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Posted Date: 24 June 2024

doi: 10.20944/preprints202406.1608.v1

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Prospect for Fine and Coarse Coal Waste Deployment for a Constructed Technosol and *Eragrostis Tef* Growth

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Abstract: The aim of this study was to evaluate soil properties and *Eragrostis tef* (teff) growth on Technosols produced from coarse and fine coal wastes from Moatize Mine, Mozambique. The experiment was performed in triplicate in 30 L containers filled with different substrate conditions, composed of fine coal waste, coarse coal waste, agricultural soil, and sewage sludge as an organic matter source. The soil analyses included bulk density, available water capacity, permeability, and fertility. Plant growth was monitored for biomass production and plant tissue composition. All the substrates presented a good available water capacity and a proper drainage condition. Regarding the soil fertility, there were shortages of potassium and boron in the substrates composed exclusively of coal wastes, which was reflected in the composition of the plant tissue. Even so, plant growth was statistically equivalent to the control in all conditions, except for the substrate produced exclusively with fine coal waste and sewage sludge, which presented a better performance. Technosols are an alternative for reducing the final mine waste volume, and *Eragrostis tef* used as a means for land use after the mining process, with social gains, and as a tool in an ecological process for restoring coal mining sites.

Keywords: coal tailings; ecological restoration; mine waste management; mine soil; teff

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1. Introduction

Sustainability practices are increasingly being applied to coal mining and are essential throughout all stages of the production cycle [1–4]. This includes implementing cleaner technologies, saving water, reducing greenhouse gas emissions, proper exploitation, improving waste management, and restoring degraded areas [5–8]. In waste management, exploring options for reuse and recycling is crucial [9,10]. If these options are not feasible, it is important to properly dispose of the coal waste, restore the disposal sites, and address any potential environmental hazards that may result [10–12].

Coal waste discharge can occur through backfill systems, pit reshaping, surface piles, or in dams, depending on the type of mining and waste produced. The volume and its characteristics vary according to the geology of the extraction site, the mineral contents as well as the exploitation and coal preparation procedures needed to meet market specifications [13,14]. Coal wastes resulting from operations such as jigging and dense medium cyclones are referred to as "coarse waste" and waste materials derived from a parallel circuit in unit operations such as spirals and flotation as "fine waste". Pulp containing fine coal may be pumped to dams or settling basins or, alternatively, dewatered and destined for dry stacking [15,16]. Both surface and dam discharge are environmental liabilities since they occupy large areas, harm vegetal coverage, alter ecological processes, and pose a risk of soil, water, and air contamination in the short and long term [5,11,17,18].

 doi:10.20944/preprints202406.1608.v1

The most common recovery process in areas degraded by mining and waste discharge sites consists of topographical reshaping and soil coverage for revegetation [19,20]. A lending area is usually used, leading to another environmental impact due to removing this site's native soil [21]. An alternative to natural soils is the Technosols derived from a mixture of anthropic materials whose properties and pedogenesis depend on their origin [22]. The materials used can be residues from the mining activity itself, corrected with other organic and inorganic materials [23–28]. The production involves selection, characterization, material preparation and conditioning, considering that soils must have: a pH close to neutral, a proper physical structure and nutrient contents and organic material able to sustain life [21,29]. The constructed soil will have its pedogenesis, as well as successional ecological steps that depend on the materials employed in its production [30,31] and the chosen vegetal coverage [32].

Table 1 presents a resumé of past studies of constructed soils using coal wastes as the main component. All studies were conducted with fine wastes or materials that were comminuted for pyrite separation. Indeed, if the substrate has an acid generation potential, minerals that generate alkalinity must be added to achieve neutrality. Therefore, this work aims to advance the subject with two peculiarities: (a) the coal tailings from the Moatize-Mozambique mine have an acid-base balance close to neutrality [33]; and (b) the Technosols are composed by including fine and coarse tailings in different configurations. None of the previous works has evaluated the possibility of simultaneous use of coarse and fine tailings.

Table 1. Research related to the application of Technosols with mineral coal wastes.

Country	Amendments	Vegetation	Reference
Brazil	Steel slag and sewage sludge	*Sorghum bicolor*	Firpo *et al.*, 2015
Brazil	Husk ash, steel slag, and sewage sludge	*Megathyrsus maximus*	Weiler *et al.*, 2018
Mozambique	Organic compost from urban waste	*Medicago sativa*	Weiler *et al.*, 2020a
South Africa	Compost, anaerobic digester sludge and malt residue	*Eragrostis tef*	Amaral Filho *et al.*, 2020
Brazil	Husk ash, steel slag, and sewage sludge	*Avena strigosa* *Zea mays*	Firpo *et al.*, 2021
Poland	Sewage sludge, crushed stone (angular sandstone) and fly ash	Trees, shrubs, herbs and grasses	Halecki and Klatka, 2021
Brazil	Rice processing waste, poultry agroindustry sludge, gypsum	Not measured	Zocche *et al.*, 2023

We chose to use *Eragrostis tef*, also known as teff, a grass native to Africa, especially from Eritrea and Ethiopia, since it is adaptable to different environmental conditions [34]. Studies with this plant have also been conducted in Technosols by Amaral Filho [23]. It is a plant ancestrally cultivated in agroforestry systems, often in association with other yearly perennial, bushy, and arboreal cultures. It also has potential to become a vegetal species to be included in the process of ecological restoration. Ecological restoration is understood by the Society for Ecological Restoration as "the process of helping to restore an ecosystem that was degraded, harmed, or destroyed" [35].

Within this context, considering: (i) the search for more sustainable technical applications in the mineral coal production chain, (ii) the problem of the discharge of the waste produced during processing, and (iii) the need to recover areas degraded by mining, the aim of this article was to explore the potential utilization of both fine and coarse waste obtained from coal mining by creating a Technosol. This research's hypothesis is that a Technosol made from coal mining waste as the soil's mineral matrix and a source of organic material can produce a suitable soil for the growth of *Eragrostis*

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tef, helping the restoration of mine sites. The benefits of this approach may include social, environmental, and economic advantages.

2. Materials and Methods

The coal waste used in this study comes from the province of Tete, Mozambique, in Africa, which is considered one of the largest coal deposits in the southern hemisphere [36,37]. Coal wastes were collected during coal preparation of the Chipanga Layer, given that the coarse waste (1 mm < d < 50 mm) comes from the operation of dense medium cyclones while the fine waste is from the processing through spirals, elutriation (0.25 < d < 1 mm) and flotation (d < 0.25 mm). The source of the organic material used was sludge digested from the activated sludge process in a sewage water treatment plant with 52.5% of organic matter (OM) and 0.5% organic nitrogen. An agricultural soil was used as the control and is classified as a Red Nitisol [22].

Table 2 gives the information about proximate analysis, total sulfur and sulfur speciation, mineralogical composition, and acid generation behavior of both coarse and fine wastes. More complete data, including granular properties and kinetic trials conducted in humid cells can be found in Weiler et al. [33], which demonstrated that there are no metals at toxic levels that might harm its use as agricultural soil (considering the criteria of many countries in the world), nor any potential for acid mine drainage generation.

Table 2. Proximate analysis (ash, volatile matter and fixed carbon), total sulfur content and its speciation (pyritic, sulfate and organic sulfur), major and minor crystalline components and acid-base accounting balance for the fine and coarse coal wastes produced from coal beneficiation (in dry basis) of Moatize Mine, Mozambique [33].

Property	**Fine waste (< 1.0 mm)**	**Coarse waste (1.0 – 50 mm)**
Proximate analysis		
Ashes (%)	58.4	58.9
Volatile material (%)	16.6	16.5
Fixed carbon (%)	25.0	24.6
Sulfur		
Pyritic (%)	0.6	0.4
Sulfate (%)	0.2	0.1
Organic (%)	0.5	0.4
Total (%)	1.3	0.9
Crystalline compounds		
Majority	Quartz	Quartz and alumina
Minority	Calcite, hematite, and halite	Calcite and hematite
Acid generation according to modified acid-base accounting (ABA) method [38]		
AP (kg $CaCO_3$ t^{-1})	19.0	14.0
NP (kg $CaCO_3$ t^{-1})	25.3	23.5
NNP (kg $CaCO_3$ t^{-1})	+ 6.3	+ 9.5

The soil substrates were manufactured by the combined use of coal waste as raw material and sewage sludge as the source of organic matter and nutrients. The plant growth experiment was conducted in 30-liter polyvinyl chloride (PVC) containers 35 cm high and 30 cm in diameter, in which

 doi:10.20944/preprints202406.1608.v1

about 20 kg of material was added according to Figure 1. The soils were designed comprising seven configurations, each one performed in triplicate with the following composition:

I. Fine coal waste (FCW);
II. FCW + coarse coal waste (CCW), composing two seams;
III. FCW + CCW as a mixture;
IV. Agricultural soil (AS) + FCW + CCW, composing three seams;
V. AS + a mixture of FCW + CCW, composing two seams;
VI. AS +FCW + CCW as mixture; and
VII. Agricultural soil (AS) used as control.

Sewage sludge was added to obtain 3% of organic material (OM) in all the containers. It was chosen to use 3% of organic matter because it is suitable for most soils and sufficient to support plant development. In mineral surface soils, the concentrations of organic matter range, on average, from 0.5 to 5% [39]. However, a separate and preliminary study on a minor scale of Technosols with coal fines from Moatize Mine amended with 2.5% OM of organic compost from urban waste was successful for *Medicago sativa* [27]. Table 3 depicts the composition of the Technosols in terms of the mass of the materials utilized.

Table 3. Mass of components used in each composition of Technosols.

Treatment	Fine coal waste (kg)	Coarse coal waste (kg)	Soil (kg)	Sewage sludge (kg)	Total (kg)
I	18.9	-	-	1.1	20
II	7.7	11.2	-	1.1	20
III	7.7	11.2	-	1.1	20
IV	5.1	7.4	6.3	1.1	20
V	5.1	7.4	6.3	1.1	20
VI	5.1	7.4	6.3	1.1	20
VII	-	-	18.9	1.1	20

From the setting up of the culture pots, several plant species have been introduced since December 2018. The consecutive growth cycles were: *Medicago sativa, Zea mays*, *Eragrostis tef*, spontaneous vegetation and *Lavandula dentata*. This work evaluates the growth of the grass *Eragrostis tef*. On initiation, approximately 30 seeds of teff were planted in each container and, after 30 days, the number of plants was reduced to 20 per pot. Plant growth was carried out in the state of Rio Grande do Sul in southern Brazil (30°04'33´S, 51´07´06´´W) from December 2020 to February 2021 and covered the stages of germination, growth and seed production of the plant. The area has a subtropical humid climate (Cfa according to the Koppen classification), with temperatures ranging from 14 to 29.5°C, with an annual average of 19.7°C, humidity between 72 and 82% monthly, and precipitation between 109 and 144 mm monthly (INMET, 2023). The containers were arranged randomly and exposed to natural environmental conditions of sun and rain. Local data precipitation was obtained during the experiment [40], averaging 114 mm per month (1595 mm total during 14 months). Irrigation was carried out with rain water just when necessary, not exceeding an addition to natural precipitation greater than 20 mm. Figure 1 illustrates the substrate configurations employed in this work and the plant cycles developed in the project.

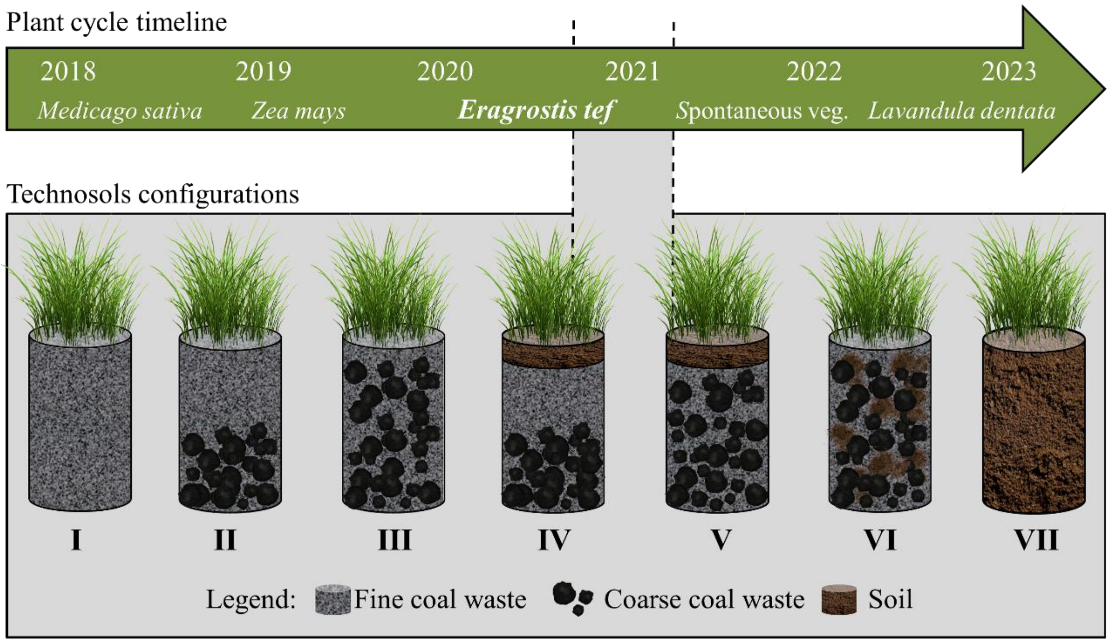

Figure 1. Configurations of the Technosols produced with fine and coarse coal waste and natural soil in different layers and plant cycle timeline. Emphasis on the cultivation of this study, *Eragrostis tef*, from December 2020 to February 2021.

Approximately in the middle of the growing season, the bulk density of the Technosols was determined after a drought period (bulk density – dry) and the saturated bulk density (bulk density – saturated with water) after heavy rain that took place subsequently. The difference between the masses was measured, transformed to volume (considering that the density of water is 1 kg L^{-1}) and reported as m^3 of water retention per m^3 of soil, which provides an estimate of the available water capacity [41]. With the difference that it was carried out on a larger scale and using rainwater, the procedure was similar to that adopted by Amaral Filho et al. [23]. Soil permeability (k) (hydraulic conductivity) was determined by Darcy's law, by the constant head test method [42]:

$$Q = k.\frac{h}{L}.A$$

where:
Q – water flow (cm^3 s^{-1})
k – soil permeability coefficient (cm s^{-1})
h – hydraulic load (cm)
L – depth of the porous media (cm)
A – cross-sectional area of the porous medium (cm^2)

At the end, the substrates samples were analyzed for fertility parameters – pH, soil organic matter (SOM), cation exchange capacity (CEC), Al saturation, macronutrients (nitrogen, phosphorus, potassium, calcium and magnesium) and micronutrients (copper, zinc, manganese, iron and boron) according [43]. The results were compared with the Brazilian guidelines for soils [44]. We also evaluated the plant tissue in terms of the shoot mass and essential elements for plant growth. Therefore, the dry mass plant tissue (shoot) was weighed after being dried at 60 °C in a constant flux oven and analyzed in terms of macronutrients and micronutrients. The results of the dry mass were assessed using an analysis of variance (ANOVA) with a significance level of $p \leq 0.05$ and a Tukey test to compare the differences between averages among the different configurations studied. The results of the elemental composition were compared to an *Eragrostis tef* plant tissue nutrient reference for grasses [45].

3. Results and Discussion

Table 4 shows some physical and hydraulic properties of the substrates studied. The bulk density of soil reflects the mass or weight of a certain volume of soil and determines the water infiltration, available water capacity, soil porosity, microorganism activity, root proliferation and nutrient availability [46]. The bulk density values obtained (Table 3) ranged from 943 to 1284 kg m^{-3} (dry) to 1151 to 1440 kg m^{-3} (saturated with water), which are values appropriate for plant cultivation [47]. A previous assessment of the granular properties of coarse and fine waste from Moatize mine [27] indicates a dry bulk density of 1180 kg m^{-3} for coarse waste, 1090 kg m^{-3} for fine waste, and 1520 kg m^{-3} for the co-disposal of packed coarse-grained and fine-grained waste, which occurs in the mass coarse:fine ratio of 1:0.29. Back to the experiment conducted in this work, higher bulk densities were obtained in configurations III, V and VI, which incorporate fine material in the empty spaces between coarse particles. However, the bulk density values were lower than 1520 kg m^{-3}, which can be explained by the incorporation of roots and organic matter in the soil development progress during the previous cultures of *Medicago sativa*, *Zea mays* and now by *Eragrostis tef*. According to several research works, there is a strong and negative correlation between soil organic matter and bulk density [48–50] and a good explanation of the soil bulk density decrease caused by *Zea may* was given by Silva et al. [51].

The available water capacity (AWC) indicates the ability of soils to store and supply water available to plant roots [52]. Data from the literature suggest that AWC ≥ 0.20 m^3 m^{-3} is considered ideal, 0.15 ≤ AWC < 0.20 m^3 m^{-3} is good, 0.10 ≤ AWC < 0.15 m^3 m^{-3} is limited, and AWC < 0.10 m^3 m^{-3} is poor, also known as droughty [53,54]. Soil like the substrates constructed in this work presented an AWC varying from 0.09 m^3 m^{-3} to 0.22 m^3 m^{-3}. Most are considered ideal or good, except treatments II and IV, which were categorized as poor and limited. This happened in the two configurations where the coarse waste was placed at the base of the containers, providing a smaller depth of fine waste on the top. Coarse waste acts as a drain, and the system as a whole retains less water. Still comparing these two situations, configuration IV has soil on the upper surface, which has a higher AWC, so the drain effect was not so evident. Previous study of 'Fabsil' (a Technosol) carried out with a South African coal waste found water capacity values in the order of 0.43 to 0.46 m^3 m^{-3}. However, those Technosols were composed of mixtures of ultrafine coal obtained by flotation (D_{50} of 141 μm) with a natural soil in ratios of 3:1 and 1:1. The coal fines used in the present study have a D_{50} of approximately 500 μm, denoting that water retention is negatively correlated with particle size. This is confirmed by the permeability values (k), which ranged from 0.03 to 0.06 cm s^{-1}, showing that all the substrate configurations built in this work are well drained.

Table 4. Mean values and standard deviation (SD) for bulk density, available water capacity and permeability of the different Technosols configurations and the soil used as control (n=3).

Treatment	Bulk density dry (kg m^{-3})		Bulk density saturated (kg m^{-3})		Available water capacity (m^3 m^{-3})		Permeability (k) (cm s^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
I	943.6	13.7	1151.5	22.2	0.208	0.015	0.04	0.01
II	1166.0	22.5	1256.1	48.0	0.090	0.033	0.04	0.02
III	1284.7	16,1	1440.5	0.1	0.156	0.016	0.03	0.01
IV	1140.4	48.3	1288.0	53.9	0.148	0.027	0.06	0.01
V	1207.3	147.0	1388.1	8.7	0.181	0.152	0.03	0.02
VI	1244.7	42.6	1408.8	67.4	0.164	0.036	0.03	0.02
VII	1100.8	22.8	1324.7	16.6	0.224	0.006	0.07	0.01

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Table 5 presents the average results obtained for each of the different treatments in terms of fertility (pH, organic matter), cation exchange capacity (CEC), aluminum (Al), macronutrients, and micronutrients. The ideal pH must be between 5.0 and 6.0 for better plant nutrient absorption for most commercial cultures [44]. Among the treatments, only numbers IV and VII were out of this range. Teff is usually cultivated on pH-neutral soils, but it was noticed that it could sustain acidity up to a pH below 5 [55]. So, generally, the treatments' pH is around the values accepted in the literature, as well as the macronutrients contents. An exception is the K content, which was generally deficient in all the Technosols produced. According to Sociedade Brasileira de Ciência dos Solos (SBCS) [44], reference values that ensure a good vegetation growth range from 10 to 60 mg dm^{-3} for phosphorus, and 30 to 180 mg dm^{-3} for potassium (considering a CEC in the range of 5 to 15 cmolc dm^{-3}), 2.6–5.0% of SOM, and 2.1 and 0.6 cmol dm^{-3} for calcium and magnesium, respectively. The CEC values can be considered as medium, and the aluminum contents were null or very low in all treatments. Table 4 also presents the results obtained for the concentration of soil micronutrients. According to the reference values, the Technosols are considered high for all micronutrients, providing the necessary condition for vegetation growth.

Table 5. Mean values for soil fertility parameters of the different Technosols configurations and native soil used as control (n=3), and value reference ranges (ref.) for fertility analysis according to SBCS [44].

					Macronutrients					Micronutrients				
Treatment	**pH**	**SOM**	**CEC**	**Al**	**N**	**P**	**K**	**Ca**	**Mg**	**Cu**	**Zn**	**Mn**	**Fe**	**B**
		%	**cmolc dm^{-3}**		**%**	**mg.dm^{-3}**		**cmolc dm^{-3}**		**mg dm^{-3}**				
I	6.1	3.5	7.24	0	0.42	145.8	17.2	3.1	2.7	9.5	25.6	4.6	> 5.0	0.30
II	6.0	3.5	6.96	0	0.49	136.1	22.6	3.2	2.1	10.8	26.0	5.1	> 5.0	0.17
III	60	3.5	5.56	0	0.54	76.0	17.2	1.5	1.7	11.2	25.6	3.7	> 5.0	0.30
IV	5.9	3.2	8.59	0	0.51	113.9	33.4	4.3	1.7	7.3	23.7	6	> 5.0	0.27
V	6.4	3.2	15.32	0.1	0.56	98.8	71.1	10.7	2.4	5.9	24.1	16.3	> 5.0	0.23
VI	5.7	4.1	8.69	0	0.61	94.5	43.1	3.9	2.7	7.5	23.8	15.9	> 5.0	0.40
VII	6.5	2.0	16.45	0	0.16	71.9	303.6	11.1	2.8	3.4	23.9	23.4	> 5.0	0.27
Ref.	5-6	2.6-5	5.0-15	-	-	10-60	31-180	2.1- 4	0.6-1	0.2-0.4	0.2-5	2.5- 5	-	0.2- 0.3

Figure 2 presents a graph comparing the above-ground productivity expressed in straw yield (dry basis) for each treatment. The best growth result occurred in Treatment I, which is the one that has only fine wastes and STP sludge, with a straw yield of 4500 kg ha^{-1}. Other treatments presented similar medium results and equivalent to the natural soil amended with sewage, which varied in the range of 1700 to 3000 kg ha^{-1}. It is interesting to note that previous studies carried out with fine coal waste, properly amended for pH, SOM and nutrients, found higher plant growth rates than the native soil used as control for alfalfa [27] and teff [23].

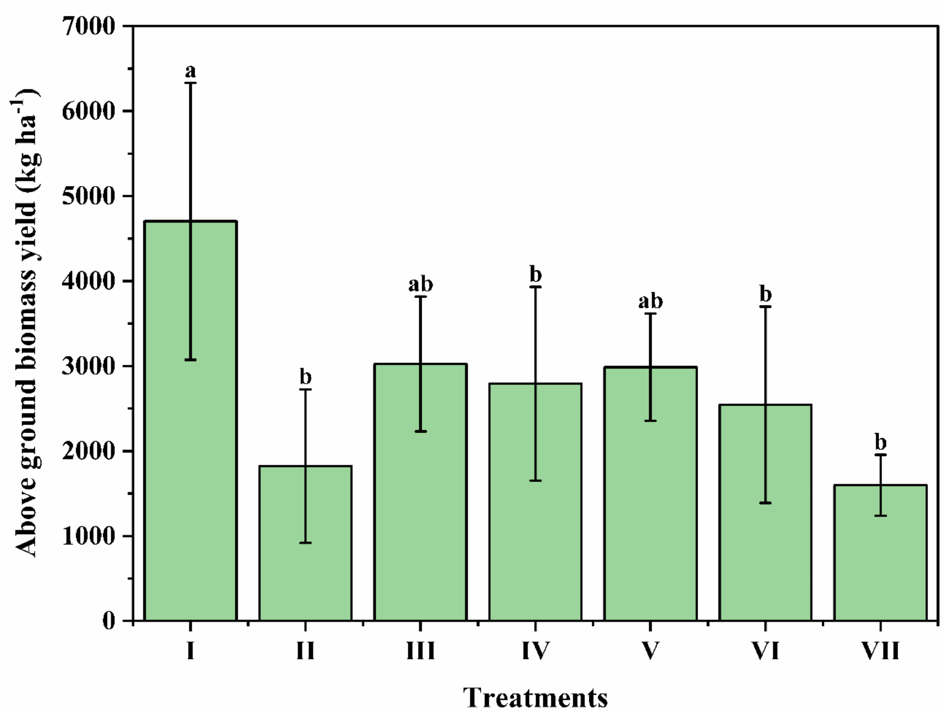

Figure 2. Mean and standard deviation (SD) for *Eragrostis tef* (teff) above-ground biomass yield in a complete growth cycle in Technosols and the native soil used as control. Means that differ significantly are indicated by different lower case letters (Tukey's test, $p < 0.05$).

The results of the vegetal tissue analysis of the *Eragrostis tef* vegetation for each treatment are listed in Table 6. For comparison purposes, grass data by Raij et al. [45] were used. Generally, the macro and micronutrient concentration in the teff tissue is within or above the standard range established by the authors for grasses. Considering that STP sludge was used in all treatments, an additive with high organic material contents, this result is no surprise, and it repeats the behavior observed by Firpo et al. [25]. An exception occurs in the soil configurations composed only of coal wastes, in which the potassium and boron contents are below the recommended levels. It can be affirmed that, in this study, potassium and boron are strongly related to the presence of agricultural soil.

Table 6. Mean macro and micro nutrients values for *Eragrostis tef* above ground plant tissue analysis in the Technosols and native soil used as control (n = 3) and value reference (Ref.) according with Raij et al. [45].

	Macronutrients (g kg^{-1})					Micronutrients (mg kg^{-1})			
Treatment	**N**	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Cu**	**B**
I	21	3.8	8.2	8.6	3.2	174.4	169	9.6	0.7
II	20.3	4.2	10.2	6.6	3.0	149.5	239.7	8.7	0.5
III	17.5	3.6	10.8	7.9	3.8	116.1	249.5	6.4	0.9
IV	18.2	4.5	12.2	9.3	2.7	131	117.7	5.5	0.9
V	21	4.1	13.6	7.8	2.6	121.6	154.5	5.3	0.6
VI	25.9	5.1	14.6	9.8	3.2	89.1	106.1	4.0	3.2
VII	25.2	6.6	22.8	8.9	1.6	134.9	69.2	4.5	8.2
Ref.	12–26	1–3	12–30	2–8	1.5–5	50–250	20–300	4–20	5 – 30

The results of this research contribute to the use of mine materials for plant growth. It validated that coal fine wastes can be used for teff growth [23] and introduces advances for the embedded use of coarse and fine wastes. We also considered teff as a plant to be integrated into an ecological succession process for the recovery of degraded areas, considering its possible use in a crop rotation system. The biomass yield achieved with fine coal waste amended with sewage sludge was 4500 kg ha^{-1}, allowing a soil nitrogen incorporation rate of 95 kg ha^{-1} in three months. Those values reached the average levels of teff productivity in Ethiopia in situations where nitrogen fertilization and irrigation were carried out [56]. In the other Technosol configurations, the production and nitrogen incorporation were slightly below average, but still within the range of variation.

Eragrostis tef is a plant with multiple uses, finding applications in animal and human nutrition and as a construction material when mixed with mud. It has been the target of studies to increase productivity to meet the increase in global demand [56–58]. Teff cultivation provides benefits for erosion control, unleashes processes and successional routes, regains ecological functions that were absent due to degradation, maximizes the recovery of local resilience and landscape, and speeds up the natural succession [59–61]. Therefore, it is a cultivar that, together with Technosols, can assist in the mining restoration process [62] with social benefits, enabling the strengthening of the territory through cultivation in agroforestry systems and increasing food and nutritional security. In this context, it is fundamental to use mineral processing, agronomic and environmental knowledge to ensure the security and effectiveness of the site restoration plan.

5. Conclusions

Moatize coal waste presents a circumneutral behavior and did not present expressive concentrations of toxic metals, and is thus able to be used in Technosols, provided they also receive organic material and nutrients. Regarding the different Technosol configurations, it was observed that all the mixtures employed had a satisfactory performance, with a highlight on the composition made up exclusively of fine coal waste with organic material. Configurations containing coarse coal wastes perform less well in terms of vegetation growth, possibly due to the fact that they have lower AWC and that the coarse particles may hinder the development of roots. All the configurations presented good micro and macronutrient levels in the substrate employed as soil, except for potassium and boron, elements that are less available in the coal waste and sewage sludge, but that could be incorporated into the mixture through fertilization.

Regarding the vegetal tissue analysis of *Eragrostis tef*, the results in terms of macronutrients were satisfactory, with the exception of potassium and boron. Even so, the deficiency of these elements was not reflected in the leaf mass quantity and appearance. Therefore, based on the obtained results, it is possible to conclude that the wastes of the Moatize Mine Chipanga Layer, added to the STP sludge and agricultural soil, performed well as Technosols for *Eragrostis tef* cultivation, with a high potential for use in the ecological restoration of coal mining areas.

Acknowledgments: The authors acknowledge the support of CNPq, CAPES, FAPERGS, UFRGS, and VALE for the development of this work. We also thank Esher Kern Pires and Laura Zannata Lermen for their help with the experimental work.

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