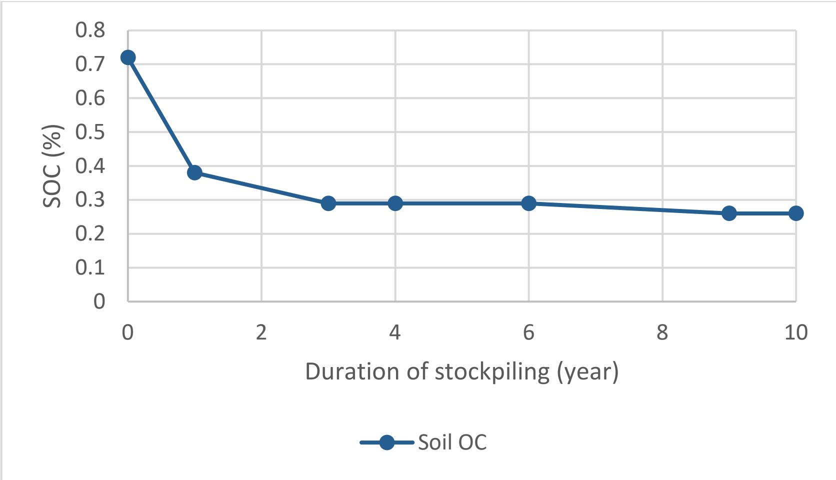
# 3 Stage 2: identifying and characterising available growth media resources

Having defined the target PMLU and the associated soil quality requirements, the second stage of the framework involves identifying all available growth media materials and characterising their physico-chemical properties. The objective is not to measure every conceivable growth media property but to understand the functional limitations of available materials and whether they can be ameliorated to support the target vegetation.

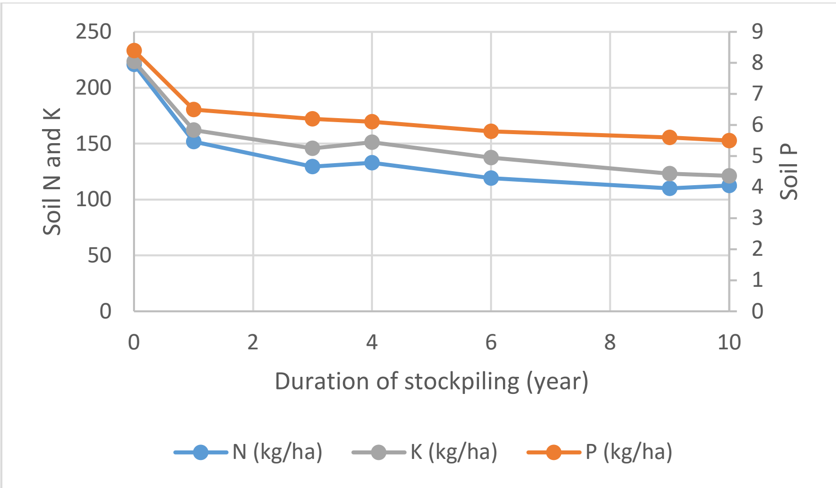
## 3.1 Identifying and inventorying materials

Soil and mine geological surveys undertaken prior to land disturbance are essential for identifying the location and depth of topsoil, subsoil and spoil materials (Isbell 2021; National Committee on Soil and Terrain 2024). These surveys inform soil maps and stripping procedures that preserve valuable resources and prevent contamination of the topsoil via mixing with hostile subsoil (Wehr et al. 2026). A materials inventory should quantify the volumes and spatial distribution of available materials, enabling calculation of topsoil shortfalls and identification of subsoil or spoil materials that may serve as bulk growth medium components. Volume calculations should be based on grid sampling of material thickness and areal extent.

Topsoil should be stockpiled and managed separately from subsoil and spoil, and direct placement (immediate relocation without stockpiling) is strongly preferred where operationally feasible. Where stockpiling is unavoidable, piles should be constructed as low as possible, have a large surface area and be vegetated where practicable, and the duration of storage should be minimised as soil quality may rapidly deteriorate (Ghose 2004) (Figure 3). In particular, the rapid loss of microbial activity in stored topsoil limits nutrient cycling. Topsoil stockpiled for longer than 12 months should be re-analysed prior to use as pH, salt content and biological properties can change substantially during storage (Ghose 2004; Hernandez et al. 2024).




(a)

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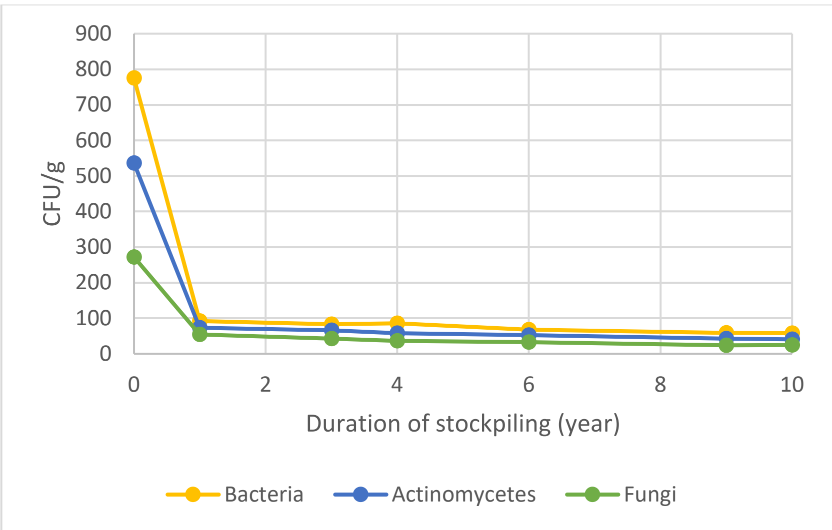


(c)

**Figure 3 Effect of soil storage duration on: (a) Soil organic carbon (SOC); (b) Mineralisable nitrogen (N) (permanganate oxidisable); phosphorus (P) (Olsen method) and potassium (K) (1M ammonium acetate exchangeable); (c) Microbial activity (CFU). Data are for stripped soil stored in 7–8 m-high piles without vegetation cover. Data calculated from Ghose (2004)**

### 3.2 Physico-chemical characterisation

All candidate growth media materials, including stockpiled topsoil, subsoil and spoil, should be sampled and analysed by an accredited laboratory for the suite of physico-chemical parameters detailed in Wehr et al. (2026, Table 3). Key parameters include: pH (both 1:5 water and 1:5 calcium chloride ($CaCl_2$) methods; the latter being less sensitive to the effects of ionic strength); electrical conductivity (EC1:5 and converted to saturated extract (ECse) using texture-specific multipliers); particle size analysis; exchangeable cations (Na, K, Mg, Ca, Al) and cation exchange capacity (CEC) (after pre-washing if applicable); slaking and dispersion behaviour (assessed by physical crumb tests, which are more reliable than chemical indices for predicting field behaviour); plant-available P (Colwell method for soils with $pH_w$ < 7.5, Olsen method for higher pH); available N and S; organic carbon; and trace elements by diethylenetriaminepentaacetic acid (DTPA) extraction. Plant-available water content (measured as the difference in water content at -0.1 and -15 bar) is also important since water availability is a critical driver of nutrient availability, and vegetation establishment and survival.

It is important to recognise that there is considerable redundancy among soil properties: clay content, clay mineralogy, organic matter, soil depth and aggregation all independently contribute to water-holding capacity, and it is not necessary to achieve identical values to the reference site for each individual parameter. What matters is whether the functional capacity of the manufactured medium to supply water, nutrients and physical support for roots is adequate for the target vegetation. Some constraints that are not individually limiting may, in combination, produce hostile conditions. For example, a moderately magnesic and sodic spoil may be highly dispersive when wetted, even though exchangeable sodium percentage (ESP) does not exceed the commonly accepted threshold of 6% (Northcote & Skeene 1972).

Nutrient availability in the growth medium depends not only on total nutrient concentrations but on the ability of plant roots to reach and access nutrients. This point is critical, adding nutrients to a growth medium achieves little if compaction, pH extremes or toxic ions prevent root growth in the longer term.

Leaching of soluble nutrients is an additional consideration, particularly relevant in high-rainfall areas or where growth media are sandy in texture. Nitrate and S are highly mobile under leaching conditions, and inorganic nutrients applied to bare, unvegetated surfaces are especially vulnerable to loss during rainfall events before vegetation establishes. The aim should be to 'move' nutrients from the soil-applied fertiliser into the biomass as soon as possible to prevent leaching losses. This can be achieved by re-establishing vegetation through a successional seed mix comprising fast-growing, short-life cover crops in combination with slower-establishing species that progressively create the final vegetation composition (Skousen & Zipper 2018; Ribeiro et al. 2025)

# 4 Stage 3: developing amelioration strategies to address soil constraints

The third stage involves translating the physico-chemical characterisation into a specific amelioration strategy for each growth medium material (Table 1). This stage requires identification of the constraints present, selection of appropriate ameliorants, calculation of application rates and consideration of practical interactions between amendments. The process is necessarily bespoke: there is no universal amelioration prescription applicable across all mine sites and materials, or even to different materials within a mine site. A soil science professional or agronomist will be able to provide practical recommendations based on the soil analyses. More detail can be found in Wehr et al. (2026). Maintaining adequate surface physical conditions for water infiltration is a fundamental prerequisite for all other amelioration strategies to function as intended. A dispersed or sealed soil surface – even a layer less than 1 mm thick – can act as a choke point that prevents rainfall from entering the growth medium, resulting in run-off and erosion rather than root-zone wetting (Queensland Government 2018; Wehr et al. 2026), thus preventing the function of soil ameliorants. Likewise, application of ameliorants needs to be timed with periods of low but frequent rainfall to ensure dissolution before storms wash away the growth medium. Alternatively, ameliorants should be irrigated into the soil without causing run-off and losses of growth medium and ameliorants.

**Table 1 Key questions and recommended responses for soil sample analyses (taken from Wehr et al. 2026)**

| Question | Risk | Response | |
|---|---|---|---|
| | | Yes | No |
| Is the pH outside the required range? | Low pH causes aluminium toxicity, high pH causes nutrient immobilisation/precipitation | Apply limestone if too acidic, or apply sulphur if too alkaline | ✓<br>No action required |
| Is the material dispersive? | Hardsetting and crusting soils impair water infiltration. Check soil pH is below 8.5, otherwise gypsum will precipitate. Organic matter works together with gypsum to overcome dispersion | Determine the rate of gypsum required and if material is responsive to gypsum. Mix well and ensure sufficient water and time are given for the gypsum to dissolve | ✓<br>No action required |
| When selecting organic matter, is the carbon to nitrogen ratio (C/N) of the material sufficiently low, i.e. C/N < 30? | N immobilisation likely if high C/N ratio (> 30)<br>Select organic matter that is labile (i.e. biologically broken down) | ✓<br>No action required | More N fertiliser is required to compensate for N immobilisation |
| Is the electrical conductivity (EC) above the required range? | Saline soils with low hydraulic conductivity are very difficult to leach by rainfall. Be aware that dispersion may increase when EC is lowered without adding gypsum | Mix material with clean material to lower EC or select other sources of material. Saline soil cannot be remediated effectively in low rainfall environments | ✓<br>No action required |
| Are essential plant nutrients missing? | Phosphorus can be immobilised in soil by iron oxide minerals. Apply fertiliser by banding, split fertiliser applications across years | Calculate required fertiliser rates to overcome deficiencies. Be aware of fertiliser reactions in soil | ✓<br>No action required |
| Is there an excess of nutrient or contamination in the materials? | Unlikely to be an issue when using subsoil or spoil, but contaminants may affect the quality of pasture for grazing use | Mix with clean material or additional ameliorant to lower contaminant levels (e.g. lime to precipitate metals, organic matter to bind heavy metals, charcoal to adsorb organic contaminants) | ✓<br>No action required |
| Does the water-holding capacity meet the requirement of the desired cover? | Low water-holding capacity imposes water stress and poor survival, leads to low vegetation density. Irrigation can aid initial establishment but is not useful in the long term | ✓<br>No action required | Add a thicker layer of cover, or mix cover with finer textured material, or add organic matter to increase water-holding capacity |
| Is the infiltration rate sufficient to wet up the growth medium? | Organic matter input through fibrous root systems improves soil surface stability, straw or wood chip mulch incorporation increases infiltration rate | ✓<br>No action required | Increase surface roughness and infiltration rate by contouring or incorporating coarse porous material into topmost layer to improve infiltration |

# 5 Stage 4: trialling amelioration strategies

Before large-scale commitment to a particular amelioration approach, leading practice recommends the establishment of small-scale trials to test the efficacy and practicality of proposed strategies under site-specific conditions (Wehr et al. 2026). The complexity and cost of manufactured growth media production, combined with the long time frames required to evaluate outcomes, means that errors at the design stage can be extremely costly to remedy. Trials provide an opportunity to identify unanticipated interactions between amendments, assess the practicality of proposed mixing and placement methods using available equipment, and establish locally calibrated fertiliser rates before full-scale implementation.

Strip trials – linear plots of individually varying treatments – are an operationally practical trial design for large mine sites as they can be established and managed using the same machinery used in full-scale rehabilitation. A minimum of 3 to 4 replications per treatment is desirable for reliable statistical interpretation, and inclusion of an untreated control and a best-available topsoil reference treatment is essential for contextualising results (Wehr et al. 2026). Trial plots should be a minimum size that reflects available machinery, be clearly marked and be assessed at regular intervals over a minimum of 5 years.

Practical considerations for trial establishment deserve specific attention. Soil and amendments should be fairly dry (friable consistency) when mixed, to prevent smearing and structural damage. Antagonistic interactions between amendments must be managed in the mixing sequence: limestone must not be combined with ammonium-based fertilisers, and phosphate fertilisers should not be co-mixed with gypsum or lime (Wehr et al. 2026). Application of gypsum to the surface without mixing throughout the profile may not achieve effective soil amelioration due to its low solubility. Gypsum added to correct sodicity is only effective after it has dissolved in the soil and exchanged with sodium on the cation exchange complex, and approximately 40 mm of rainfall is required to dissolve 1 t/ha of surface-applied gypsum (Hira & Singh 1980). Recommended best practice for sodic soils is to incorporate gypsum to the maximum practical depth of the replaced spoil before application of appropriately amended topsoil or artificial growth media (Dale et al. 2022, 2018).

# 6 Stage 5: monitoring vegetation performance and growth medium development

The final stage of the framework is ongoing monitoring of both vegetation performance and the physico-chemical properties of the growth medium over time. This stage serves 2 purposes: demonstrating that rehabilitation is progressing on a trajectory towards achieving the target PMLU; and providing an early warning of conditions that might cause deviation from the trajectory or rehabilitation failure, enabling adaptive management interventions before problems become irreversible.

There are cases of revegetation that initially appeared successful but which subsequently failed after several years (Harries et al. 2024) due to plants exhausting the available nutrients or water pooling within the soil profile (Wehr et al. 2026). Amelioration treatments including gypsum and fertiliser may also require repeated application as nutrients are depleted and structural stability declines without sufficient organic matter inputs.

Regular soil sampling is recommended annually until vegetation is well established, then at less frequent intervals as nutrient cycling and erosional stability are demonstrated across a range of climatic disturbances including drought and flood. Sample depths of 0–20 cm and 20–60 cm (or to effective rooting depth) should be analysed for the suite of parameters detailed in Wehr et al. (2026, Table 7), including: pH (water and $CaCl_2$); electrical conductivity; colour; slaking and dispersion behaviour; exchangeable cations (Na, K, Mg, Ca, Al) and CEC; carbonates and chloride; available N, P, K and S; organic carbon; and trace elements where toxicity or deficiency was identified at the characterisation stage. Monitoring results will inform early interventions.

SOC is a particularly important monitoring parameter because it integrates biological activity, nutrient cycling, aggregate stability and water-holding capacity. However, it must be assessed against realistic targets that account for the clay content and mineralogy of the manufactured medium rather than against absolute reference-site values (Wehr et al. 2026). Where SOC is increasing year-on-year and microbial activity indicators are improving, the trajectory is positive even if absolute SOC values remain below reference levels for many years. Trajectories for SOC show carbon accumulation rates of 0.4–5.7 t/ha/yr in a variety of soils and climates (Misebo et al. 2022). The total N and total P in rehabilitated spoil reached values of 47 and 33% of the control, respectively, after 16 years in India (Ahirwal & Maiti 2018) with similar climate to Central Queensland, indicating that the timelines are slow.

The integration of soil and vegetation monitoring data within an adaptive management framework is the ultimate objective (Harries et al. 2024). Where monitoring reveals that the trajectory is deviating from expectations — for example, stalled SOC accumulation, persistent high EC in the growth medium root zone (indicating failure to establish soil structure and promote leaching), or failure of target species to establish — an adaptive intervention should be triggered. The framework presented in this paper, with its structured approach to constraint identification and amelioration, provides the diagnostic tools to design appropriate corrective actions.

# 7 Conclusion

This paper has presented a structured 5-stage framework for creating alternative growth media for mine site revegetation, grounded in the principle that growth media must replicate the functions of natural soil for the target post-mining land use, even if they cannot replicate its exact composition. The framework addresses the identification and characterisation of available materials, the development of site-specific amelioration strategies for common constraints including pH extremes, dispersion, salinity and nutrient deficiency, the trialling of amelioration approaches, and the ongoing monitoring of both soil and vegetation development.

For mine operators the practical implications are clear: invest in soil surveys of reference sites and characterisation of topsoil and subsoil materials prior to stripping; conduct a materials inventory; directly place and protect topsoil wherever possible; characterise subsoil and spoil materials comprehensively before use; design bespoke amelioration strategies for each material; trial amelioration approaches before full-scale commitment; and monitor soil and vegetation parameters over the long term within an adaptive management framework. These actions, implemented systematically, will substantially increase confidence in the ability to meet, and reduce the cost of achieving, sustainable closure outcomes across diverse mine rehabilitation contexts.

# Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Claude AI (Version 3.4) to condense and clarify expression of the document. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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