

Effects of Red Mud on Plant Growth in an Artificial Soil Mixture

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Abstract – Transforming economies towards the increased circular use of raw materials and keeping resource consumption within planetary boundaries is a major challenge. In our previous research, we utilized sewage sludge to produce artificial soil mixtures well-suited to the biological recultivation of degraded areas. The present study investigated how we can integrate red mud, often considered waste, into this circular management form. With red mud volume ratios of 15% and 30%, we experienced good germination and growth in Siberian elm (*Ulmus pumila* L.), white poplar (*Populus alba* L.), black locust (*Robinia pseudoacacia* L.) and the perennial multipurpose crop, Virginia mallow (*Sida hermaphrodita* L.). Our results indicate that it is worthwhile to scale up this cheap, economically and ecologically favourable combined waste recovery and mine reclamation technology and to expand its use to full-scale operation.

circular economy / waste utilization / mine recultivation

Kivonat – A vörös iszap hatása a növényi növekedésre mesterséges talajkeverékekben. Az emberiség egyik legnagyobb kihívása a jövőnk szempontjából, hogy gazdaságát a nyersanyagok fokozott körforgásos felhasználása felé alakítsa át, az erőforrás-felhasználást 'bolygóhatárokon' belül tartva. Korábbi kutatásainkban olyan mesterséges talajkeverékeket sikerült előállítanunk, melyek szennyvíziszap hasznosításával kiválóan alkalmasak voltak degradált területek biológiai rekultivációjára. Most azt vizsgáltuk, hogyan tudjuk e körkörös gazdálkodási formába beilleszteni az egyébként hulladékként jelentkező vörösiszapot: 15% és 30%-os térfogat-arányú adagolása mellett jó megeredést és növekedést tapasztaltunk pusztaszil, nemesnyár, fehér akác fajokkal és sida energianövényvel. Eredményeink szerint érdemes ezt az olcsó, gazdaságilag és ökológiailag kedvező kombinált hulladékhasznosítási és bányahasznosítási technológiát működő üzleti környezetben tesztelni és alkalmazását teljes körű működésre növelni.

körforgásos gazdaság / hulladékgyártás / bányarekultiváció

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1 INTRODUCTION

The ‘planetary boundaries’ approach sets scientifically-based limit values for resource use, above which the functioning of critical Earth-systems processes may permanently be disturbed (Steffen et al. 2015). The European Union has drafted an action plan to transform its economies towards significantly increasing the circular use of raw materials and keeping resource consumption within planetary boundaries (European Commission 2020).

On average, every ton of alumina results in 1.0–1.8 tons of red mud (Wang – Liu 2021). The annual production of this bauxite residue reaches approx. 175.5 million tons worldwide annually (>20 kg/head of the global population). Only 1–2% is recycled, leaving a global stock of over 4 billion tons (Liu et al. 2021). This inefficient resource exploitation has raised far less attention than the much-reported burst of a disposal dam in Hungary in 2010. In 2017, we entered into a cooperative venture with MAL Ltd., the main alumina producer in Hungary, with over a million cubic meters of red mud in its reservoirs. Our task was to tackle the challenge of changing the operations from a linear to a circular economy.

Pure aluminium does not occur naturally and has only been utilized in the past two centuries. Aluminium production requires bauxite, which is the product of natural soil formation (intense weathering), predominantly formed by the residual enrichment of Fe and Al, comparable to tropical-subtropical lateritization. Bauxite is a typical geological formation in the Transdanubian Central Mountains of Hungary, and it is also one of Hungary’s most valuable mineral raw materials (Fülöp 1969; Schellmann 1994).

The Bayer process, which adds high amounts of sodium hydroxide to the finely-milled basic material, is the most important industrial process used to extract aluminium from bauxite ore. Consequently, red mud, the main solid by-product, has very fine particle size distribution and a pH value of around 12.5. Red mud consists mainly of hydrated forms of Fe_2O_3 , Al_2O_3 , Na_2O , SiO_2 and TiO_2 , and small quantities of trace elements like K, P, Mn, Mg, Cu, Zn, Pb, Cr, V, Ni, Ba, Sr, Zr, Y, Sc, G and other rare earth elements (Luidold – Antrekowitsch 2011).

Due to its composition, red mud must be treated as hazardous waste; however, its many valuable components have inspired numerous technological developments to permit utilization. To date, no operable and cost-effective large-scale solutions have been developed. The options vary, ranging from soil improvement to metallurgical processing: construction utilization, chemical use, environmental protection, agriculture and metallurgy (Lengyel – Lakatos 2011).

Previous studies examining the possibility of red mud utilization in the recultivation of infertile land in abandoned mines (Feigl 2011, Gray et al. 2006) have concluded that using hazardous wastes for chemical stabilization can be safe and beneficial because the additives have the potential to reduce the extractable and plant available heavy metal content and toxicity of soils. These wastes can be considered low-cost and long-lasting additives that can be used in artificial soil mixtures in certain quantities without harmful consequences. Furthermore, red mud has also been touted as an effective adsorbent for water pollution control due to its significant adsorption potential and ability to remove toxic pollutants from wastewater (Bhatnagar 2011).

Our investigations on the use of red mud were linked to the in-situ production of a soil substitute based on a recent invention (Heil et al. 2019) related to the utilization of sludge from the treatment of urban wastewater and other non-hazardous waste suitable for biological treatment, in combination with recultivating degraded lands and generating green energy on this new artificial surface. The proven advantage of this technology is its ability to protect valuable organic material from rapid decomposition through the formation of organo-mineral complexes and the degradation stabilization of organic matter (Lachmann 2018).

Using the addition of red mud in different proportions (based on Berta et al. 2021), the present study investigated the physical and chemical properties of an artificial soil mixture

made from quaternary clayey loess (Pleistocene), sewage sludge and other biological waste materials, monitoring their effects on the growth of three herbaceous and five woody plants in a pot experiment over two consecutive vegetation periods. We hypothesized that the appropriate addition of red mud to the above artificial soil mixture may create adequate growth conditions for some plant species, allowing them to utilize the large amounts of water and nutrients it contains. Over time, the initially high salinity of red mud is expected to decrease, which may positively affect plant growth.

2 MATERIALS AND METHODS

2.1 Recipe of the artificial soil mixtures used as pot substrate

Artificial soil mixtures were prepared in March 2019. *In situ* red mud from aluminium production (EWC 01 03 09) was sampled from Reservoir Nr. IX. of MAL Ltd., H-8400 Ajka, Gyártelep hrsz.: 598/15; 47°05'12.45" N, 17°30'07.08" E); the composition given by the producing company was described by Pekler (2020). Loess was taken from the Székesfehérvár II. clay mine, the recultivation of which was performed by Fehérvári Téglaiipari Kft (47°13'21.66" N, 18°24'50.97" E) (Figure 1). Sewage sludge (EWC 19 08 05) originated from the municipal wastewater treatment facility of Fejérvíz Ltd., which treats ca. 12 million m³ of wastewater yearly (H-8000 Székesfehérvár, Bakony u. 10., hrsz.: 020023/5-6; 47°11'05.57" N, 18°23'17.66" E).

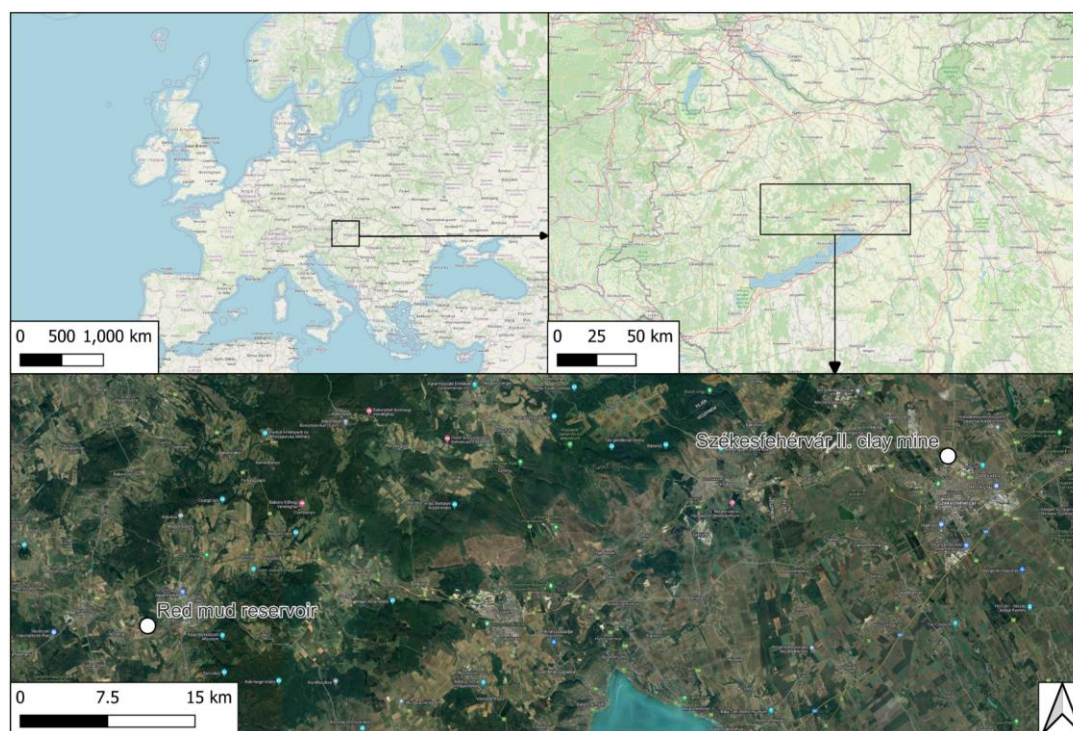


Figure 1. The place of origin of the red mud and the location of the experimental area

We established a long-term batch pot experiment in open-air conditions on the recultivated surface of the Székesfehérvár II. clay mine. The site is in the warm temperate forest zone (mean annual temperature 9.8–10.2°C) and is dominated by deciduous broadleaf tree species. The elevation is 135 m. The mean annual precipitation is about 530–560 mm, of which ca. 310–330 mm falls in the growing season. According to the Hungarian forest climate classification, the area's climate is suitable for sessile oak / Turkey oak because the 30-year (1961–2010) average of the Forestry Aridity Index (FAI) interpolated to the area is between 6.00–7.25 (Führer 2017), indicating rather dry conditions for trees.

Two differing red mud soil mixtures were prepared with the same artificial soil mixture as basic material, as described in the patent of Heil et al. (2019), and seven-fold repetitions were prepared for each condition and plant species. Based on previous literature data, we chose a 15% red mud addition by volume (RM15) as a likely non-harmful ratio for plant cultivation. The 30% addition (RM30) was expected to be an extreme scenario with potential negative effects on vegetation used in recultivation. We mixed the additives thoroughly with a shovel and performed the planting directly after we produced the soil mixture.

The open-air pot experiments were conducted in 9 L plastic pots, weighing in equal amounts of the different soil mixtures to ensure comparable conditions for root development. The moisture content was set to reach field capacity: this was the water content of the soil mixture three days after irrigation, as gravity had removed the water surplus. Rainwater collected in tanks was used for irrigation. The experiments were conducted in the growing seasons (from March to September) over two consecutive years, 2019 and 2020.

2.2 Plant species used for comparison

Three herbaceous and five woody plant species were used for the tests: giant reed (*Arundo donax* L.) was set with two rhizomes per pot, Virginia mallow (*Sida hermaphrodita* L.) and Jerusalem artichoke (*Helianthus tuberosus* L.) with two medium root tubers per pot. One bare-root field maple seedling (*Acer campestre* L.), pedunculate oak (*Quercus robur* L.), white poplar (*Populus alba* L.), Siberian elm (*Ulmus pumila* L.) and black locust (*Robinia pseudoacacia* L.) was planted per pot (Figure 2).

Seedlings were purchased from a forestry nursery in the nearby village of Moha (47°14'22.20" N, 18°20'44.89" E).



Figure 2. Plants collected for final measurements in the second year of the pot experiment in Székesfehérvár. The black planting pots are: 22.5 cm * 22.5 cm at top, 18.0 cm * 18.0 cm at bottom, height 26 cm. Plant species from left to right: 1.) *Quercus robur* L.; 2.) *Ulmus pumila* L.; 3.) *Acer campestre* L.; 4.) *Populus alba* L.; 5.) *Robinia pseudoacacia* L.; 6.) *Sida hermaphrodita* L.; 7.) *Arundo donax* L.

2.3 Soil analyses and measurement of plant parameters

By examining the artificial soil mixtures created in the experiment, we tried to propose the use of mine reclamation methods that could be applied to make degraded surfaces suitable for non-food crop production purposes. In this regard, soil is the main nutrient source for plants and supports growth in various ways. To assess the health of this medium, we investigated soil quality with detailed physical and chemical analyses and measured the main plant growth parameters grown in them.

The main soil parameters were pH(H₂O), H% (calculated from C_{org}%), total soluble salt content, CaCO₃ content, amounts of extractable plant available essential nutrients (P, K, N, Ca, Mg, S, Zn, Cu, Mn, Mg), according to the Hungarian standards (MSZ-08-0206-2 2.1, 2.2:1978; MSZ-08-0205-2: 1978; MSZ-08-0206-2: 1978; MSZ-08-0452: 1980; MSZ-20135:1999). This soil parameter range corresponds to Decree No. 4 of 2004 (I. 13.) FVM of the Hungarian Ministry of Agriculture and Rural Development, released to determine the minimal requirements of agricultural and environmental management, foreseen by national and EU legislation as necessary conditions to use rural development subsidies according to the National Rural Development Plan and financed by the European Agricultural Guidance and Guarantee Fund.

To determine the bulk density of the artificial soil mixtures, ten repetitions per treatment and plant species of 100 cm³ samples were taken from the pots at the end of each year with 'Vér' soil-core sampling cylinders (100 cm³ metal cylinder for undisturbed soil sampling).

We determined the following measurements. For herbaceous plants, the subsurface root mass, the aboveground biomass and the height of the plants, and for woody plants, the same parameters plus woody stem diameter at stem basis. We determined all of the above at the end of both growing seasons by breaking down the pots.

2.4 Data procession and statistical analyses

Statistical analyses were conducted with help of the StatSoft Statistica software, according to the following order: preparation of descriptive statistics; plotting the mean and confidence intervals by factors (separately and together); graphical examination of the normal distribution; test of homogeneity of variances with Bartlett Chi-Square test; two-factorial ANOVA; and the Duncan test as a post hoc test. The soil parameters of the pots of different treatments were compared in both the first and second years of the experiments and between the two consecutive years. Plant growth parameters were compared between treatments in each year separately.

3 RESULTS

3.1 Relationships between treatments and soil parameters

Table 1 shows the soil analysis data for both consecutive years. Based on substrate pH(H₂O)-values, the red mud treatment significantly altered the chemical state of the soil as expected. In the control samples, the sewage sludge developed a weakly acidic pH in the first year, while the values increased to slightly alkaline with the addition of red mud. The red mud exhibited no change in the second year, and the initial acidifying effect of the sewage sludge disappeared by the second year in the control plots, as shown by the increase in the mean pH values.

Water-soluble salt concentrations were relatively high in the first year; on a scale comparable to that of low-salinity, saline soils. This is mainly due to the well-known high salt content of municipal sewage sludge caused by detergents, but the red mud also contained soluble Na salts. By the second year, salt concentrations decreased significantly (<0.1%) (*Figure 3*). The artificial provision of climate-appropriate rainfall amounts (supplemented up

to the amount of the mean average precipitation of the growing season, 390 mm, added on a bi-weekly basis, 151 mm in the first year, 168 mm in the second) allowed the salinity of the soil mixtures to normalize within a year, with soil mixtures transformed from a saline status into soils with non-saline soil properties.

Table 1. Means and homogeneous subsets of soil parameters of the two consecutive years of the pot experiment.

Variable	1 st year			2 nd year		
	Mean/hom.subset*			Mean/hom.subset*		
	Control	RM15	RM30	Control	RM15	RM30
pH(H ₂ O)	6.7 ^a	7.5 ^b	7.6 ^b	7.4 ^c	7.6 ^b	7.6 ^b
total soluble salt (%)	0.18 ^a	0.16 ^a	0.23 ^b	0.07 ^c	0.04 ^d	0.09 ^c
CaCO ₃ (%)	7.8 ^a	5.0 ^b	3.8 ^c	6.2 ^d	4.2 ^{bc}	2.7 ^c
H (%)	3.8	4.4	4.0	3.6	4.4	3.6
AL-P ₂ O ₅ (mg/kg)	2863	1883	1394	1591	1464	1152
AL-K ₂ O (mg/kg)	543	573	449	216	252	257
AL-Na (mg/kg)	397 ^a	3974 ^b	5133 ^c	406 ^a	2747 ^d	5138 ^c
KCl-(NO ₂ +NO ₃)-N (mg/kg)	317 ^a	302 ^b	320 ^a	64 ^c	76 ^c	134 ^d
KCl-SO ₄ ²⁻ -S (mg/kg)	205 ^a	138 ^b	208 ^a	153 ^c	75 ^d	149 ^c
KCl-Mg (mg/kg)	539 ^a	335 ^b	370 ^c	466 ^d	374 ^c	339 ^b
EDTA-Cu (mg/kg)	18 ^a	21 ^b	20 ^c	18 ^a	23 ^d	20 ^c
EDTA-Mn (mg/kg)	37 ^a	38 ^a	53 ^b	30 ^c	34 ^a	42 ^d
EDTA-Zn (mg/kg)	23 ^a	22 ^b	21 ^c	23 ^d	22 ^b	21 ^c

*small letters (a, b, c) indicate homogeneous subsets according to Duncan-test procedure; colour codes: black letters indicate common values for soils in Hungary; orange – unfavourable values for plants; green – good conditions

The CaCO₃ content was high in the control mixture, typical for the loess bedrock (Stefanovits et al. 1999), and only moderate in the red mud mixtures. Red mud contains no CaCO₃ due to the intensive leaching during bauxite formation. Hence, CaCO₃-proportion naturally decreases with the mud addition. Data from the two study years revealed that lime leaching was relatively rapid.

In the case of humus-related organic carbon contents expressed in H% on a theoretical basis ($H\% = C_{org}\% * 1.72$ (Stefanovits 1999)), no significant difference could be described based on the statistical analysis. Although the samples proved to be normally distributed, the homogeneity of the standard deviations was not given. Therefore, the values can be considered of the same order of magnitude, and no significant differences were found.

The amount of ammonium-lactate-soluble P₂O₅ (AL-P₂O₅) was significantly higher in the control samples than in those treated with red mud. Such differences were not detected between the red mud treatments. Concerning plant nutrition, phosphorus uptake in all three media refers to excellently supplied soils (Buzás 1999), regardless of significant differences between the samples. By the second year of the study, the AL-P₂O₅ content was significantly reduced for both treatments and the control.

The AL-K₂O values scattered highly, so no normal distributions were found, and the homogeneity of variances was not ensured, indicating that the results cannot be proven statistically. The magnitude of potassium available to plants was very high in the first year for all three substrate types. Values decreased in the second year.

Upon examining the amount of AL-soluble Na, the Na content of the control samples was significantly lower than that of the samples treated with red mud. The same results were shown for both consecutive years of the study, and no clear changes with time were detected.

The KCl-soluble nitrite + nitrate contents displayed no significant difference between the treatments in the first year, but values were on the level of good N-supply for plants from soil

(Buzás 1999). We found much lower values in the second year. Unfortunately, sample homogeneity was inadequate, which prevented the verification of statistical differences.

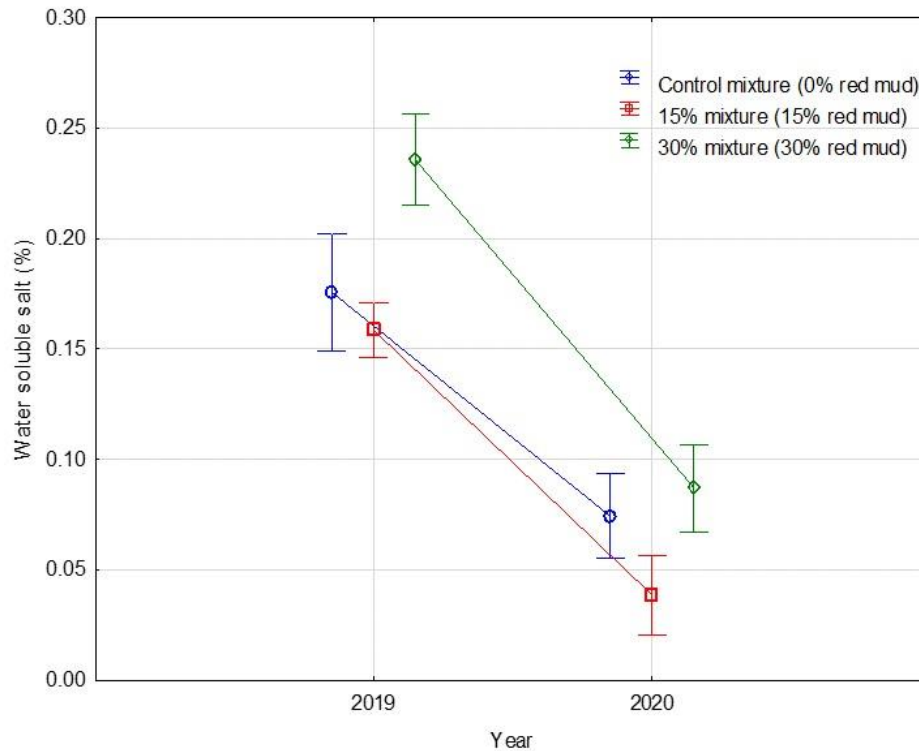


Figure 3. Means and 95% confidence intervals of water-soluble salt contents in the two consecutive years of the open-air pot experiments with red mud treatments.

The KCl-soluble sulphate content for RM15 was considerably lower in both years compared to the control and RM30. In addition, significantly lower concentrations were measured in the second year for all three substrates. The high sulphate content provided a good supply to the plants in both the first and second years.

Significantly higher values for KCl-soluble Mg contents were measured in the control than in the red mud mixtures. No clear trend emerged over time. While the control and RM30 showed significantly lower magnesium values in the second year, the RM15 showed the opposite, a significant increase.

Based on the present statistics, EDTA-extractable copper content exhibited no clear difference between the treatments or the years. Copper content was only slightly increased in the samples treated with red mud, but the RM15 values were higher than the RM30 values.

The addition of red mud considerably increased the EDTA-extractable Mn contents in the soil mixtures. Although Mn levels decreased over time for all three substrates, they remained high.

The addition of red mud significantly decreased EDTA-extractable Zn contents in the soil mixtures. However, a slight increase in concentrations over time was not statistically significant. These values are favourable for the nutrient supply; there will be no limiting factor for plant growth.

The bulk density determined at the end of both growing seasons for the RM30 was 0.89 g/cm³, 0.90 g/cm³ for RM15 and 0.94 g/cm³ for the control. We detected no significant differences between these values nor in the relationship between the bulk density and the soil samples of each plant species.

3.2 Relationships between plant growth parameters and treatments

Table 2 presents the height, the stem diameter, the aboveground stem+shoot-biomass and the belowground root-biomass measured in the second year of the experiment for each plant species per treatment. Pekler published first-year data in 2020.

Table 2. Means and homogeneous subsets of plant growth parameters in the second year of the pot experiment.

Variable	ARUN.	ARTIC.	SIDA	ROBIN.	POPU.	QUER.	ACER	ULMUS
<i>Height (cm)</i>								
Control	109 ^a	144 ^a	124 ^a	95 ^a	99 ^a	23 ^a	46 ^a	115 ^a
RM15	115 ^a	148 ^a	137 ^a	150 ^b	137 ^b	23 ^a	61 ^b	156 ^b
RM30	97 ^a	145 ^a	134 ^a	148 ^b	121 ^a	19 ^a	21 ^c	146 ^b
<i>Above ground biomass (g/pot)</i>								
Control	210 ^a	785 ^a	383 ^a	142 ^a	146 ^a	11.9 ^a	20.5 ^a	317 ^a
RM15	104 ^b	844 ^a	474 ^a	257 ^b	299 ^b	12.8 ^a	38.0 ^b	425 ^b
RM30	61 ^c	711 ^a	435 ^a	315 ^c	145 ^a	6.3 ^a	13.0 ^c	466 ^b
<i>Belowground biomass (g/pot)</i>								
Control	278 ^a	853 ^a	516 ^a	83 ^a	95 ^a	16.4 ^a	29.4 ^a	151 ^a
RM15	231 ^b	915 ^a	396 ^a	163 ^b	272 ^b	27.9 ^a	54.6 ^b	255 ^b
RM30	141 ^c	907 ^a	317 ^a	157 ^b	209 ^b	15.0 ^a	24.5 ^a	189 ^a
<i>Stem diameter (mm)</i>								
Control	-	-	-	11.3 ^a	13.1 ^a	5.8 ^a	6.5 ^a	15.5 ^a
RM15	-	-	-	15.2 ^b	17.6 ^b	5.8 ^a	8.1 ^b	17.9 ^a
RM30	-	-	-	14.8 ^b	12.7 ^a	4.9 ^a	4.6 ^c	17.8 ^a

small letters (a, b, c) indicate homogeneous subsets according to the Duncan-test procedure.

Arundo showed no different plant heights from red mud treatments. However, the aboveground and the belowground biomass significantly decreased as the red mud addition increased.

Jerusalem artichoke exhibited no notable difference in terms of either aboveground biomass, underground biomass or height between treatments.

Based on the statistical analyses, the same can be said for Sida, even if the belowground biomass seemed to decrease with the addition of red mud. However, the aboveground biomasses were approx. 15–25% higher than the control.

Due to its intensive growth, the roots of the black locusts largely filled the entire volume of the culture pots by the end of the growing season, which limits the comparison of the data magnitude. The height growth of black locust was best with RM15. A significant difference was found compared to the control but not between the mud treatments. Aboveground biomass was highest for RM30, but this positive effect was not significantly proportional to the amount of red mud. The same positive influence of red mud was found for root mass, and again no significant differences were found between different proportions of red mud. Differences in stem diameter show a positive effect only for RM15 treatment.

The height increment of white poplar was significantly higher for the RM15 compared to the other two treatments, where no such difference could be reported. The same statistically significant pattern was detected for the aboveground biomass and stem diameter. Belowground biomass was again higher for both mud treatments, but in this respect, RM30 was not significantly behind RM15.

Plant parameters of pedunculate oak did not meet the assumptions of ANOVA since both the normality and the homogeneity of variances were violated. This means that the differences between treatments cannot be proven statistically. Still, while no RM15 effects were visible, a slight decrease in plant height, aboveground biomass and stem diameter was detected for RM30.

Field maple grows better with the RM15 as in the control mixture, but the higher dose already had a limiting negative effect. This was observable for height, aboveground biomass and stem diameter. Only in belowground biomass did RM30 not differ from the control.

The height and aboveground biomass of Siberian elm plants were considerably higher in the red mud-treated soil mixtures than in the control. The root biomass (*Figure 4*) showed quite the same effect, but with RM30, this difference was not significant. The roots showed such intensive growth that they nearly filled the entire volume of the culture pots by the end of the growing season, which again limited the magnitude assessment of the data. Although stem diameter was slightly higher for both mud treatments, no significant difference was detected.



Figure 4. One-year-old Siberian elm roots (Ulmus pumila L.) washed for weight; measurement at the end of the second year of the experiment.

4 DISCUSSION

As expected, the red mud treatments caused significant changes in the chemical status of the soil mixtures, the extent of which was demonstrably related to the intensity of the treatments for several parameters.

Soil pH(H₂O) values presumably indicated that the organic acids previously present in the soil solution were leached and/or bound on the mineral surfaces of the fine particles of red mud. Similarly, the initial high amounts of salts not bound by organic compounds were largely leached during the experiment. Compared to the experiment of Lockwood et al. (2015) – who investigated the polluting effects of red mud that reached the ground in connection with the red mud spill in Ajka in 2010 – our mixtures exhibited a much smaller pH-value increase. The pH values of the original soil in Lockwood et al. were 7–8 in the 33%. The red mud mixture increased these to 9.5–11.5, and in the 9% red mud mixture, to 8.5–10.0 in different types of

soil. Our study observed a pH increase of only 0.2–0.9, likely due to the compensatory effect of the organic acids found in large quantities in sewage sludge, which neutralized alkalinity.

At the same time, we reduced the drastic pH-increasing effect of the red mud in soil much more effectively than what Lockwood et al. were able to achieve in damage prevention at the time with the Dudarit (lignite-based additive) treatment used during the Ajka disaster: Filep et al. (2015) described only a minor change from 9.49 to 9.33 with their highest mud addition treatment. Szabó (2011) reported toxic effects starting at pH-level 10.5 upwards in a soil column experiment with different red mud contamination levels. This supports our conclusion that the pH values of our substrates do not present any risk for soil biology.

High soluble salt contents had a magnitude comparable to saline soils (salinity class II on a III-step Hungarian scale (de Sigmond 1927)) in the first year. This is probably unfavourable for plants lacking proper mechanisms to deal with this. It can cause problems for the water and nutrient management of plants and, ultimately, for land use. However, salt concentrations decreased in the second year under the 0.1% limit, under which soils are not classified as saline. With this, a significant expansion of the range of applicable plant species is expected (Tóth 2010).

While in the first year of the treatment, salt contents of the substrates were high compared to forest soils of Hungary, the treatments slightly decreased the CaCO_3 content. CaCO_3 ‘dilution’ caused by mixing in the mud low in carbonate due to the former strong leaching of bauxite was a positive effect – taking into account the local climate – decreasing the negative impact of CaCO_3 on the amount of water available to plants (Füleky 2011). Therefore, this change can be assessed as beneficial for the vegetation. The relatively fast leaching of calcium carbonate during the experiment can probably be deduced from the acidity of rainwater and sewage sludge.

The amount of organic matter corresponds to that of natural soils with a good supply of nutrients. The presence of a Mollic horizon is one of the most important diagnostic criteria of the naturally occurring Kastanozems soil type in the surroundings of our experimental area (IUSS Working Group WRB, 2022). Their average humus contents in the area are between 1.3–2.5% (unpublished soil survey data of the authors Kovács and Heil), whose values are much lower than those of our substrates. If the mineralization processes can take place – based on our previous studies on the artificial soil mixture (Lachmann 2018) – it is expected that the organic matter will stabilize quickly compared to the natural soil formation processes, with the formation of organic-mineral complexes. At the end of the two-year experiment, stable soil and pore structure could be seen, enabling the presence of earthworms (*Figure 5*).

Anton et al. (2012) modelled the potential effects of the Hungarian red mud disaster in Ajka in 2010. Based on their results, we assume this process is accelerated due to the fine grain distribution of red mud (on average about 40% silt, 50% clay content) and the large specific mineral surface area resulting from the latter.

All three substrates had high amounts of ammonium-lactate soluble phosphorus (P) available for plants in the soil solution (Füleky 1999). The pH of the medium decreased with the addition of red mud, which leads us to believe that the P in the organic-mineral bonds formed in the alkaline medium was converted to an insoluble form, so its uptake decreased with increasing pH. Previous studies demonstrated that red mud can bind high amounts of dissolved phosphate and is, therefore, also used as an adsorbent (Huang et al. 2008). Similarly, the presence of secondary CaCO_3 in the substrates originating from the loess parent material contributes significantly positively to reducing leaching losses of P through the secondary precipitation of Ca–P minerals and/or a strong sorption reaction of P with CaCO_3 , as shown by Carreira et al. (2006).

Third, the addition of red mud simultaneously reduced the proportion of high-P sewage sludge within the mixtures. When the amount of P leached from each culture pot during the

study is converted to 1 hectare of production area, 134 kg P/ha is obtained for the control, 44 kg P/ha for RM15 and 26 kg P/ha for RM30. As a comparison, ca. 2.92 kg P/ha active ingredient must be added to reach 1 t/ha yield of agricultural crops (Füleky 1999).



Figure 5. Initial soil formation resulting in soil structure can be detected with the naked eye, during the breaking of the pots in the second year of the experiment.

No effects on AL-K₂O could be linked statistically to the red mud treatments. We assume that the original bauxite leaching removed most of the potassium from the mineral particles of red mud; however, a sufficient amount remained from the loess, so no resulting nutrient deficiency symptoms are expected (Buzás 1999). Ujaczky et al. (2014; 2015) found similar values of AL-K₂O in artificial soil-red mud mixtures ten months after their field trial started. They measured average concentrations of 217 mg/kg for a 20 vol% red-mud/soil mixture and 256 mg/kg for a 50% mixture, representing an average to good supply for plants.

The sewage sludge was the main source of sodium in the soil mixtures, originating typically from the salt content of foods and detergents. Adding red mud caused a strong mobilisation of this ingredient, resulting in very high concentrations available to plants. This may be related to the poorer growth of some plant species in the red mud treatments. The Na amounts were still quite high in the red mud treatments in the second year; thus, the Na tolerance of plants is probably required. Feigl et al. (2013) set a limit of 600 mg/kg AL-Na as an indicator of the red-mud contaminated soils after the Ajka spill: the initial toxic effects on the test organisms *Vibrio fischeri* (bacteria), *Lemna minor* (aquatic plant), *Sinapis alba* (plant) and *Heterocypris incogurens* (ostracod) only occurred with 20-30% red mud contamination.

Due to the alkalinity of the soil solution of the soil substrate treated with red mud, variable charge surfaces are mostly terminated by nonbridging hydroxyls carrying a partial negative charge, which impedes nitrate-nitrite bonding. These readily soluble nutrient forms experienced rapid leaching over time. If the amount of nitrogen leached from each culture vessel is converted to 1 hectare of production area, 109 kg N/ha is obtained for the control, 98 kg N/ha for RM15 and 80 kg N/ha for RM30. This is the amount of the additional nitrate supply from precipitation

for this region. However, the source of these N-forms was not the red mud that is the focus of our present study, as the field experimental results of Feigl et al. (2013) prove. They measured concentrations of only 1.2–1.7 mg NO₃-N/kg in their soil samples mixed with red mud in the area of the Ajka reservoirs.

The amount of KCl-soluble sulphates easily absorbable by plants was significantly reduced with RM15, but again, it did not differ from the control with a higher dose of red mud. Under aerobic conditions of the upper soil layers – with similarly low bulk density values as our soil mixture shows – sulphur is mainly present in organic bonds. As we have seen, H% values were highest for RM15, while they were approximately the same for the other two substrates. This may explain the similar evolution of sulphate concentrations. Although Feigl et al. (2013) determined total sulphur contents in their experiment on red-mud-contaminated soils, they did not find increased concentrations due to red mud compared with the control. Overall, sulphate concentrations of all three substrates were so high that the plants had adequate sulphur supply (Buzás 1999).

The concentration of KCl-Mg in the red mud is much lower than in the base soil mixture; it is obvious that the magnesium concentration decreases when it is added. However, the extent of this reduction is insufficient to have the expected negative effect on plant growth. For arable soils, Mg contents above 200 mg/kg can be considered as well supplied, which is true for all soil mixtures of the clayey and loamy types (Buzás 1999).

Above 3.2 mg/kg EDTA-extractable copper concentrations, arable land is considered to be well supplied. This value was significantly exceeded in our mixtures. According to KvVM-EüM-FVM Joint Decree No. 6/2009. (IV. 14.) on the limits needed for the protection of water and soil against pollution and the measurement of pollution, this quantity is still far below the contamination limit value, so no direct harmful effect on plant growth is expected. Anton et al. (2012) also found red mud entering the soil did not cause toxic heavy metal concentrations.

The manganese content available to plants from the soil mixtures increased with the increasing amount of red mud in the pots with RM15 and RM30. This element behaves like iron in soils, presumably appearing in the red mud in an absorbable form, which explains such an effect. Arable soils can be considered well supplied – with a clayey soil texture in the neutral pH range – from an EDTA-soluble Mn concentration above 30 mg/kg (Buzás 1999). Overall, this shows that all of our mixtures ensure a good supply of Mn.

The physical properties of the soil are determined by the properties of the raw materials of the mixture. These properties changes are difficult to track during the short duration of the experiment, and former studies indicated no detectable changes in this manner (Anton et al. 2012). We examined only the bulk density because it is closely related to mixing quality and refers to the framework for water and air management of the resulting mixtures. Bulk densities can be considered low for all substrates, and are usually found in cultivated upper layers of arable soils or upper layers with high humus contents of forest soils. This shows that in one year, the root system does not affect the soil structure to such an extent that it can have a detectable effect on bulk density neither for herbaceous nor for woody vegetation.

The plant species included in the study responded differently to the red mud treatments. Among the herbaceous plants, giant reed, known for its intensive biomass production and grown for energetic purposes, exhibited good growth in our previous experiment (unpublished) in our basic mixture used here as control. Nevertheless, with the addition of red mud we observed growth inhibition and this negative effect even increased with higher mud concentrations. This contradicts Nsanganwimana et al. (2014), who recommended *Arundo donax* plantations for phytomanaging constructed wetlands, marginal and contaminated sites. The red mud treatments had no statistical effect on Virginia mallow and Jerusalem artichoke, the other two herbaceous species. Notwithstanding, our results could address some of the research gaps Nahm and Morhart (2018) mention for *Sida*, which are needed for a wider use of

this plant in Central Europe. Similar to recent literature reviews, our results support Abdalla et al. (2014), who suggested that the artichoke should be used more widely in recultivation areas, and Rossini et al. (2019), who recommended its use as a sustainable energy crop.

In our experiment, we used tree species widespread in Hungarian forestry practice and known for their tolerance to high salt concentrations and drought. To compare tree dimensions with the forestry practice, we used quality requirements on forest reproductive material described for the purpose of defining “common commercial quality” in the 110/2003. (X.21.) decree of the Ministry of Agriculture. With tree species where the legal provision did not prescribe requirements for certain parameters, we compared the growth of our plants to the size of the propagating material traded in the Hungarian forestry trade.

The height growth of the black locust reached that of best-quality class seedlings in Hungarian forestry practice. Root development did at least reach the minimum requirements of 25 cm depth after one year, but the pot size limited growth. Both aboveground and underground biomass showed that black locust biomass was significantly higher in the mixture treated with red mud than in the control, even if this tree species is known not to tolerate higher salt conditions seen in the mixtures with mud. This clearly shows the beneficial effect of red mud on the growth of *Robinia* seedlings.

For white poplar, dimensions exceeded those of normal seedlings used in forestry practice. The most vital growth of these plants was found for RM15. With the addition of higher amounts, plant growth was the same as in the control. White Poplar in forests can tolerate salt contents of 0.1–0.2% (Járó 1960), but probably due to the higher Na-concentrations, tolerance limits were reached in this study.

Pedunculate oak demonstrated good growth in all three substrates; even if a slight but statistically unverified decrease in plant dimension was found with RM30. However, our seedlings still reached all minimum requirements for use in forestry practice (height min. 18 cm, diameter min. 4 mm, root length min. 20 cm).

The treatments caused field maple to behave like black locust. RM15 was the best medium in the critical first year of growth for this species.

Finally, the Siberian elm achieved the strongest growth and highest biomass production among tree species. The species was unquestionably able to make the best use of the conditions our artificial soil mixtures provided.

When comparing the ability of colonization of surfaces covered by pure red mud (Terpó – Bálint, 1985) with that on our substrates, we could present a good alternative for the ecological utilization of red mud.

5 CONCLUSIONS

Our study investigated whether the use of a well-proven sewage sludge combined mining reclamation method can be combined with the high-volume, low-cost utilization of additional waste material – red mud. In our artificial soil mixtures, we examined the growth of herbaceous and woody plant species widespread in Hungarian agricultural and forestry practices. Of the herbaceous species included in the experiment, the addition of red mud inhibited only giant reed growth. Jerusalem artichoke and Virginia mallow developed similarly well to the control medium. Woody plants taken from forestry practices all exhibited good growth. Red mud treatment was particularly beneficial for black locust and Siberian elm. According to these first studies, we consider it worthwhile to scale up this cheap, economically and ecologically favourable combined waste recovery and mine reclamation technology, to test the innovation in an operational business environment and to grow its use to full-scale operation.

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