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From spoil to soil: utilising waste materials to create soils for mine rehabilitation

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Abstract

The Latrobe Valley in Victoria, southeast Australia, is home to three large open-cast brown coal mines. Due to the nature of the mining operations, there is a lack of topsoil to cover the whole area that is to be progressively rehabilitated. This has led to the development of technosols, employing the ideas of the circular economy by using waste products from three industries located in the Latrobe Valley: mining and energy production (overburden, subsoil, topsoil, waste brown coal and fly ash from the powerplant), paper milling and recycling (effluent sewage recovery and recycling waste) and municipal green waste collection (compost). These waste products have been mixed at different ratios and tested in laboratory, greenhouse and field conditions to establish the best type of technosol that is safe for the environment and can turn into a productive soil in the long-term. If proven suitable, this new concept will not only aid in rehabilitation of large post-mining areas but also help in waste reduction. In a greenhouse study, we tested plant germination and growth in seven different mixtures. Although grass germination was highest in natural topsoil, both grass and clover biomass and leaf length were generally higher in technosols than in topsoil. Also, the plant tissue nutrient levels were similar or higher in technosols than in topsoil. Four out of seven technosols were then transferred into a field trial. Preliminary results from the trial have shown that plant biomass in three out of four technosols is greater than in natural topsoil. Further monitoring of soil properties is being undertaken to assess long-term performance of these soils.

Keywords: *technosol, mine rehabilitation, waste utilisation, plant growth*

1 Introduction

The process of mine rehabilitation seeks to remediate the condition of previously mined land with the goal of achieving a particular post-mining land use (Favas et al. 2018). At the Loy Yang mine in the Latrobe Valley, rehabilitation efforts seek to restore mined lands to pastural use. The process of open-cast mining, as is the case in the brown coal-mining district of Latrobe Valley, reshapes the landscape and creates large areas of exposed overburden, which cannot be sufficiently covered by previously removed topsoil. This makes mine rehabilitation more complicated, because the overburden material presents a poor growth medium for plants as it lacks essential nutrients and organic matter. The lack of plant growth then leads to high rates of erosion and potential batter instability, hindering site rehabilitation efforts. Previously mined batters also contain coal, which poses a fire risk. To manage the heightened risk of erosion, slope instability and fire, progressive rehabilitation of mine batters is a common procedure in the Latrobe Valley brown coal mines (Birjak et al. 2019; Yellishetty et al. 2014). This process involves reshaping and capping the batters with clay overburden, covering them with a growth medium (traditionally topsoil) and establishing plant growth by the application of a pasture seed mix plus fertiliser in order to stabilise the capping material and prevent exposure of overburden through erosion (Birjak et al. 2019). The short supply of topsoil in the Latrobe Valley coal mines poses a limiting factor in mine rehabilitation efforts, creating difficulties in achieving post-mining land use objectives. To address the shortage of topsoil, technosols, consisting of mine waste and other industrial waste streams, have been proposed as an alternative plant growth substrate and cover material for mine batter rehabilitation. The target land use at this mine is commercial pasture, with sheep and cattle grazing; therefore, the soils have to provide adequate growth substrate for pasture plants but also possess high structural integrity and stability, in order to avoid land degradation at the post-mining sites.

Initial research by Taylor et al. (2014) tested a combination of overburden (OB), kraft mill rejects (from paper mill), biosolids and green waste compost. These soils were found to be potentially suitable for use in mine rehabilitation, although relatively high electrical conductivity (EC) of the leachate raised concerns about salinity and sodicity issues. Further research (Mundodi 2020) has established an ideal mixing ratio of OB and fly ash (FA) in order to neutralise acid mine drainage and avoid heavy metal leaching from the substrates. The addition of anaerobically digested paper mill waste, called effluent sewage recovery (ESR), and waste lignite from the mine (BC) has increased the organic matter and nutrient content of the soils. A lysimeter field study deemed these soils safe for mine rehabilitation, and further greenhouse study (Mundodi 2020; Mundodi et al. 2019) showed that they provide a substrate suitable for plant growth, although relatively high salinity has delayed germination of clover. Table 1 summarises all the substrates used in the present study and their basic properties.

Table 1 Waste materials utilised in our study, their source and brief characterisation

Industry	Material	Abbreviation	Properties
Coal mining	Overburden	OB	Acidic, low in nutrients, high in clay content
Coal mining	Brown coal dust	BC	Acidic, high in organic matter
Coal mining	Topsoil	TS	Acidic, high in silt content, living microbes
Coal mining	Subsoil	SS	pH neutral, high in Ca, Mg, K
Power generation	Fly ash	FA	Alkaline, high in Mg, Ca, K, sandy texture
Paper industry	Effluent sewage recovery	ESR	Alkaline, high in Ca and organic matter
Green waste collection	Green waste compost	GW	pH neutral, high in P, N, K, organic matter, living microbes

In the current study, we present results from a greenhouse mesocosm experiment and a field trial. In a greenhouse pot experiment, we tested plant germination, plant growth and biomass, soil leachate properties and changes in soil chemistry in seven technosol mixtures (T1–T7) and topsoil control (C) over a period of three months. From these, we selected four mixtures to be used in the field trial (Figure 1). In a trial on the mine batter, we have assessed plant growth and biomass and soil chemical properties. Further assessment of soil physical properties, soil water retention and microbial community composition are being performed, to assess all aspects of soil health. Additionally, the soil properties of technosols in the field trial will be monitored over five years to assess development over time. Together with a cost estimate on production of each individual mixture, the current research will aid in selecting the most suitable technosol for mine rehabilitation in the given area.

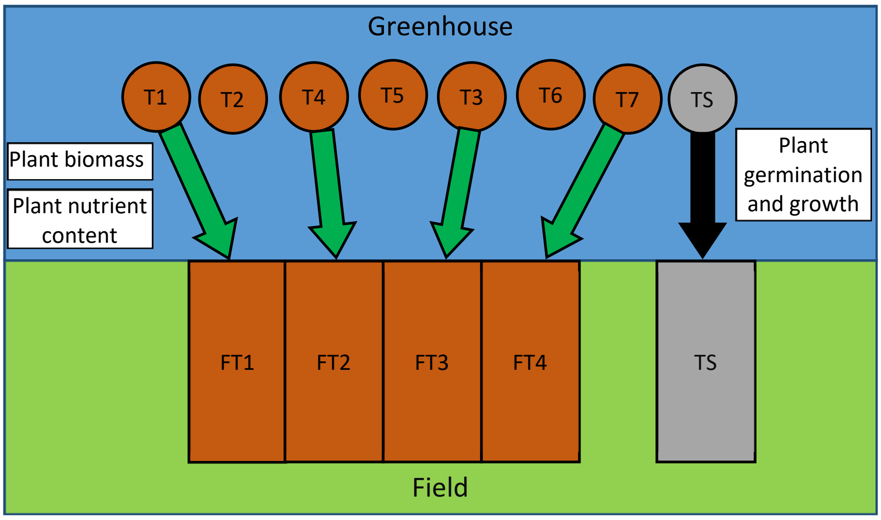

Figure 1 Scheme of the greenhouse and field experiments. White boxes on the side indicate which parameters were used during selection of technosol mixtures for the field trial

2 Materials and methods

2.1 Site description, material description

The experiment was situated in the Latrobe Valley, a lignite coal-mining district in Victoria, southeast Australia, at the Loy Yang mine, 150 m RL, with an average annual temperature of 13.5°C and 700 mm annual rainfall. The natural topsoil in the area belongs to the sodosol family, with a thin layer of loamy topsoil and dense sodic subsoil. The topsoil is stripped as mining progresses and is then either directly transported to rehabilitated areas or stockpiled for up to three months.

All the materials were analysed for initial nutrient content, pH, moisture content, bulk density (BD), EC and cation exchange capacity (CEC). The soil analyses were performed at a National Association of Testing Authorities accredited laboratory (Environmental Analysis Laboratory [EAL], Southern Cross University, Australia). The substrates were measured for pH and EC in 1:5 water suspension using a Model-WP-81 Waterproof Conductivity/TDS-pH/mV-temperature meter. The soluble calcium, magnesium, potassium and phosphorus was calculated using Morgan 1 method (adapted from Wheeler & Ward 1998). The available phosphorus was determined using Colwell method (Rayment & Lyons 2011), the total sulfur was tested according to APHA 4500 (American Public Health Association 2017), and the total nitrogen and total carbon were measured using LECO Trumac Analyser. The effective cation exchange capacity (ECEC) calculated is the sum of exchangeable calcium (mg/kg), exchangeable magnesium (mg/kg), exchangeable potassium (mg/kg), exchangeable sodium (mg/kg) and exchangeable aluminium (mg/kg) measured in the sample. The micronutrients, such as zinc (mg/kg) and iron (mg/kg), were tested based on the method mentioned in Rayment & Lyons (2011). Bulk density was measured using BD rings, by drying out undisturbed soil samples. Average values of these parameters are summarised in Table 2.

Table 2 Major soil nutrients and selected chemical and physical soil parameters

Parameter	OB	BC	TS	SS	FA	ESR	GW
P(ext.)	2.6	12	44	39	12	45	1,347
S	79	146	21	19	324	722	857
pH	5.68	3.90	5.30	7.2	9.19	8.05	7.54
EC	0.17	0.78	0.13	0.17	0.65	1.45	5.71
Ca	284	924	1,130	983	3,135	16,680	13,504
Mg	1,211	1,251	371	327	841	817	3,759
K	71	56	123	130	163	421	17,462
Na	739	2,065	116	832	1,538	2,232	5,174
Al	118	449	38	261	5	22	4
CEC	7.52	15.47	4.64	5.59	13.27	45.09	73.90
Zn	2.6	7.1	4.4	6.1	20	29	84
Fe	27	362	656	429	23	67	288
C	0.21	57.50	2.77	1.43	2.31	23.30	20.90
N	0.02	0.53	0.16	0.08	0.02	0.86	2.08
Moisture	11.9	33.6	15.3	6.3	20.5	65.2	28.9
BD	1.83	0.69	1.13	1.38	1.15	0.63	0.75

2.2 Greenhouse experiment

2.2.1 Material mixing ratios

Based on the chemical and physical properties, seven different mixtures of the materials were established. The ratios were initially calculated in weight units and then converted to volume units, so it can be easily transferred into the field, where materials are measured in cubic metres. The ratios of materials in these mixtures and topsoil control can be seen in Table 3.

Table 3 Ratios of materials in each of the technosol mixtures

Label	OB	BC	TS	SS	FA	ESR	GW
T1	–	–	–	4	–	–	1.2
T2	3	–	–	–	–	1	1.2
T3	2.5	–	1.5	–	–	–	1.2
T4	3	0.2	–	–	1	–	1
T5	3	–	–	–	1	–	1.2
T6	–	–	–	3	–	1	1.2
T7	1.5	0.2	–	–	1	–	1
TS	–	–	5.2	–	–	–	–

Note: ratios are based on volume of material.

2.2.2 Experimental setup and monitoring

All the materials were mixed in a concrete mixer and each mixture was divided between five pots (150 mm width, 150 mm height). Thirty grass seeds and 20 clover seeds were sown in each pot. A small bowl was then placed underneath each pot. The pots were placed into an open greenhouse in a randomised way and watered twice a week. Seed germination and seedling recruitment were monitored twice a week for the first two months. Leaves and stems of the largest plants out of each pot were measured twice a week to follow growth progress. After three months, the experiment was terminated and all the plants harvested.

2.2.3 Plant tissue analysis

Above-ground and below-ground biomass was separated and weighed while fresh (from each pot), then dried at 70°C, weighed again for dry biomass and fine grinded for further analyses. Plant biomass has been analysed according to Reuter & Robinson (1997) for macronutrients and basic micronutrients.

2.2.4 Data analyses

Numbers of successfully germinated grass and clover seeds after two months were tested for normal distribution (Shapiro & Wilk 1965) and compared using one-way ANOVA. If ANOVA indicated significant difference, Tukey's honestly significant difference test (Tukey's HSD test) was applied for multiple pairwise comparisons of means. The maximum plant leaf and stem length from each pot was also tested for normal distribution and analysed using one-way ANOVA and Tukey's HSD test. The dry plant biomass from all five pots containing the same technosol mixture was combined; the values were compared in a graph (Figure 3). The plant tissue nutrient content in technosol mixtures was compared to plant nutrient content in the natural topsoil. All statistical analyses were performed in program Statistica (TIBCO Software Inc 2020).

2.2.5 Cost estimate

Based on the distance of transport, cost of extraction or manufacturing of each material and the cost of mixing the materials together, a cost estimate (in AUD) for each technosol mixture has been created.

2.3 Field trial

2.3.1 Site preparation, material mixing, experimental setup

The field trial site was selected on the southwest batters (sloping north). The batter of a width ranging from 25 to 45 m was shaped into a 4:1 slope, with a 1 m layer of clay capping (overburden) on top. Then it was divided into 15 25 m-wide strips. From the greenhouse experiment, mixtures T1, T3, T4 and T7 were selected (labels FT1, FT3, FT2 and FT4 were used for these in the field trial, respectively) based on the best plant performance in these mixtures (Figure 1). The materials were heaped at the top of the batter and mixed with a row turner at appropriate ratios. Each mixture was then divided into three parts and placed on three different plots, together with three topsoil control plots in a randomised design (Figure 2).

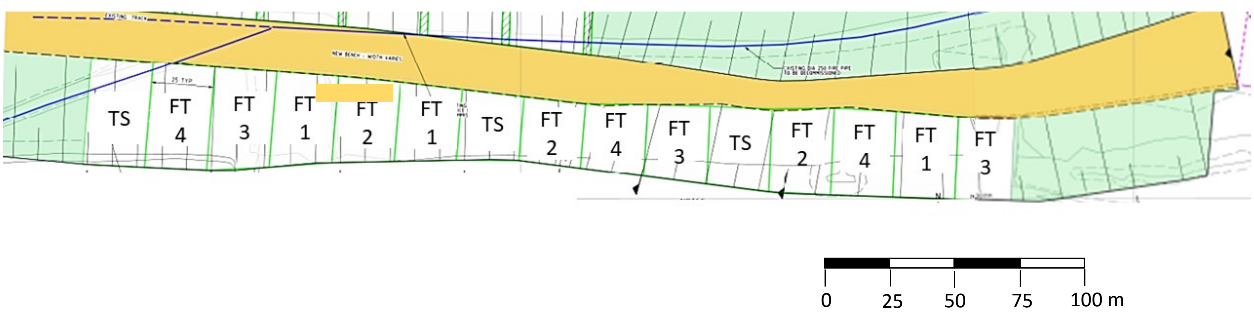

Figure 2 Drawing of the field trial site on the southern batter and placement of individual technosol mixtures and topsoil control (TS)

At the start of June 2020, each plot was sown by a fodder pasture seed mix, which contained perennial ryegrass (*Lolium perenne),* cocksfoot (*Dactylis glomerata*), white clover (*Trifolium repens*) and subterranean clover (*Trifolium subterraneum*). This mixture is being used for revegetation of the freshly rehabilitated mine batters at Loy Yang, in order to establish a pasture that can be used for livestock production in the near future. The varieties and species of plants have been selected to suit the Latrobe Valley region and the soil type, which has dense sodic subsoils (which is the same case at the rehabilitated site, as the clay liners are dense and sodic).

2.3.2 Monitoring of the field trial

Each soil mixture was tested for major chemical parameters, plant macronutrients and micronutrients, prior to spreading it onto the batter.

One month after the trial establishment, in July 2020, length of grass and clover shoots was measured, at three points on each plot – on the top, middle and bottom part of the slope.

Plant biomass, soil microbial populations (DNA and RNA sequenation), soil physical properties (BD, water retention capacity, hydraulic conductivity, aggregate stability) and organic matter content have then been monitored over time (results are presented elsewhere).

3 Results and discussion

3.1 Greenhouse experiment

3.1.1 Seed germination success

The highest germination of grass seeds was in the TS – on average, 19.4 seeds per pot. In T1, T4, T5 and T6, germination was comparably high – on average, 17.8, 17.2, 17.6 and 17.8 seeds per pot, respectively. In T2, grass germination was 14; in T3, 15.8; and in T7, 13.75 seeds per pot on average. Highest clover germination was in T3 and T4, 10.6 and 10.4 seeds per pot on average, respectively. In other mixtures, the numbers of germinated seeds ranged from 4.2 to 7 (8 in T1, 4.2 in T2, 5.4 in T5, 5.4 in T6, 7 in T7 and 6.8 in TS). There were no statistical differences in seed germination between treatments. The results of plant germination can be seen in Figure 3.

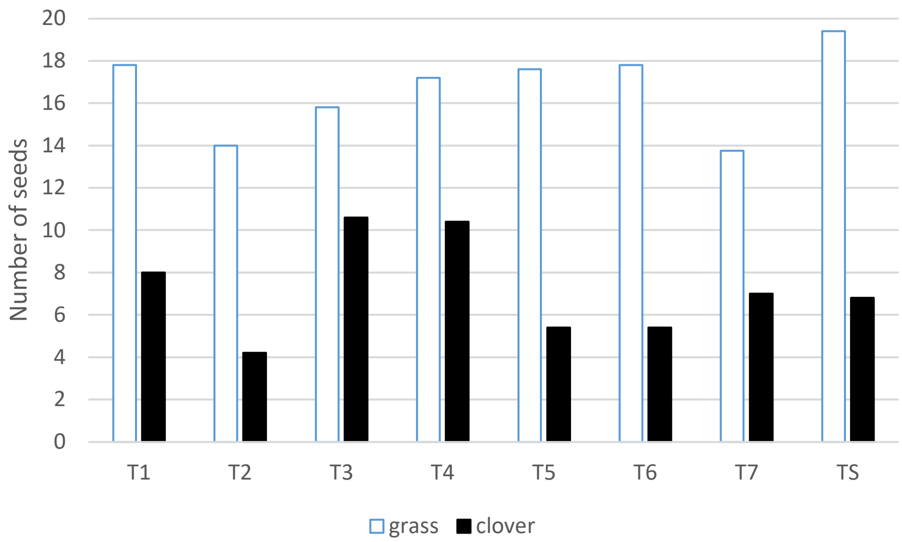

Figure 3 Average number of seeds of both grass and clover that have successfully germinated in the greenhouse experiment

3.1.2 Plant leaf length

The longest grass was in T3 and T7, 34.2 cm and 34.5 cm, respectively. In the other mixtures, grass length ranged from 26.2 to 32.4 cm (32.4 in T1, 30 in T2, 27.6 in T4, 31 in T5, 32.2 in T6 and 26.2 in TS). There were no significant differences in leaf length between treatments. The longest clover leaves were in T4 (12.4 cm), followed by T1 (11.2 cm). In other treatments, the leaf lengths were as follows: 5.6 (T2), 9.4 (T3), 7.6 (T5), 10.25 (T7) and 7.8 (TS). In T2, the clover leaves were significantly shorter than in all the other treatments and in topsoil control.

3.1.3 Plant biomass

Dry biomass of grass was highest in the T1 mixture, whereas clover biomass was highest in the T4 mixture. In T2, clover growth was minimal, not producing enough biomass for plant tissue analysis; therefore, the results were not considered. The poor performance of clover in T2 and T5 was caused by high N content, as high available nitrogen levels inhibit biological nitrogen fixation in legumes and therefore gives them a competitive disadvantage (Annicchiarico & Tomasoni 2010; Dogra & Dudeja 1993). In the T2 mixture, we used two composted materials rich in N (ESR and GW) in combination with OB, which are slightly acidic and contain a very small amount of C (Table 2), which contributed to nitrogen mobilisation, and this was directly available to the plants. The best grass performance was in mixtures T1 and T4, although this was not accompanied by the highest protein (N) content in the grass. The dry biomass of grass and clover can be seen in Figure 4.

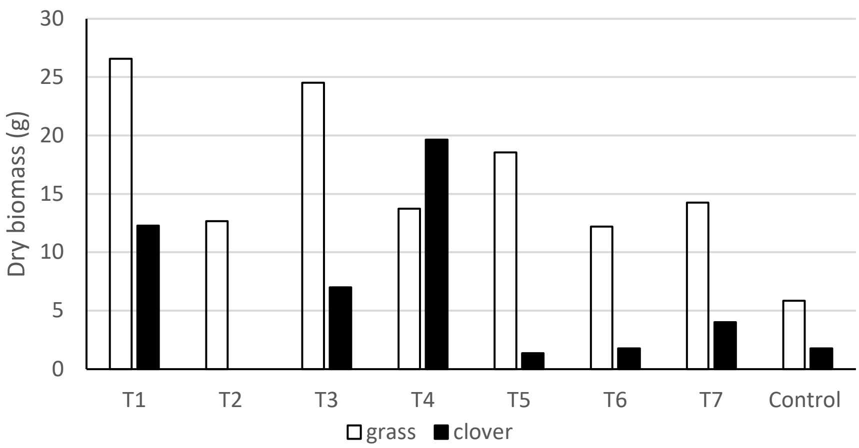

Figure 4 Sum of dry biomass of grass and clover from five experimental pots with respective technosol mixtures. Control pots are filled with topsoil (TS)

3.1.4 Plant tissue analysis

The macronutrient content in plant tissue is shown in Table 4. The N levels in all grasses were very low, as compared to the adequate levels for *Lolium perenne* (Reuter & Robinson 1997), apart from grass in T2. The fact that plant leaf length and biomass was negatively correlated with soil C:N ratio indicates that the plant communities on these soils are limited by N. The C:N ratio in these new soils may change quite rapidly, due to various different forms of organic material, presence of recalcitrant C and also due to changes in pH (Monserie et al. 2009; Panico et al. 2019). The levels of P, K, S, Na in grass were adequate in all mixtures; content of Ca and Mg was high both in technosols and natural topsoil (Reuter & Robinson 1997). The N levels in clover were also below adequate levels in all treatments. P levels in clover were adequate in TS, T7 and T4. K was present in sufficient amounts in all treatments; Na was higher than adequate (potentially toxic) in all technosol mixtures, and in topsoil, the levels were acceptable. Ca and Mg were also adequate to high, both in technosols and natural topsoil. Further data from the plant tissue analysis can be found in the supplement (S1).

The fact that nitrogen levels in plant tissue were critically low (apart from T2), although the total nitrogen content in the technosols is satisfactory (Table 6), can be attributed to the fact that there are low amounts of readily available nitrogen (see the data in supplement S2). This is most likely the result of the biological community not fully functioning in the rootzone yet; consequently, the nutrients aren't being recycled effectively (Epelde et al. 2019; Li et al. 2015).

Table 4 Selected results from plant tissue analysis

Crop	Grass				Clover			
Nutrient	N (%)	P (%)	K (%)	Na (%)	N (%)	P (%)	K (%)	Na (%)
T1	0.82	0.305	2.94	0.35	0.8	0.241	2.56	1.58
T2	2.95	0.25	3.43	0.70	N/A	N/A	N/A	N/A
T3	0.76	0.326	3.04	0.62	1.53	0.292	2.88	1.43
T4	0.75	0.292	2.54	0.87	2.0	0.3	2.56	1.69
T5	0.72	0.256	2.33	0.88	1.8	0.142	2.32	2.29
T6	0.96	0.339	3.5	0.58	2.9	0.2	3.5	1.14
T7	0.75	0.332	2.45	0.66	1.52	0.414	2.73	2.47
TS	0.97	0.329	2.85	0.38	1.53	0.368	2.06	0.76

Note: numbers signify the average nutrient content in plant tissue in dry weight percentage. N/A indicates that there was not enough biomass for tissue analysis.

3.1.5 Cost estimate

The main cost associated with technosol manufacturing is the cost of transport and mixing of materials with the row turner. The cost of topsoil transport is generally equal or higher than the cost of transport of the materials used for technosols; therefore, the cost of mixing the substrates presents the only extra expense. The cost estimate for each of the considered technosols can be seen in Table 5.

Table 5 Cost estimate (per m^3) for acquisition of material and preparation of the seven technosols and topsoil (TS)

Soil	Cost without mixing (AUD)	Cost including mixing (AUD)
T1	13.25	23.25
T2	11.92	21.92
T3	10.65	20.65
T4	11.37	21.37
T5	12.55	22.55
T6	13.65	23.65
T7	12.05	22.05
TS	12.73	12.73

Note: TS does not require mixing; therefore, the cost includes only transport.

3.2 Field trial

The initial chemical analysis of technosol mixtures prior to spreading them showed high initial pH in all mixtures, as well as high ECEC. Most macronutrients, such as P, K, Ca and Mg, were higher in technosols than in TS, as can be seen in Table 6. The T2 and T4, which contain FA in different ratios, had high pH and relatively high Mg content in relation to Ca, which could negatively affect plant nutrient supply. On the other hand, the high CEC of these soils signifies that they have a large buffering capacity, which may eliminate these issues. Complete results from the initial analysis can be found in the supplement (S2).

Table 6 Selected results from the initial analysis of the technosol mixtures and natural topsoil (TS) used in the field trial

	Sol P (mg/kg)	S (mg/kg)	pH	EC (dS/m)	ECEC ($cmol_+$/kg)	Ex Ca (mg/kg)	Ex Mg (mg/kg)	Ex K (mg/kg)	Ex Na (mg/kg)	TC (%)	TN (%)
FT1	48.40	45.07	7.93	0.33	16.62	2,130	407	816	124	3.42	0.22
FT2	7.17	168.26	8.22	0.90	27.74	2,463	1,130	780	949	4.06	0.17
FT3	22.45	116.04	7.43	0.81	24.09	2,436	873	1,049	474	3.72	0.24
FT4	20.05	100.80	8.38	0.67	30.45	3,238	1,076	1,033	640	4.97	0.25
TS	1.02	38.10	5.79	0.17	9.25	717	539	150	173	3.09	0.15

The grass growth after a month of trial duration was highest in FT1, where it reached 12.6 cm on average. In FT2, the grass length was only 8 cm on average, while in FT3 and FT4, it was comparable to the TS. Clover leaf length ranged from 2 to 3 cm in all treatments. Average plant growth after one month can be seen in Figure 5. The grass leaf length was significantly (negatively) correlated with the C:N ratio and positively correlated with extractable P in the soil (p = 0.0002 and p = 0.0004, respectively; Figure 6).

The lower plant growth in FT2 was presumably caused by a combination of low amounts of soluble P, high pH and Ca:Mg ratio. The high pH, which is typical for technosols containing FA, makes some nutrients, such as P, less available to plants (Leclerc 2003).

Further research is focused on changes in soil BD, the soil aggregate stability, soil water retention and saturated hydraulic conductivity. The results from this research have not been finalised and are therefore not part of this paper. Long-term monitoring of this trial is crucial, as soil properties of technosols can change dramatically over time (Panico et al. 2019). After five years, all the soil conditions and plant growth will be reassessed and further trials with animal grazing will take place in order to establish whether the soils are suitable for the target land use.

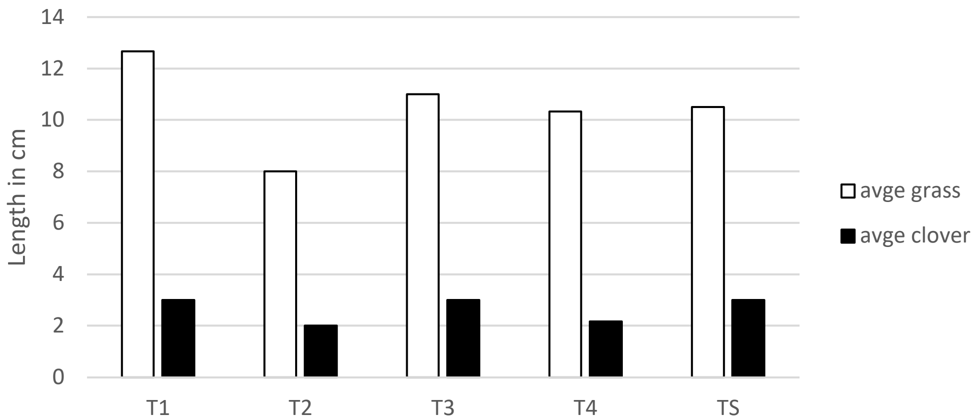

Figure 5 Average length of grass and clover above-ground parts after one month of trial duration

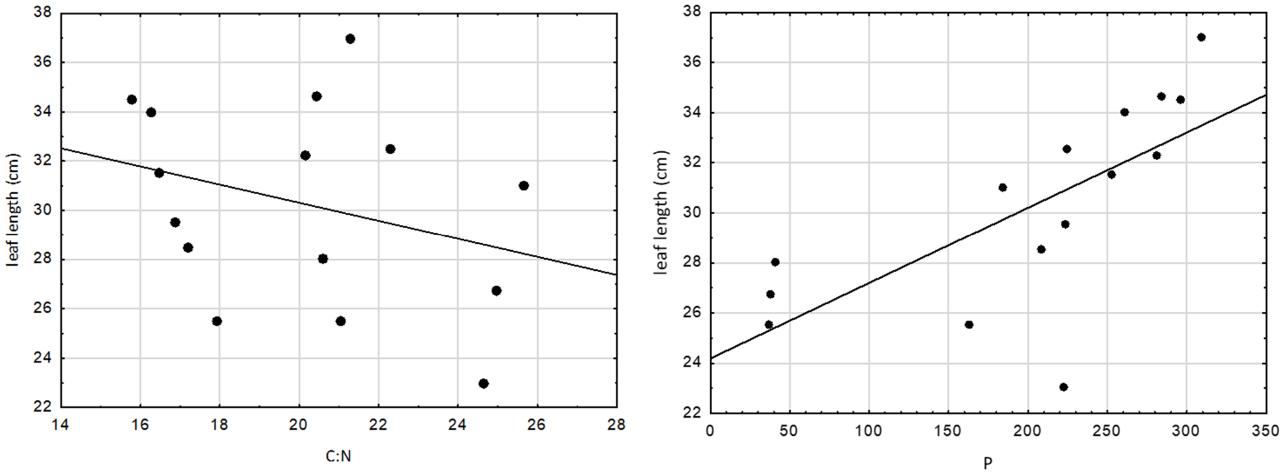

Figure 6 Scatter plot showing the relationship between (a) C:N ratio and (b) extractable P of the soil and the grass leaf length in the greenhouse experiment

4 Conclusion

Technosols manufactured from locally sourced materials have been successfully used in a greenhouse experiment, in which we tested mostly plant growth parameters and biomass. The technosol mixtures that showed better plant growth than natural topsoil were then transferred to the field, where they are being monitored in a long-term mine rehabilitation trial. Early results from the field trial suggest that the plant growth is comparable in our technosol mixtures and in natural topsoil. The best grass and clover growth in the greenhouse and in the first month of trial duration was observed in T1, which contains subsoil from the mine and green waste compost. This mixture also had the highest amount of soluble P and highest Ca:Mg ratio. However, long-term monitoring of soil chemical and physical properties, soil structure, carbon sequestration and of plant growth in these technosols is needed to determine whether they are a suitable medium for mine rehabilitation in the long-term.

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