NEUTRALISATION, REVEGETATION AND BEYOND: AN OVERVIEW OF A DECADE OF Bauxite Residue RESEARCH

Ronan COURTNEY

Department of Life Sciences, Materials and Surface Science Institute, University of Limerick
Co. Limerick, Ireland
ronan.courtney@ul.ie

Abstract

The bulk of globally produced bauxite residue is stored in land based impoundments despite numerous attempts to find re-use and recovery options. These residue storage areas (RDAs) can each contain several million tonnes of the alkaline waste and thus present a pollution risk to their surrounding environments. Although residues are inherently alkaline, saline and highly sodic, it has been demonstrated at numerous sites that vegetation establishment is possible once the residue has been effectively amended or treated. This paper presents an overview of over a decade of research on bauxite residue amendment and revegetation approaches. The trajectory of research from residue characterisation, rehabilitation, vegetation establishment and ultimately ecosystem reconstruction is presented. Profiling of microbial DNA show that communities in revegetated residue are analogous to soil and soil development processes stabilise the residue against erosion risk. This development of ecological function and habitat for faunal assemblages within revegetated residues allow for alternative land use options with rehabilitated and closed sites.

Introduction

Bauxite residue

Bauxite residue is the waste by-product generated by the extraction of alumina from bauxite ore via the Bayer Process. Approximately 1-2 tonnes of residue are generated for every tonne of alumina produced. Consequently there is an estimated 3 billion tonnes of residue globally growing at approximately 120 million tonnes per annum. Although there have been multiple attempts to utilise these residues in the areas of construction, chemical, agronomic and metallurgical applications, less than 2% of residues are currently re-used or further processed. Consequently, the vast majority of the residue remains in residue disposal areas (RDAs).
The large and continually growing mass of stored bauxite residue highlights the need for effective rehabilitation strategies to manage the environmental impacts of aluminium production and contribute to industry sustainability. As with other mine processing wastes (tailings) there is potential pollution risk from exposed residue surfaces include stability issues, and contamination of soils, groundwaters and surface waters in the surrounding environment through leachates, surface run-off and dusting. It is generally accepted that vegetation cover is a suitable method for effectively stabilising the surface of tailings\(^3\) and this approach is now widely adopted by the alumina industry.

This direct revegetation of residue is a significantly cheaper option than engineered lining and capping systems. Establishing sustainable plant cover systems on bauxite residue is challenging because of its extreme chemical, physical, and biological properties. Bauxite residues are typically characterised by high pH (pH >10), high electrical conductivity (EC >30 dS m\(^{-1}\)), and high exchangeable sodium percentage (>70 %).\(^4,5,6\) Consequently, these limitations of the residues must be addressed prior to revegetation if the residue is to form a part of the plant growth medium.

Although residue amendment and revegetation was addressed almost 40 yrs ago\(^4\) and was followed by a number of studies\(^5\) much of the published work on residue characterisation, rehabilitation and revegetation has been from pot based research with limited multi-site publications on large scale field based revegetation.

However, the earlier research has produced the basic tenets of the rehabilitation processes for bauxite residue and has led to some large-scale revegetation programmes initiated at a number of refineries. The rehabilitation and revegetation approach should alleviate the inhibitory properties of the residue; high salinity, sodicity and alkalinity whilst improving soil structure and providing adequate nutrient supply in order to promote ecosystem development. Gypsum is commonly used as an effective amendment to reduce pH and ESP of residue but can results in increased EC content. Sufficient improvement of the texture and structure of the residue substrate is also required.

Based on a review of soil function and sustainability, Gräfe et al.\(^7\) defined ‘rehabilitation goals’ that must be achieved and sustained in order to support ecosystem development on bauxite residue. These are listed in Table 1 alongside values obtained from some revegetation research at pot level and in field trials.\(^6,8,9\)
Table 1: Selected substrate parameters for unamended residue and amended residue plus recommended rehabilitation goals for ecosystem development

<table>
<thead>
<tr>
<th></th>
<th>Unamended</th>
<th>Amendment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pot trials</td>
</tr>
<tr>
<td>pH</td>
<td>10.5 - 1.9</td>
<td>8.6 – 10</td>
</tr>
<tr>
<td>EC (ms/cm)</td>
<td>5.5 - 4</td>
<td>4.2 – 13</td>
</tr>
<tr>
<td>ESP</td>
<td>70 - 85</td>
<td>27 -50</td>
</tr>
</tbody>
</table>

Demonstration of vegetation establishment on amended residues has been shown at sites in Jamaica, Australia and Ireland and has demonstrated that a wide variety of plants and plant types can grow on residue. However, plant establishment on residue is only part of a revegetation or rehabilitation process. Unfortunately, there is limited published literature on the longevity or ‘success’ of bauxite residue revegetation schemes or if the developing ecosystems are stress free. Evidence of follow on monitoring once the vegetation has been established requires further research. Indeed, the creation of a suitable ‘soil’ type medium, necessary to promote the sustained growth of vegetation also requires further attention.

Nutrient requirements

Unamended residue is deficient in nutrient content (Table 2). Nutrient additions to residue through either organic or inorganic application are essential and the difficulty in adequately assessing nutrient bioavailability is receiving increasing interest. Nutrient deficiencies have been reported for plants growing in residue sand, even after fertiliser or organic addition. Due to the hostile nature of residue there is potential for loss or adsorption of added nutrients. The required nutrient input and further management will be dependent on the stated or required end landuse of the residue area.
Table 2: Selected substrate parameters for different residue treatments and desired range for plant growth\textsuperscript{10}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unamended</th>
<th>Amended</th>
<th>Desired range</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (g kg\textsuperscript{-1})</td>
<td>n.d</td>
<td>n.d - 0.10</td>
<td>&lt; 1.6*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 5.0 - 9.1</td>
<td>0.96 - 2.30</td>
</tr>
<tr>
<td>P (mg kg\textsuperscript{-1})</td>
<td>&lt; 5</td>
<td>1.10 - 1.55</td>
<td>&lt; 1.6*</td>
</tr>
<tr>
<td>C (%)</td>
<td>n.d</td>
<td>0.34 - 2.27</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Bulk density (g cm\textsuperscript{3})</td>
<td>1.67</td>
<td>0.31 - 2.27</td>
<td>0.2 – 2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.25 - 0.54</td>
<td>0.1 - 2.5</td>
</tr>
<tr>
<td>Mn (mg kg\textsuperscript{-1})</td>
<td>n.s</td>
<td>n.s</td>
<td></td>
</tr>
<tr>
<td>Zn (mg kg\textsuperscript{-1})</td>
<td>n.s</td>
<td>n.s</td>
<td></td>
</tr>
<tr>
<td>Cu (mg kg\textsuperscript{-1})</td>
<td>n.s</td>
<td>n.s</td>
<td></td>
</tr>
</tbody>
</table>

The success of bauxite residue revegetation has largely been assessed by soil chemical analyses and short-term vegetation growth trials.\textsuperscript{8,9} Increasingly it is recognised that for successful cover systems on mine residues the formation of soil and a greater understanding of the processes in soil development is crucial.\textsuperscript{17} This area of research has received scant attention in bauxite residue.

Physical properties

The formation and accumulation of organic matter and nutrient cycling are major processes determining the direction and rate of initial pedogenesis (soil development) in restored mine soils. Although the effects of residue properties on plant establishment and growth are well reported on, the effects of amendments and restoration on soil biota and ensuing ecological function are less well known.

The creation of an appropriate soil environment, such as capacity to resist structural degradation, is necessary for successful ecosystem development. High sodium content causes swelling and dispersion of colloids and microaggregates and improvement of the soil structure requires the application of appropriate amendments in order to promote clay flocculation. Examples of improvement in...
structure in bauxite residues following amendment and revegetation at field level are shown in Figure 1. Similar findings have been reported in pot trials investigations.9

Bulk density of unamended residue is high and is representative of poorly structured substrates with low organic matter status. High bulk density (exceeding 1.6 g cm⁻³) hinders root penetration and plant establishment. Addition of organic matter is effective in reducing bulk density with values strongly related to residue carbon content, and is an effective part of the rehabilitation process in overcoming physical limitations of the residue.

**Figure 1:** Water stable aggregates (WSA) proportions in different residue treatments

The issue of long term slow dissolution of desilication product is of concern in amended residues.6 Dissolution implies that alkalinity and salinity will be a long-term problem that requires the use of salt- and alkali-tolerant plants.18 However, field evidence of exchangeable sodium in the residue soil and plant of revegetated residue indicate that sufficient amendment and leaching removes this threat (Figure 2).

**Figure 2:** Sodium content in grassland herbage growing in field trials on revegetated bauxite residue
Is revegetation successful?

Although several researchers have investigated ecosystem recovery of bauxite mine sites with emphasis on terrestrial invertebrate activity\(^{19}\) relatively few studies have transferred to the revegetation of the bauxite processing residues.\(^{20,21}\)

Microorganisms play crucial roles in soil formation, nutrient cycling, vegetation establishment and long-term ecosystem stability but the high alkalinity may weaken soil microbial activity in the residues.\(^{9}\) In a series of studies assessing soil biology and function within restored bauxite residues a number of specific groups have been studied. Courtney et al.\(^{20}\) examined overall invertebrate species presence in bauxite residue and followed this survey with an examination of litter decomposition and soil faunal activity.\(^{22}\) Ability of key species (e.g. earthworm) to survive and establish is currently being studied. These studies have shown that bauxite residue can support a wide range of soil invertebrate communities leading to soil development and system self-regulation.

Recent research has focused on microbial communities in rehabilitated residue on BRDAs.\(^{22,23,24,25}\) These studies have shown that reduction in pH and sodicity greatly enhances microbial diversity and activity. Extraction and profiling of microbial DNA demonstrated microbial communities analogous to natural soils.\(^{24}\) Microbial colonisation and community development is driven by the variations within the rehabilitation process.\(^{22,25}\) Potentially, future amendment procedures could address the biological requirements of the rehabilitation process in addition to the standard physical and chemical parameters.

Conclusions and Required Future Directions

Unamended bauxite residues exhibit properties inhibitory to plant germination and growth. Application of gypsum with organic wastes is an effective method for overcoming the physical and chemical restraints and nutrient deficiencies exhibited by the residue. As a result of this process a wide range of plant species can establish and achieve sustained growth on the amended residue surface.

Evidence of soil development and support of soil functions is emerging from revegetated bauxite residue field plots. Additionally, assessment of microbial and biological communities in revegetated residue has shown that rehabilitation processes can influence the rate and extent of biological activity. These areas warrant further study.
Future rehabilitation practices should consider amendment procedures to optimise conditions for the necessary soil microbial communities required to promote sustainable ecosystem establishment.

Robust monitoring programmes are required to build sufficient evidence of sustained and stress free ecosystem development on revegetated residue sites. In the absence of such evidence there is greater possibility of regulators enforcing the more costly (ca. x 12 – 15) closure options of capping layers.

Further evidence from a variety of residue sites reflecting site, climatic and environmental conditions are required using multi-disciplined approach.

References