Coal discard dump rehabilitation using kenaf: proof of concept study

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Abstract. Coal discards are a side effect from coal mining and beneficiation. There are currently billions of tons of discards, with South Africa reporting over 1000 Mt, mainly fine and ultra fine coals. This number increases annually by 60Mt, creating a twofold situation of a) potential lost product and b) cost intensive future rehabilitation. This paper focusses on the latter, presenting an alternative way to rehabilitate current discard dumps aiming to create a new market whilst enhancing job security. During this study, coal discards from two sites near Witbank, South Africa, were sampled and analysed for quality. It was found that there was no difference in plant growth and physiology between the plants grown in the three different samples (pure soil or discard coal and a 50/50 mixture). Germination time was measured to be between three and four days for all the repetitions and samples. Kenaf showed the propensity for moderate metal absorption including heavy metals and rare earth elements (REEs). These metals concentrated in different parts of the plant with REEs being mostly absorbed in the roots of the plants while other metals will diffuse into the stems and leaves of the Kenaf. It opens possibilities for additional metal recovery.

1 Introduction

Coal still contributed 26.8% of the world energy demand, increasing to 40% for electricity generation [1]. To supply these this demand, coal production continue to rise and consequently produce a greater volume of waste, often referred to as tailings, which are being disposed of in tailings facilities. Another significant contributor to tailings generation is the automation of mining processes [2]. Collectively, these factors result in approximately 60 Mt of fine coal discards annually in South Africa. If improperly managed or rehabilitated, tailing disposal sites pose substantial environmental risks, including spontaneous combustion, acid mine drainage (AMD), and groundwater contamination [2]. Additional challenges include safety hazards, health risks, and the occupation of land that could otherwise be valuable [3,4].

Historically, little effort was devoted to exploring methods of beneficiating tailings, largely due to their classification as low-quality or excessively fine material. As a result, the accumulation of tailings continues to grow [4]. The utilization of fine and ultra-fine discard coal is expected to gain prominence as South Africa's coal reserves become increasingly depleted, and the quality of mined coal diminishes [5]. In this context, the composition and

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quality of coal discards in South Africa have been investigated, as summarized in Table 1 [4,6]. The findings highlight the diverse characteristics of fine coal discards from slurry ponds, which generally exhibit high ash content, low calorific values, limited volatile matter, and elevated sulphur levels compared to currently utilized coal [7]. Although certain power stations, such as the Lethabo facility in the Free State Province, successfully operate using low-quality coal with calorific values of 15–16 MJ/kg and ash yields of approximately 42%, most discards are unsuitable for direct reprocessing and therefore require rehabilitation [8,4,7].

Table 1: Quality of South African discard coal [4,5,7].

Quality	Value
Ash yield (%)	10 – 70
Calorific Value (MJ/kg)	8 – 26
Volatiles (%)	8 – 30
Sulphur content (%)	0.8 – 8

One approach to rehabilitating coal discard sites is their conversion into farmland. While these sites are unsuitable for cultivating crops intended for human consumption due to the excessive absorption of metals and other toxic elements [9], they are well-suited for growing plants that can be harvested for raw materials, such as fibres. An exemplary candidate for this purpose is Hibiscus cannabinus, commonly known as kenaf [10]. Kenaf is a highly versatile plant noted for its rapid growth and substantial biomass yield, which are essential for achieving quick vegetation cover. The deep root of this vegetation is critical for mitigating dust dispersion, controlling sediment runoff, and increasing soil health.

Kenaf is distinguished by its tall, fibrous stalks that can grow up to 4 meters within just a few months. It flourishes in tropical and subtropical climates, making it suitable for cultivation across diverse regions. Its fibres are renowned for their strength and durability, making them ideal for applications in textiles, paper production, and bio-composites [11]. Additionally, kenaf is environmentally advantageous, as it requires minimal use of pesticides and fertilizers.

This study investigates the feasibility of cultivating kenaf in coal tailings and assesses its metal absorption potential within such environments. The specific objectives include analysing physiological parameters with a Multi-Function Plant Efficiency Analyser (M-PEA) fluorimeter, determining chlorophyll content, and conducting comprehensive initial and final analyses of soil and plant samples.

2 Materials and methods

2.1 Soils treatments

Coal discards were sourced from two different discard dumps near eMalahleni in the Mpumalanga province of South Africa and used as received. A proximate analysis and calorific value test were done on the coal discards. These results, shown in Table 2, clearly indicate the poor quality of the coal samples, rendering it as final discards. Additional processing of these coal samples will not yield any feasible results, and hence this samples were ideal for rehabilitation testing.

Table 2: Proximate analysis of discard coal.

Quality	Coal A	Coal B	Standard
Ash yield (%)	58.08	57.93	SANS 131:1997
Calorific Value (MJ/kg)	10.74	10.78	SANS 1928:2009
Volatiles (%)	15.33	16.87	SANS 50:1998
Moisture (%)	1.30	1.43	SANS 5925:2007
Fixed carbon (%)	25.29	23.77	By Difference

Five different soil profiles were prepared and placed in different 30 cm diameter pots for the kenaf to be planted. These soil profiles were as follow:

- Pure commercial soil
- Pure coal, both for coal A and coal B
- 50% weight mixture of the commercial soil and coal, again for both coal A and coal B.

After planting the seeds (commercial grade), the pots (two of each profile) were placed in a controlled environment within a greenhouse with a day and night air temperature of 26°C and 18°C respectively, having a 13-hour day photoperiod and a dark period of 11-hours. The pots were manually watered every 2 to 3 days throughout the 8-week experimental period to ensure adequate soil moisture. Germination rates were recorded 10-days after sowing within the uniform environmental conditions.

In vivo analysis of the fluorescence kinetics of polyphasic chlorophyll a, indicative of reduction in primary quinone electron acceptor (QA) in photosystem II (PSII), was performed using an M-PEA fluorimeter (Hansatech Instrument Ltd., King's Lynn). The leaves were dark-adapted for 1 hour prior to measurements. Fluorescence was recorded on the adaxial side of three fully expanded leaves per plant from three different plants per treatment. Fluorescence was induced using red actinic light at an intensity of 3000 µmol photons m^{-2} s^{-1}, delivered by three 5 mm-diameter light-emitting diodes with a 12-bit resolution and 1-second duration. Fluorescence transients were processed using the M-PEA Plus software (version 1.10, Hansatech Instrument Ltd.). Data points were captured at intervals ranging from 0.02 ms to 0.05 ms for the initial O step (Fo), 2 ms for the J step, 30 ms for the I step, and 300 ms for the P step (Fm) of the different growth stages. The transient OJIP fluorescence, plotted on a logarithmic timescale, reflected the typical rise from minimal fluorescence (Fo, where all PSII reaction centres are open) to maximum fluorescence (Fm, where all PSII reaction centres are closed or reduced).). The Fv/Fm ratio, calculated from Fo and Fm (Fv is the variable fluorescence calculated as Fm – Fo), was used as an indicator of the PSII quantum efficiency [12]. The Fv/Fm ratio is a widely used indicator of the maximum quantum efficiency of PSII photochemistry. It reflects how efficiently PSII can convert absorbed light into chemical energy under optimal conditions, which is an indicator of the ability of a plant to grow healthy in the environment it was planted.

At the end of the growing cycle, the plants were removed from the pots, weighed and dried in an oven at 80°C for 3 days. The dry mass was recorded and used to determine the total biomass. In addition, the plants were sent for analysis to determine the metal absorption into the plant by Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

3 Results

3.1 Sample analysis

Sample analysis was done for each of the five treatments. The pH (pH analyser) and density (by mass) results are shown in Table 3.

Table 3: Soil analysis.

Sample treatment	pH		Bulk density (g/ml)	
	Prior to planting	After harvest	Prior to planting	After harvest
Pure soil	7.19	7.11	1.34	1.36
Coal A	6.11	6.19	1.18	1.07
Coal B	5.98	6.05	0.91	0.94
Coal A mixture	6.52	6.65	1.31	1.36
Coal B mixture	6.81	6.88	1.31	1.35

Table 3 shows the rehabilitation potential of kenaf. In terms of the pH, there is an overall movement to neutralize the soils in which the plant growth occurred. The pure coal as well as coal/soil mixtures all tended to be slightly acidic. After harvesting the kenaf, most of the samples were still acidic, but less so than the initial values. The opposite can be seen for the pure soil, which initially was found to be slightly more basic. After harvesting, the pH for the pure soil decreased minimally to be closer to the absolute neutral point. In a similar way, apart from Coal A, the bulk density of the samples increased slightly after harvesting, this shows how kenaf can help to combat dust formation and hence lower the possibility of particulate pollution.

3.2 Plant growth

Throughout this study plant growth was defined as the rate by which the stem of the plant has grown in both the height of the stem and the thickness thereof, as well as the final height of the stem. This is summarized in Figures 1 and 2. Initially it seems as though the growth rate of kenaf performs best for mixtures of coal and soil. This is evident from the faster growth rate and higher plant height after four weeks. However, after six weeks, it seems as if there are no real difference in plant growth height for all samples, apart from the kenaf planted in pure Coal B. This may be attributed to the complexity and abundance of the nutrients in coal which are initially difficult to for the plant to absorb. After some time, there are still enough nutrients available in the coal rich samples to continuously aid in plant growth, causing the plant to yield similar results after six weeks than was the case for the plants in the pure soils.

The significance of these findings relates to the possibility of rehabilitating coal discard dumps without having to import and mix rich soils into the coal. By ploughing the surface of the dumps, the soil will be suitable for direct planting of the crop, followed by normal irrigation.

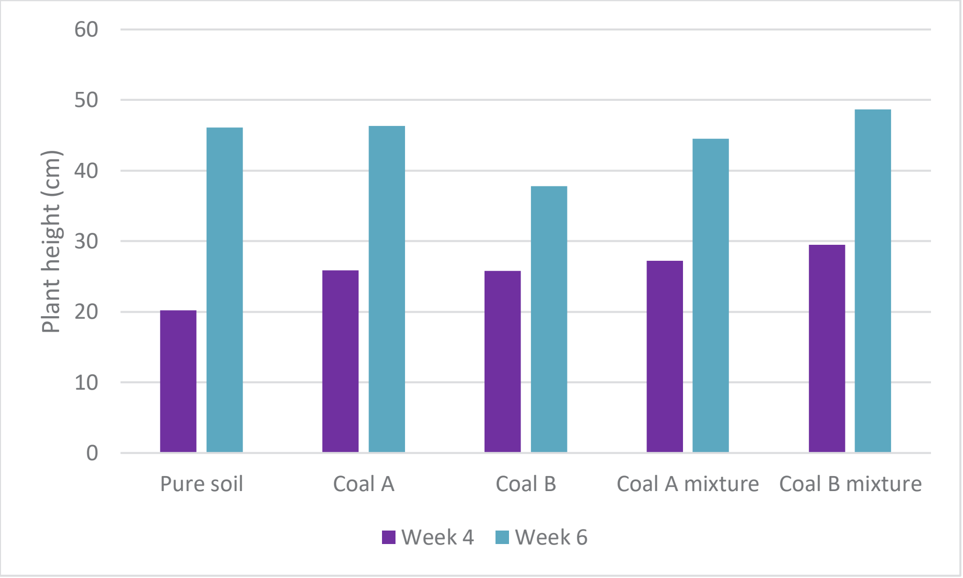

Fig 1: Plant height after 4- and 6-weeks 'growth for different samples.

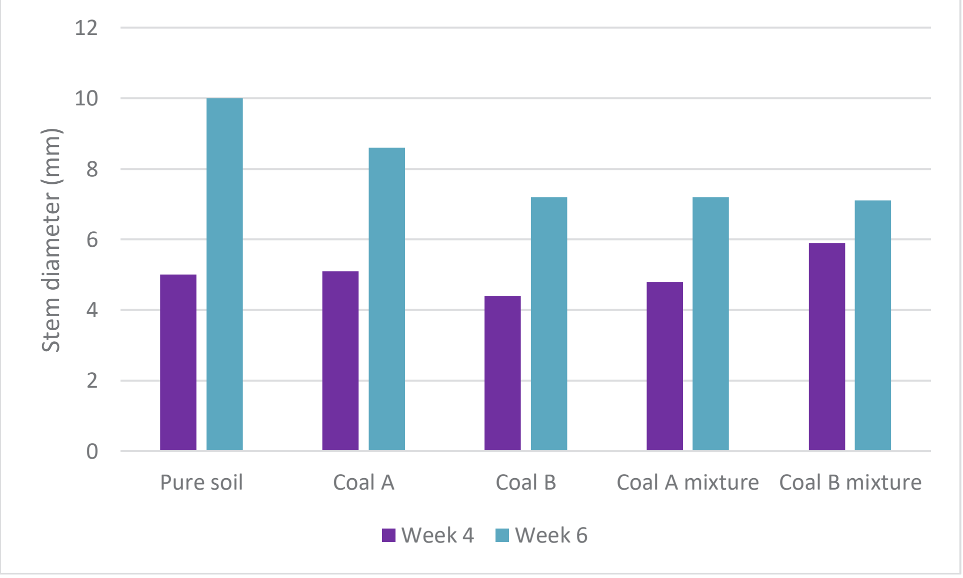

Fig 2: Plant **s**tem diameter after 4- and 6-weeks' growth for different samples.

Chlorophyll a fluorescence is another powerful, non-invasive tool used to assess a plant's growth and physiological status. It is used to determine the different growth stages of plants to determine if the plant is experiencing any additional stress when there are changes in the immediate environment. For this study, it was used to determine if there are any additional stresses in the plants growing in the five different sample treatments. Figure 3 shows the OJIP-curve, analysing the dynamics of energy transfer and electron transport within the photosynthetic apparatus, providing insights into the health and efficiency of the photosynthetic process [12]. It shows the different stages as follows:

- O: Origin (the initial fluorescence level when the light is first turned on)
- J: A point on the curve that appears after a few milliseconds, indicating the reduction of the primary QA in PSII
- I: A point that appears after the J phase, indicating further reduction processes within PSII
- P: Peak (the maximum fluorescence level reached during the induction curve).

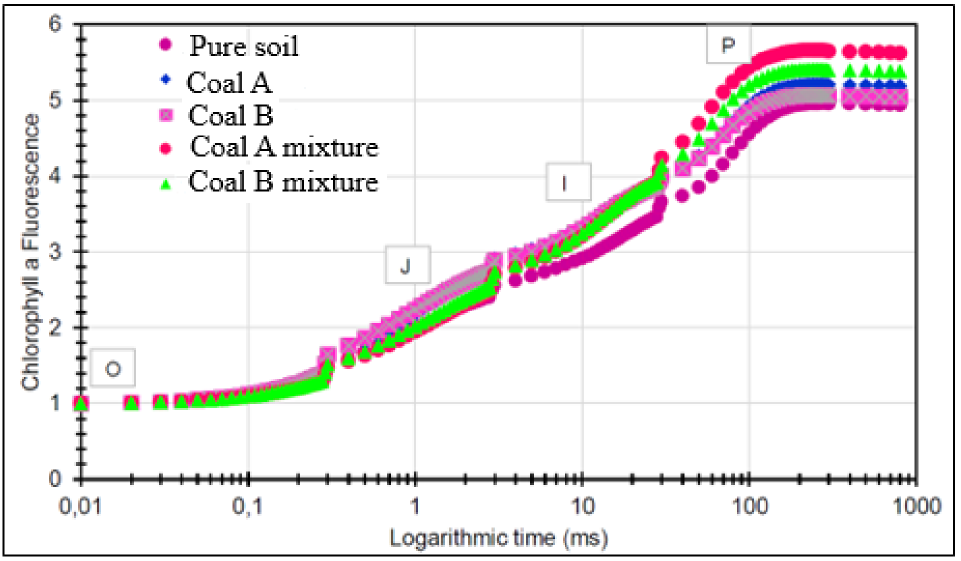

Fig 3: Chlorophyll a fluorescence measurement in different growth mediums.

Each point labelled O, J, I, and P on the graph in Figure 3 represents potential stress factors influencing plant growth. A flattening of the graph at any of these points signifies that the plant is experiencing growth stress, likely attributable to changes in soil composition. For all the tested samples, the graph maintains a consistent shape, with no flattening observed at any stress points. This consistency indicates that, compared to standard soil, kenaf does not encounter additional stress when cultivated in coal tailings or their mixtures. These findings further underscore the potential of kenaf as a viable rehabilitation crop for direct planting in coal tailings.

This observation is corroborated by the maximum quantum yield efficiency and the total performance index of the plants across the samples, as shown in Figures 4 and 5. The maximum quantum yield efficiency (Fv/Fm) quantifies the effectiveness with which light absorbed by chlorophyll is converted into chemical energy during photosynthesis. For healthy plants, this value typically falls within the range of 0.7 to 0.9, with an optimal value of 0.83 [8]. Deviations from this range often indicate disruptions in the Photosynthetic Electron Transport Chain [12].

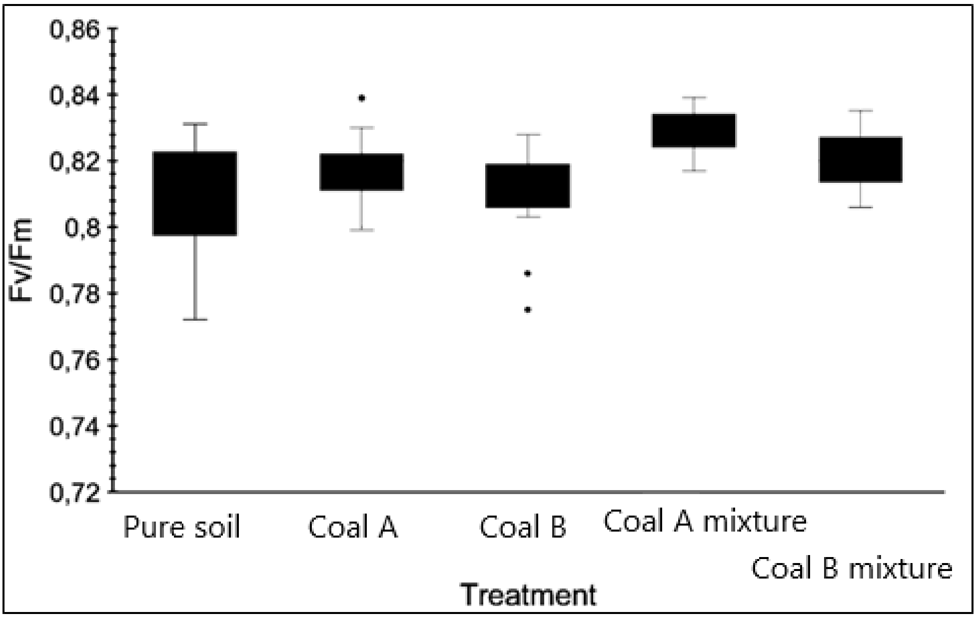

Fig 4: Maximum quantum yield efficiency for the growth of kenaf in different mediums.

Figure 4 shows that the response for all the different plants varied around the optimum value of 0.83, indicating that photosynthesis occurred at a similar rate in all the plants. It serves as a further indication that no stress was detected within the plants and that the growth potential will be the same, irrespective of planting it in pure soil, pure coal tailings or a mixture of the two.

The total performance index (PI) of the plant is a comprehensive parameter that integrates several aspects of photosynthetic performance. These aspects include (a) the efficiency of light absorption by chlorophyll, (b) the efficiency of energy transfer from chlorophyll to the reaction centres, and (c) efficiency of electron transport within PSII. An optimal PI index value for healthy plants typically ranges from 2 to 10 [8], indicating efficient photosynthetic performance. Lower values suggest that the plant species are experiencing stress, while PI values higher than 10 indicate that the plant is experiencing optimal conditions for photosynthesis and overall health. This is a positive sign of robust growth and high productivity potential [12].

From Figure 5 shows that for all samples, the PI values are within the optimum range or higher. It supports the previous findings that all five samples are ideal for the growth of kenaf, which supports the hypothesis of kenaf being suitable for use as a rehabilitation crop on coal discard dumps.

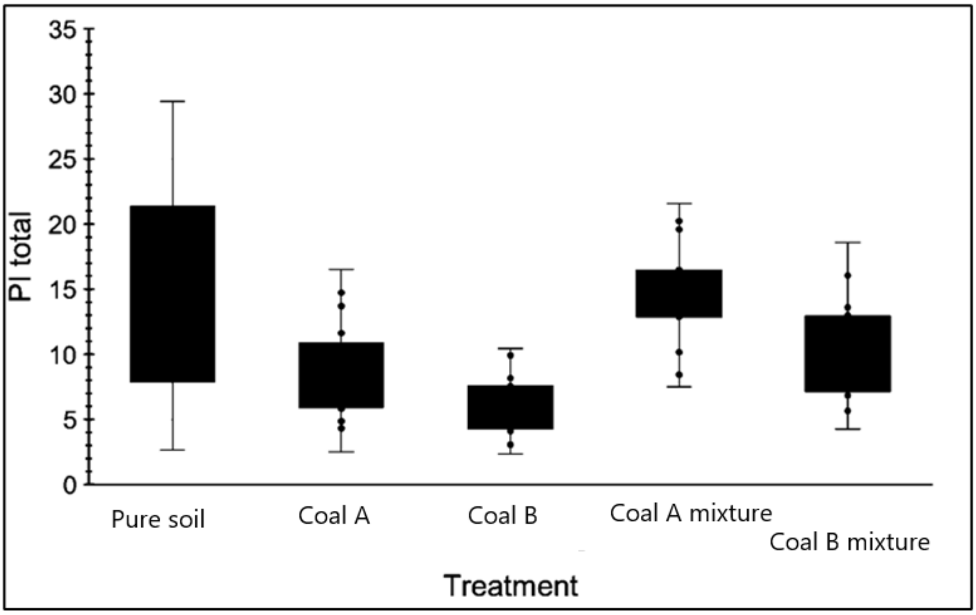

Fig 5: Maximum quantum yield efficiency for the growth of kenaf in different mediums.

3.3 Absorption potential

Analyses of the studied samples and plants indicate that kenaf can absorb heavy metals, light rare earth elements (LREEs), and heavy rare earth elements (HREEs). Grab samples of the different treatments were submitted for analysis both before planting and after harvesting the crops. Similarly, pieces of the roots, leaves and stems were sampled and sent for similar analysis. Due to the vast range of metal species detected, only the most prominent and/or important ones are highlighted in this study.

3.3.1 Heavy metals

The results for lead (Pb), cadmium (Cd), mercury (Hg) and arsenic (As) analysis done on both the soil treatments and the plants, after harvesting, are shown in Table 4 and Figure 6 respectively. From Table 4, there is a general reduction in the metal content of the samples at the completion of the tests, compared to the initial amounts at the start. This is however not always the case. In some instances, the sample analysis done after harvesting shows an increase in the metal amounts compared to the initial value. This increase in metal content is attributed to the heterogeneous nature of both the soil and the coal.

The plants did however show an uptake of metal species, as indicated by Figure 6. The concentration range of metal species at the completion of the tests in the plants are as follows:

- Lead – 2.3 to 16.1 mg/kg
- Cadmium – 0.09 to 0.38 mg/kg
- Mercury – 0.25 to 0.49 mg/kg
- Arsenic – 1.30 to 3.90 mg/kg

It was further found from Figure 6 that the heavy metals uptake into the plants were similar, irrespective of the substrate used. Lead and arsenic tend to accumulate more in the roots, where the other metals disperse more evenly across the roots, stem and leaves of the plant.

Table 4: Sample analysis for heavy metals.

Heavy metal	Concentration (mg/kg)									
	Soil		Coal A		Coal B		Coal A mixture		Coal B mixture	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Pb	2.50	4.10	26.0	27.5	32.0	19.0	10.5	5.20	14.8	5.10
Cd	0.02	0.29	0.28	0.52	0.18	0.29	0.13	0.03	0.28	0.03
Hg	0.28	0.19	0.56	0.48	0.64	1.09	0.42	0.18	0.51	0.22
As	2.00	1.90	4.80	6.10	27.0	13.5	3.00	2.50	7.50	5.50

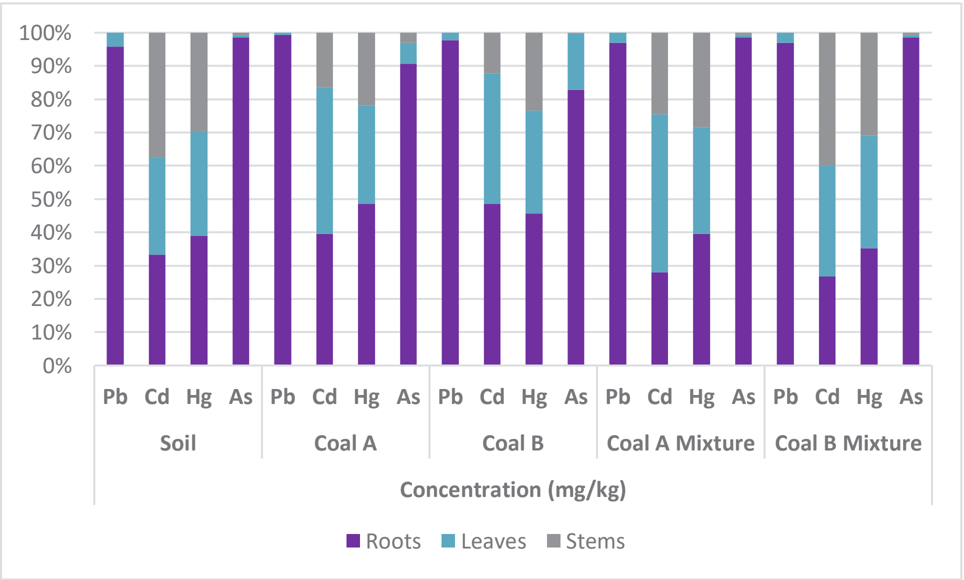

Fig 6: Heavy metal dispersion after absorption into kenaf.

3.3.2 Light rare earth elements

For light rare earth elements (LREEs), cerium (Ce), praseodymium (Pr), neodymium (Nd) and samarium (Sm) are reported. From the treatment sample analysis in Table 5 it can be concluded that absorption of LREEs is constant across all the different samples. It was noted that the contracted laboratory used to do these analyses, returned a zero value for all LREEs for the soil/coal A mixture. This is assumed to be incorrect and hence no final values for this sample treatment are reported.

Figure 7 shows that for all the cases, the LREEs were absorbed into the roots of the plant with no LREEs detected in either the leaves or the stems. It holds true for all samples. This is a very important finding since it opens the possibility to further process the roots of the kenaf plant to extract the valuable metals after harvesting. It therefore serves as both a rehabilitation and extraction vehicle. The concentration ranges of the LREEs within the plants were found to be:

- Cerium – 9.0 tot 62.0 mg/kg
- Praseodymium – 1.1 to 6.4 mg/kg
- Neodymium – 4.1 to 23.2 mg/kg
- Samarium – 0.7 to 3.8 mg/kg.

Table 5: Treatment sample analysis for LREEs.

Light REE	Concentration (mg/kg)									
	Soil		Coal A		Coal B		Coal A mixture		Coal B mixture	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Ce	18.1	18.2	112	88.2	95.3	73.8	42.1	-	59.1	22.4
Pr	2.09	1.98	11.4	9.62	9.97	7.52	5.13	-	6.23	2.31
Nd	8.32	8.28	42.5	36.8	36.7	28.2	18.1	-	21.7	9.83
Sm	1.18	1.18	6.78	5.84	5.78	4.45	2.98	-	3.50	1.28

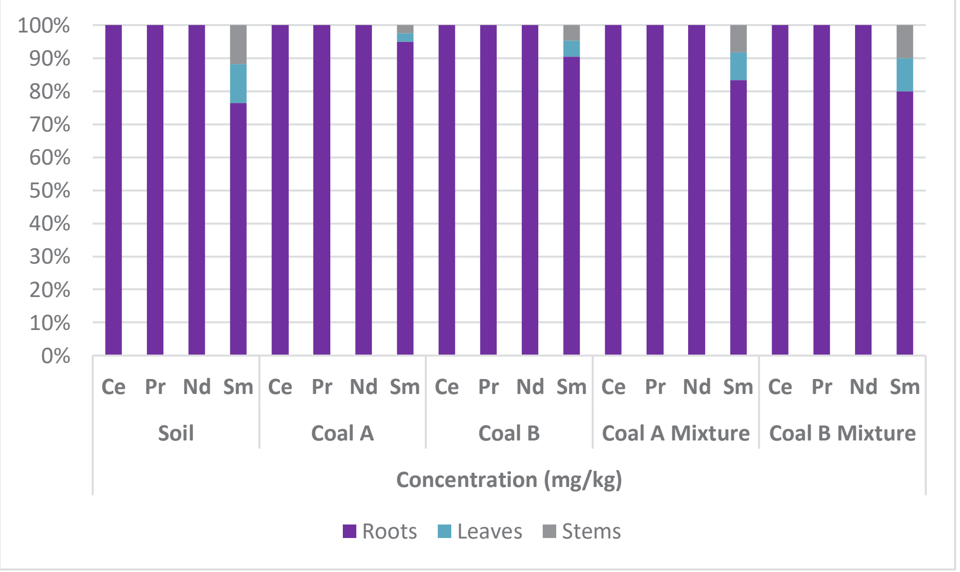

Fig 7: LREE dispersion after absorption into kenaf.

3.3.3 Heavy rare earth elements

The heavy rare earth elements (HREEs) of terbium, dysprosium, holmium, and erbium follow the same trend as the light rare earth elements in both the treatment sample analysis (Table 6) and the plant dispersion analysis (Figure 8). It shows an absorption of HREEs into mainly the roots of the plant. There are however some elements present in the leaves and the stems of the different plant material, but in low enough concentrations that the possibility still exists to extract these elements from the roots. The concentration ranges absorbed into the plants are:

- Terbium – 0.1 to 1.3 mg/kg
- Dysprosium – 0.38 to 1.4 mg/kg
- Holmium – 0.09 to 0.66 mg/kg
- Erbium – 0.24 to 1.75 mg/kg.

Table 6: Sample analysis for HREEs.

Heavy REE	Concentration (mg/kg)									
	Soil		Coal A		Coal B		Coal A mixture		Coal B mixture	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Tb	0.17	0.17	1.12	1.02	0.93	0.68	0.48	0.04	0.51	0.20
Dy	0.80	0.95	5.86	5.23	4.28	3.76	2.61	0.02	2.58	1.04
Ho	0.13	0.17	1.12	0.97	0.78	0.69	0.41	0.04	0.53	0.19
Er	0.45	0.48	2.97	2.76	2.15	2.14	1.23	0.03	1.26	0.61

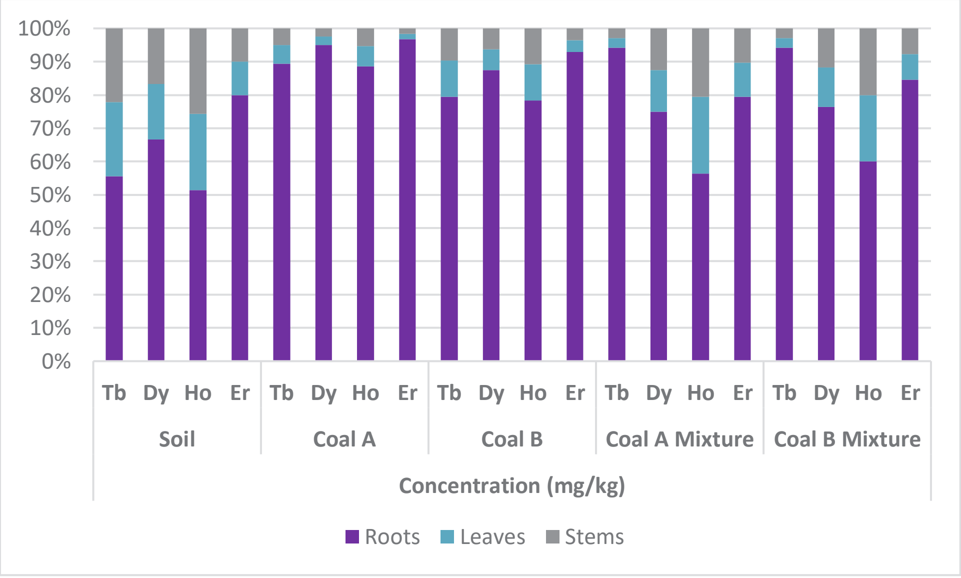

Fig 8: HREE dispersion after absorption into kenaf.

4 Conclusions

This study showed clear evidence that kenaf can be suitable to be used as a rehabilitation crop for coal discard dumps in South Africa. Analysis of plant physiological responses demonstrated that kenaf exhibits comparable growth potential in pure coal discards and in mixtures of coal discard with soil. This finding supports the feasibility of directly sowing kenaf onto coal discard dumps. During the life cycle of the plants, it showed potential to rehabilitate the soils it was planted in by a) creating pseudo large particles through its extensive root systems while b) absorbing heavy metals, LREEs as well as HREEs. This all contribute to kenaf's ability to neutralise different samples.

During absorptions, both the LREEs and the HREEs tend to concentrate mainly in the roots of the kenaf which allows for possible extraction in adjacent processes. The heavy metals do however disperse more heterogeneous within the plant's roots, leaves and stems which does not allow for further processing.

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References

1. IEA. World Energy Balances: Overview, IEA, Paris https://www.iea.org/reports/world-energy-balances-overview, License: CC BY 4.0 (2021)
2. Le Roux, M., Campbell, Q.P., Watermeyer, M. & De Oliviera, C. The optimization of an improved method of fine coal dewatering. Minerals Engineering 18(9) P931-934 (2005).
3. Karombo, T. South Africa has the world's highest number of environmentally dangerous tailing dams. https://qz.com/africa/1786297/south-africa-has-most-environmentally-dangerous-tailing-dams. (2020)
4. Belaid, M., Falcon, R. & Vainikka, P. Pulverized coal versus circulating fluidized-bed boilers perspectives and challenges for South Africa. South African Journal of Chemical Engineering, 19(3): 77. (2014).
5. Jeffrey, L.S. Characterization of the coal resources of South Africa. The Journal of The South African Institute of Mining and Metallurgy: 95-102. (2005).
6. DMRE. National inventory of discard and duff coal. http://www.dmre.gov.za/coal_discard_report. (2001).
7. Wagner, N.J. The characterization of weathered discard coals and their behaviour during combustion. Fuel, 87(8-9):1687-1697. (2008).
8. Pierce, W. & Le Roux, M. Statistics of utility-scale power generation in South Africa. CSIR Energy Centre. South Africa. (2023).
9. Zocche J.J., Rohr P., Damiani A.P., Leffa D.D., Martins M.C., Zocche C.M., et al. Elemental composition of vegetables cultivated over coal-mining waste. An Acad Bras Ciênc. 89(3):2383–98. (2017).
10. Webber, C.L. and Bledsoe, V.K. Kenaf yield components and plant composition. In: Janick, J. and Whipkey, A. (eds). Trends in new crops and new uses. ASHS Press. Alexandria, VA. pp. 348-357. (2002).
11. Coetzee, R., Characterization of kenaf (Hibiscus cannabinus L.) cultivars in South Africa. M.Sc. dissertation, University of the Free State. Bloemfontein. South Africa. (2004).

12. Govindjee. Chlorophyll a fluorescence: a bit of basics and history. In Chlorophyll a fluorescence: a signature of photosynthesis. Dordrecht: Springer Netherlands. Pp 1-41. (2004).