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Bauxite residue tailings amelioration and revegetation: roots growth assessment using μCT-scanning and image analysis

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ABSTRACT

The amelioration of Bauxite residue (BR) followed by the establishment of vegetation, which is important for the ecosystem restoration of mines, was investigated. Seeds of ryegrass (Lolium perenne) were planted on cylinders filled with five different combinations of bauxite residue from Bacarena (Brazil), and amendments. The combinations used were: (i) 90% of BR mixed with 10% gypsum, (ii) 90% of BR mixed with 5% of organic food waste and 5% of gypsum, (iii) 85% of BR mixed with 5% of organic food waste and 10% of gypsum, (iv) 90% of BR with 5% of açai waste (Euterpe oleracea) and 5% of gypsum and (v) 85% of BR mixed with 5% of açai waste and 10% of gypsum. The five cylinders were scanned using a micro-CT before and after grass seeds were planted and scanned before the seeds were planted and after ca. 2 weeks. The Root Volume Density (RVD), Root Depth (RD), Root Area Ratio (RAR), were systematically determined from the CT-scans using image analysis techniques. Additionally, the changes in soil porosity and the development of root features over time were investigated. By only visually observing the grass growth, it was concluded that the best amelioration used was the gypsum at 10%, as it allowed a good shoot development rather quickly. This was confirmed by quantitative image-based results, indicating that this amelioration allowed the grass to thrive and to develop a deeper and stabilizing root system. Even though less vegetation growth was observed for the mixture of 10% gypsum and 5% açai, this mixture allowed the roots to grow deeper. This preliminary study highlights the importance of using gypsum and açai waste for vegetation growth and provides valuable insights about the best mixture (from the ones considered in this study) to be possibly used in the amelioration and revegetation of mine bauxite residual soil. Note that a comprehensive and long-term field study will be needed to corroborate the findings of this research.

Keywords: Revegetation, organic waste, roots, soil structure

1 INTRODUCTION

The most important aluminium ore is bauxite, which is found in large deposits in the north of Brazil in the Amazonia region (Schneider, 2020). Production of aluminium (Al) from bauxite in the Bayer process create large volumes of waste, called bauxite residue (BR). This waste is mainly disposed off in landfills, BR disposal areas. The closure of disposal areas in mining regions is becoming a global environmental concern, following increased awareness of the need for environmental protection. The disposal area DRS1 by Alunorte in Barcarena (Brazil) still needs to be closed properly and environmentally-friendly solutions are prioritized. The main environmental concerns associated with the deposition of the BR in the DRS1 at Barcarena site are (i) erosion caused by the wind, (ii) dust clouds forming causing disturbance to population groups around the refinery, and (iii) dust clouds generating a negative visual impact and covering the existing forest remaining in the vicinity of the deposit (Capobianco, 2020).
In situ establishment of vegetation is so-far the most promising solution for the management of the bauxite residue disposal areas. It helps to limit wind and water erosion, minimizes environmental pollution, encourages organic matter build-up, and provides an aesthetically pleasing landscape (Wehr et al. 2006), besides the multiple environmental benefits that it can provide to the area.

Plant growth on bauxite residues however is limited both due to geochemical properties (high alkalinity, metal toxicity, salinity/sodicity), and physical properties (low hydraulic conductivity, porosity). Rehabilitation of the BR is thus needed prior to the establishment of vegetation. Among rehabilitation alternatives, natural rehabilitation in-situ (amendment of bauxite residue with local materials) is considered a viable and more sustainable alternative to soil capping, avoiding demand and thus costs for external resources, such as sand, geosynthetic liners (for the lining) and topsoil (Bray et al. 2018; Di Carlo & Courtney 2018; Santini & Fey 2018). Torgersrud et al. (2019) compared different in situ rehabilitation measures and suggested that use of organic waste amendments can be a win-win solution for bauxite residue amelioration, but further evidence -especially for the effects on plant growth- is needed.

This work presents the results obtained from an experimental study at laboratory scale on the effects of BR amelioration using organic waste amendments (food waste and açai residues) and gypsum on the plant growth. Root features growing into different mixtures of ameliorated BR, after about two weeks, were analysed using a micro computed-tomography (µCT) scanner. This experimental study investigates the mutual influence of revegetation techniques and soil amelioration on BR soil properties from a Disposal Area in Brazil by image analysis of roots features.

2 RESEARCH METHODOLOGY

The amended BR tested, the X-ray scanner and procedures and the image analysis process is described herein.

2.1 Materials tested and procedures

A particle size distribution curve of the bauxite residue (BR) tested is presented in Figure 1a. The BR has a coefficient of curvature C_c = 0.8, and a coefficient of uniformity C_u = 9.9, and is classified as silty clay (after ASTM D2487, 2017) and contains about 9% sand, 53% silt and 38% clay. The main elements are iron (27%), aluminium (11%), silicon (8%), sodium (6%), titanium (3%), and calcium (1%), while the main minerals are zinc oxide, hematite, gibbsite and anatase. The soil plastic and liquid limits are w_p = 34% (following NS 8003) and w_L = 47% (following NS 8002 in ISO 1982) respectively (see Schneider, 2020). The clay content plasticity is low (plasticity index Ip = 13%).

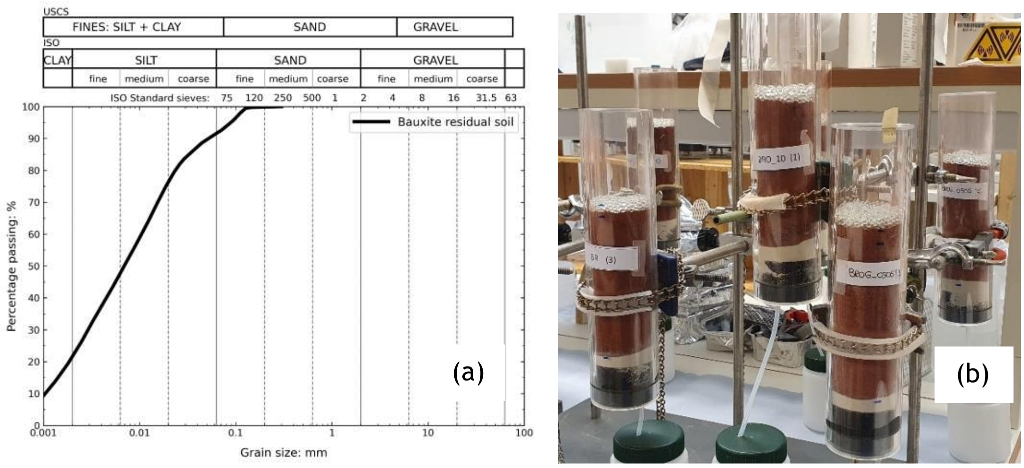

Figure 1. *Particle size distribution of bauxite residual soil tested and experimental set up cylinders containing amended bauxite residue for the leaching process*

2.1.1 Experimental set up and specimen preparation

Five series of transparent plastic cylinders were constructed to test the amelioration and establishment of vegetation of the BR. The equipment consisted of X-ray transparent plastic cylinders with inner diameter of 5 cm and a total height of 25 cm (Figure 1b). The top boundary of the cylinder was exposed to the atmosphere, while the bottom was closed with a rubber cup where drainage was allowed through a hole connected to a plastic pipe (to collect the leachates for analysis). First, a geotextile was placed at the bottom of each column and then 1 cm of sand was filled, followed by a layer of 12 cm of amended bauxite residue and finally glass beads at the top, to allow a homogeneous distribution of infiltration water during the leaching tests (Figure 1b). For each test series, three column replicates were adopted. Based on chemical analysis of e.g. sodium absorption ratio, NH4OAc extract, KCl displacement, etc. there was no significant difference between the replicates (see Stubhaug, 2022).

The columns were filled with a mixture of BR and amendments in different percentages and a preliminary leaching test was performed. The different mixtures and percentages were chosen by considering the cost related to amelioration and revegetation. The combination used were: (i) BR90-G10 with 90% of BR mixed with 10% gypsum, (ii) BR90-G5-O5 with 90% of BR mixed with 5% of organic food waste and 5% of gypsum, (iii) BR85-G10-O5 with 85% of BR mixed with 10% of gypsum and 5% of organic food waste, (iv) BR90-G5-A5 with 90% of BR with 5% of açai waste (Euterpe oleracea) and 5% of gypsum and (v) BR85-G10-A5 with 85% of BR mixed with 5% of açai waste and 10% of gypsum. Gypsum ($CaSO_4$) was added to reduce pH and Na content, which will facilitate better aggregation and thereby porosity in the BR. Organic matter will provide nutrients and higher porosity to the BR. When organic matter is degraded, plant-available nutrients will be produced together with CO_2. The latter will cause a decrease in pH. The food waste used in this study is produced locally in Bacarena, Brazil (it was mixed and dried at 100°C before storage), and the açai waste (Euterpe oleracea seeds and fibres) is a residue from processing seeds of açai berries. Açai is a palm species native to the northern area of Brazil, with reddish-purple berries, the berry production results in a waste consisting of the seed that remains after pulp extraction process and fibres. The waste from açai production used in this thesis was collected at a local açai natural pellet producer (Ecobiomassa) close to Barcarena, upon collection, the açai waste was air dried in the laboratory. Pictures of açai waste, food waste and bauxite residue are shown in Figure 2.

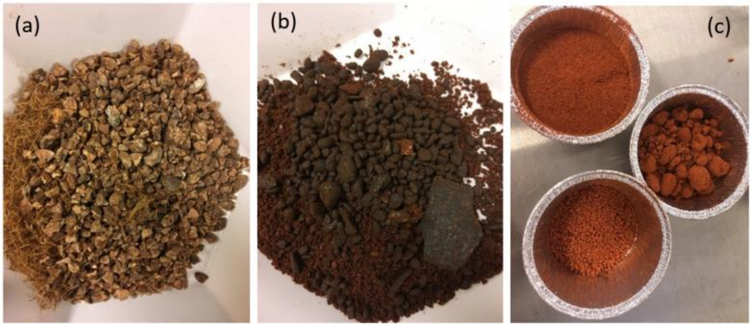

Figure 2. *Pictures of (a) Açai waste, (b) dry food waste, (c) Bauxite residue (Stubhaug, 2022)*

2.1.2 Leaching tests

Approximately every third day, 150 ml of distilled water was applied to the cylinders, for a total of 2360 ml over 40 days, to a liquid solid ratio (L/S) of 10 (236 grams total dry mass was used in the cylinders). This was to improve the chemical properties of the amended BR before ryegrass (Lolium) seeding. The leachate was collected in 150 ml plastic containers (Figure 1b), which were stored in the refrigerator for analysis. Leachate concentrations of sodium (Na), calcium (Ca) potassium (K) and magnesium (Mg) were analysed with an Agilent 4100 microwave plasma atomic emission spectrometer (MP-AES). Leachates were diluted with 1 ml 65% (w/w) HNO_3 and distilled water to a total of 10 ml and added to 15 ml centrifuge tubes. The volume of leachate depended on element to be analysed, as Na required 3000x dilution factor, whereas no dilution was needed for Mg (1.1x dilution, as 0.1 ml CsCl was added). Blank solutions were made using distilled water that had percolated through the same type of glass beads and sand (acid washed) that was used in the column experiment. Control standards were used to create a standard curve prior to leachate analysis, and a reference material was added to determine the accuracy of the analysis.

In addition, the leachate's electric conductivity (EC) and was determined. EC was determined with a Metrohm 712 conductometer, where the electrode was lowered into the leachate solution and conductance read after one minute or until it stabilized. Thereafter, pH was determined using a PHM210 standard pH meter, with calibration buffer 4 and 7 and a reference electrode filling solution with 3M KCl. Dissolved organic carbon (DOC) was analysed for the two first and last leachates after filtration through a 0.45 µm filter, using a TOC analyser.

2.1.3 Vegetation growth

After the leaching, the glass beads were gently removed from the top surface and 30 seeds of ryegrass were evenly placed into the top centimetre of the soil. Ryegrass is an introduced and widely distributed species in Brazil and has demonstrated to be a useful species for revegetation of amended bauxite residue in Ireland (Courtney & Mullen 2009). The columns were placed in a climate room at the laboratory of the Norwegian University of Life Sciences (NMBU), keeping 21°C and 18 hours per day with light. In the first week after planting, distilled water was sprayed gently on the top layer, to prevent flooding the seeds while keeping them from drying out. When the grass emerged, more water could be added. The process of watering by spraying induces a consolidation of the soil surface (1-2 cm).

The average annual rainfall in Barcarena is 3308 mm (INMET, 2021), which corresponds to 276 l/m^2/month. As the surface area of the columns was 19.6 cm^2, 438 ml water was added for one month to simulate local precipitation. 14 ml of distilled water was added to each column every day with a dispenser, with 7 ml in the morning and 7 ml in the afternoon. Based on weight-loss, approximately 5 ml evaporated from the columns overnight. To keep the same treatment throughout the study, the same amount water was added to every column, independent on growth performance.

2.2 Micro CT-scanning and image analysis

2.2.1 CT scanner

Previous studies using μCT scanning techniques to investigate root changes within the soil have been presented for instance in Anselmucci et al. 2021, and Gerth et al. 2021. The μCT scanner used in this research is a Nikon Metrology XT H-225 LC device, located at NGI laboratories in Oslo, Norway. The beam of X-rays generated is conical and polychromatic. The maximum voltage is 225 kV and the maximal current is 500 μA. The detector panel has 4.2 Megapixels (active pixels 2880 x 2880, and pixel size of 150 μm) and its size is 450 mm x 450 mm. A mechanical arm controls the position of the object with reference to the X-ray source and the detector; hence, remote zooming is possible. The source of this scanner allows a minimum voxel size of 3 μm (spot size), which implies that, theoretically, at maximum resolution, almost all silt particles could be observed. However, the geometry of the scanned specimens determines the spatial resolution (voxel size) to be achieved (see Quinteros and Carraro, 2021). The voltage and current used to scan the cylinders were 150 kV and 120 μA respectively and a cupper filter of 1 mm thickness. The voxel size obtained in this study was 37.8 μm, which means that roots with a size above ~0.04 mm in thickness could be identified in this study. Beam hardening corrections were applied on the 3D scans. Beam hardening artefacts arise when scanning water saturated soil as is the case of this study. The five cylinders with the different percentages of BR and amendments were scanned before and after grass seeds were planted (at 0, 2 and 4 weeks; results for the second week are presented in this paper). Image analysis techniques were used then on the 3D μCT scans to obtain quantitative information about the ryegrass root development. An example of μCT scanning a BR filled cylinders with grown ryegrass and the 3D resulting image is shown in Figure 3.

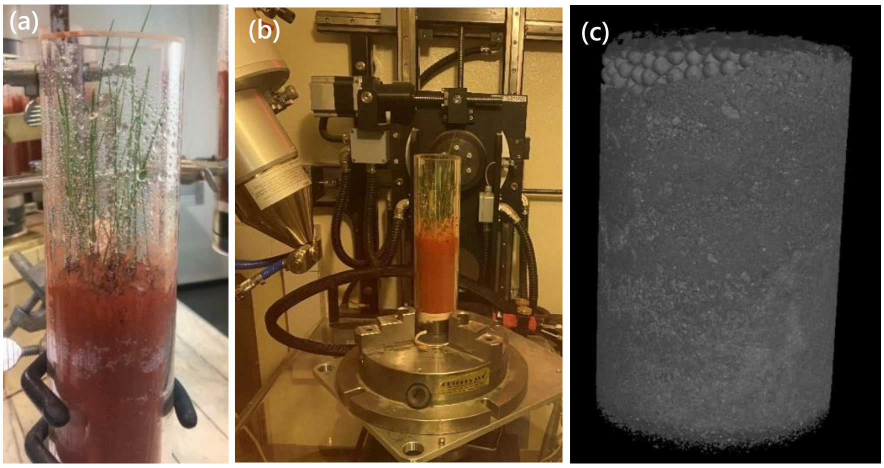

Figure 3. *(a) Ryegrass growing inside cylinder; (b) μCT scanning at NGI; (c) 3D image*

2.2.2 Image analysis and calculation of descriptors

The thousands of radiograms obtained in the µCT were reconstructed using the filtered back projection technique to a 3D volume by the software VG-Studio Max (volumegraphics.com). The image analysing steps included: preparation, filtering, enhancing and binarization, of the roots for data analysis. Binarization was done using the ITK Snap software (Yushkevich et al. 2006) and implemented codes in the programming language python (Van Rossum & Drake, 2009), including the package Porespy (Gostick et al. 2019). Based on the segmented images, the following descriptive parameters were systematically calculated:

- Root Depth (RD in mm), which is the average depth of the roots.
- Root Volume Density (RVD in %), which is total volume of roots divided by the volume of the root-permeated soil sample (Zhu & Zhang, 2016).
- Root Area Ratio (RAR in %), which is the surface of the amended BR permeated by the roots divided by the area of the root-permeated amended BR soil.
- Soil porosity and it changes during development of root features over time.

The porosity of the soil was calculated from the binary 3D µCT-scans using Fonseca 2011 by $n_{CT} = (N_t-N_s)/N_t$, where n_{CT} = porosity based on CT images, N_t is the total number of voxels and Ns is the number of voxels of the solid particles on a 3D µCT scan.

3 RESULTS

3.1 Vegetation growth from visual observations

Visual observation of the grass growth after two weeks suggested that the best amelioration used was the BR90-G10 mixture, as this allowed a rather quick leaves development, followed by BR85-G10-A5, where fewer leaves where observed (Figure 4). BR90-G5-A5 and BR85-G10-O5 showed very little leaves development, while the worst combination was BR90-G5-O5, where no leaves were observed. These observations were consistent across the three replications for each treatment.

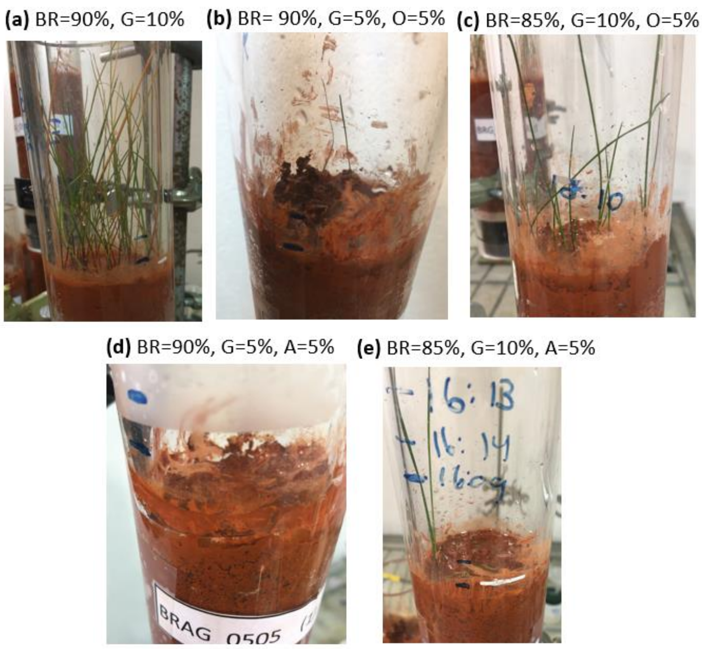

Figure 4. *Pictures of bauxite residual mixtures after leaching: (a) BR90-G10; (b) BR90-G5-O5; (c) BR85-G10-O5; (d) BR90-G5-A5; (e) BR85-G10-A5*

Cross sections of the top part of the cylinders, containing the different mixtures of bauxite residue after leaching, are shown in Figure 5. Note the glass beads on the top of the cylinders and the different grey scales for clumps of bauxite residue, the organic food and açai seeds waste products. The 3D images were also used for the calculation of porosity as described below in detail.

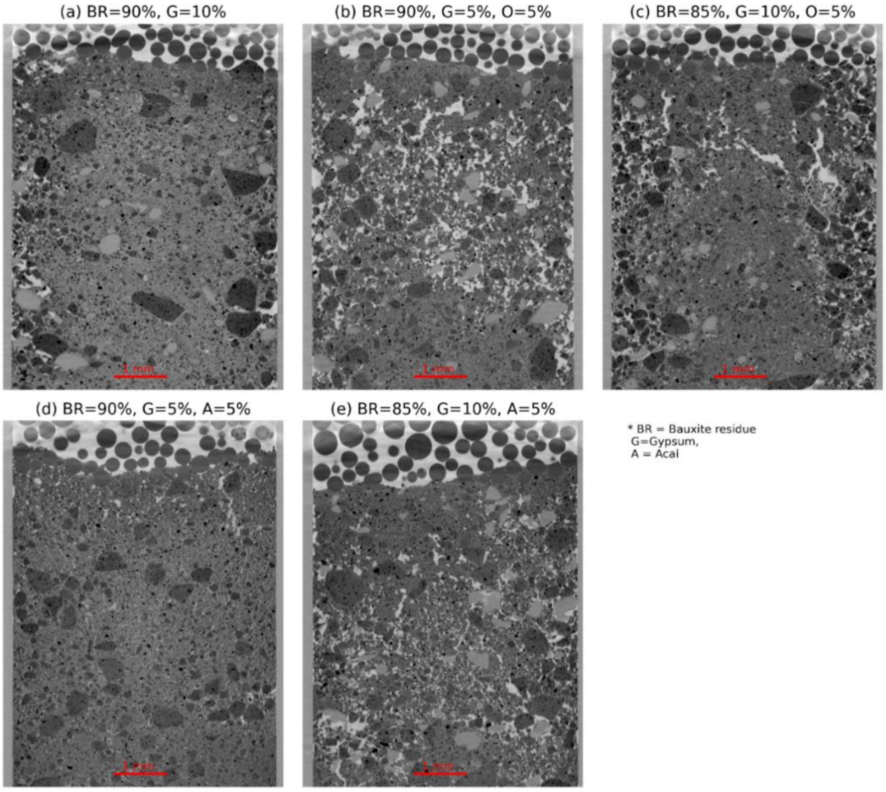

Figure 5. *μCT scans of bauxite residual mixtures after leaching: (a) BR90-G10; (b) BR90-G5-O5; (c) BR85-G10-O5; (d) BR90-G5-A5; (e) BR85-G10-A5 (red line = 1 cm for scale)*

3.2 Root features based on µCT image analysis

The binarized 3D volumes obtained from the µCT scans were analysed to rank the ability of the grass seeds to grow in the different mixtures. The root depth, root volume density and root area ratio calculated from the binary volumes are presented below. Figure 6 shows 3D images of the binarized roots systems based on the image analysis of the µCT scans.

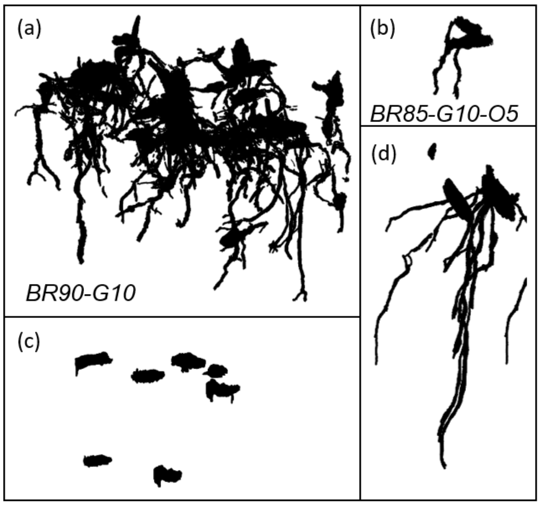

Figure 6. *Binarized roots obtained from 3D μCT scans 2 weeks after seeds planting: (a) BR90-G10; (b) BR85-G10-O5; (c) BR90-G5-A5; (d) BR85-G10-A5 No data for BR90-G5-O5 is reported, because no roots were observed in this mixture)*

3.2.1 Root depth (RD)

The average values of RD are shown in Figure 7a. It is possible to observe that mixtures that allowed the roots to develop were (v) BR85-G10-A5 with roots deeper than about 40 mm at maximum and 20 mm in average and, followed by (i) BR90-G10 with roots of maximum 25 mm and 15 mm in average, and (iii) BR85-G10-O5 with about 9mm maximum and about 8 mm in average. Finally, seeds planted in (iv) BR90-G5-A5 developed roots of less than 5 mm, and BR90-G5-O5 showed no roots at all.

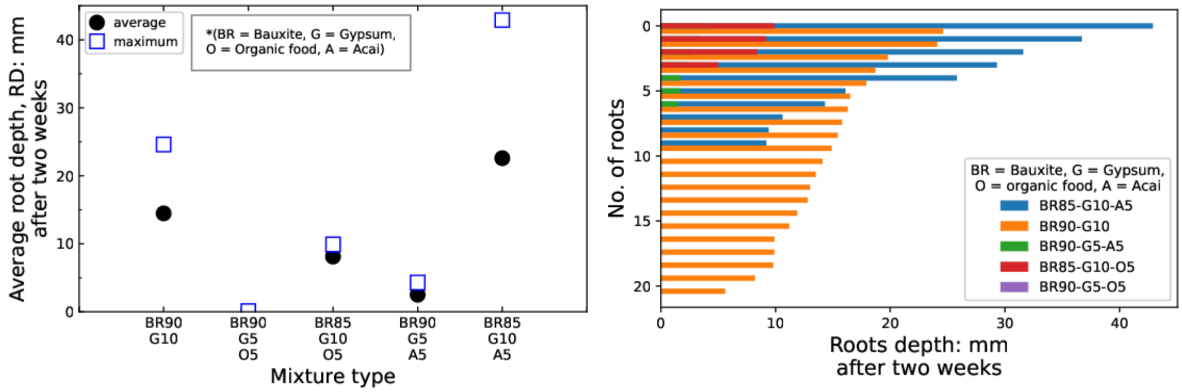

Figure 7. *(a) average root depth and, (b) number of roots and root depth (RD) two weeks after seeding*

Figure 7b shows the root depth and the number of roots that were identified for each mixture. As inferred from this plot, the combination (i) BR90-G10 allowed the larger number of roots to grow, while the (v) BR85-G10-A5 mixture allowed the roots to grow deeper; however, almost half of the amount of the roots was observed as compared with the best mixture (BR90-G10). The other two mixtures (iv) BR90-G5-A5 and (iii) BR85-G10-O5 allowed less roots to grow, in the order of 7 and 4 roots respectively. These results are in agreement with the visual observations of leaf development reported in Section 3.1, with the only peculiar difference that despite of the fact that more leaves (and roots) where observed in the BR90-G10 mixture, the roots on BR85-G10-A5 reached greater depth.

3.2.2 Root volume density (RVD in %)

Figure 8 shows the calculated values of RVD from the image analysis. The RVD values were calculated using the average root depth to calculate the volume of soil in which roots have grown. The results show a similar pattern as in the visual observation, where the best amelioration mixture was BR90-G10, followed by BR85-G10-A5.

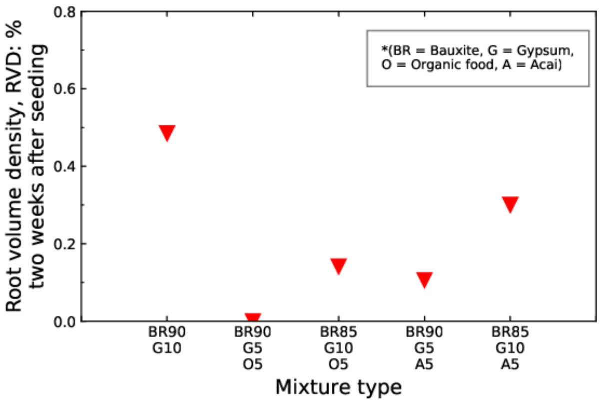

Figure 8. *Root volume density (RVD) two weeks after seeding*

3.2.3 Root area ratio (RAR in %)

The RAR was calculated per depth considering the maximum depth of the observed roots. Figure 9 plots the logarithmic RAR values per depth. Note that at depths between 0 and 10 mm most of the seeds were found, and since the seeds were also binarized in the analysis, those upper RAR values correspond to the living seeds and not necessarily to the roots. Nevertheless, a comparison of RAR is possible, because only the seeds that developed any root were systematically included in the analysis. All RAR profiles have the same trend, which reaches a peak in the first mm and then decreases with depth. This is typical of grass species, where usually most roots are observed in the shallowest layers, tending to decrease exponentially with depth (Foresta et al. 2020). The RAR indicates that there is a larger number of roots developed in BR90-G10 mixture, followed by BR85-G10-A5 as expected from the previous observations.

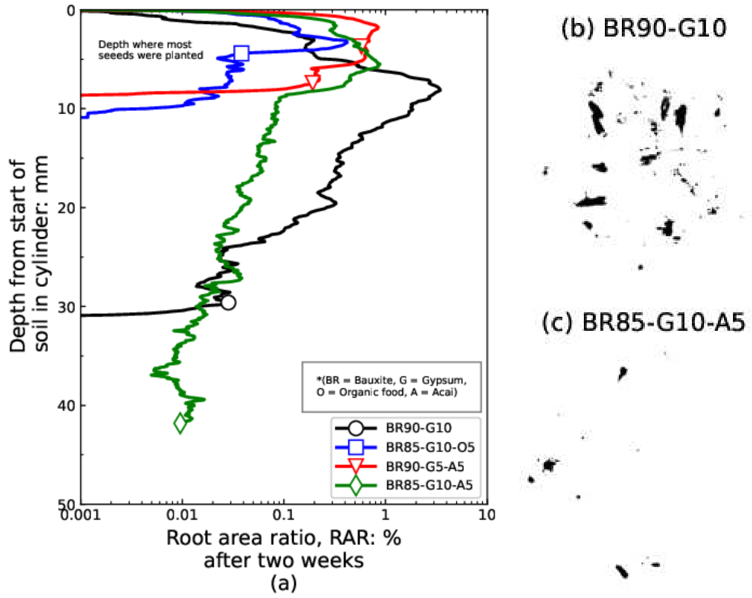

Figure 9. *Root area ratio RAR two weeks after seeding for one cylinder, (b) cross section on BR90-10 and (c) cross section on BR85-G10-A5 at about 3 mm depth beneath the soil*

3.2.4 Porosity (n, in %)

Amended BR porosity profiles obtained with µCT scanning are presented in Figure 10. The soil porosity after leaching was relatively uniform with depth, with variations of max. ±10% (Figure 10a). Most soils presented a porosity of about 65% at 25 mm depth after leaching, mean values of porosity are listed in Table 1. Note that two weeks after the seeding the upper 10 mm of the soil showed a large decrease in porosity, and that there is a slight overall decrease in the porosity versus depth. This might be due to the root's growth, which occupy the available voids and thus reduce the actual soil porosity, or due to some level of consolidation of the surface. This phenomenon has been also demonstrated in a recent study by Capobianco et al. (2020).

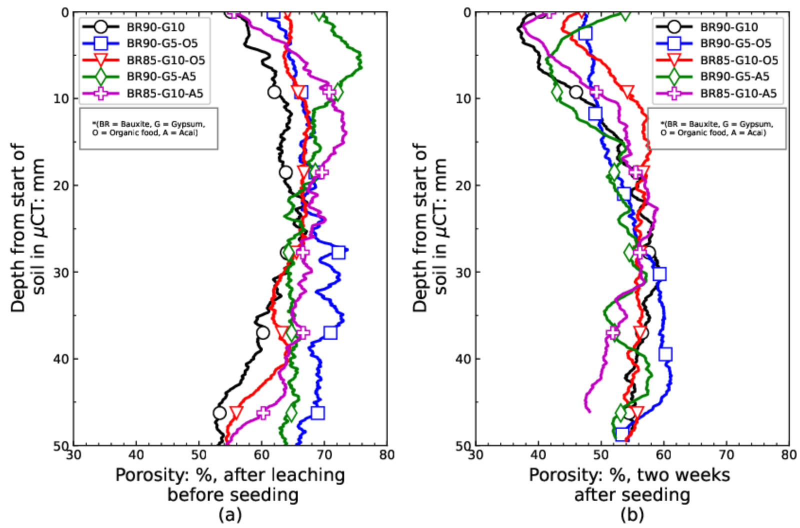

Figure 10. *Porosity profiles of mixtures for the individual cylinders tested (a) after leaching before seeding and (b) two weeks after seeding*

Most soils presented a porosity of about 65% at 25 mm depth after leaching, mean values of porosity are listed in Table 1.

***Table 1.** Parameters investigated to determine the best amelioration method that allow grass growth*

Parameter	Weeks after planting	Bauxite residue and amendment mixtures[a]				
		(i) BR90-G10	(ii) BR90-G5-O5	(iii) BR85-G10-O5	(iv) BR90-G5-A5	(v) BR85-G10-A5
RVD[b]	2	0.49	0	0.14	2.13	0.30
RD[c]	2	14.5	0	8.1	2.5	22.6
Porosity (%)[d]	0	65	62	63	65	64
	2	55	54	53	53	55

[a] BR= Bauxite residue, G = Gypsum, O = organic food waste, A = Açai; [b] RVD = Root Volume Density (%); [c] RD = Root Depth (mm); [d] Mean values of mage-based porosity.

4 DISCUSSION OF RESULTS

The above observations on the leaves and roots development on each of the individual amelioration mixtures are summarized in Table 2. In general, for the limited time of this study, BR90-G10 is apparently the best amelioration mixture (since 21 out of 30 seeds developed), followed by BR85-G10-A5, where despite of the fact that half of the seeds have grown (9 out of 30), the root depth was almost double as in the BR90-G10 mixture. All other amelioration mixtures are less effective, as far less seeds have grown (7 to 5 out of 30).

***Table 2.** Summary of the performance of different amendments*

Mixture	ID[a]	Parameter to assess the performance of ameliorated bauxite mixtures			
		VO[b]	RVD[c]	RD[d]	RAR[e]
(i)	BR90-G10	✔	✔	✓	✔
(ii)	BR90-G5-O5	X	X	X	X
(iii)	BR85-G10-O5	✓	✓	✓	X
(iv)	BR90-G5-A5	X	✓	✓	X
(v)	BR85-G10-A5	✓	✓	✔	✔

Symbols: good = ✔ , medium = ✓ , bad = **X**
[a] BR= Bauxite residue, G = Gypsum, O = organic food waste, A = Açai; [b] VO = visual observation of vegetation growth; [c] RVD = Root Volume Density (%); [d] RD = Root Depth (mm); [e] RAR = Root Area Ratio (%)

5 CONCLUSIONS

Major insights into the root growth on different amelioration mixtures were demonstrated in this study. Based on qualitative visual observation and qualitative analysis of the 3D µCT images it can be concluded that:

- µCT scanning and image analysis of roots is extremely useful to identify the performance of the roots that will be otherwise hidden inside the soil during root grow.
- The best amelioration used was the mixture with 90% bauxite soil and 10% gypsum. Using this amelioration mixture allowed the grass to thrive and to develop a deeper and stabilizing root system. Out of 30 seeds, 21 were able to grow. RVD and RAR were high, meaning that there is a healthy root system.
- The second-best amelioration method was the mixture of 85% bauxite, with 10% gypsum and 5% of açai seeds. In this mixture fewer seeds germinated, but deeper roots were observed. Out of 30 seeds, 9 grow to develop individual long roots, but no comprehensive root system.
- The mixtures of 90% bauxite with 5% gypsum and 5% açai allowed only 7 seeds to germinate, but the root depth was quite shallow. The same conclusion is applicable for the mixture of 85% bauxite, 10% gypsum and 5% organic food waste with only 5 seeds germinating.
- The mixture of 90% bauxite, 5% gypsum and 5% organic soil appears to inhibit seed germination.

Based on this laboratory study, performed under controlled environment conditions for two weeks, the BR90-G10 and BR85-G10-A5 mixtures are allegedly beneficial for the purpose of revegetation but yet to be proven in-situ. A comprehensive and long-term field study will be needed to corroborate the findings of this research. Note that the second-best combination (BR85-G10-A5) may perform better with time, since it also has an organic component (açai waste), hence nutrients will be much needed during the plant's growth also in particular after 2 weeks. Further work is needed to monitor the performance in plants growth also after the first two weeks of germination.

6 ACKNOWLEDGEMENTS

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