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Amelioration of bauxite residue sand by intermittent additions of nitrogen fertiliser and leaching fractions: The effect on growth of kikuyu grass and fate of applied nutrients

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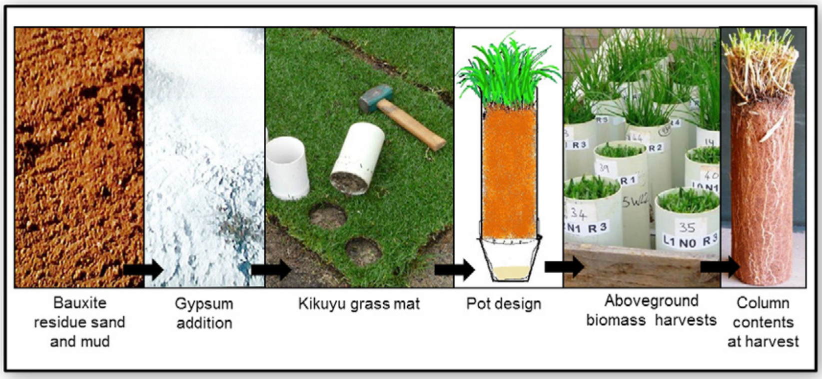
HIGHLIGHTS

- Bauxite residue poses physical and chemical constraints to plant growth.
- Use of $(NH_4)_2SO_4$ fertiliser is proposed in conjunction with leaching.
- Compartmentation of nutrients is calculated in plant, residue and leachate samples.
- Nitrogen loss in leachate and potential NH_3 volatilisation reduced by 80%.
- Leaching of salts to a 'threshold' is essential to maximise N use by the plant.

GRAPHICAL ABSTRACT



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ABSTRACT

Bauxite residue, a waste product of aluminium processing operations is characterised by high pH, salinity and exchangeable sodium which hinders sustainable plant growth. The aim of this study was to investigate the uptake form, optimum application rate and timing of nitrogen fertiliser to improve bauxite residue characteristics for plant growth. Kikuyu grass was grown in plastic columns filled with residue sand/carbonated residue mud mixture (20:1) previously amended with gypsum, phosphoric acid and basal nutrients. The experiment was set up as a 4 × 4 factorial design comprising four levels of applied nitrogen (N) fertiliser (0, 3, 6 and 12 mg N kg^{-1} residue) and four frequencies of leaching (16, 8 and 4 day intervals). We hypothesised that the use of ammonium sulfate fertiliser would increase retention of N within the rhizosphere thereby encouraging more efficient fertiliser use. We found that N uptake by kikuyu grass was enhanced due to leaching of excess salts and alkalinity from the residue profile. It was also concluded that biomass production and associated N uptake by kikuyu grass grown in residue is dependent on the type of fertiliser used.

Abbreviations: EC, electrical conductivity; ESP, exchangeable sodium percentage; i.d, internal diameter; LF, leaching frequency.

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1. Introduction

Production of aluminium ranges from 45–60 Mt per annum globally, and typically 2 t of bauxite residue is generated per tonne Al produced (International Aluminium Institute, 2013). In Western Australia, bauxite-processing residue from Alcoa of Australia (Alcoa) alumina refineries is stored in engineered facilities. Residue sand (>150 μm fraction) is used to construct these facilities into which the residue mud (<150 μm) is stored (Anderson et al., 2011). Although re-use of residue is possible (Hik and Jefferies, 1990; Liu et al., 2009; Snars et al., 2004; Summers et al., 1996; Zhang et al., 2011), the large volumes of residue produced will require long term storage. Closure strategies involve a partial capping system which often incorporates a vegetation cover. Consequently, chemical, physical and microbial factors affecting the sustainability of such cover systems need to be understood.

Vegetation covers using pasture (ryegrass) species have been trialled by Alcoa for control of dust blown from embankments at residue storage areas (Jones et al., 2012). In context of west-Australian climate, little information is available on alternative grass species that could be used, particularly species that could improve the residue characteristics. This study investigated the suitability of an alternative species; kikuyu grass (*Cenchrus clandestinus* (Chiov.) Morrone). Kikuyu grass is a fast-growing, rhizomatous C_4 grass species with good drought tolerance (Marais, 2001), characteristics which can be particularly beneficial for establishing thick vegetative covers. It can be categorised as a low-moderate salinity tolerant because it has been found to grow successfully on scalds with EC_e values in the range 12–20 dS m^{-1} (Barrett-Lennard, 2003). It is of similar salt tolerance as Rhodes grass (*Chloris gayana* Kunth) (Barrett-Lennard, 2003), which has been used previously in residue (Meecham and Bell, 1977). In those trials, Rhodes grass exhibited poor germination due to physical limitations of mechanical resistance and low water-holding capacity, which have been largely attributed to the textural range of residue (predominantly silt and fine sand). In residue mud, more than 50% of particles are smaller than 20 μm (Pradhan et al., 1996; Thornber and Binet, 1999; Thornber and Hughes, 1987). When closely packed, it results in poor hydraulic conductivity and bulk densities approaching 2.5 ± 0.7 g cm^{-3}, where values exceeding 1.5 g cm^{-3} impede root penetration and above 1.6 g cm^{-3} healthy plant growth is unlikely (Gräfe et al., 2011). On the other hand, the coarser sand fraction lacks physical structure and exhibits low water- and nutrient-holding capacity (Anderson et al., 2011; Gwenzi et al., 2011; Jones et al., 2011; Thiyagarajan et al., 2012). Recent studies by Banning et al. (2011) and Buchanan et al. (2010) explored the addition of mud fractions (fines) to sand in order to improve the physical attributes. Anderson et al. (2011), however, found that mixing residue fines (unamended and amended with seawater or carbonation) to residue sand adversely affected *Acacia saligna* growth due to high levels of exchangeable Na. The effect of residue fines additions to sand on plant growth and nutrient uptake remains poorly understood.

Plants growing on bauxite residue storage areas endure moderate to low nutrient concentrations (Courtney and Timpson, 2004; Meecham and Bell, 1977; Wong and Ho, 1991; Xue et al., 2015). The high pH in the rhizosphere affects the solubility and availability of nutrients such as P, Fe, Mn, Cu and Zn (Gahoonia, 1993; Hedley et al., 1982). Various fertilisers have been used for amelioration of bauxite residue. The use of organic forms such as composts, poultry manure (Courtney et al., 2009; Jones et al., 2012) and sewage sludge (Fuller et al., 1982) has been investigated. Although, organic amendments lead to the development of soil structure, improved fertiliser-use efficiency and increased soil water availability and permeability (Eastham et al., 2006), their slow decomposition limits fast biomass production (Banning et al., 2014). Commonly used inorganic fertilisers in residue disposal areas such as ammonium nitrate and ammonium phosphate-based salts can be an effective and economical alternative to organic counterparts for use on bauxite residue (Eastham and Morald, 2006), but losses of nitrogen via volatilisation (as NH_3) and leaching (NO_3^-) can be considerable. Chen et al. (2010) found that high pH can cause up to 85% N loss from di-ammonium phosphate-based fertilisers. More research is needed to identify suitable fertiliser types which would minimise losses and also decrease the need for future supplements.

A practical insight into (1) the transformation and losses of nutrients from fertilisers under the chemical conditions of bauxite residue, and (2) the nature of nutrient uptake in the presence of widely used ameliorant, gypsum can provide the basis for long-term sustainable rehabilitation. An experiment testing this proposition was performed and the results regarding growth and nutrient status of kikuyu grass in relation to soil properties, pH and EC have been discussed in Fey et al. (2010). We established that kikuyu could be used to generate large amounts of organic matter, because of the synergistic effect of fertiliser application and leaching of salts. The study objectives documented in this paper are (i) quantification of the uptake and leaching losses of nitrogen fertiliser by kikuyu, and (ii) determination of the chemical changes in residue growing medium.

2. Materials and methods

Bauxite residue sand (field-moist) was obtained from Alcoa's Kwinana Refinery (Western Australia) 32°12′S; 115°49′E. Material passing through 5 mm sieve was air-dried and retained for the leaching experiments. Residue sand (pH_{water} 10.18) was thoroughly mixed with wet carbonated residue mud (pH_{water} 10.16) (5% on dry weight basis) to improve texture and increase water holding capacity of the medium. The sand-mud mixture was then sprayed with a dilute phosphoric acid solution to apply an equivalent of 150 mg P kg^{-1}, followed by (<2 mm) 4% gypsum application ($CaSO_4 \cdot 2H_2O$). Approximately 100 g of natural sandy topsoil was also added for microbial inoculation of the whole mixture (~200 kg). The homogenised mixture, hereafter referred to as residue loam, exhibited an initial water content of 9.3%, pH_{water} 8.12, and field capacity water content 14.6%. Approximately 3.1 kg of residue loam was placed in each of 64 cylindrical pots (plastic column of 0.5 m long × 0.09 m i.d.) perforated at base with ten 3 mm diameter holes for drainage. To accelerate reactions between added chemical species and residue, each pot was brought to field capacity by adding 150 ml of de-ionised water.

Trace elements were added to each pot to achieve approximate concentrations (in mg kg^{-1}) of: Cu (1), Zn (2), Mn (50), B (1), Mo (0.1), Mg (40), K (150) and N (50 (NH_4^+) + 30 (NO_3^-)). This was done by extruding the residue loam from each pot separately, mixing with the nutrient solution. The material was then returned to the pot and brought to field capacity. Circular discs were cut from pre-grown kikuyu (sterile variety 'Village Green') grass mat, placed on top of the residue in a pot and lightly sprayed with de-ionised water daily for three weeks. The pots were randomised and grass growing above the rim of the pots was clipped prior to fertiliser treatment application.

Every fourth day, 10 ml of N fertiliser ($(NH_4)_2SO_4$) solution was applied. The zero (control), low, medium and high N treatment level pots received 0, 3, 6 and 12 mg N kg^{-1} residue loam, respectively, with each addition. All solutions also contained KCl and $MgSO_4$ at same concentrations that provided 5.5 mg K and 3 mg Mg kg^{-1} residue loam with each addition. Following N application, pots were brought to 70% field capacity and subjected to a leaching frequency (LF), defined as high (received leaching fraction every 4 days), medium (8 days), low (16 days), and control (received no water). The treatment application was conducted over a period of 98 days, and during this period samples of the kikuyu grass were obtained every 33 days (subsequently referred to as cut 1, cut 2 and cut 3). Potentiometric titration of residue loam showed that 0.4 mol H^+ acidity would be required to neutralise 1 kg of residue loam to pH 6. Assuming all neutralisation was to be achieved through nitrification, an equivalent amount of fertiliser was calculated. This amount was found to be impractical for field application in a single year. Therefore, aiming for one-third neutralisation over a period of