Office of the **Queensland Mine Rehabilitation Commissioner**

Review of techniques to address topsoil deficit in open cut coal mines under rehabilitation in Queensland

Student report

Queensland Government

Prepared by: Office of the Queensland Mine Rehabilitation Commissioner

Citation

da Silva GOA, Dunlop J, Nicolson L & Purtill J. 2024. Review of techniques to address topsoil deficit in open cut coal mines under rehabilitation in Queensland: Student report. Brisbane: Queensland Mine Rehabilitation Commissioner, Queensland Government.

Acknowledgements

This report was prepared as part of a student industry placement project with the University of Queensland. The authors also thank Dr Glenn Dale for input and review.

February 2024

Foreword

This report is an output from a student project undertaken as part of a three-month higher degree Industry Placement program with the University of Queensland. The review is not intended to provide a full representation of the scientific literature on the subject matter, but rather provide a summary of issues and relevant references.

Contents

Figures

Tables

Executive Summary

Topsoil is one of the most important factors in successful rehabilitation for vegetated post-mining land uses. Correspondingly, a lack of topsoil, or reduced topsoil quality from storing soil pose a challenge for mine rehabilitation where a vegetated landscape is the final land use. The shortage, or deficit, of topsoil is caused by several interrelated issues. The surface area requiring rehabilitation after mining is typically larger than the area from which topsoil was originally extracted. This means there is less soil to distribute on post mining landforms. In the Bowen Basin in Central Queensland, there is often naturally shallow topsoil depths that limit the volume of topsoil available for rehabilitation. This issue becomes more pronounced when topsoil is not completely removed ahead of mining. Improper topsoil storage practices can also lead to a reduction in the quality of topsoil available for rehabilitation after mining.

In the Bowen Basin, Central Queensland, coal mines frequently grapple with the issue of topsoil deficit. In response, mines may opt to replace or supplement topsoil with coal overburden, or spoil, as a growth medium. However, coal mine spoil often lacks the essential soil properties required for a reliable substrate. The relatively unfavourable physiochemical characteristics of spoil, coupled with a lack of topsoil, has prompted mining companies to investigate alternatives such as amending spoil or importing suitable topsoils. Such options may increase rehabilitation costs substantially and may not be viable. Often, the upfront costs to build suitable growth media with the necessary quality and quantity to ensure successful rehabilitation outcomes, will help to avoid the liability to repair failed works. Improved practices to address the challenges posed by topsoil deficit could not only enhance rehabilitation efficiency and effectiveness but also yield cost savings for mine operators.

The objectives of this study were to two-fold. Firstly, we identify approaches used to address topsoil deficit in open cut coal mine rehabilitation and secondly, we describe the attributes of growth media needed to support successful rehabilitation efforts. To achieve this, the current literature on the techniques available were reviewed and their potential application to the coal mining industry in Central Queensland was evaluated. The study identified knowledge gaps and provides recommendations to improve practices to address topsoil deficit.

We identified the key attributes a suitable growth medium needs to support vegetation growth for successful rehabilitation. While spoil often possesses physicochemical characteristics that limit its fertility, each spoil can be unique and requires a site-specific approach to address factors that can limit healthy soil function. This underscores the importance of tailoring solutions to each site's particular challenges. A comprehensive assessment of spoil properties is an essential part of the process. This should encompass aspects such as nutrient levels, chemical composition, physical structure, and the composition and functioning of microbial communities.

A holistic evaluation is necessary to gain a complete understanding of the deficiencies in each spoil or stored topsoil and to apply the appropriate techniques or amendments to rectify these constraints. Despite the progress in scientific understanding and a few international examples where spoil has successfully been converted into viable soil, our review of the literature showed that there is not a one-size-fits-all strategy suitable for all mines in Central Queensland.

One effective method for assessing the suitability of a substrate for plant growth is to compare its key attributes with those of an adjacent natural, unmined reference site. Analysing and evaluating the soil from a reference or analogue site can provide valuable insights into the requirements for achieving the ideal growth media for the desired post-mining land use. It is recognised that soil conditions could be expected to vary from reference conditions in some instances. In those circumstances it may be necessary to describe what the fundamental plant nutrient, physical, chemical and biological soil requirements are.

Despite advancements in scientific trials to find solutions for mine rehabilitation in Central Queensland, numerous gaps in knowledge remain and many obstacles must be tackled to enhance rehabilitation outcomes. The key areas that require attention for successful future mine rehabilitation in Central Queensland coal mines include:

- addressing the lack of information collected to describe spoil physiochemical properties and identify constraints limiting its function as a growth medium
- a perceived absence of large-scale field trials
- a lack of long-term studies and insights on rehabilitation (>10 years)
- challenges associated with identifying suitable reference or analogue sites and criteria
- defining the key ecological attributes of growth media that align with the requirements to

achieve a nominated post mining land use
- addressing plant water stress in a hot and dry climate
- a need for reliable growth media biogeochemical indicators
- finding consensus on how to measure rehabilitation success.

To ensure the long-term recovery and stability of mining sites and establishment of a self-sustaining landscape, it is crucial to recognise that the full soil profile quality plays a pivotal role. Where a topsoil deficit exists, rehabilitation strategies must be informed by research that addresses the above gaps, to enable successful rehabilitation in Central Queensland coal mines facing topsoil deficit.

1 Introduction

The absence of sufficient quality and quantity of topsoil is one of the main challenges for effective mine rehabilitation of coal mines in Queensland (Da Silva et al., 2022). A key reason for this shortage, or deficit, is that the post-mining surface area to be rehabilitated is usually greater than the area from which topsoil was previously removed (Office of the Queensland Mine Rehabilitation Commissioner, 2022). The situation is particularly aggravated when the topsoil is not completely removed prior to mining or is not stored properly. Topsoils can be exposed to high temperatures and desiccation during processing and storage, leading to “intense disturbance” (Ngugi et al., 2018). The disturbance can cause long-term damage to soil physicochemical and biological properties, including a decline in microbial activity and organic matter content (Sheoran et al., 2010). Sodicity and extreme pH have also been a major constraint limiting the functionality of this substrate, especially in Central Queensland coal mines (Da Silva et al., 2022). Accordingly, care must be taken to ensure harvested topsoil is properly segregated and not mixed with sodic sub-soil and spoil.

To address the challenge of topsoil deficit, many mines turn to coal overburden (spoil) as a growth medium. However, coal mine spoil often lacks essential soil properties required for a reliable substrate (Gunathunga et al., 2023). The nature of spoil and the absence of proper environmental management can complicate mine site rehabilitation efforts and inflate costs (Dale et al., 2018). Dispersive spoil and topsoil pose significant economic and environmental challenges for numerous Australian mines (Vacher et al., 2004). For instance, in Queensland's Bowen Basin, it is estimated that dispersive spoil constitutes an instantaneous liability estimated at $2 to $3 billion for rehabilitation plans (Dale et al., 2018).

This report aims to identify and describe approaches used to address topsoil deficit in open cut coal mine rehabilitation. It also describes the attributes necessary to create a successful growth medium to support rehabilitation efforts. The report focusses on managing topsoil shortages in Central Queensland coal mines. The report identifies knowledge gaps and provides recommendations to initiate discussions on leveraging current practices to inform rehabilitation goals and address the topsoil deficit issue.

2 Implications of topsoil deficit for mine rehabilitation

Topsoil is one of the most important factors in successful rehabilitation (Australian Government, 2016). The nature and distribution of soil and overburden types should be evaluated and used to inform soil conservation practices in readiness for the rehabilitation program. This step is particularly important when the overburden material or tailings alone are expected to be incapable of sustaining the post mining land use (PMLU) (Australian Government, 2016) and overburden will often form part of the resultant anthropogenic profile.

The replacement of topsoil after mining is usually constrained by the effect of material swelling when overburden is placed in backfill areas. As a result, the mining area requiring topsoil coverage has a larger surface area than the one originally harvested before mining. Even when topsoil is available to cap a re-contoured spoil profile with a superficial layer (typically 100-300 mm) and able to reduce negative physiochemical effects in the short-term, it may still present a risk of failure as a result of erosion, hindering rehabilitation (Maiti and Maiti, 2015; Spargo and Doley, 2016). The problem is more severe in many older mines or legacy mines, where the topsoil was not saved at all, or where it has been stored in piles, often for decades, without proper environmental management (Karan et al., 2017).

Ideally, topsoil should be directly returned to areas for use in revegetation rather than stored for later use. This environmental management strategy avoids the loss of soil’s essential properties, such as soil structure, organic matter, nutrients and microorganisms (Valliere et al., 2022). However, direct transfer is often not feasible, necessitating storage in stockpiles. When stockpiled, progressive rehabilitation should prioritise use of stored topsoil to minimise degradation of the topsoil quality.

To address topsoil shortages, some authors suggest supplementary growth materials produced during mining operations should be explored, as long as they are proven not to adversely affect plant establishment and overall restoration success (Merino-Martín et al., 2017 and da Silva, 2024). Over the past twenty years, this has led to increasing interest in spoil selection for cover, landform planning, the use of rock cladding, and the use of a limited depth of topsoil as a rehabilitation methodology on steeper slopes (Emmerton, 2019). In Central Queensland, the use of coal mine spoil as a growth medium for mine rehabilitation offers a valuable strategy to achieve rehabilitation goals (Da Silva et al., 2022). Spoil is the material that has been excavated, removed, or displaced during mining operations (Sarkar et al., 2017). Spoil can include the overburden that was removed to access the mineral deposit, as well as any waste rock, tailings, or other materials that are separated from the ore during processing and is often considered a waste material because it typically lacks economic value (Sarkar et al., 2017).

Although it is used as a mine rehabilitation substrate in central Queensland, mine spoils usually lack the essential physiochemical and biological properties of topsoil. Due to their nature, they may not have a viable seedbank and can often be sodic and dispersive materials with low infiltration rates, extreme acid or alkaline pH, high salinity, high erodibility and weak aggregate stability, hindering rehabilitation success when used as a substrate for plant establishment (Vacher et al., 2004; Dale et al., 2018; Emmerton et al., 2018; da Silva et al., 2021).

The poor physiochemical characteristics of spoil, together with topsoil deficit can lead mine operators to invest considerable resources on ameliorating spoil or importing suitable topsoils, increasing rehabilitation costs. Better practices to manage the challenge imposed by topsoil deficit would not only increase rehabilitation efficiency and effectiveness, but may also lead to cost savings for mine operators (Queensland Government, 2017). Where spoil is used as a growth medium it will likely require augmenting with amendments to make up for its lack of essential soil physiochemical and biological properties, or even accelerate pedogenesis in this substrate (da Silva, 2024).

3 Defining ‘growth media’ for rehabilitation purposes

For mine rehabilitation purposes, a growth medium is defined as a substrate that provides an alternative to topsoil and is capable of hosting plants to sustain a vegetated post mine land use (Australian Government, 2016; Queensland Government, 2021). Cook (1976) showed that a full description of the physical and chemical features of the substrate, along with an assessment of the general plant growth potential are needed to identify whether a substrate can be used as a plant-growth medium. A substrate can be described by its contribution to key ecological attributes. According to Young et al. (2022), a substrate is the soil, sand, rock, shell, debris or any other medium where organisms can grow and ecosystems develop.

For spoil and topsoil conditions in Central Queensland coal mines, information regarding the organic matter content, texture, salts concentration, water holding capacity and pH values should be a prerequisite for determining whether the material will be an adequate plant growth media. Native microbiome is another key feature in soils. Microorganisms play a critical role in natural soil forming processes, nutrient cycling, soil aggregate stabilisation and plant growth promotion (Hayat et al., 2010; Kleber et al., 2015). However, soil microbiota and their impact on soil chemistry and structure has traditionally been overlooked in mine site remediation and mine spoil amelioration (Da Silva et al., 2022).

The use of a mixture of stockpiled spoil and topsoil in different ratios and depths as growth medium often requires adding gypsum, mulch and inorganic fertilisers to improve soils and prevent erosion. This is becoming a standard technique used at Central Queensland coal mines (Da Silva et al., 2022). However, some treatments may only offer short-term effects and require ongoing site-specific interventions, hindering long-term vegetation establishment and limiting floral diversity (Pedrol et al., 2010), thus impeding landscape transition into a self-sustaining PMLU.

Site-specific strategies in mine rehabilitation refer to tailored approaches and methods that are specifically designed to address the unique conditions, challenges, and goals of a particular substrate. Rather than applying a standard solution, site-specific strategies consider the specific characteristics of the mining site and surrounding natural area, including its geological, ecological, topographic, hydrologic and environmental features (Gunathunga et al., 2023). These strategies involve a detailed assessment of the site's soil, vegetation, climate, and other relevant factors. Based on this assessment, customised plans and techniques can be developed to improve growth media conditions and consequently, mine rehabilitation outcomes. This approach recognises that each mining site is unique, and therefore, the rehabilitation process must be tailored to address its distinct challenges and opportunities (Perring et al., 2015; Young et al., 2022).

Leading practice requires that the availability of soil resources and capping material is assessed prior to the commencement of mine operations (Queensland Government, 2021). The quality and quantity of available resources (such as topsoil, clay material and competent rock) required as substrate to complete the target rehabilitation must be included in the evaluation along with an assessment of the need for ameliorants and fertilisers, and the relationship between soils and vegetation ecosystems for the PMLU and rehabilitation methodology. A site-specific characterisation of the key physicochemical attributes of the growth medium (either remaining topsoil or spoil) provides a basis to establish effective rehabilitation strategies (Gunathunga et al., 2023). These analyses should include not only surface soil but also the analysis of displaced subsoil horizons down to the rooting depth of vegetation. When mixed with the topsoil, the subsoils' low organic matter content leads to a loss of organic matter and consequently poor structure of the growth media for plant establishment, especially for deep-rooting trees (Schwenke et al., 2000).

Table 1 presents data describing natural soils, as well as areas under rehabilitation from the Bowen Basin region and their measured physicochemical properties. The data in Table 1 is provided here to give an indication of general soil conditions for unmined natural soils and materials used for rehabilitation in Central Queensland. The data has been collated from publicly available sources including Progressive Rehabilitation and Closure Plans (PRC plans) and the published scientific literature.

The data suggests the predominance of clay soils in the region, with many exhibiting high pH levels. These conditions may account for variations in the Cation Exchange Capacity (CEC), a measure of the soil's ability to retain positively charged ions. The CEC of soils varies based on clay percentage, clay type, soil pH, and the amount of organic matter (McKenzie et al., 2004).

Table 1 Chemical properties of reference soils for growth media, spoil and stored topsoil used for rehabilitation in the Bowen Basin region

Mine site	Site type	pH	Electrical Conductivity (EC) – dS/m	Organic Carbon Content - %	Soil Texture	Cation Exchange Capacity (CEC)	References
Dysart site 1	Reference soil	7.1	0.7*	0.91	Clay	–	(da Silva, 2024)
Emerald (various sites)	Reference soil (grazing property)	5.7-7.3	0.02-0.2	–	–	2.2-6.9	(Sangha et al., 2005)
Dysart site 1	Rehabilitation (Spoil stockpile)	8.3	3.9*	0.87	Clay	39.6	(da Silva, 2024)
German Creek East	Rehabilitation (Spoil capped with topsoil)	5.8	1.9	0.45	–	3.0	(Dale et al., 2018)
Moranbah North	Rehabilitation (Spoil capped with topsoil)	8.9	0.3	0.06	–	16.0	(Dale et al., 2018)
Dysart site 2	Rehabilitation (Spoil stockpile)	7.8	0.3	–	–	–	(Kopittke et al., 2004)
Middlemount	Rehabilitation (Spoil stockpile)	7.8	0.2	1.1	–	–	(Shrestha et al., 2019)
Baralaba (various sites)	Rehabilitation (Topsoil stockpile)	>9	0.4-0.9	–	–	11-33	(Bramston and Brown, 2023)
Curragh (various sites)	Rehabilitation (Topsoil stockpile)	7.3-9.2	0.03-3.2	0.5-4.2	Clay loam	17.1**	(Williams and Radloff, 2022)

*Data reported is the EC saturation Index (dS/m).

** Average among all sites.

(–) Data not available.

3.1 Key attributes of growth media

Growth media should provide a substrate that is stable, not dispersive or hostile to root growth or penetration, has adequate water holding capacity and has enough nutrients to allow plants to establish. Moreover, the attributes will be driven by the nature of vegetation that is to be established, and this must be included as part of the planning and design process (Young et al., 2022).

The International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites describe six key ecosystem attributes, which can be used to evaluate the degree to which biotic and abiotic properties and functions of an ecosystem are recovering (Young et al., 2022). Attributes relevant to the key characteristics of growth media include the absence of erosion (absence of threats), the physical and chemical conditions of soil (physical conditions) and nutrient cycling (ecosystem function). These are important to ensure a growth medium will provide the necessary support and functions for resilient and sustainable vegetation communities. As a guide, Young et al., (2022) recommends the use of adjacent or locally relevant reference survey sites to describe the ecological conditions present in the local area. Such an approach would also be relevant where pastures are the desired land use. While reference conditions offer a valuable indication of ideal soil conditions for an area, there may be challenges in replicating these conditions. Careful consideration of the rehabilitation objectives is required when defining what a suitable growth medium is at a site-specific scale.

The quality of growth media and its ability to support self-sustaining vegetation can be described using a range of physical and chemical indicators. Examples include infiltration capacity, available water capacity, aeration, rooting depth, plant nutrients, salinity, acidity/alkalinity and microbial associations as key parameters (Australian Government, 2016). In the following sub-sections, we introduce and discuss some of the key attributes of growth media.

3.1.1 pH

Soil pH is a major driver of soil biogeochemical processes, influencing plant growth and biomass yield (Neina, 2019). Many of these biogeochemical processes may also modify the pH in a bidirectional relationship (Figure 1). Soil pH influences a range of chemical processes including dissolution, precipitation, adsorption, dilution and volatilisation of ions in soil. Soil pH also affects the solubility, mobility and bioavailability of trace elements, which in turn determines their translocation in plants (Carrillo-González et al., 2006; Kulikowska and Klimiuk, 2008; Msimbira and Smith, 2020). Additionally, the quantity of dissolved organic carbon, which also influences the availability of trace elements, is controlled by soil pH (Neina, 2019).

Soil pH also exerts a large effect on microbial community structure and activity (Neina, 2019; Msimbira and Smith, 2020). All living cells require an optimum pH for normal physiological functions (Msimbira and Smith, 2020). Although many plants can tolerate extreme pH, most agricultural plants perform optimally at a neutral pH range (pH 6 – 8), as the availability of nutrients is greatest in this range (Läuchli and Grattan, 2012). This is also the case for most soil microbes, in part because in this range plants grow well and produce more root exudates as a carbon source available for survival and multiplication of microbes (Msimbira and Smith, 2020).

Because it affects almost every aspect of nutrient uptake, soil pH has a significant impact on plant health. For example, in acidic soil, plants face three major toxicities, Al^{3+}, Mn^{2+} and H^{+}, which inhibit plant growth, while in alkaline soils the effects on crop plants may be related to salt stress (Msimbira and Smith, 2020). It is important to note that the alkaline conditions which lead to nutrient deficiencies may be associated with soil sodicity (Hazelton and Murphy, 2016). Alkaline soils are a common issue in Australia, especially in low rainfall locations and high slopes, due to dispersive subsoils with transient waterlogging and anoxic conditions (Rengasamy et al., 2022). This leads to a higher concentration of carbonate species, generating the alkaline condition. One of the major causes of pH variation is the inherent mineral composition of the parent soil material (Msimbira and Smith, 2020). A full understanding of soil pH variations and implications is necessary for optimising nutrient cycling, soil remediation and plant nutrition, as it affects the entire interacting system and is particular to the requirements of the target vegetation.

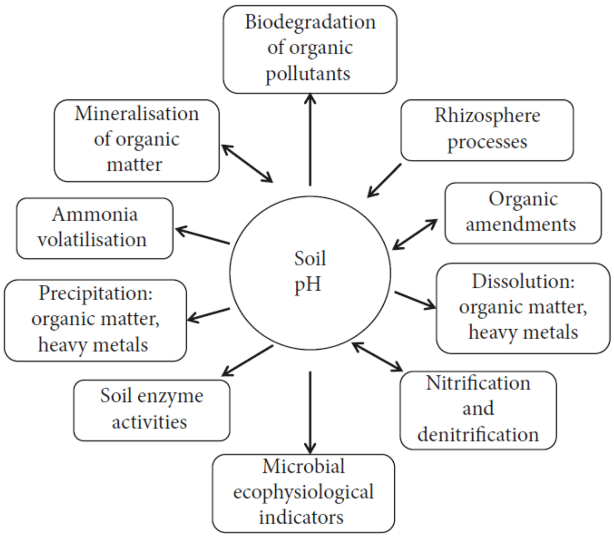

Figure 1 Biogeochemical processes in soil and their relationship with soil pH (Source: Neina, 2019)

3.1.2 Salinity and Sodicity

Plants are affected by salt stress in two main ways: osmotic stress and ionic toxicity. These stresses affect all major plant processes, including photosynthesis, cellular metabolism, and plant nutrition (Safdar et al., 2019). Some authors suggest a soil can be considered saline when the electrical conductivity of the saturation extract (EC) is >4 dS/m (Hazelton and Murphy 2016). However, to appropriately consider the effects of salinity on vegetative growth a number of factors must be considered, such as the salt tolerance of the intended vegetation, plant stage of growth and root zone salinity (Queensland Department of Environment and Resource Management, 2011). The common cations associated with salinity are Na^+, Ca^{2+} and Mg^{2+}, while the common anions are Cl^-, SO_4^{2-} and HCO^{3-}. However, Na^+ and Cl^- ions are considered the most important, since Na^+ in particular causes deterioration of the physical structure of the soil and both Na^+ and Cl^- are toxic to plants (Hasegawa et al., 2000).

In soil, the amount of sodium ions relative to other cations is referred to as sodicity, often measured as Exchangeable Sodium Percentage (ESP). Australian soils are generally classified as sodic when the ESP value is ≥ 6, and an ESP > 14 is considered to represent strongly sodic conditions. The impact of soil sodicity and its interplay with the total cation concentration can significantly affect soil structural stability and, consequently, soil degradation (Sumner, 1993). The problems associated with sodic soils include surface crusting, low infiltration and hydraulic conductivity, hard dense subsoil conditions and susceptibility to gully and tunnel erosion (Hazelton and Murphy, 2016).

The abundant quantity of sodium ions bound to clay surfaces in sodic soils can cause clay dispersion upon wetting (Odeh and Onus, 2008; Tang et al., 2021). Dispersion can result in a compacted structure that hinders root growth, seedling establishment, and the movement of air and water (Rengasamy, 2010; Tang et al., 2021). The resultant poor physical condition can harm crop growth and make soil management challenging. Additionally, there is a risk of soil physical breakdown, which can lead to soil erosion and complete soil loss (Odeh and Onus, 2008).

Saline soils are also vulnerable to erosion due to the lack of vegetative surface cover. While salinity can have a negative effect on plant growth, in certain circumstances and despite the presence of sodium ions, it has a stabilising impact on soil structure by flocculating clay particles. However, when salinity is below a threshold electrolyte concentration (TEC), flocculation of the clay particles is inhibited and the adverse effects of sodicity on soil structure are observed (Rengasamy and Olsson, 1991).

The interactions between soil salinity, sodicity and dispersion are important as they inform soil behaviour and impact plant health. These interactions should be carefully considered during soil biochemistry assessments, to improve understanding of salts dynamics and its effects on soil quality.

3.1.3 Organic matter and plant nutrients

Soil organic matter (SOM) is any living or dead animal and plant material, including plant roots and animal remains at various stages of decomposition, and the soil microbiome, which represents the dynamic community of microorganisms associated with plants and soil, including bacteria, fungi, actinomycetes and microalgae, and their excretions. The process of decomposition releases nutrients which can be taken up by plant roots. Humus, the product of decomposition is a complex chemical substance, which stores plant nutrients, holds moisture and improves soil structure (Department of Primary Industries, 2019). SOM is a key component of any ecosystem, and variation in its abundance and nature has profound effects on many of the processes that occur in soil (Voltr et al., 2021; Cotrufo and Lavallee, 2022). The amount of soil organic matter necessary for plant growth success will depend on the form and intensity of land use (Jakovac et al., 2021). However, it is crucial to consider an appropriate level of SOM to maintain soil structure and land stability, since a reduction in SOM can lead to loss of structure and erosion in many soils (Shi and Schulin, 2018). Organic carbon contributions from SOM play an important role in contributing to nutrient storage and exchange, improved water storage capacity and microbial activity. Therefore, increased levels of SOM assist in returning carbon to the soil and soil organic carbon is used as a proxy measure for SOM (Baumgartl et al., 2015). As SOM acts as a reservoir of nutrients, releasing them slowly over time, it is essential to sustain plant growth and health. Conversely, low organic matter content may lead to nutrient deficiencies, poor soil structure, and reduced water-holding capacity, negatively affecting vegetation vigour (Manning, 1979).

Plant growth and development are influenced by nutrient availability (Kumar et al., 2021). Plant nutrients are chemical elements that are essential for plant growth and reproduction (Barker and Pilbeam, 2006). These elements have specific functions in plant metabolism, and in the absence of them or with severe deficiency, the plant will present abnormal growth or symptoms of deficiency and death before it completes the cycle from seed to seed (Barker and Pilbeam, 2006; Kumar et al., 2021). Seventeen elements are considered plant nutrients, 14 of these are obtained from soil or nutrient solutions, while carbon, hydrogen, and oxygen are derived from air or water (Barker and Pilbeam, 2006). The Carbon/Nitrogen (C:N) ratio of soil (and any organic amendments) is an important measure of the relative nitrogen content of the material. The C:N ratio provides an indication of the rate of decomposition of organic material and its impact upon N levels. C:N ratios greater than 25 indicate slow decomposition of the organic material and will require additional nitrogen to support plant growth (Hazelton and Murphy, 2016).

While macronutrient deficiency is a more common issue for soil fertility, micronutrient depletion is often encountered as a constraint in Australian soils, primarily due to the prevalence of highly weathered soil parent material (Brennan et al., 2019). The presence of micronutrients in soil is influenced by various factors, including the geochemical composition of the soil parent material, soil characteristics such as clay mineralogy, particle size distribution, soil horizon, age, and formation processes (Shukla et al., 2021). Intrinsic soil properties like pH and the quality and quantity of SOM also play a crucial role. For example, Hayes and collaborators (2019) demonstrated that soils in the Bowen Basin are prone to zinc deficiency. However, data on micronutrient depletion in the area are scarce and relatively old, emphasising the need for a more comprehensive understanding of the soil-related risk of micronutrient deficiency in Australia (Hayes et al., 2019).

A table presenting information on nutrients available from soil extracts and what implications their deficiency can have on plant metabolism is presented in Appendix Table 1. Soil testing is a common and essential approach to assess soil fertility and plant nutrition and indicates the capacity of soils to supply plant nutrients (Rayment and Lyons, 2011). Interpretation of soil tests provides an assessment of the amount of available nutrients which plants may absorb from a soil and will guide recommendations for fertilisation (Barker and Pilbeam, 2006).

3.1.4 Soil texture and aeration

Soil texture is the composition of mineral grain particle sizes. There are three categories of grains controlling soil texture, *i.e.*, sand (2 – 0.05 mm), silt (0.05 – 0.002 mm) and clay (< 0.002 mm). Proportions of these soil particles depend on parent material mineralogical composition and the pedogenesis environment (Ouyang et al., 2021). Soil texture influences nutrient availability, water holding capacity, soil porosity, infiltration, air-water circulation and soil density (Chakraborty and Mistri, 2015). Along with these properties, soil texture is also a determinant of crop selection, irrigation practices, soil management and fertiliser application (Mustafa et al., 2017). Plant growth will be highly influenced by the size and distribution of soil particles as this is a limiting factor for nutrient availability and root growth. Soil texture also has a significant effect on soil aggregate stability and erosion risk (Mamedov et al., 2017; Rivera and Bonilla, 2020). Soil mineralogy is strongly associated with microaggregate stability since clay particles act as binding agents, forming organo-mineral assemblages with the soil organic matter, and influencing the mechanical strength and differential swelling of soil aggregates (Wu et al., 2017). Weak aggregate stability and dispersion of clay particles may result in the mobilisation of clay particles, blocking soil pores and leading to the development of surface sealing and crusting, increasing runoff and risk of erosion failure (Dale et al., 2018).

Hypoxia, or oxygen deficiency in a biotic environment, is also considered one of the main environmental factors limiting plant growth (Marti et al., 2015). Soil aeration is a determinant for vegetation establishment, since it can enhance soil enzyme activity and consequently plant growth due to variations in soil microbial diversity and plant root development (Li et al., 2019, 2020). Plant roots require oxygen for respiration, a process essential for water and nutrient absorption. In flooded soil conditions, plants experience drought stress and are unable to take up water. Soil flooding stress may reduce water and ion uptake by increasing root permeability and decreasing root size and volume (Alam, 1999). This disruption in root metabolism, caused by a lack of oxygen, reduces the effective root surface area available for ion uptake (Alam, 1999). For example, plants growing on dense/poorly aerated soils may develop a root system that is horizontal and shallow in an effort to obtain oxygen (Larcher, 2003; Xiao et al., 2023).

A balanced gas-liquid-solid phase in soil is crucial for plant growth, and soil texture and water stress will be the two major factors affecting aeration and consequently, crop productivity (Li et al., 2020). A balanced soil has equilibrium between gases in soil pores, water content, and soil particles (Or and Wraith, 2002). This harmony supports plant growth and soil health, reflecting good soil structure and fertility. Studies also suggest that the negative effect of NaCl stress can be offset by soil aeration, as it promotes root growth, increasing the photosynthetic rate and chlorophyll content, thus reducing the plant death rate under NaCl stress conditions (Li et al., 2019).

3.1.5 Water holding capacity, infiltration and root systems

Soil is like a “big sponge”, it can only soak up a certain amount of water and at a certain rate (infiltration rate) (Cotching, 2011). The soil water holding capacity (WHC), which represents the total amount of water the soil can retain after excess water has drained away, plays a crucial role in plant growth (Abdallah et al., 2021). A low WHC may result in significant water loss through deep percolation, leading to nutrient leaching and resource inefficiency, limiting plant establishment (Abdallah et al., 2021). WHC is crucial for vascular plant growth, as it influences soil water uptake by plant roots, especially in water-limited areas (Sun et al., 2021). In contrast, there are no benefits to watering soil above its saturation point. Excess water may generate plant stress through waterlogging, drainage to the water table below the root zone, run-off and leaching of fertilisers, potentially contributing to erosion failure (Cotching, 2011). Excess of water can also induce secondary salinisation. Secondary salinity is salting that results from human activities, usually land development and agriculture (Pitman and Läuchli, 2002; Queensland Government, 2013). It can be generated through excess irrigation or poor water quality, absence of irrigation (drylands), sea water intrusion or point source, when large levels of salt are present in the effluent from intensive agriculture and industrial wastewater. The total WHC of saturated soils is generally 400–600 mm of water per metre of soil depth, but this depends very greatly on the clay content or soil texture and organic matter content (Cotching, 2011).

In addition to WHC, the Plant Available Water Holding Capacity (PAWHC) is crucial for the establishment of plant roots. PAWHC denotes the soil moisture retained within the optimal range for plant roots, spanning from field capacity (maximum soil water retention) to the wilting point (where plants can no longer extract water) (Hunt and Gilkes, 1992; Leenaars et al., 2018). This is typically measured over 100 cm or maximum rooting depth (Hunt and Gilkes, 1992). Beyond the wilting point, there is water in the soil profile, but it resides in pores too small for plant roots to access. Soil texture, sodium levels, and rooting depth are key factors influencing soil capillarity, determining the available water for plants, particularly in dry conditions (Leenaars et al., 2018).

Infiltration refers to the penetration of water into the soil profile, a process influenced by both water availability and soil permeability (Liu et al., 2019). Soil water infiltration is a crucial component of the terrestrial water cycle, with significant implications for vegetation water budgets, the risk of topsoil erosion, runoff rates, and groundwater recharge (Sun et al., 2018). Numerous soil characteristics affect soil water infiltration capacity (WIC), including soil texture, structure, mineral composition, soil organic matter (SOM), and moisture content within the soil profile (Liu et al., 2019). Surface roughness also plays a vital role in water infiltration and is extremely important for rehabilitation of mine-site landforms (Australian Government, 2016). A rough surface is effective in trapping water and seeds, and it is widely acknowledged that compared to a smooth surface, promotes better vegetation establishment (Australian Government, 2016). These variables can influence the infiltration process by promoting the formation of a soil surface seal. This seal arises as a result of physical compaction and physicochemical dispersion processes triggered by the impact of raindrops during a rainfall event (Liu et al., 2019). Research has elucidated the connections between vegetation and WIC, underscoring that plants, primarily through their root systems, can influence soil water infiltration (Canadell et al., 1996). These studies have shown that the presence of vegetation often enhances soil infiltrability. For instance, studies of reclaimed mine soils in arid climates showed that dense root systems and the creation of deeper root channels significantly improved soil infiltrability by augmenting the soils matrix water infiltration capacity (Gao-lin et al., 2016; Wu et al., 2017). A previous study also showed that even low percentages of vegetative cover improved infiltration and reduced runoff and erosion on a topsoiled spoil profile under rehabilitation (Loch, 2000).

3.1.6 Soil microbiome

Soil microorganisms (fungi and bacteria) play a key role on nutrient cycling, plant growth and soil aggregate stability (Da Silva et al., 2022). Figure 2 shows the biological processes that affect nutrient availability by fixation of atmospheric N, and P solubilisation in topsoils. Fungal hyphae and bacterial exopolymeric substances (EPS) production, together with the organic matter recycling imparted by these microorganisms also regulate the soil structure (Da Silva et al., 2022). The success of establishing ecological function in reclaimed soils is commonly influenced by microbial biomass, functional capacity, and community composition after mine site reclamation (Gunathunga et al., 2023). However, the current practices for overburden rehabilitation often fail to consider the importance of evaluating these parameters in coal spoils as a plant growth medium prior to initiating the rehabilitation process (Dangi et al., 2012; Da Silva et al., 2022). Understanding the metabolic capacity and function of soil microbes is critical for identifying potential deficiencies that may impede the accelerated spoil-to-soil transformation during reclamation (Da Silva et al., 2022; Gunathunga et al., 2023).

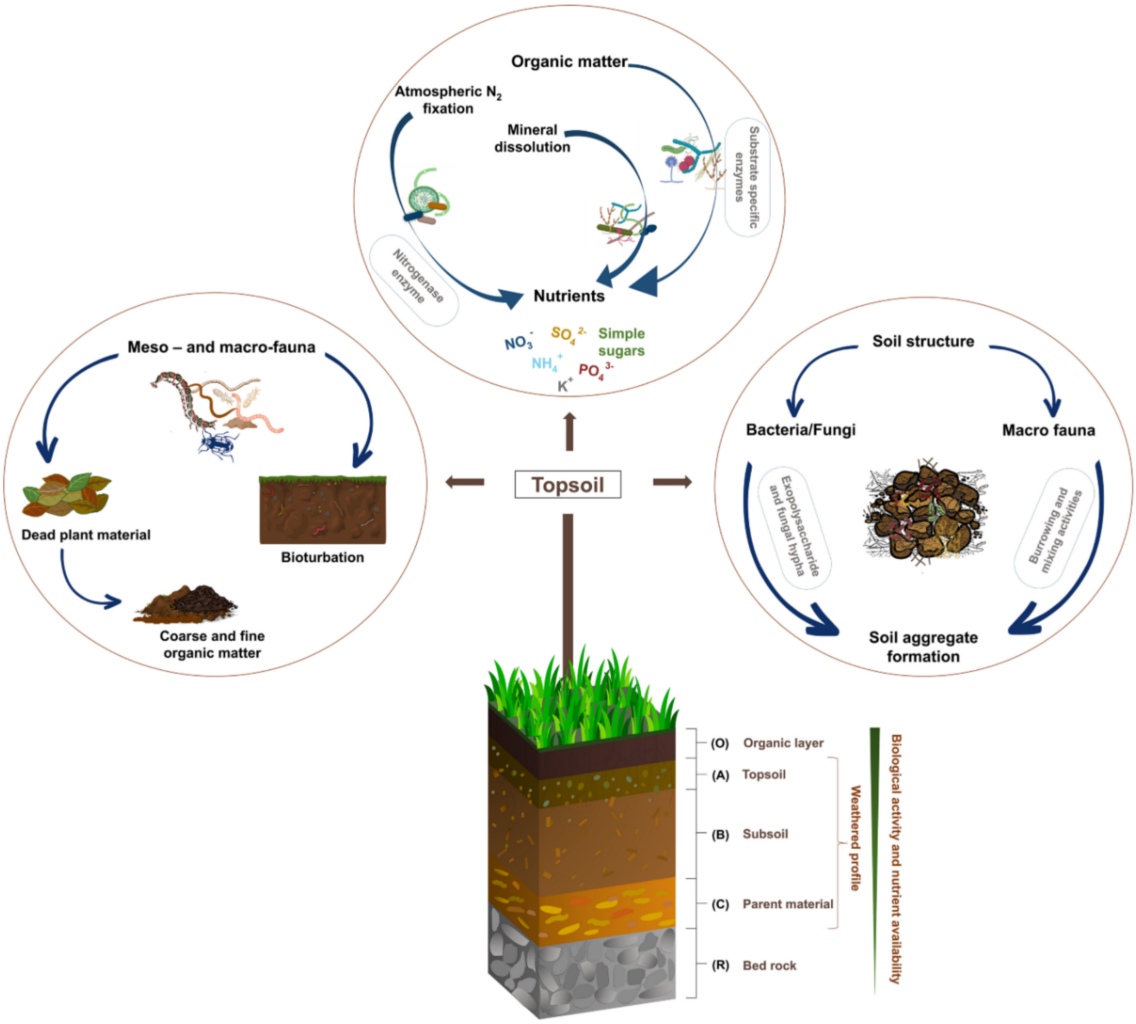

Figure 2 A schematic diagram of a generalised soil profile depicting the classic horizons and major biological functions that affect nutrient availability (Source: Gunathunga et al., 2023)

3.2 Plant suitability and selection

One of the first steps of a rehabilitation process involves the selection of plant species that will be reintroduced into degraded areas. This selection must be guided by the specific properties of the growth medium, together with rehabilitation objectives, completion criteria, and the planned PMLU (Gann et al., 2019). The nature of soil, shaped by its chemical, physical and biological properties, plays a key role in determining the growth, productivity and reproductive success of individual plants, the relative performance of coexisting plant species, and plant community composition and productivity (Van der Putten et al., 2013). The understanding of plant–soil feedbacks and underlying mechanisms improves our ability to predict consequences of these interactions for plant community composition and productivity under a variety of conditions (Van der Putten et al., 2013).

In cases where the growth medium on a mining site significantly differs from the local environment, a helpful approach for species selection involves identifying naturally occurring environments and soil attributes necessary to achieve the target vegetation community and then construct/amend the growth medium to match the natural soil key attributes and suit those species. This process can aid in creating reference models for the planned mine site restoration (Young et al., 2022). The soil attributes (also referred to as functional traits) can be very useful to orient plant selection when addressing these areas. These traits are the main ecological attributes that can influence ecosystem processes and services (de Bello et al., 2010). However, returning to a model starting point from disturbed to undisturbed paths is often impractical. Mined sites differ significantly from undisturbed ones, and relying on an undisturbed model site may not be suitable due to the hysteresis concept. Hysteresis is a phenomenon that occurs in a system whose current trend cannot be predicted without knowing its history (Dey et al., 2017). Growth media used in mine rehabilitation typically exhibit different soil properties due to long-term manipulation (removal, stockpiling, and replacement). Hysteresis in water content during wetting and drying cycles can also impact soil strength, with the water content being higher for the drying path than the wetting path at a given soil and suction (Vidler, 2022). This history results in a distinct soil structure and water-holding capacity compared to an undisturbed reference site, influencing plant selection and growth during rehabilitation.

The occurrence underscores the importance of referencing fundamental plant nutrient, physical, chemical, and biological soil requirements to enhance the rehabilitation process. Focusing on the attributes outlined in section 3.1 could serve as a practical starting point for selecting suitable plants based on soil characteristics. While pedogenesis and soil quality in mine waste are not extensively understood, monitoring soil attributes in the growth media has demonstrated notable establishment and improvement of specific indicators, and ability to improve vegetative cover (van Deventer et al., 2008; van Soest et al., 2011).

4 Current practices to overcome topsoil deficit

To achieve the functional characteristics of soils required to support plant growth, it is encouraged to improve stockpiled topsoil and spoil quality by accelerating pedogenesis, establishing a self-sustaining plant-soil ecosystem, as an integral part of the rehabilitation process (Gunathunga et al., 2023). In an effort to reduce deleterious effects of spoil on plant establishment, the application of stored topsoil onto mine spoil is the usual method used by the coal mining industry during rehabilitation activities (Maiti and Maiti, 2015). Despite initial success, long-term evaluations after the early stage of rehabilitation demonstrated that this method often fails to restore the soil nutritional status, structure, and hydrological properties necessary to support plant growth (Cejpek et al., 2013; Lamb et al., 2015; Haigh et al., 2020).

Any remaining benefits present in topsoil after it has been harvested and stored, can be diluted by mixing with spoils during rehabilitation (Bateman and Chanasyk, 2001). Amendments such as the application of inorganic fertilisers, different seeding techniques and biological agronomic treatments are among the common practices available to improve the poor nutritional condition of spoil and stored topsoil. In this section we review the current practices used by coal mines in Queensland to address a deficit of topsoil, discuss what has been effective, what has not, and the future perspectives on the use of alternative techniques. The objective is to achieve a post-mine condition where the land is safe, stable, non-polluting, supports a PMLU that has no greater management requirements than surrounding comparable land and achieves the intended level of productivity. Data evaluated and presented here were collected from the online available scientific literature, and publicly available Environmental Authorities (EAs) and PRC plans.

From the twenty-seven PRC plans available to June 2023, six sites presented topsoil deficits that varied from 13,000 m^3 to more than 1 million m^3 to meet rehabilitation requirements (Table 2). All sites, including those that did not identify a topsoil deficit, provided analysis of stored topsoil demonstrating the need for specific amelioration interventions to overcome issues such as sodicity and low levels of essential nutrients (N, P and K). Out of the six sites with a topsoil deficit, five plan to overcome this by amending their spoil to make a growth medium, while one indicated plans to use ash material and/or biosolids sourced externally, to improve their growth medium. According to the PRC plans, NPK fertilisation, gypsum addition and topsoil ripping are among the most common techniques used to ameliorate topsoil chemistry and structure in Queensland coal mines (Figure 3). Mulching was proposed by ten of the sites to address soil aggregate stability by applying rock mulch or to ameliorate low organic matter content in topsoil though the addition of organic mulch. The use of lime, biosolids and fly ash were also mentioned as alternatives to ameliorate topsoil as a growth medium. The next section will discuss each of those practices, their pros and cons, applicability in Central Queensland coal mines and alternatives to ameliorate topsoil in a mine rehabilitation context.

Table 2 Review of topsoil deficits in Queensland open-pit coal mines based on information provided in 27 PRC plans (June 2021-June 2023)

PRC plans (2021-2023)	Total number of mine sites	Sites with topsoil deficit*	Topsoil needing amelioration
Approved	11	4	11
Proposed	16	2	16
Total	**27**	**6**	**27**

*Deficit was calculated based on the use of topsoil being between 100-300 mm as a capping strategy.

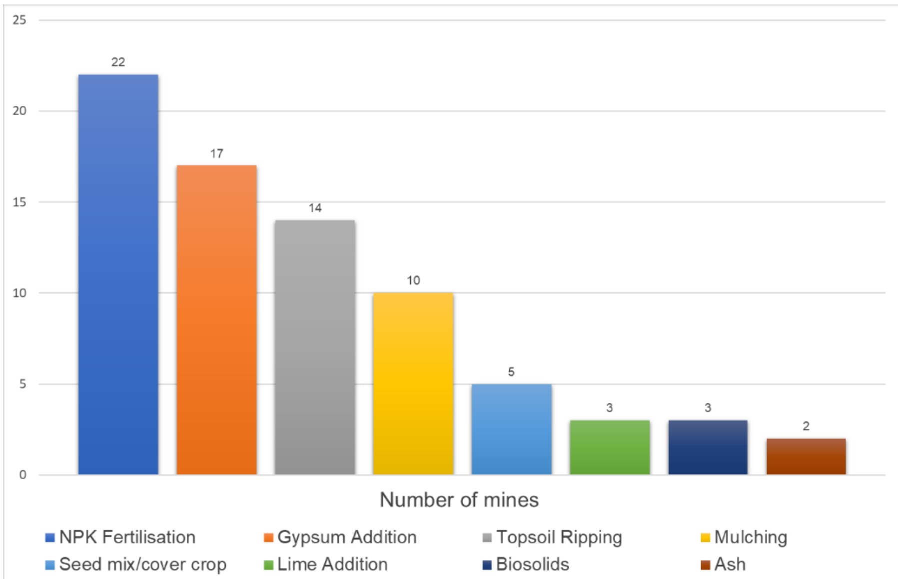

Figure 3 Current practices for topsoil amelioration in Queensland coal mines in approved and proposed PRC plans between June 2021 and June 2023

4.1 Inorganic fertilisation

Application of inorganic fertilisers (NPK) is the most common practice adopted by mines to ameliorate spoil and topsoil where nutrients are limited (Kumari and Maiti, 2022). Of the macronutrients, nitrogen is reported to be the predominant plant growth-limiting element in coal mine spoil, followed by phosphorus, suggesting typical early successional systems (Verhoeven et al., 1996; Nussbaumer et al., 2016). Nutrient depletion can affect plant density by limiting germination, seedling establishment and long-term survival (Nussbaumer et al., 2016; Yuan et al., 2020). The application of inorganic fertiliser is recognised in the estimated rehabilitation cost guideline for Queensland mines as an option to rehabilitate topsoil for coal mines. In situations where application rates are not prescribed in the EA or PRC plan schedule, the costs are estimated at particular rates of application for both topsoil amelioration or the manufacture of a growth medium (Department of Environment and Science, 2022).

Several studies have demonstrated the benefits of applying NPK fertilisers during mine rehabilitation, especially regarding short-term rapid effects on plant growth (Schoenholtz et al., 1990; Chen et al., 1998; Truong, 1999; Mushia et al., 2016; Cao et al., 2020). However, a few studies have established that the effect of inorganic fertilisation was neutral or did not last for long and led to nutrient leaching and a decrease in plant diversity across the long term (Pedrol et al., 2010; Bateman et al., 2019; Daws et al., 2022). Depending on the spoil properties, ions released from inorganic fertiliser can be rapidly leached (Wilden et al., 2001) or bound, making them unavailable to plants. Consequently, a regular application of fertiliser to maintain a primary nutrient source may be required, which can be a costly operation since mine rehabilitation may last for decades (Nussbaumer et al., 2016).

Specifically at Bowen Basin coal mines, the literature shows that the use of NPK fertilisers is unlikely necessary to facilitate the development of native vegetation, but high doses of fertilisers when combined with exotic plant species, had the capacity to increase vegetation growth and reduce erosion (Erskine and Fletcher, 2013). The authors of that paper suggest exotic pasture species such as buffel and Rhodes grasses, tended to be dominant over slower growing native species under these conditions. Erskine and Fletcher (2013) suggest minimising fertiliser supplementation, particularly avoiding the application of large quantities of phosphorus to retain native grasses. Grazing is the main PMLU selected by Central Queensland coal mines. Inorganic fertilisation requirements of pastures for grazing will vary from site to site, and application requirements will depend on whether other techniques have been put in place (e.g., deep ripping, biosolids amendments) (Maczkowiack et al., 2009; Murdoch and Karunanithi, 2017). Erskine and Fletcher (2013) also stated that although a high dosage of N/P fertiliser offered erosion protection at some level on most sites in the Bowen Basin, the land stability condition was still uncertain, which was an impediment to grazing.

4.2 Gypsum and lime addition

In agriculture, the most commonly used method to ameliorate sodic soil is via the application of calcium in the form of gypsum ($CaSO_4 \cdot 2H_2O$). The incorporation of gypsum into sodic soils addresses both primary pathways with an initial electrolyte effect (due to gypsum being a salt) and the progressive displacement of Na via cation exchange over the longer-term due to the preference for the divalent cations, such as Ca^{2+} to bind with clay (Ahmad et al., 2006).

Low soil pH caused by the presence of acid forming materials can impede plant growth and block spontaneous vegetation succession (Więckol-Ryk et al., 2023). In this scenario, amelioration by the addition of lime (calcium oxide) as a neutralising agent, is undertaken to increase soil pH. Combinations of both strategies (gypsum and lime) with other common source of ameliorants such as mulch, have been reported in the literature with positive outcomes in ameliorating both sodic and acidic environments. The addition of a combination of lime and organic matter is capable of both increasing soil pH and favouring biological processes that increase organic matter cycling (and hence macroaggregate stability and nutrient availability) (Baldock et al., 1994). When lime and gypsum are added together, their different rates of dissolution and the differing effects they have on the soil can act together to improve soil structure and yield at rates beyond what is observed when either are added alone (Valzano et al., 2001). However, inorganic amendments such as gypsum and lime, rely on water availability to allow ion dissolution and exchange. Therefore, constituents only become available after application, with their effect on soil dispersion and vegetation growth possibly being neutral or significant only after several years (Reid and Naeth, 2005; Ghahramani et al., 2021). Moreover, in the case of gypsum, its solubility in soil can be affected by many factors such as the application rate, soil moisture, texture, grain size and incorporation, increasing or decreasing its effect over time (Kuttah and Sato, 2015).

Sodicity is a common constraint of natural vertosols and spoils used for rehabilitation in Central Queensland and can be a major limiting factor for successful rehabilitation. In the absence of sufficient rainfall, dissolution rates of Ca from applied gypsum are low and as such, there is little reduction in ESP. As a result, the addition of these ameliorants might not exert the expected effect in a short period of time, as observed by Grigg et al. (2006) in the Central Queensland region. The addition of gypsum combined with other materials, such as organic amendments or polyacrylamide, was shown to control soil dispersive conditions and inhibit sediment runoff in Central Queensland coal mines (Mahardhika et al., 2008). One of the key effects of polyacrylamide is its ability to preserve aggregate structure, thereby minimising surface sealing and enhancing increased infiltration (Peterson et al., 2002).

The addition of these amendments helps to retain moisture in the soil system and may facilitate the Ca^{2+} exchange from gypsum. The efficacy of both lime and gypsum will also depend on the application form. Both amendments can be incorporated to the soil layers or surface-applied. Lime addition may be more effective if it is applied as a fine-grained material and thoroughly mixed with the top layers of spoil or topsoil (Vermaak et al., 2004). The neutralisation components are then placed near the acid-generating material, thereby inhibiting the formation of pockets of acidic environment (Vermaak et al., 2004). Zoca and Penn (2017) conducted a comparison of various lime and gypsum application forms on different types of soil, including mine soils. Their conclusion emphasised that the form and rate of application should be determined by soil characteristics, such as sodicity and clay content (Zoca and Penn, 2017). It is crucial to characterise soils to decide whether amelioration or a combination thereof is necessary for improving conditions while also avoiding unintended outcomes or excessive costs.

4.3 Topsoil ripping

Contour ripping is a common rehabilitation practice in Bowen Basin coal mines (Erskine and Fletcher, 2013). The main purpose is to reduce soil compaction and improve water infiltration and the distribution of amendments. Deep ripping mechanically breaks up compacted soil layers down to 30-50 cm (Department of Primary Industries and Regional Development, 2017). However, not all soils respond positively to deep ripping, and the benefits are temporary, usually lasting for about three seasons (Department of Primary Industries and Regional Development, 2017). When the substrate presents other constraints, such as acidity, poor structure from sodicity or subsoil salinity, the benefit of deep ripping will be limited, due to erosion failure risks, and addition of soil ameliorants such as lime or gypsum may be required to stabilise the soil (Department of Primary Industries and Regional Development, 2017).

Despite several studies showing the benefits of deep ripping for water infiltration and plant growth, studies did not commonly evaluate the effect on different subsoils (de Oliveira and Bell, 2022). A trial conducted in a southeast Queensland open-cut coal mine showed that placement of 20–30 cm of topsoil followed by deep ripping to 70–80 cm depth prior to seeding exposes the coarse overburden material and facilitates greater water loss through deep drainage (Ngugi et al., 2015). On top of that, if carried out in dry conditions, it can also create channels in the soil/spoil that become initiation points for erosion (G. Dale, personal communication, 16 October 2023). To avoid this, it was recommended that the depth of ripping should be no more than the depth of the applied soil layer (shallow ripping) (Ngugi et al., 2015). Moreover, Cole et al. (2006) found that deep ripping soil promoted weed growth in a Hunter Valley coal mine trial, and increased competition with the native woodland species. Mines often undertake deep ripping to reduce compaction and “key” topsoil into the spoil. Care needs to be exercised during this process to avoid bringing hostile (often sodic) spoil to the surface. An additional challenge lies in preventing compaction, and the usual recommendation is to address this by improving the spoil before applying topsoil (G. Dale, personal communication, 16 October 2023).

4.4 Organic amendments

The addition of organic matter as an ameliorant for sodic soils is well described in the literature. There is general agreement that addition of organic matter improves water holding capacity, and soil structure through the binding of soil particles into aggregates (Nelson and Oades, 1998). However, while most studies report positive effects (e.g. Tisdall and Oades, 1982; Clark et al., 2009; Rani and Khetarpaul, 2009; Ghosh et al., 2010), some report increased dispersion through an increase in negative charge and complexing of Ca^{2+} (Aylmore and Sills, 1982; Sumner, 1993). Bennett et al. (2015) found that the addition of organic matter in combination with gypsum extended the effects of the gypsum compared to gypsum alone, although this effect did not persist beyond two years in that study. In the short term, organic amendments usually present more positive effects on seedling survival and growth than inorganic amendments, however, this is dependent upon specific conditions such as the most limiting parameter associated with the soil. This effect is also dependent on the site abiotic conditions, such as rainfall and temperature (Navarro-Ramos et al., 2022).

The incorporation of organic amendments such as compost, manure and different types of mulch has been used as an alternative technique to achieve revegetation goals during mine rehabilitation (Drebenstedt and Singhal, 2013; Courtney et al., 2014; Srivastava et al., 2014; Lei et al., 2016). While some strategies allowed plant growth, they were unable to support plant establishment in the long-term (Drebenstedt and Singhal, 2013) nor improved soil nutrient profiles (Lei et al., 2016; Srivastava et al., 2014). Soil analyses performed by Rothman et al. (2021), suggest that compost may be beneficial to address surface mine restoration goals by improving important soil parameters, such as organic matter, labile carbon, nitrate content, and pH, that could lead to ecosystem recovery. However, further studies are required to determine whether compost will be able to replace gypsum as an effective treatment for sodic mine soils (Spargo and Doley, 2016). Municipal solid waste compost application to both topsoil and coal spoil increased total N and P, and reduced Na and pH in a coal mine in the Hunter Valley, New South Wales, facilitating early establishment of both pasture and native woodland plant species (Spargo and Doley, 2016). Besides that, municipal waste can present a risk due to the presence of solid contaminants, such as plastic and glass (Xiong et al., 2019). Emerging contaminants such as per- and polyfluoroalkyl substances (PFAS) can be present in waste streams from landfills and wastewater treatment facilities (Heads of EPA Australia and New Zealand, 2020). Contaminant risks require consideration before organic amendments from municipal waste streams such as biosolids, mulch and wastewater are used in rehabilitation.

Green manure application, mulching and succession planting increased microbial activity in a Central Queensland coal mine spoil, two years after incorporation, leading to a greater rate of carbon recycling (Shrestha et al., 2019). Literature showed that organic mulching is a cheap alternative to reduce weed infestation and to conserve the soil moisture to a certain level (Iqbal et al., 2020). However, the success of mulch application relies on the careful selection of the specific type of mulch (i.e., wheat straw, cotton sticks, maize straw) and properly managed mulching strategies, especially on sites presenting water deficit/drought conditions (Iqbal et al., 2020). Grigg et al. (2006) determined that mines in Central Queensland will experience improved surface infiltration and subsurface permeability associated with straw and sawdust mulch when mulch is incorporated into spoil rather than applied to the spoil surface.

4.5 Rock cover mulching

The application of a surface rock layer, also called rock mulch, has been a common method used to minimise erosion and loss of slope stability (Fehmi, 2018). Rock mulch acts directly by reducing soil detachment caused by raindrop or other disturbances and by reducing the energy of surface runoff (Wang et al., 2012). In some instances rock mulch can be applied to function solely as an erosion control strategy and it is not intended to act as a growth medium (Ghahramani et al., 2021), while some mining companies used it as a capping strategy, designed to support vegetation (Sojitz Minerva Mining, 2022).

Williams (2001) showed that the incorporation of rocks on the soil surface has the potential to limit erosion loss in the short-term and promote the establishment of a sustainable vegetative cover for long-term erosion control, especially in steeper slopes. However, Poesen et al. (1994) concluded that the effectiveness of rock mulching as a means to reduce erosion is variable and will depend on the soil porosity, soil surface slope, size of rock fragments, the type of erosion and on the spatial scale.

Using a probabilistic predictive framework modelling approach for three coal mines in the Bowen Basin, Ghahramani et al. (2021) predicted that sheet and rill erosion increased with decreasing rock armouring. However, there was limited data available to validate the model. The authors affirmed that more observations and collaboration with industry are necessary, enabling a more comprehensive dataset, and increasing confidence in decision making around rock mulch usage for dispersive spoil materials (Ghahramani et al., 2021).

Among the PRC plans reviewed as part of this study, Sojitz Minerva Mining (2022) performed trials using rock mulching as a capping strategy to overcome topsoil deficit, providing a growth medium to support grass and trees. The trials showed that the application of 0.5 m basalt rock mulch cover provided high levels of surface roughness and infiltration rates, and was capable of reducing the reliance of vegetative cover and root structures for erosion protection of the spoil dumps (Sojitz Minerva Mining, 2022). Despite the authors of that study suggesting the use of a rock mulch cover, the surface would still require deep ripping, prior to seeding, in order to achieve the PMLU of grassy open woodlands (Sojitz Minerva Mining, 2022). However, according to the plan, no application of fertilisers or other ameliorants would be necessary on the rock mulched areas (Sojitz Minerva Mining, 2022).

A study by Dale et al., (2018) directly compared a rock mulch treatment with amelioration treatments in soils under rehabilitation in Central Queensland. That study reported that the soil treated with rock mulch had a lower surface area available for plant growth and was subject to erosion where no chemical amendment was incorporated with the rocks (other than fertiliser) (Dale et al., 2018). In comparison, the soil where rock mulch was not adopted was dispersive, and presented a higher risk of erosion failure, often requiring considerable remedial work. Results from this work encourage the placement of a hybrid strategy, where rock mulch is applied in combination with soil amendments (Dale et al., 2018).

In this regard, there can be some advantages and disadvantages with rock mulching. On one hand it may provide some benefit from surface armouring and by increasing water infiltration. At the same time it can reduce the total volume of soil available for plant growth and limit the volume of water that can be held in soils. This can in turn, reduce the capacity to retain the same density of vegetation as a non-rock mulched site.

Only a small sample of literature was discovered regarding the use of rock mulch as either growth medium or an erosion control strategy for mine rehabilitation, especially on effectiveness of rock mulch over highly dispersive surfaces, such as the spoils present in Central Queensland.

4.6 Seeding selection and techniques

The identification of appropriate plant/seed mixes for the PMLU, as well as the identification of seed density application rate and timing of seeding are general rehabilitation practices that should be included in rehabilitation plans (Queensland Government, 2021). Based on growth media assessments, seed selection can be tailored to the site's conditions (considering the hysteresis concept), and native plant species or species adapted to the local environment would be preferred, since they can grow with minimal depth of topsoil (Maiti and Saxena, 1998; Sheoran et al., 2010; Alday et al., 2011). This is pertinent considering the topsoil conditions associated with coal mines in Central Queensland.

These species should also be selected for their ability to improve soil/growth media quality, stability, and fertility. Revegetation constitutes the most widely accepted and useful way to reduce erosion and protect soils against degradation during reclamation (Sheoran et al., 2010). For example, the selection of N-fixing species of legumes, grasses, herbs, and trees have proved to be crucial to reinstate N fixation in mine rehabilitation substrates (Sheoran et al., 2010). Maiti and Saxena (1998) observed that virgin spoil dumps sown with legume (*Stylosanthus humilis*) and grass (*Pennisetum pedicellatum*) presented an improved organic carbon, mineralisable nitrogen, phosphorous and potassium in the short-term, avoiding the need of topsoil addition.

The use of native plant seed is fundamental and often encouraged in large-scale rehabilitation (Erickson et al., 2017). However, in the Bowen Basin region, the exotic grasses, Buffel and Rhodes, are commonly used to revegetate land disturbed by coal mining where a pasture PMLU is the objective (Harwood et al., 1999). Although able to establish quickly under favourable conditions, neither species has proven entirely suitable for use in this situation, particularly in providing effective ground cover for erosion control on the re-contoured post-mining landscape. Rhodes can fail to persist and Buffel has a tussocky form which does not provide effective ground cover (Harwood et al., 1999). Buffel grass can also inhibit native ecosystem development and truncate biodiversity (Spain et al., 2022). However, in some cases, the use of exotic species is inevitable and necessary since those species can perform essential functional roles, such as soil stabilisation and nitrogen fixation, in mine rehabilitation, especially due to the substrate constraints (Spain et al., 2022).

In central Queensland, climatic conditions can influence the selection of plant species. A study by Harwood et al., (1999) suggested Sabi grass (*Urochloa mosambicensis*) exhibited a better seedling survival rate and provided greater ground cover than Rhodes grass (*Chloris gayana*) under low rainfall. The same pattern was observed by Naidu et al. (1997), when comparing pasture species for post-mining revegetation in central Queensland. Some legume species were also found to be able to grow in spoil and topsoils from central Queensland (Naidu et al., 1997). Selecting legumes suited to site-specific conditions can be a more sustainable alternative to improve nitrogen fixation and resistance to erosion.

Quality of topsoil was found to be a critical factor in the establishment of native grasses, with key factors including the chemical and physical attributes of the soil and the seed bank (Huxtable, 1999). Recommendations regarding how to establish native grasses in rehabilitated areas are provided including topsoil selection and stockpiling, sowing into raw spoil, landscape position, recommended species, seed supply and provenance, sowing rates and techniques, multi-phase sowings, fertiliser application, weed control and ongoing management options (Huxtable, 1999). Grasses and legume selection should be performed based on the characteristics of those plants to grow under a low moisture environment, being salt tolerant and adapted to extreme pH, as well as to a nutrient deficient (N and P) substrate (Radloff, 2003). In Central Queensland, it is also important to synchronise seeding with the rainy season/availability of soil moisture to improve the chances of germination.

The use of seed mixes including sterile cover crops (e.g., sorghum, millet) is also a current practice. The use of cover crops affects the support capacity of soil and the least limiting water range (de Lima et al., 2012). Plants with aggressive root systems that have the ability to break the layer of compacted soil, besides protecting the soil surface, form pores important for soil water movement and diffusion of gases (de Lima et al., 2012). According to Lima et al. (2012), cover crops were able to reduce compaction on constructed soils after coal mining in Brazil, after six years of rehabilitation.

Some native species seeds can also be treated prior to broadcast with smoke, or water through which smoke has been bubbled, improving the success rate of germination (Bell, 2001). The treatment can also be applied *in situ* or prior to broadcast, increasing germination rate and reducing rehabilitation costs associated with purchasing seed (Bell, 2001). Damptey et al. (2020) also showed that using potted seedlings can overcome the need for wholesale application of topsoil where there is a deficit. Nussbaumer et al. (2011) performed trials in an open-cut coal mine in the Hunter Valley, NSW, to test the effective establishment of tubestock plants during rehabilitation. The trial showed that direct seeding was not feasible due to the high weed and grass emergence from the topsoil seed bank over-competing the native seeds. Trials showed that planted tubestock survived well in coal spoil because it gives the native plants the advantage of accessing light above the level of the emerging groundcover and a more established root system to access nutrients and water (Nussbaumer et al., 2011).

4.7 Alternative techniques and growth media

Innovative techniques to ameliorate spoil and stored topsoil, as well as alternative growth media have been gaining attention. The use of fly ash and biochar as growth media has been researched and showed some potential in initial trials. Biopolymers and biofertilisers containing soil microorganisms have also been tested for their capacity to improve spoil/topsoil structure and nutritional status in field trials. The following sections discuss the outcomes from these trials and their potential to improve rehabilitation where there is a topsoil deficit.

4.7.1 Biosolids

Biosolids is a broad term that includes all types of treated household organic waste, including treated sewage, that can provide organic matter, nutrients and microorganisms to the soil (Cole et al., 2006). In Queensland, biosolids are defined as residues associated with sewage treatment plants, and their use as a resource is subject to an End of Waste Code (Department of Environment and Science, 2023). The Queensland Government End of Waste Code for Biosolids (ENEW07359617) provides guidance on the proper management and use of biosolids as a resource for application to land (Department of Environment and Science, 2023). The management of emerging contaminants such as per and poly-fluoroalkyl substances (PFAS) is an issue that requires careful consideration for the application of biosolids to land. Contaminants such as PFAS are known to be highly persistent and highly resistant to physical, chemical and biological degradation (Heads of EPA Australia and New Zealand, 2020). Existing advice should be consulted to assess and manage risks to human health and the environment.

Application of biosolids has been used in mine rehabilitation globally (Maddocks et al., 2004; Rate et al., 2004; Mercuri et al., 2005; Wijesekara et al., 2016; Harris et al., 2021) and may provide a sustainable alternative end use for this waste. Biosolids properties can be highly variable depending on their source (Oliver et al., 2004). Careful testing should be performed to determine the suitability of this waste, and avoid any adverse effects on plants and other organisms as they can contain toxic substances or weeds (Cole et al., 2006). To ensure appropriate application of biosolids to land as a fertiliser or soil ameliorant, the Queensland Government (2023) specifies biosolids quality criteria, application and management criteria. Main benefits from biosolid application to a substrate are the slow release of plant nutrients, organic carbon input and increased microbial activity, due to new extra carbon sources (Kelly, 2006) However, significant deleterious effects have been registered on microbial populations due to high heavy metal content in the waste, reinforcing the need of a site-specific response assessment and biowaste testing prior to application (Jacquot et al., 2000; Cole et al., 2006).

Biosolids also have the potential to promote beneficial changes to the chemistry of the soil, generating improvements on soil electrical conductivity, pH neutralisation, cation exchange capacity, and N and P intake (Cole et al., 2006). The high organic content of biosolids improves water infiltration, water holding capacity, soil structure and bulk density, reduces erosion and regulates surface temperatures of the substrates on which they are applied (Ros et al., 2003; Cole et al., 2006). Cole et al (2006) found an improved growth of *Eucalyptus maculata* and improved survival for up to four years when amended with municipal biowaste compared to spoil at a Hunter Valley coal mine, in New South Wales. Similar trends for plant growth were also observed in previous studies (Rate et al., 2004; Mercuri et al., 2005).

Further research is necessary to evaluate the limitations of biosolid and other biowaste (such as animal and poultry manure and plant residue) application on Queensland mine sites, related to its availability, transportation costs, public acceptance and political ramifications, suitability of biowaste to site-specific spoils and application rate (Wijesekara et al., 2016).

4.7.2 Polymers and biopolymers

The use of polymeric substances is a novel method that has been trialled to improve soil aggregate stability and reduce erosion risk. The approach is based on anionic polymers bonding with soil particles via cation bridging, Van der Waals interactions and hydrogen bonds (Theng, 1982), leading to soil aggregation and increased porosity. The application of polyvinyl acetate or polyacrylamide improved soil stabilisation, water retention and resistance to erosion on rock slopes (Vacher et al., 2004; Wang et al., 2022). However, the effectiveness of polymer application is directly related to clay percentage in soil, producing better outcomes in clay-rich mine soils (>10 % clay) (Wang et al., 2022). Both polyvinyl acetate and polyacrylamide are biodegradable materials, that can reach up to 60% microbial degradation in 32 days depending on the degree of solubility of the polymer, attesting to its non-polluting characteristics when applied *in situ* (Alonso-Lopez et al., 2021). Biopolymers are polymers produced by the metabolism of living organisms, such as plants, microorganisms and algae. Mahamaya et al. (2021) showed that biopolymer solutions such as xanthan gum (produced by *Xanthomonas campestris*), guar gum (extracted from guar plant seeds), and carboxymethyl cellulose can effectively control erosion of spoil materials with low costs compared to conventional techniques. However, this method can become prohibitively expensive when applied to large areas. Further research would be required to assure the feasibility of polymer and biopolymer application for rehabilitation of Queensland coal mines.

4.7.3 Biofertilisers

Microbial inoculation has shown value for improving plant tolerance of saline conditions in agricultural situations and much could be gleaned from these studies for application to saline, sodic coal mine spoils (Ashraf et al., 2004). The most direct way to alter the soil microbiome is through inoculation. Biofertilisers containing one or several species of bacteria or fungi have been commercially available for decades (Calvo et al., 2014). However, most of these species have been isolated under traditional culturing conditions that do not mimic the chemical environment of the soil and the discussion around their use on mine waste rehabilitation is rare (Da Silva et al., 2022; Gunathunga et al., 2023).

The majority of published research projects on biofertilisers for coal mine spoil rehabilitation have used plant seedlings inoculated with arbuscular mycorrhizal fungi and nitrogen fixing bacteria (namely, *Azotobacter*, *Rhizobium* and *Frankia* species) combined with various inorganic and organic fertilisers (Gryndler et al., 2008; Juwarkar and Jambhulkar, 2008; Wong et al., 2022). Short-term results (<2 years) demonstrated improved N, P and K nutrition and steady establishment of plants in mine waste material (Gryndler et al., 2008; Juwarkar and Jambhulkar, 2008; Karthikeyan et al., 2009; Wong et al., 2022). However, seedling preparation and inoculation of microorganisms onto plants under sterile conditions requires technical expertise and labour, turning it into an expensive operation, especially when employing inoculants for the rehabilitation of hundreds of hectares of mined land (Gunathunga et al., 2023).

In South Africa, a novel method was implemented for the *in-situ* bioremediation of coal spoils, using a coal degrading fungus, *Neosartorya fischeri* and arbuscular mycorrhizal fungi with weathered coal as a co-substrate (Cowan et al., 2016). The approach proved to enrich the spoils with humic acid-like substances, alleviating soil acidification and salinity (Cowan et al., 2016). Nevertheless, the potential of the approach was hindered by its dependency on the presence/absence of the co-substrate and its oxidation status (Gunathunga et al., 2023). Currently, the first *in situ* large-scale trial in Australia using a microbial inoculant, containing both fungi and bacteria to induce soil formation in coal mine spoil is underway at a Central Queensland coal mine. Preliminary results showed that the microbial inoculant containing tolerant microorganisms isolated from the reference site was able to accelerate shifts on spoil microbial community that led to increased microbial activity and nutrient cycling in spoil. On the downside, drought conditions found in Central Queensland during the trial (2021-2022) was a limiting factor for the site-specific microbial inoculant performance, due to water stress (da Silva, 2024).

4.7.4 Fly Ash

Fly ash is a waste product of coal-fired power generation plants, that is usually alkaline and contains high amounts of essential minerals and trace elements, making it an environment-friendly remediation substrate/ameliorant (Cole et al., 2006; Ram and Masto, 2010). The capacity of fly ash to modify soil texture and improve pore structure has previously been demonstrated (Ram and Masto, 2010). However, fly ash may contain some heavy metals and potentially toxic elements and organic compounds, that can limit its use (Cole et al., 2006). Because fly ash is composed mostly of silt-sized particles with low bulk density, its addition to sandy soils can change the soil texture, enhancing micro porosity, and improving its water-retention capacity (Ghodrati et al., 1995). Alkaline fly ash has also the potential as a substitute for lime to neutralise soil acidity to a level suitable for agriculture in mine spoil (Seoane and Leirós, 2001; Ram and Masto, 2010). Despite the significant potential demonstrated in these studies, the effectiveness of fly ash in amending spoils for agricultural uses will vary due to variability in ash characteristics, mine soil types and agro-climatic conditions (Ram and Masto, 2010). pH neutralisation is probably the most important factor in determining the suitability of ash for soil application, while possible leaching of toxic trace metals, soluble salts and radioactive materials could be the most significant limiting factor for this technique (Ram and Masto, 2010; Park et al., 2014). Because of this limitation, there must be a careful assessment of the fly ash product before its application (Ram and Masto, 2010). Park et al. (2014) pointed out that the general lack of information on the practical use of coal combustion by-products, as well as the lack of guidelines, is a limiting factor to its use for mine site rehabilitation.

4.7.5 Biochar

Biochar is an amorphous carbonaceous material produced by the pyrolytic conversion of organic biomass in an oxygen deficient environment (Ghosh and Maiti, 2020). The resulting solid has a higher degree of porosity, increased surface area, and stabilised nutrients, compared to conventional organic matter types (Ghosh and Maiti, 2020). This biological soil amendment can effectively alter the soil physiochemical properties, enhancing carbon sequestration, microbial activity and consequently plant growth in mine affected landscapes (Ghosh and Maiti, 2020). Some studies in Indian coalfields showed that incorporation of biochar into coal spoils can increase water holding capacity and reduce bulk density, compared to usual organic matter amendments, enhancing microbial biogeochemical cycling of nutrients (Jain et al., 2016; Ghosh et al., 2020). On the other hand, Macdonald et al. (2014) found no significant effect of biochar on plant growth when applied to acidic soil in Australia. Given the results demonstrated within that study, guidelines for use of biochar should take into account soil-specific constraints on plant growth and likely vulnerabilities within particular soil types, especially mine affected soils (Macdonald et al., 2014). In Queensland, a field trial was performed using freshwater macroalgae feedstock for biochar production, then the biochar was applied to two types of stockpiled soil in a coal mine in southeast Queensland. Results showed that the biochar application did not result in leaching of metals into the pore water of soil-biochar mixtures (Roberts et al., 2015). Moreover, the biochar application contributed essential trace elements and had a very strong positive effect on the establishment and growth of native plants, reducing the time for grasses to germinate and increasing plant biomass (Roberts et al., 2015). The authors affirmed the potential of biochar as a soil ameliorant to accelerate early establishment of native grasses with the benefit of reducing the amount of time the mining industry is responsible for land, and also the return of that land to a PMLU (Roberts et al., 2015).

4.8 Summary of practices

A summary of site-specific techniques applied at some Bowen Basin coal mines to overcome topsoil deficit is provided at Appendix Table 2. It contains information about which soil attribute is the target by each technique and how the technique can improve those attributes. In addition, an evaluation of the benefits and the flaws of each technique was performed, based on trials reported in the literature.

5 Gaps and barriers to be addressed

The challenge of addressing topsoil deficit in mine rehabilitation has concerned the coal mine industry and stakeholders for some time (Keipert et al., 2002; Henderson, 2008; Dale et al., 2018). Several techniques and amendments are available and can be helpful to improve the substrate condition for plant growth. However, studies also reported that many of these amendments have been failing or that the positive effects do not last for extended periods. In many cases there are practical limitations around the costs of sourcing and transporting amendments to sites. It may also be logistically difficult to apply amendments to rehabilitation areas. The large volumes that may be required can mean it is not feasible to use certain techniques in practice. Site specific considerations such as the relationship between the slope angle and slope length can also influence decisions around what is required to stabilise soils. The following sub-sections discuss some gaps in knowledge about the topsoil deficit issue and the barriers to overcome this problem.

5.1 Spoil physiochemical properties – need for a site-specific approach

According to the PRC plans evaluated, few mines in Central Queensland are proposing to use spoil as growth media. Although approved PRC plans provide some insight, there remains little information describing the use of spoil as alternative media in Central Queensland. International examples of spoil to soil transformations are described in studies such as Angel et al., (2009); Sena et al., (2015); Cowan et al., (2016); and Zipper et al., (2020). These studies vary widely in the approaches used to convert spoil to soil and no single approach appeared to be widely recommended in the literature.

Although spoil commonly has physicochemical properties that limit its fertility, each spoil can be unique (da Silva, 2024). This highlights the need for a site-specific approach to the problem. A wide assessment of spoil properties must be conducted, including evaluation of nutritional status, chemical composition, physical structure, and microbial community composition and function, to fully comprehend the deficiencies of each spoil or stored topsoil and address the right constraints, with the appropriate techniques/amendments required.

5.2 Need to establish key soil attributes and reference sites

Coal mine rehabilitation is a long and costly process and can be improved by taking a holistic approach to the problem, integrating soil chemistry, physical structure, and biology. Assessing the substrate's capacity to support plant growth involves identifying key soil attributes conducive to vegetative cover, as discussed in Section 3.1. However, matching to a natural site adjacent to the mine is often impractical due to the hysteresis concept explained in Section 3.2. Therefore, the selection and physiochemical evaluation of the soil attributes would provide a reference for achieving the target PMLU. For example, in Central Queensland, grazing is usually the most common PMLU. To achieve success, the reference site should be selected based on its use, including key floristic composition. This strategy is not always employed by Central Queensland coal mines.

Developing ‘anthroposols’ (i.e., soils produced by human activities which have caused a profound modification, mixing, truncation or burial of the original soil horizons, or the creation of new soil parent materials) (Isbell, 2002), is crucial for rehabilitation when there is a lack of topsoil for large, disturbed sites (Miller and Naeth, 2017, 2021). Dealing with ‘anthroposols’, such as spoil, is a barrier, since there is not much information available regarding the use of anthroposols for rehabilitation, especially field studies (Miller and Naeth, 2017). As a result, it is difficult to establish valuable comparisons with other soil types present in Central Queensland.

5.3 Lack of trials and long-term insights

Another gap hindering the success of rehabilitation strategies is the lack of long-term insights, especially *in situ* large scale trials to test these strategies. In Australia there is a lack of detailed reporting of mine disturbance and progressive rehabilitation at regional, jurisdictional and national scales making it difficult to readily assess long-term impacts on the natural environment (Lechner et al., 2016). Long-term monitoring of restoration transects generally occurs within sites/operations, with individual site successes and failures reported back to regulators (Shackelford et al., 2018). Shackleford et al. (2018) suggested the synthesis of these data into a comprehensive larger dataset would allow the overall effectiveness of restoration treatments to be evaluated, improving and hastening the decision-making step on rehabilitation of coal mines under topsoil deficit. Often, available rehabilitation data on open cut coal mines in Australia is for periods no longer than 5 years of assessment (Hancock et al., 2006; Lechner et al., 2016; Shackelford et al., 2018). However, pedogenic process in spoil can take decades or even hundreds of years to occur (Gunathunga et al., 2023). Long-term studies will be critical for providing key insights in ecology, environmental change, natural resource management and biodiversity conservation in future mine rehabilitation strategies (Lindenmayer et al., 2012).

Because not all subsoils will be suitable for rehabilitation due to their highly dispersive nature, they should be trialled in a properly designed scientific experiment prior to large-scale use (Gunathunga et al., 2023). Since soil is a highly heterogeneous material, and rehabilitation areas large, the sampling method can influence the interpretation of results and assessment of soil properties. Where there exists a topsoil deficit, thorough sampling and analysis of spoil stockpiles is essential to determine if the material’s characteristics are suitable or are amendable, prior to using this material as growth media. Information and guidelines for soil description, classification, characterisation, interpretation and use are available in McKenzie et al. (2008), and soil chemical methods in Rayment and Lyons (2011). Field sampling procedures are also described in the Australian Soil and Land Survey Field Handbook (2009). These guidelines can be feasibly applied to coal mine spoil assessments.

The establishment of new soil biogeochemical indicators, used to fast track the collection of reliable information describing substrate conditions can be considered. Spoil microbiome status has emerged in recent studies as a reliable bioindicator of spoil biogeochemical condition and could pave the future of next generation rehabilitation programs (Ngugi et al., 2018; da Silva, 2024). Understanding the spoil microbial activity and community structure is usually overlooked in mine rehabilitation processes because of the lack of information and data available for mine rehabilitation practitioners. However, scientific advances are making it cheaper and more accessible to track soil microbiome, and it will be essential to facilitate the transformation of spoil to functional soils (Gunathunga et al., 2023).

5.4 Water stress in Central Queensland

Water availability is frequently a constraint for mine rehabilitation in Central Queensland coal mines. Natural sites in Central Queensland present a great capacity for resilience after long dry seasons, however, the disturbed topsoil and spoil material does not show the same capacity, limiting its improvement over rehabilitation years. Da Silva (2024), through a glasshouse trial simulating Central Queensland rainfall and an ideal water irrigation regime, confirmed that water stress was the main limitation for plant establishment in central Queensland coal mine spoils, due to the low rainfall and absence of irrigation systems. This limitation resulted in a poor soil structure for plants to grow due to the accumulation of salts on the spoil surface, and it was an impediment to their establishment during dry seasons (da Silva, 2024). In Central Queensland, irrigation is a complex and costly operation to achieve in mining operations because of the large areas to be covered and difficulty in finding water sources close to the irrigation area.

5.5 How to measure rehabilitation success

How to measure rehabilitation success is a challenging task for everyone involved (Manero et al., 2020; Ahirwal and Maiti, 2022; Daws et al., 2023). Plant germination, survival, growth and reproduction are examples of rehabilitation success that can be readily measured early during community establishment. However, a lack of information about the soil condition and its key attributes after rehabilitation was observed in both PRC plans and the scientific literature, reporting rehabilitation. Measuring key attributes of topsoil and spoil during, and after rehabilitation offers valuable insights into soil conditions and can be used to assess rehabilitation success. Evaluating soil attributes can help establish clear targets for achieving self-sustainable vegetation and PMLU. Furthermore, it enables the definition of rehabilitation objectives based on reference site attributes, which can be integrated into rehabilitation milestones and completion criteria within PRC plan schedules.

Bandyopadhyay and Maiti (2019) proposed that rehabilitation success should be assessed using four indicators, evaluated alone or in combination: assemblage of the plant and animal communities, enzyme activity, litter accumulation and decomposition, and the improvement of soil quality. Their study also highlighted that even though the Society for Ecological Restoration provided a guideline with nine key attributes to use as standards for measuring ecological restoration, only three of these attributes could be easily applied as the remainder required high cost and time inputs: diversity, vegetation structure, and ecological processes (Bandyopadhyay and Maiti, 2019).

Measuring rehabilitation success remains a significant challenge in Australian rehabilitation practices, and additional research is needed to establish a consensus on effective assessment methods that can enhance rehabilitation outcomes. One crucial initial step to address this gap is identifying the necessary characteristics for a growth medium and subsequently establishing completion criteria. The scarcity of scientific data regarding the physicochemical condition of spoil in Central Queensland, coupled with the expense associated with converting spoil into functional soils, presents a barrier to the widespread use of spoil for constructing large volumes of growth medium.

6 Conclusion

A shortage of topsoil is a challenge for coal mine rehabilitation in Central Queensland. This report reviews strategies currently used to address this and those reported in the scientific literature. Often a ‘growth medium’ is used to grow vegetation on rehabilitated land that is a mixture of topsoil and mine spoil. In some cases, the growth medium requires physical armouring or chemical amendment to reduce erosion potential and provide conditions suited to vegetation growth. This review considers the effectiveness and suitability of these strategies within the context of rehabilitation plans for open-cut coal mines. As a first step in establishing the growth medium, it is important to ensure the key physical and chemical attributes of soils available are defined. These include pH, salinity and sodicity, organic matter, nutrients, soil texture and aeration, water holding capacity, infiltration and the soil microbiome. Understanding these characteristics before soil is disturbed helps to provide a benchmark to work with for rehabilitation.

The selection of the most effective approach to address topsoil deficit also relies on a site-specific evaluation of any deficiency associated with the growth medium. In addition, it is necessary to define the objectives for rehabilitation with consideration to the post mining uses for the land. A good way to determine the characteristics of a growth medium is to match those conditions found in similar, unimpacted local environments. While this may be achievable in some instances, a suitable reference or control may not be available. In some cases, soils/growth media may also not be able to be reconstructed to exhibit the same properties as unimpacted examples. Given these constraints, a holistic process will be required to define suitable characteristics and address the chemical demand of each spoil (i.e., alternate growth medium) and topsoil material. Assessing the key attributes outlined in this report before any amendments are made is critical and continuing to evaluate them throughout the rehabilitation process is also necessary. Insights into soil and spoil conditions obtained through these key attributes can provide clear targets for achieving self-sustaining vegetation and the desired PMLU in the absence of sufficient topsoil. Ultimately, the key attributes of the selected growth medium for revegetation should closely match those found in the natural, unmined reference site selected for the local area or represent the fundamental soil properties required for healthy growth of the target vegetation.

Despite advancements in mine rehabilitation strategies, there are still some gaps in scientific understanding and barriers to addressing topsoil deficit in Central Queensland. Addressing these gaps will enhance and improve successful open-cut coal mine rehabilitation outcomes in Queensland. In conclusion, the gaps that should be addressed for success of future mine rehabilitation in Central Queensland coal mines include:

- lack of information to describe spoil physiochemical properties and understand constraints
- lack of large-scale field trials on practices to overcome topsoil deficit
- lack of long-term studies that provide insights on rehabilitation success (>10 years)
- identification of suitable reference sites and criteria for rehabilitation of topsoils
- addressing the key ecological attributes of the growth media that align with the requirements to achieve a nominated PMLU
- matching species to soil/growth media properties
- classification of species by functional characteristics
- addressing water stress
- need for new reliable growth media biogeochemical indicators
- consensus on how to measure rehabilitation success.

It is clear that soil quality is an important factor in successful rehabilitation. Effective topsoil harvesting, storage and placement is likely to assist with maintaining the quality of topsoils. However, where a topsoil deficit exists due to historic practices or a lack of available material prior to mining, rehabilitation strategies must be guided by research that addresses these gaps to encourage successful rehabilitation of land disturbed by coal mining in central Queensland.

7 References

Abdallah AM, Jat HS, Choudhary M, Abdelaty EF, Sharma PC and Jat ML (2021) 'Conservation agriculture effects on soil water holding capacity and water-saving varied with management practices and agroecological conditions: A review', *Agronomy*, 11(9), doi:10.3390/agronomy11091681.

Ahirwal J and Maiti SK (2022) 'Restoring coal mine degraded lands in India for achieving the United Nations-Sustainable Development Goals', *Restoration Ecology*, 30(5):1–14, doi:10.1111/rec.13606.

Ahmad S, Ghafoor A, Qadir M and Abbas Aziz M (2006) 'Amelioration of a Calcareous Saline-Sodic Soil by Gypsum Application and Different Crop Rotations', *International Journal of Agriculture and biology*, 8:142–146, Available at: https://www.researchgate.net/publication/298397133_Ahmad_S_A_Ghafoor_M_Qadir_and_MA_Aziz_2006_Amelioration_of_a_calcareous_saline-sodic_soil_by_gypsum_application_and_different_crop_rotations_Int_J_Agri_Biol_82142-146.

Alday JG, Marrs RH and Martínez Ruiz C (2011) 'Vegetation succession on reclaimed coal wastes in Spain: The influence of soil and environmental factors', *Applied Vegetation Science*, 14(1):84–94, doi:10.1111/j.1654-109X.2010.01104.x.

Alonso-Lopez O, Lopez-Ibanez S and Beiras R (2021) 'Assessment of Toxicity and Biodegradability of Poly(vinyl alcohol)-Based Materials in Marine Water', *Polymers*, 13:1–9, doi:https://doi.org/10.3390/polym13213742.

Angel PN, Burger JA, Davis VM, Barton CD, Bower M, Eggerud SD and Rothman P (2009) 'The Forest Reclamation Approach and the Measure of its Success in Appalachia', in *Revitalizing the Environment: Proven Solutions and Innovative Approaches*, 18–36, doi:10.21000/JASMR09010018.

Ashby WC (1997) 'Soil ripping and herbicides enhance tree and shrub restoration on stripmines', *Restoration Ecology*, 5(2):169–177, doi:10.1046/j.1526-100X.1997.09720.x.

Ashraf M, Hasnain S, Berge O and Mahmood T (2004) 'Inoculating wheat seedlings with exopolysaccharide-producing bacteria restricts sodium uptake and stimulates plant growth under salt stress', *Biology and Fertility of Soils*, 40(3):157–162, doi:10.1007/s00374-004-0766-y.

Australian Government (2016) *Leading Practice Sustainable Development Program for the Mining Industry: Mine Rehabilitation*. Australian Government. Avialable at: https://www.industry.gov.au/publications/leading-practice-handbooks-sustainable-mining/mine-rehabilitation.

Aylmore LAG and Sills ID (1982) 'Characterization of Soil Structure and Stability Using Modulus of Rupture-Exchangeable Sodium Percentage Relationships', *Soil Research*, 20(3):213–224. Available at: https://www.publish.csiro.au/sr/pdf/sr9820213

Baldock JA, Aoyama M, Oades JM, Susanto and Grant CD (1994) 'Structural Amelioration of a South Australian Red-brown Earth using Calcium and Organic Amendments', *Australian Journal of Soil Research*, 32:571–594. Available at: https://www.publish.csiro.au/sr/sr9940571

Bandyopadhyay S and Maiti SK (2019) 'Evaluation of ecological restoration success in mining-degraded lands', *Environmental Quality Management*, 29(1):89–100, doi:10.1002/tqem.21641.

Barker A V. and Pilbeam DJ (2006) *Handbook of Plant Nutrition*. 1st edn. Edited by A. V. Barker and D.J. Pilbeam. Boca Raton, FL, USA: CRC Press, doi:10.1016/B978-0-12-819096-8.00068-9.

Bateman AM, Erickson TE, Merritt DJ and Muñoz-Rojas M (2019) 'Inorganic soil amendments alter seedling performance of native plant species in post-mining arid zone rehabilitation', *Journal of Environmental Management*, 241:179–186, doi:10.1016/j.jenvman.2019.04.022.

Bateman JC and Chanasyk DS (2001) 'Effects of deep ripping and organic matter amendments on Ap horizons of soil reconstructed after coal strip-mining', *Canadian Journal of Soil Science*, 81(1):113–120, doi:10.4141/S00-105.

Bell LC (2001) 'Establishment of native ecosystems after mining - Australian experience across diverse biogeographic zones', *Ecological Engineering*, 17(2–3):179–186, doi:10.1016/S0925-8574(00)00157-9.

Bennett JM, Cattle SR and Singh B (2015) 'The Efficacy of Lime , Gypsum and Their Combination to Ameliorate Sodicity in Irrigated Cropping Soils in the Lachlan Valley of New South Wales', *Arid Land Research and Management*, 29:17–40, doi:10.1080/15324982.2014.940432.

Bramston G and Brown E (2023) *Baralaba Coal Mine Transitional Progressive Rehabilitation and Closure Plan*. Brisbane, Australia. Available at: https://apps.des.qld.gov.au/public-register/search/prc.php

Calvo P, Nelson L and Kloepper JW (2014) 'Agricultural uses of plant biostimulants', *Plant and Soil*, 383(1–2):3–41, doi:10.1007/s11104-014-2131-8.

Canadell J, Jackson RB, Ehleringer JR, Mooney HA, Sala OE and Schulze E-D (1996) 'Maximum rooting depth of vegetation types at the global scale', *Oecologia*, 108:583–595. Available at: https://link.springer.com/article/10.1007/BF00329030

Cao Y, Zhou B, Wang X, Meng H, Zhang J, Li L and Hong J (2020) 'Different fertilization treatments in coal mining-affected soils change bacterial populations and enable soil reclamation', *Annals of Microbiology*, 70(1), doi:10.1186/s13213-020-01589-2.

Carrillo-González R, Šimůnek J, Sauvé S and Adriano D (2006) 'Mechanisms and Pathways of Trace Element Mobility in Soils', *Advances in Agronomy*, 91(06):111–178, doi:10.1016/S0065-2113(06)91003-7.

Cejpek J, Kuráž V and Frouz J (2013) 'Hydrological properties of soils in reclaimed and unreclaimed sites after brown-coal mining', *Polish Journal of Environmental Studies*, 22(3):645–652. Available at: https://www.pjoes.com/Hydrological-Properties-of-Soils-in-Reclaimed-r-nand-Unreclaimed-Sites-after-Brown,89018,0,2.html

Chakraborty K and Mistri B (2015) 'Importance of soil texture in sustenance of agriculture: a study in Burdwan-I CD Block, Burdwan, West Bengal', *Eastern Geographer*, 21(1):475–482. Available at: https://www.researchgate.net/publication/315533272_Importance_of_Soil_Texture_in_Sustenance_of_Agriculture_A_Study_in_Burdwan-I_CD_Block

Clark GJ, Sale PWG and Tang C (2009) 'Organic amendments initiate the formation and stabilisation of macroaggregates in a high clay sodic soil', *Australian Journal of Soil Research*, 47(8):770–780, doi:10.1071/SR09119.

Cole M, Nussbaumer Y, Castor C and Fisher N (2006) *Topsoil Substitutes and Sustainability of Reconstructed Native Forest in the Hunter Valley*. ACARP Project C12033. Australian Coal Association Research Program. Available at: https://www.acarp.com.au/reports.aspx

Cook CW (1976) 'Surface-mine Rehabilitation in the American West', *Environmental Conservation*, 3(3):179–183, doi:10.1017/S037689290001852X.

Cotching B (2011) *Water available in soil [Fact Sheet]*, *Tasmanian Government*. Tasmania, Australia. Available at: https://nre.tas.gov.au/Documents/Soil-water%20availabe_factsheet.pdf.

Cotrufo MF and Lavallee JM (2022) 'Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration', in Sparks, D.L. (ed.) *Advances in Agronomy*. 1st edn. Elsevier Inc., 1–66, doi:10.1016/bs.agron.2021.11.002.

Courtney R, Feeney E and O'Grady A (2014) 'An ecological assessment of rehabilitated bauxite residue', *Ecological Engineering*, 73:373–379, doi:10.1016/j.ecoleng.2014.09.064.

Cowan A, Lodewijks H, Sekhohola L and Edeki O (2016) 'In situ bioremediation of South African coal discard dumps', in *Proceedings of the 11th International Conference on Mine Closure*. Perth, Australia, 507–515, doi:10.36487/acg_rep/1608_37_cowan.

da Silva GOA (2024) *Understanding the microbiology behind transformation of coal mine spoils to soils, in the Bowen Basin*, *Thesis*. The University of Queensland.

da Silva GOA, Gunathunga S, Southam G and Gagen EJ (2021) 'Understanding the microbiology behind transformation of coal spoil to functional soils in the Bowen Basin [conference presentation]', in *Soils: investing in our future. Proceedings of the 2021 Joint SSA and NZSSS National Soil Science Conference*. Cairns, Australia: Soil Science Australia, Available at: https://indd.adobe.com/view/f83ed103-09c2-44f2-842b-b04ab98ea9f9 (Accessed: 18 August 2023).

Da Silva GOA, Southam G and Gagen EJ (2022) 'Accelerating soil aggregate formation: a review on microbial processes as the critical step in a post-mining rehabilitation context', *Soil Research*, 61(3):209–223, doi:10.1071/SR22092.

Dale G, Thomas E, McCallum L, Raine S, Bennett J and Reardon-Smith K (2018) *Applying risk-based principles of dispersive mine spoil behaviour to facilitate development of cost-effective best management practices*. ACARP Project C24033. Australian Coal Association Research Program.

Available at: https://www.acarp.com.au/reports.aspx.

Damptey FG, Birkhofer K, Nsiah PK and de la Riva EG (2020) ‘Soil Properties and Biomass Attributes in a Former Forest Restoration’, *Land*, 9(6):1–18. https://doi.org/10.3390/land9060209.

Dangi SR, Stahl PD, Wick AF, Ingram LJ and Buyer JS (2012) ‘Soil Microbial Community Recovery in Reclaimed Soils on a Surface Coal Mine Site’, *Soil Science Society of America Journal*, 76(3):915–924, doi:10.2136/sssaj2011.0288.

Daws MI, Barker JM, Blackburn C and Grigg AH (2023) ‘Overstorey-understorey interactions reveal trade-offs for achieving competing land-use goals in jarrah forest restored after bauxite mining: Initial prescription and targets affect restoration success over 32 years’, *Ecological Engineering*, 189:106913, doi:10.1016/j.ecoleng.2023.106913.

Daws MI, Blackburn C, Standish RJ and Tibbett M (2022) ‘Canary in the coal mine: Lessons from the Jarrah Forest suggest long-term negative effects of phosphorus fertilizer on biodiverse restoration after surface mining’, *Frontiers in Forests and Global Change*, 5:1–9, doi:10.3389/ffgc.2022.786305.

de Bello F, Lavorel S, Díaz S, Harrington R, Cornelissen JHC, Bardgett RD, Berg MP, Cipriotti P, Feld CK, Hering D, da Silva PM, Potts SG, Sandin L, Sousa JP, Storkey J, Wardle DA and Harrison PA (2010) ‘Towards an assessment of multiple ecosystem processes and services via functional traits’, *Biodiversity and Conservation*, 19(10):2873–2893, doi:10.1007/s10531-010-9850-9.

de Lima CLR, Miola ECC, Timm LC, Pauletto EA and da Silva AP (2012) ‘Soil compressibility and least limiting water range of a constructed soil under cover crops after coal mining in Southern Brazil’, *Soil and Tillage Research*, 124:190–195, doi:10.1016/j.still.2012.06.006.

de Oliveira TS and Bell RW (2022) *Subsoil Constraints for Crop Production*. Edited by T.S. de Oliveira and R.W. Bell. Switzerland: Springer International Publishing. Available at: https://link.springer.com/book/10.1007/978-3-031-00317-2.

Department of Environment and Science (2022) *Estimated rehabilitation cost under the* Environmental Protection Act 1994. ESR/2018/4425. Department of Environment and Science, Queensland Government. Available at: https://www.des.qld.gov.au/policies?a=272936:policy_registry/rs-gl-erc-ep-act.pdf.

Department of Environment and Science (2023) *End of Waste Code Biosolids (ENEW07359617) Waste Reduction and Recycling Act 2011*. Queensland Government, Available at: https://www.des.qld.gov.au/policies?a=272936:policy_registry/wr-eowc-approved-biosolids.pdf.

Department of Primary Industries (2019) ‘Soil organic matter: Benefits of organic matter’, 4–5, Available at: https://www.dpi.nsw.gov.au/agriculture/soils/structure/organic-matter.

Department of Primary Industries and Regional Development (2017) *Deep ripping for soil compaction*, *Department of Primary Industries and Regional Development’s Agriculture and Food division*, Available at: https://agric.wa.gov.au/n/105 (Accessed: 9 August 2023).

Drebenstedt C and Singhal R (2013) ‘Mine Planning and Equipment Selection’, in Drebenstedt, C. and Singhal, R. (eds) *Proceedings of the 22nd mpes conference, Dresden, Germany, 14th–19th october 2013*. Dresden, Germany: Springer Science & Business Media. ISBN: 331902678X, 9783319026787.

Emmerton B, Burgess J, Esterle J, Erskine P and Baumgartl T (2018) ‘The application of natural landform analogy and geology-based spoil classification to improve surface stability of elevated spoil landforms in the Bowen Basin, Australia—A review’, *Land Degradation and Development*, 29(5):1489–1508, doi:10.1002/ldr.2908.

Erickson TE, Muñoz-Rojas M, Kildisheva OA, Stokes BA, White SA, Heyes JL, Dalziell EL, Lewandrowski W, James JJ, Madsen MD, Turner SR and Merritt DJ (2017) ‘Benefits of adopting seed-based technologies for rehabilitation in the mining sector: A Pilbara perspective’, *Australian Journal of Botany*, 65(8):646–660, doi:10.1071/BT17154.

Erskine PD and Fletcher AT (2013) ‘Novel ecosystems created by coal mines in central Queensland’s Bowen Basin’, *Ecological Processes*, 2(1):1–12, doi:10.1186/2192-1709-2-33.

Fehmi JS (2018) ‘Research note: A rock mulch layer supported little vegetation in an arid reclamation setting’, *Arid Land Research and Management*, 32(2):253–256, doi:10.1080/15324982.2017.1391356.

Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J, Hallett JG, Eisenberg C, Guariguata MR, Liu J, Hua F, Echeverría C, Gonzales E, Shaw N, Decleer K and Dixon KW (2019) 'International principles and standards for the practice of ecological restoration. Second edition', *Restoration Ecology*, 27(S1):S1–S46, doi:https://doi.org/10.1111/rec.13035.

Gao-lin W, Zheng Y, Zeng C, Yu L, Nu-fang F and Zhi-hua S (2016) 'Mixed artificial grasslands with more roots improved mine soil infiltration capacity', *Journal of Hydrology*, 535:54–60, doi:10.1016/j.jhydrol.2016.01.059.

Ghahramani A, Bennett JM, Ali A, Reardon-smith K, Dale G, Roberton SD and Raine S (2021) 'A Risk-Based Approach to Mine-Site Rehabilitation : Use of Bayesian Belief Network Modelling to Manage Dispersive Soil and Spoil', *Sustainability*, 13:11267, doi:https://doi.org/ 10.3390/su132011267.

Ghodrati M, Sims JT and Vasilas BL (1995) 'Evaluation of Fly Ash as a Soil Amendment for the Atlantic Coastal Plain: I. Soil Hydraulic Properties and Elemental Leaching', *Water, Air, and Soil Pollution*, 81:349–361. Available at: https://link.springer.com/article/10.1007/BF01104020.

Ghosh D and Maiti SK (2020) 'Can biochar reclaim coal mine spoil?', *Journal of Environmental Management*, 272:111097, doi:10.1016/j.jenvman.2020.111097.

Ghosh D, Masto RE and Maiti SK (2020) 'Ameliorative effect of *Lantana camara* biochar on coal mine spoil and growth of maize (*Zea mays*)', *Soil Use and Management*, 36(4):726–739, doi:10.1111/sum.12626.

Ghosh S, Lockwood P, Hulugalle N, Daniel H, Kristiansen P and Dodd K (2010) 'Changes in Properties of Sodic Australian Vertisols with Application of Organic Waste Products', *Soil Science Society of America Journal*, 74(1):153–160, doi:10.2136/sssaj2008.0282.

Grigg AH, Sheridan GJ, Pearce AB and Mulligan DR (2006) 'The effect of organic mulch amendments on the physical and chemical properties and revegetation success of a saline-sodic minespoil from central Queensland, Australia', *Australian Journal of Soil Research*, 44(2):97–105, doi:10.1071/SR05047.

Gryndler M, Sudová R, Püschel D, Rydlová J, Janoušková M and Vosátka M (2008) 'Cultivation of high-biomass crops on coal mine spoil banks: Can microbial inoculation compensate for high doses of organic matter?', *Bioresource Technology*, 99(14):6391–6399, doi:10.1016/j.biortech.2007.11.059.

Gunathunga SU, Gagen EJ, Evans PN, Erskine PD and Southam G (2023) 'Anthropedogenesis in coal mine overburden; the need for a comprehensive, fundamental biogeochemical approach', *Science of the Total Environment*, 892:164515, doi:10.1016/j.scitotenv.2023.164515.

Haigh M, Woodruffe P, D'aucourt M, Alun E, Wilding G, Fitzpatrick S, Filcheva E and Noustorova M (2020) 'Successful ecological regeneration of opencast coal mine spoils through forestation: From cradle to grove', *Minerals*, 10(5):1–27, doi:10.3390/min10050461.

Hancock GR, Grabham MK, Martin P, Evans KG and Bollhöfer A (2006) 'A methodology for the assessment of rehabilitation success of post mining landscapes - Sediment and radionuclide transport at the former Nabarlek uranium mine, Northern Territory, Australia', *Science of the Total Environment*, 354(2–3):103–119, doi:10.1016/j.scitotenv.2005.01.039.

Harris ME, Gardner WC and Pypker T (2021) 'Influence of a one-time biosolids application on elemental and nutrient concentrations on mine tailings', *Canadian Journal of Soil Science*, 101(4):703–716, doi:10.1139/cjss-2020-0022.

Harwood MR, Hacker JB and Mott JJ (1999) 'Field evaluation of seven grasses for use in the revegetation of lands disturbed by coal mining in Central Queensland', *Australian Journal of Experimental Agriculture*, 39:307–316, doi:10.1071/EA97144.

Hasegawa PM, Bressan RA, Zhu J-K and Bohnert HJ (2000) 'Plant Cellular and Molecular Responses to High Salinity', *Annual Review of Plant Physiology and Plant Molecular Biology*, 51:463–499, doi:1040-2519/00/0601-0463$14.00.

Hayat R, Ali S, Amara U, Khalid R and Ahmed I (2010) 'Soil beneficial bacteria and their role in plant growth promotion: A review', *Annals of Microbiology*, 60(4):579–598, doi:10.1007/s13213-010-0117-1.

Heads of EPA Australia and New Zealand (2020) *PFAS National Environmental Management Plan Version 2.0*. National Chemicals Working Group of the Heads of EPAs Australia and New Zealand. Available at: https://www.dcceew.gov.au/sites/default/files/documents/pfas-nemp-2.pdf.

Henderson S (2008) *Specifications of Overburden for Use as Spoil Cover*. Available at:

https://www.acarp.com.au/abstracts.aspx?repId=C14042.

Huxtable CHA (1999) *Rehabilitation of open cut coal mines using native grasses: Management guidelines*. Available at: https://www.acarp.com.au/abstracts.aspx?repId=C6004

Iqbal R, Aown M, Raza S, Valipour M, Saleem MF, Zaheer MS, Ahmad S, Toleikiene M, Haider I, Aslam MU and Nazar MA (2020) 'Potential agricultural and environmental benefits of mulches — a review', *Bulletin of the National Research Centre*, 44(75):1–16. https://doi.org/10.1186/s42269-020-00290-3.

Isbell RF (2002) *The Australian soil classification*, *The Australian soil classification - Revised Edition*. CSIRO Australia, doi:10.4324/9781849774352-35.

Jacquot E, van Tuinen D, Gianinazzi S and Gianinazzi-Pearson V (2000) 'Monitoring species of arbuscular mycorrhizal fungi *in planta* and in soil by nested PCR: Application to the study of the impact of sewage sludge', *Plant and Soil*, 226(2):179–188, doi:10.1023/A:1026475925703.

Jain S, Mishra D, Khare P, Yadav V, Deshmukh Y and Meena A (2016) 'Impact of biochar amendment on enzymatic resilience properties of mine spoils', *Science of the Total Environment*, 544:410–421, doi:10.1016/j.scitotenv.2015.11.011.

Jakovac CC, Junqueira AB, Crouzeilles R, Peña-Claros M, Mesquita RCG and Bongers F (2021) 'The role of land-use history in driving successional pathways and its implications for the restoration of tropical forests', *Biological Reviews*, 96(4):1114–1134, doi:10.1111/brv.12694.

Juwarkar AA and Jambhulkar HP (2008) 'Phytoremediation of coal mine spoil dump through integrated biotechnological approach', *Bioresource Technology*, 99(11):4732–4741, doi:10.1016/j.biortech.2007.09.060.

Karan SK, Kumar A and Samadder SR (2017) 'Evaluation of geotechnical properties of overburden dump for better reclamation success in mining areas', *Environmental Earth Sciences*, 76(22):1–8, doi:10.1007/s12665-017-7116-5.

Karthikeyan A, Deeparaj B and Nepolean P (2009) 'Reforestation in bauxite mine spoils with Casuarina equisetifolia Frost. and beneficial microbes', *Forests Trees and Livelihoods*, 19(2):153–165, doi:10.1080/14728028.2009.9752661.

Keipert N, Grant C, Duggin J and Lockwood P (2002) *Effect of Different Stockpiling Operations on Topsoil Characteristics for Rehabilitation in the Hunter Valley - ACARP PROJECT C9029*. Available at: https://www.acarp.com.au/abstracts.aspx?repId=C9029.

Kleber M, Eusterhues K, Keiluweit M, Mikutta C, Mikutta R and Nico PS (2015) 'Mineral-Organic Associations: Formation, Properties, and Relevance in Soil Environments', in Sparks, D. (ed.) *Advances in Agronomy*. 1st edn. Academic Press, 1–140, doi:10.1016/bs.agron.2014.10.005.

Kopittke G, Mulligan D, Grigg A and Kirsch B (2004) 'Development of reconstructed soils and vegetation communities at a central Queensland coal mine: a preliminary investigation of twelve years of monitoring', in *SuperSoil 2004: 3rd Australian New Zealand Soils Conference*. Sydney, 1–10, Available at: http://www.regional.org.au/au/pdf/asssi/supersoil2004/1540_kopittkegr.pdf.

Kulikowska D and Klimiuk E (2008) 'The effect of landfill age on municipal leachate composition', *Bioresource Technology*, 99(13):5981–5985, doi:10.1016/j.biortech.2007.10.015.

Kumar S, Kumar S and Mohapatra T (2021) 'Interaction Between Macro - and Micro-Nutrients in Plants', *Frontiers in Plant Science*, 12:1–9, doi:10.3389/fpls.2021.665583.

Kumari S and Maiti SK (2022) 'Nitrogen recovery in reclaimed mine soil under different amendment practices in tandem with legume and non-legume revegetation: A review', *Soil Use and Management*, 38(2):1113–1145, doi:10.1111/sum.12787.

Lamb D, Erskine PD and Fletcher A (2015) 'Widening gap between expectations and practice in Australian minesite rehabilitation', *Ecological Management & Restoration*, 16(3):186–195, doi:https://doi.org/10.1111/emr.12179.

Läuchli A and Grattan SR (2012) 'Soil pH extremes', in Shabala, S. (ed.) *Plant Stress Physiology*. 1st edn. Wallingford, UK: CABI Publishing, 194–209, doi:10.1079/9781845939953.0194.

Lechner AM, Kassulke O and Unger C (2016) 'Spatial assessment of open cut coal mining progressive rehabilitation to support the monitoring of rehabilitation liabilities', *Resources Policy*, 50:234–243, doi:10.1016/j.resourpol.2016.10.009.

Lei H, Peng Z, Yigang H and Yang Z (2016) 'Vegetation and soil restoration in refuse dumps from open pit coal mines', *Ecological Engineering*, 94:638–646, doi:10.1016/j.ecoleng.2016.06.108.

Li X, Hee J, Mansour P and Baumgartl T (2014) 'Understanding the salinity issue of coal mine spoils in the context of salt cycle', 1970:453–465, doi:10.1007/s10653-013-9573-4.

Li Y, Niu W, Cao X, Wang J, Zhang M and Duan X (2019) 'Effect of soil aeration on root morphology and photosynthetic characteristics of potted tomato plants (*Solanum lycopersicum*) at different NaCl salinity levels', *BMC Plant Biology*, 19(331):1–15. https://doi.org/10.1186/s12870-019-1927-3.

Li Y, Niu W, Zhang Z and Wang J (2020) 'Artificial soil aeration increases soil bacterial diversity and tomato root performance under greenhouse conditions', *Land Degradation and Development*, 31:1443–1461, doi:10.1002/ldr.3560.

Lindenmayer DB, Likens GE, Andersen A, Bowman D, Bull CM, Burns E, Dickman CR, Hoffmann AA, Keith DA, Liddell MJ, Lowe AJ, Metcalfe DJ, Phinn SR, Russell-Smith J, Thurgate N and Wardle GM (2012) 'Value of long-term ecological studies', *Austral Ecology*, 37(7):745–757, doi:10.1111/j.1442-9993.2011.02351.x.

Liu Y, Cui Z, Huang Z, López-vicente M and Wu G (2019) 'Influence of soil moisture and plant roots on the soil infiltration capacity at different stages in arid grasslands of China', *Catena*, 182:1–7, doi:10.1016/j.catena.2019.104147.

Loch RJ (2000) 'Effects of vegetation cover on runoff and erosion under simulated rain and overland flow on a rehabilitated site on the Meandu Mine, Tarong, Queensland', *Soil Research*, 38(2):299–312, Available at: https://doi.org/10.1071/SR99030.

Macdonald LM, Farrell M, Zwieten L Van and Krull ES (2014) 'Plant growth responses to biochar addition: an Australian soils perspective', *Biology and Fertility of Soils*, 50(7):1035–1045, doi:10.1007/s00374-014-0921-z.

Maczkowiack R, Smith C, Slaughter G, Mulligan D and Cameron D (2009) 'Assessing risks of returning mined land to grazing in the Bowen Basin of central Queensland, Australia', *Proceedings of the Fourth International Conference on Mine Closure*, 345–357, doi:10.36487/acg_repo/908_26.

Maddocks G, Lin C and McConchie D (2004) 'Effects of Bauxsol™ and biosolids on soil conditions of acid-generating mine spoil for plant growth', *Environmental Pollution*, 127(2):157–167, doi:https://doi.org/10.1016/j.envpol.2003.08.001.

Mahamaya M, Das SK, Reddy KR and Jain S (2021) 'Interaction of biopolymer with dispersive geomaterial and its characterization: An eco-friendly approach for erosion control', *Journal of Cleaner Production*, 312:127778, doi:10.1016/j.jclepro.2021.127778.

Maiti SK and Maiti D (2015) 'Ecological restoration of waste dumps by topsoil blanketing, coir-matting and seeding with grass-legume mixture', *Ecological Engineering*, 77:74–84, doi:10.1016/j.ecoleng.2015.01.003.

Maiti SK and Saxena NC (1998) 'Biological reclamation of coalmine spoils without topsoil: an amendment study with domestic raw sewage and grass-legume mixture', *International Journal of Surface Mining, Reclamation and Environment*, 12(2):87–90, doi:10.1080/09208118908944028.

Mamedov AI, Huang CH, Aliev FA and Levy GJ (2017) 'Aggregate Stability and Water Retention Near Saturation Characteristics as Affected by Soil Texture, Aggregate Size and Polyacrylamide Application', *Land Degradation and Development*, 28(2):543–552, doi:10.1002/ldr.2509.

Manero A, Kragt M, Standish R, Miller B, Jasper D, Boggs G and Young R (2020) 'A framework for developing completion criteria for mine closure and rehabilitation', *Journal of Environmental Management*, 273(February):111078, doi:10.1016/j.jenvman.2020.111078.

Marti J, Savin R and Slafer GA (2015) 'Wheat Yield as Affected by Length of Exposure to Waterlogging During Stem Elongation', *Journal of Agronomy and Crop Science*, 201:473–486, doi:10.1111/jac.12118.

McKenzie NJ, Grundy MJ, Webster R and Ringrose-Voase RJ (2008) *Guidelines for surveying soil and land resources*. Edited by N.J. McKenzie, M.J. Grundy, R. Webster, and R.J. Ringrose-Voase. Australia: CSIRO Publishing. Available at: https://www.publish.csiro.au/book/5650/.

Mercuri AM, Duggin JA and Grant CD (2005) 'The use of saline mine water and municipal wastes to establish plantations on rehabilitated open-cut coal mines, Upper Hunter Valley NSW, Australia', *Forest Ecology and Management*, 204(2–3):195–207, doi:10.1016/j.foreco.2004.09.008.

Merino-Martín L, Commander L, Mao Z, Stevens JC, Miller BP, Golos PJ, Mayence CE and Dixon K (2017) 'Overcoming topsoil deficits in restoration of semiarid lands: Designing hydrologically favourable soil covers for seedling emergence', *Ecological Engineering*, 105:102–117, doi:10.1016/j.ecoleng.2017.04.033.

Miller VS and Naeth MA (2017) 'Amendments and substrates to develop anthroposols for northern mine reclamation', *Canadian Journal of Soil Science*, 97(2):266–277, doi:10.1139/cjss-2016-0145.

Miller VS and Naeth MA (2021) 'Amendments to improve plant response under simulated water-limited conditions in diamond mine anthroposols', *Canadian Journal of Soil Science*, 101(1):91–102, doi:10.1139/cjss-2019-0121.

Msimbira LA and Smith DL (2020) 'The Roles of Plant Growth Promoting Microbes in Enhancing Plant Tolerance to Acidity and Alkalinity Stresses', *Frontiers in Sustainable Food Systems*, 4(106):1–14, doi:10.3389/fsufs.2020.00106.

Murdoch D and Karunanithi R (2017) 'Profitable Beef Cattle Production on Rehabilitated Mine Lands', in Bolan, N.S., Kirkham, M.B., and Ok, Y.S. (eds) *Spoil to Soil: Mine Site Rehabilitation and Revegetation*. Boca Raton, USA: CRC Press, 111–122. ISBN: 978-1-4987-6761-3.

Mushia N, Ramoelo A and Ayisi K (2016) 'The Impact of the Quality of Coal Mine Stockpile Soils on Sustainable Vegetation Growth and Productivity', *Sustainability*, 8(6):546, doi:10.3390/su8060546.

Mustafa SMT, Vanuytrecht E and Huysmans M (2017) 'Combined deficit irrigation and soil fertility management on different soil textures to improve wheat yield in drought-prone Bangladesh', *Agricultural Water Management*, 191:124–137, doi:10.1016/j.agwat.2017.06.011.

Naidu BP, Harwood MR, Hacker JB, Thumma BR and Mott JJ (1997) 'Pasture species selection for revegetation of open-cut coal mine areas in central Queensland, Australia', *International Journal of Surface Mining, Reclamation and Environment*, 11(1):21–25, doi:10.1080/09208119708944051.

Navarro-Ramos SE, Sparacino J, Rodríguez JM, Filippini E, Marsal-Castillo BE, García-Cannata L, Renison D and Torres RC (2022) 'Active revegetation after mining: what is the contribution of peer-reviewed studies?', *Heliyon*, 8(3):e09179, doi:10.1016/j.heliyon.2022.e09179.

Neina D (2019) 'The Role of Soil pH in Plant Nutrition and Soil Remediation', *Applied and Environmental Soil Science*, 2019:1–9, doi:10.1155/2019/5794869.

Nelson PN and Oades JM (1998) 'Organic matter, sodicity and soil structure', in Sumner, M.E. and Naidu, R. (eds) *Sodic soils: distribution, properties, management and environmental consequences. Topics in Sustainable Agronomy*. New York, USA: Oxford University Press, 51–75. Available at: https://www.researchgate.net/publication/236877834_Organic_matter_sodicity_and_soil_structure

Ngugi M, Dennis PG, Neldner VJ, Doley D, Fechner N and McElnea A (2018) 'Open-cut mining impacts on soil abiotic and bacterial community properties as shown by restoration chronosequence', *Restoration Ecology*, 26(5):839–850, doi:10.1111/rec.12631.

Ngugi MR, Neldner VJ, Doley D, Kusy B, Moore D and Richter C (2015) 'Soil moisture dynamics and restoration of self-sustaining native vegetation ecosystem on an open-cut coal mine', *Restoration Ecology*, 23(5):615–624, doi:10.1111/rec.12221.

Nussbaumer Y, Cole MA, Offler CE and Patrick JW (2016) 'Identifying and ameliorating nutrient limitations to reconstructing a forest ecosystem on mined land', *Restoration Ecology*, 24(2):202–211, doi:10.1111/rec.12294.

Odeh IOA and Onus A (2008) 'Spatial analysis of soil salinity and soil structural stability in a semiarid region of New South Wales, Australia', *Environmental Management*, 42(2):265–278, doi:10.1007/s00267-008-9100-z.

Office of the Queensland Mine Rehabilitation Commissioner (2022) *Topsoil deficits affecting mine rehabilitation in Queensland*. Queensland Government. Available at: https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0016/260512/research-brief-topsoil-2022-feb.pdf (Accessed 12/02/24).

Oliver IW, Merrington G and McLaughlin MJ (2004) 'Australian biosolids: Characterization and determination of available copper', *Environmental Chemistry*, 1(2):116–124, doi:10.1071/EN04056.

Or D and Wraith JM (2002) 'Soil Water Content and Water Potential Relatioships', in Warrick, A.W. (ed.) *Soil Physics Companion*. 1st edn. Boca Raton, Florida, USA: CRC Press, 403. https://doi.org/10.1201/9781420041651

Ouyang N, Zhang Y, Sheng H, Zhou Q, Huang Y and Yu Z (2021) ‘Clay mineral composition of upland soils and its implication for pedogenesis and soil taxonomy in subtropical China’, *Scientific Reports*, 11(1):1–16, doi:10.1038/s41598-021-89049-y.

Park JH, Edraki M, Mulligan D and Jang HS (2014) ‘The application of coal combustion by-products in mine site rehabilitation’, *Journal of Cleaner Production*, 84(1):761–772, doi:10.1016/j.jclepro.2014.01.049.

Pedrol N, Puig CG, Souza P, Forján R, Vega FA, Asensio V, González L, Cerqueira B, Covelo EF and Andrade L (2010) ‘Soil fertility and spontaneous revegetation in lignite spoil banks under different amendments’, *Soil and Tillage Research*, 110(1):134–142, doi:10.1016/j.still.2010.07.005.

Perring MP, Standish RJ, Price JN, Craig MD, Erickson TE, Ruthrof KX, Whiteley AS, Valentine LE and Hobbs RJ (2015) ‘Advances in restoration ecology: Rising to the challenges of the coming decades’, *Ecosphere*, 6(8), doi:10.1890/ES15-00121.1.

Poesen JW, Torri D and Bunte K (1994) ‘Effects of rock fragments on soil erosion by water at different spatial scales: a review’, *Catena*, 23(1–2):141–166, doi:10.1016/0341-8162(94)90058-2.

Queensland Department of Environment and Resource Management (2011) *Salinity management handbook Second edition*. 2nd edn. Available at: https://www.publications.qld.gov.au/dataset/salinity-management-handbook/resource/529b12b0-8e23-4cd3-a1cd-7659d0b9b3b4.

Queensland Government (2017) *Better Mine Rehabilitation for Queensland: Discussion Paper*. Queensland Government, Available at: https://s3.treasury.qld.gov.au/files/better-mine-rehabilitation-in-qld-discussion-paper.pdf.

Queensland Government (2021) *Guideline - Progressive rehabilitation and closure plans (PRC plans)*. Department of Environment and Science, Queensland Government. Available at: https://www.des.qld.gov.au/policies?a=272936:policy_registry/rs-gl-prc-plan.pdf.

Radloff BJ (2003) *Direct Revegetation Techniques for Coal Tailings Dam No. 3 at Saraji Coal Mine Central Queensland*. Central Queensland University. Available at: https://acquire.cqu.edu.au/articles/thesis/Direct_revegetation_techniques_for_coal_tailings_dam_no_3_at_Saraji_coal_mine_Central_Queensland/20341980

Ram LC and Masto RE (2010) ‘An appraisal of the potential use of fly ash for reclaiming coal mine spoil’, *Journal of Environmental Management*, 91(3):603–617, doi:10.1016/j.jenvman.2009.10.004.

Rani V and Khetarpaul N (2009) ‘Nutrient composition of tomato products prepared using tomato grown under sodic condition with gypsum and farmyard manure treatment’, *Journal of the Science of Food and Agriculture*, 89(15):2601–2607, doi:10.1002/jsfa.3762.

Rate AW, Lee KM and French PA (2004) ‘Application of biosolids in mineral sands mine rehabilitation: Use of stockpiled topsoil decreases trace element uptake by plants’, *Bioresource Technology*, 91(3):223–231, doi:10.1016/S0960-8524(03)00206-2.

Rayment GE and Lyons DJ (2011) *Soil Chemical Methods - Australasia*, *Soil Use and Management*. Collingwood, Vic: CSIRO Publishing, doi:10.1111/j.1475-2743.2010.00322.x.

Reid NB and Naeth MA (2005) ‘Establishment of a Vegetation Cover on Tundra Kimberlite Mine Tailings: 2. A Field Study’, *Restoration Ecology*, 13(4):602–608. https://doi.org/10.1111/j.1526-100X.2005.00077.x.

Rengasamy P (2010) ‘Soil processes affecting crop production in salt-affected soils’, *Functional Plant Biology*, 37(7):613–620, doi:10.1071/FP09249.

Rivera JI and Bonilla CA (2020) ‘Predicting soil aggregate stability using readily available soil properties and machine learning techniques’, *Catena*, 187:104408, doi:10.1016/j.catena.2019.104408.

Roberts DA, Cole AJ, Paul NA and de Nys R (2015) ‘Algal biochar enhances the re-vegetation of stockpiled mine soils with native grass’, *Journal of Environmental Management*, 161:173–180, doi:10.1016/j.jenvman.2015.07.002.

Ros M, Hernandez MT and García C (2003) ‘Bioremediation of soil degraded by sewage sludge: Effects on soil properties and erosion losses’, *Environmental Management*, 31(6):741–747, doi:10.1007/s00267-002-2839-8.

Rothman SE, Cole CA, Bruns MA and Hall M (2021) ‘The influence of soil amendments on a native wildflower seed mix in surface mine restoration’, *Restoration Ecology*, 29(7):1–8, doi:10.1111/rec.13440.

Safdar H, Amin A, Shafiq Y, Ali A, Yasin R, Shoukat A, Hussan MU and Sarwar MI (2019) ‘A review: Impact of salinity on plant growth’, *Nature and Science*, 17(1):34–40, doi:10.7537/marsnsj170119.06.

Sangha KK, Jalota RK and Midmore DJ (2005) ‘Impact of tree clearing on soil pH and nutrient availability in grazing systems of central Queensland, Australia’, *Australian Journal of Soil Research*, 43(1):51–60, doi:10.1071/SR03152.

Sarkar B, Wijesekara H, Mandal S, Singh M and Bolan NS (2017) ‘Characterization and Improvement in Physical, Chemical, and Biological Properties of Mine Wastes’, in Bolan, N.S., Kirkham, M.B., and Ok, Y.S. (eds) *Spoil to Soil: Mine Site Rehabilitation and Revegetation*. CRC Press, 3–56, doi:10.1017/cbo9781139062176.003.

Schoenholtz SH (1990) *Restoration of Nitrogen and Carbon Cycling in an Appalachian Mine Spoil*. Faculty of the Virginia Polytechnic Institute and State University. Available at: https://vtechworks.lib.vt.edu/items/5abf4752-dfe5-4851-8b7a-eae434b0084f

Sena K, Barton C, Hall S, Angel P, Agouridis C and Warner R (2015) ‘Influence of spoil type on afforestation success and natural vegetative recolonization on a surface coal mine in Appalachia, United States’, *Restoration Ecology*, 23(2):131–138, doi:10.1111/rec.12164.

Seoane S and Leirós MC (2001) ‘Acidification-Neutralization Processes in a Lignite Mine Spoil Amended with Fly Ash or Limestone’, *Journal of Environmental Quality*, 30(4):1420–1431, doi:10.2134/jeq2001.3041420x.

Shackelford N, Miller BP and Erickson TE (2018) ‘Restoration of Open-Cut Mining in Semi-Arid Systems: A Synthesis of Long-Term Monitoring Data and Implications for Management’, *Land Degradation and Development*, 29(4):994–1004, doi:10.1002/ldr.2746.

Sheoran V, Sheoran AS and Poonia P (2010) ‘Soil Reclamation of Abandoned Mine Land by Revegetation: A Review’, *International Journal of Soil, Sediment and Water*, 3(2):1–20, Available at: https://scholarworks.umass.edu/intljssw/vol3/iss2/13/.

Shi P and Schulin R (2018) ‘Erosion-induced losses of carbon, nitrogen, phosphorus and heavy metals from agricultural soils of contrasting organic matter management’, *Science of the Total Environment*, 618:210–218, doi:10.1016/j.scitotenv.2017.11.060.

Shrestha P, Gautam R and Ashwath N (2019) ‘Effects of agronomic treatments on functional diversity of soil microbial community and microbial activity in a revegetated coal mine spoil’, *Geoderma*, 338(2019):40–47, doi:10.1016/j.geoderma.2018.11.038.

Sojitz Minerva Mining (2022) *Minerva Mine Progressive Rehabilitation and Closure Plan*. Brisbane, Australia. Available at: https://apps.des.qld.gov.au/public-register/search/prc.php.

Spain CS, Nuske S and Gagen E (2022) *Evaluating methods for assessing native ecosystem mine rehabilition success*. Queensland Government. Available at: https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0025/307636/evaluating-methods-assessing-native-ecosystem-mine-rehabilitation-success.pdf.

Spargo A and Doley D (2016) ‘Selective coal mine overburden treatment with topsoil and compost to optimise pasture or native vegetation establishment’, *Journal of Environmental Management*, 182:342–350, doi:https://doi.org/10.1016/j.jenvman.2016.07.095.

Srivastava NK, Ram LC and Masto RE (2014) ‘Reclamation of overburden and lowland in coal mining area with fly ash and selective plantation: A sustainable ecological approach’, *Ecological Engineering*, 71:479–489, doi:10.1016/j.ecoleng.2014.07.062.

Sumner ME (1993) ‘Sodic Soils : New Perspectives’, *Australian Journal of Soil Research*, 31:683–750. Available at: https://www.publish.csiro.au/sr/sr9930683

Sun D, Yang H, Guan D, Yang M, Wu J, Yuan F, Jin C, Wang A and Zhang Y (2018) ‘The effects of land use change on soil infiltration capacity in China: A meta-analysis’, *Science of the Total Environment*, 626:1394–1401, doi:10.1016/j.scitotenv.2018.01.104.

Sun F, Xiao B, Li S and Kidron GJ (2021) ‘Towards moss biocrust effects on surface soil water holding capacity: Soil water retention curve analysis and modeling’, *Geoderma*, 399(2):115120, doi:10.1016/j.geoderma.2021.115120.

Tang S, She D and Wang H (2021) ‘Effect of salinity on soil structure and soil hydraulic characteristics’, *Canadian Journal of Soil Science*, 101(1):62–73, doi:10.1139/cjss-2020-0018.

Theng BKG (1982) 'Clay-polymer interactions':, *Clays and Clay Minerals*, 30:1–10. Available at: https://www.academia.edu/59178846/Clay_Polymer_Interactions_Summary_and_Perspectives

Tisdall JM and Oades JM (1982) 'Organic matter and water-stable aggregates in soils', *Journal of Soil Science*, 33:141–163, doi:10.1111/j.1365-2389.1982.tb01755.x.

Vacher CA, Loch RJ and Raine SR (2004) 'Identification and management of dispersive mine spoils', *Technical Report. Australian Centre for Mining Environmental Research*, (June):1–84. Available at: http://www.acmer.com.au/research/attachments/DispersivespoilsreportfinalJune2004R.pdf

Valliere JM, D'Agui HM, Dixon KW, Nevill PG, Wong WS, Zhong H and Veneklaas EJ (2022) 'Stockpiling disrupts the biological integrity of topsoil for ecological restoration', *Plant and Soil*, 471(1–2):409–426, doi:10.1007/s11104-021-05217-z.

Van der Putten WH, Bardgett RD, Bever JD, Bezemer TM, Casper BB, Fukami T, Kardol P, Klironomos JN, Kulmatiski A, Schweitzer JA, Suding KN, Van de Voorde TFJ and Wardle DA (2013) 'Plant-soil feedbacks: The past, the present and future challenges', *Journal of Ecology*, 101(2):265–276, doi:10.1111/1365-2745.12054.

Verhoeven JTA, Koerselman W and Meuleman AFM (1996) 'Nitrogen- or phosphorus-limited growth in herbaceous, wet vegetation: Relations with atmospheric inputs and management regimes', *Trends in Ecology and Evolution*, 11(12):494–497, doi:10.1016/S0169-5347(96)10055-0.

Voltr V, Menšík L, Hlisnikovský L, Hruška M, Pokorný E and Pospíšilová L (2021) 'The soil organic matter in connection with soil properties and soil inputs', *Agronomy*, 11(779):1–21, doi:10.3390/agronomy11040779.

Wang X, Li Z, Cai C, Shi Z, Xu Q, Fu Z and Guo Z (2012) 'Effects of rock fragment cover on hydrological response and soil loss from Regosols in a semi-humid environment in South-West China', *Geomorphology*, 151–152:234–242, doi:10.1016/j.geomorph.2012.02.008.

Wang Y, Liu J, Lin C, Ma X, Song Z, Chen Z, Jiang C and Qi C (2022) 'Polyvinyl acetate-based soil stabilization for rock slope ecological restoration', *Journal of Environmental Management*, 324:116209, doi:10.1016/j.jenvman.2022.116209.

Wieckol-Ryk A, Pierzchała L, Bauerek A and Krzemien A (2023) 'Minimising Coal Mining's Impact on Biodiversity: Artificial Soils for Post-Mining Land Reclamation', *Sustainability*, 15(9707):1–16. https://doi.org/10.3390/su15129707

Wijesekara H, Bolan NS, Vithanage M, Xu Y, Mandal S, Brown SL, Hettiarachchi GM, Pierzynski GM, Huang L, Ok YS, Kirkham MB, Saint CP and Surapaneni A (2016) 'Chapter Two - Utilization of Biowaste for Mine Spoil Rehabilitation', in Sparks, D.L. (ed.) *Advances in Agronomy*. Academic Press, 97–173, doi:https://doi.org/10.1016/bs.agron.2016.03.001.

Wilden R, Schaaf W and Hüttl RF (2001) 'Element budgets of two afforested mine sites after application of fertilizer and organic residues', *Ecological Engineering*, 17(2–3):253–273, doi:10.1016/S0925-8574(00)00143-9.

Williams DJ (2001) 'Prediction of erosion from steep mine waste slopes', *Environmental Management and Health*, 12(1):35–50, doi:10.1108/09566160110381913.

Williams E and Radloff B (2022) *Progressive rehabilitation and closure plan*. Mackay, Australia, Available at: https://www.lawinsider.com/dictionary/progressive-rehabilitation.

Wong WS, Morald TK, Whiteley AS, Nevill PG, Trengove RD, Yong JWH, Dixon KW, Valliere JM, Stevens JC and Veneklaas EJ (2022) 'Microbial inoculation to improve plant performance in mine-waste substrates: A test using pigeon pea (*Cajanus cajan*)', *Land Degradation and Development*, 33(3):497–511, doi:10.1002/ldr.4165.

Wu G, Liu Y, Yang Z, Cui Z, Deng L, Chang X and Shi Z (2017) 'Root channels to indicate the increase in soil matrix water infiltration capacity of arid reclaimed mine soils', *Journal of Hydrology*, 546:133–139, doi:10.1016/j.jhydrol.2016.12.047.

Wu X, Wei Y, Wang Junguang, Wang D, She L, Wang Jie and Cai C (2017) 'Effects of soil physicochemical properties on aggregate stability along a weathering gradient', *Catena*, 156(April):205–215, doi:10.1016/j.catena.2017.04.017.

Young RE, Gann GD, Walder B, Liu J, Cui W, Newton V, Nelson CR, Tashe N, Jasper D, Silveira FAO, Carrick PJ, Hägglund T, Carlsén S and Dixon K (2022) 'International principles and standards for the ecological restoration and recovery of mine sites', *Restoration Ecology*, 30(S2), doi:10.1111/rec.13771.

Yuan Y, Ren Y, Gao G, Zhao Z and Niu S (2020) 'Intra-and interspecific interactions among pioneer trees affect forest-biomass carbon accumulation in a nutrient-deficient reclaimed coal mine spoil', *Forests*, 11(8):1–14, doi:10.3390/f11080819.

Zipper CE, Agouridis CT, Barton CD and Skousen J (2020) 'Conversion Options for Mining-Affected Lands and Waters in Appalachia', in Zipper, C.E. and Skousen, J. (eds) *Appalachia's Coal-Mined Landscapes: Resources and Communities in a New Energy Era*. United States of America: Springer, 167–192, doi:10.1007/978-3-030-57780-3_5.

8 Appendix

Appendix Table 1 Plant nutrients and example effects of deficiency (adapted from Barker and Pilbeam, 2006)

Deficient Nutrient	Effects of Deficiency
Nitrogen (N)	- Restricted growth of all plant organs, roots, stems, leaves, flowers, and fruits (including seeds); - Loss of green colour across the leaf blade; - Decreased protein in chloroplasts and a degradation of chloroplast fine (lamellar) structure.
Phosphorus (P)	- Suppress or delay growth and maturity; - Often produce small, dark-green leaves and short and slender stems; - Sustained P deficiency may produce smaller-sized fruit and limited harvestable vegetable mass; - Yellowing of Leaves (Chlorosis) and necrosis on older leaves is sometimes observed.
Potassium (K)	- Growth retardation; - Older leaves can show chlorotic and necrotic symptoms as small stripes along the leaf margins, beginning at the tips and enlarging along leaf margins in the basal direction; - Leaves can lose turgor and appear flaccid; - At an advanced stage of K deficiency, chloroplasts and mitochondria can collapse, impacting the synthesis of sugar and starch, lipids, ascorbate and also the formation of leaf cuticles.
Calcium (Ca)	- Upper parts of the shoot become yellow-green and lower parts that dark green; - Shortage of calcium in the tissues causes a general collapse of membrane and cell wall structure, allowing leakage of phenolic precursors into the cytoplasm.
Magnesium (Mg)	- Accumulation of starch in the leaves, which may be associated with early reductions in plant growth and decreased allocation of carbohydrates from leaves to developing sinks; - Chlorosis in older leaves; - Fading and yellowing of the tips of old leaves; - Loss of protein from Mg-deficient leaves, usually resulting in the loss of plastic pigments from most plants; - May lead to loss of chlorophyll as much as the loss of magnesium for chlorophyll synthesis; - May lead to disruption of the mitochondrial membrane.
Sulfur (S)	- Chlorosis, typically starting with the younger leaves at the top of the plant; - Can lead to overall reduced plant growth, including shorter stems and smaller leaves; - May cause delayed flowering and fruiting in some plants; - Plants may exhibit poor root development, which can further limit nutrient and water uptake; - Plants may have weaker, thinner stems that are more susceptible to lodging or breaking; - Can affect the plant's ability to take up other essential nutrients, leading to imbalances in nutrient levels; - Protein synthesis is compromised in S-deficient plants, resulting in reduced protein content in plant tissues; - Can impact the quality of seeds and fruits produced by plants, potentially reducing crop yields.
Boron (B)	- Plants may exhibit reduced growth, including shorter stems and smaller leaves; - B-deficient plants may display abnormal leaf coloration, including yellowing or bronzing of leaf margins or tips; - Can result in distorted or misshapen leaves; - Stems can become brittle and may snap easily, making the plant more susceptible to lodging or breakage; - Can lead to decreased flowering and fruit formation; - For fruit-bearing plants, B-deficiency can cause fruits to develop corky or rough patches on their surfaces, rendering them unattractive and unmarketable; - B-deficient plants may exhibit brown, necrotic root tips, affecting the plant's ability to take up water and nutrients; - May produce non-viable pollen, leading to poor fruit set and seed production; - Some plants may produce abnormal flowers with missing or extra floral parts due to boron

Deficient Nutrient	Effects of Deficiency
	deficiency.
Chlorine (Cl)	- Wilting of leaves, especially at the margins; - Severe deficiency may cause curling, shrivelling, and necrosis of the leaves; - Roots deformation; - Can lead to premature senescence of leaves, frond fracture, and stem cracking and bleeding.
Copper (Cu)	- Most plants will exhibit rosetting, necrotic spotting, leaf distortion, chlorosis and terminal dieback; - Many plants will show a lack of turgor and discoloration of certain tissues; - Limits the activity of many plant enzymes; - Depress carbon dioxide fixation, electron transport, and lipid synthesis.
Iron (Fe)	- Chlorosis; - Extreme deficiency can cause deformation in chloroplasts structure.
Manganese (Mn)	- Chlorosis on young leaf blades; - Severe necrotic spots or streaks may also form;
Molybdenum (Mo)	- Often manifests itself as N deficiency because of Mo function on N_2 fixation and nitrate reduction; - Mo-deficient legumes commonly become chlorotic, have stunted growth, and have a restriction in the weight or quantity of root nodules
Nickel (Ni)	- Decreased activity of urease and subsequently in urea toxicity, exhibited as leaflet tip necrosis; - Chlorosis patchy necrosis in the youngest leaves; - Enhancement in plant senescence and a reduction in tissue-iron concentrations
Zinc (Zn)	- Roots of Zn-deficient trees often exude a gummy material; - Intervenial chlorosis; - Developing leaves are smaller than normal, and the internodes are short;

Appendix Table 2 Site-specific techniques to remediate spoil and topsoil

Technique	What does it affect?	How does it work?	Pros	Cons	Reference
Inorganic Fertilisation	Soil nutrients required for plant growth	Direct supply of nutrients in soil	Improve NPKS, cations, micronutrients (short-term); Easily available	Short-term effect; Decrease in diversity; Minerals leaching.	(Pedrol et al., 2010; Bateman et al., 2019; Cao et al., 2020; Daws et al., 2022)
Gypsum addition	Soil sodicity/structure	Reduces dispersion and improves soil structure by Replacing Na^+ with Ca_2^+ on the soil cation exchange complex.	Easily available; Reduce erosion failure risk	Slow release and solubilisation rate can be affected by soil moisture; Can be lost via surface runoff, if not incorporated properly.	(Grigg et al., 2006; Ghahramani et al., 2021)

Technique	What does it affect?	How does it work?	Pros	Cons	Reference
Topsoil ripping	Soil bulk density and water infiltration	Mechanically breaks up compacted soil layers	Reduce soil compaction; Improve water infiltration; Improve trees growth and roots penetration	Can bring sodic material to the surface, increasing erosion; Can expose the coal overburden leading to water loss depending on the depth of ripping; Can negatively affect plant growth because of the exposed hostile saline conditions Can open soil cracks (if soil too dry) or smear soil (if too wet), creating channels that start erosion.	(Ashby, 1997; Li et al., 2014; Ngugi et al., 2015)
Organic amendments	Organic matter input/soil stabilisation Soil bulk density, water holding, nutrient holding, structure, permeability, infiltration, microbial activity.	Direct supply of labile organic carbon as energy source for soil microbes; binding of soil particles into aggregates,	Improved soil water and nutrient holding capacity Improved soil structure, permeability and infiltration; Increased seedling survival; Improved soil aggregate stability	Costly and logistically difficult to apply at effective rates (up to 50t/ha). May inhibit plant growth when CN ratio >20	(Aylmore and Sills, 1982; Tisdall and Oades, 1982; Sumner and Sumner, 1993; Ghosh et al., 2010; Navarro-Ramos et al., 2022)
Rock Mulching	Minimise erosion and loss of slope stability/ Increase infiltration	Acts by physically armouring the soil and reducing particle detachment caused by raindrops, runoff or other disturbances	Limit erosion loss in the short-term; promote the establishment of vegetative cover for long-term erosion control, especially in steeper slopes	Effectiveness is variable and rely on many soil features Amelioration may still be required. Very expensive if a source of rock is not readily available. Land sterilised for future use.	(Poesen et al., 1994; Williams, 2001)
Seeding/sowing	Vegetation	Re-introduces	Affects the	pre-treatment	(Bell, 2001;

Technique	What does it affect?	How does it work?	Pros	Cons	Reference
techniques/seed preparation	establishment	target plant species; Functional role in soil stabilisation Increase chances of plant survival and establishment	support capacity of soil and least limiting water range to crop growth; plants with aggressive root systems break the layer of compacted soil; improve soil water movement and gases diffusion; reduce compaction on constructed soils	requirement; Requires specialised equipment for best results.	de Lima et al., 2012)
Biosolids	Soil structure/nutritional status//organic matter/plant growth	Direct input of organic matter, nutrients and microorganisms to the soil	Increased number of microorganisms; provides slow-release nutrients and available organic matter, and consequently the improvement of substrate nutritional status and plant coverage; sustainable alternative end of waste	Must be managed in accordance with relevant regulations.	(Jacquot et al., 2000; Cole et al., 2006)
Coal “Fly” ash	Soil pH	Neutralise acid soil pH	Sustainable and practical pH neutraliser Commonly produced close to coal mines	May contain some heavy metals and potentially toxic elements and organic compounds	(Seoane and Leirós, 2001; Cole et al., 2006; Ram and Masto, 2010)
Biochar	Soil structure/nutritional status/microbial activity/plant growth	Alter the soil physiochemical properties (especially water holding and soil structure), enhancing plant growth, and consequently carbon sequestration and microbial activity	increase water holding capacity and reduce bulk density,	Costly and logistically difficult to apply at effective rates No significant effect on acidic soils; can lead to metals leaching	(Macdonald et al., 2014; Roberts et al., 2015; Jain et al., 2016; Ghosh et al., 2020)
Polymers and	Soil aggregation	Anionic polymers	improves soil stabilization,	Effectiveness is directly related	(Vacher et al., 2004;

Technique	What does it affect?	How does it work?	Pros	Cons	Reference
Biopolymers	and porosity	bonding with soil particles via cation bridging, Van der Waals interactions and hydrogen bonds	water retention and resistance to erosion on slopes; biopolymer can effectively control erosion of spoil materials with low costs compared to conventional techniques;	to clay percentage in soil; Can become expensive with the increasing area that requires rehabilitation Effect may dissipate quickly as polymers degraded.	Mahamaya et al., 2021; Wang et al., 2022)
Biofertilizers	Soil microbiology/ organic matter input/nutritional status	Reintroduction of essential microorganisms in soil	Improves N, P and K nutrition and steady establishment of plants; able to accelerate shifts on spoil microbial community that led to increased microbial activity and nutrients cycling in spoil	seedlings preparation and inoculation of microorganisms onto plants under sterile conditions require technical expertise and more manpower, turning it into a more expensive operation; Water stress imposes a limitation	(Wong et al., 2022; da Silva, 2024; Gunathunga et al., 2023)