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Research article

Assessing phytoremediation potentials of selected plant species in restoration of environments contaminated by heavy metals in gold mining areas of Tanzania

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ABSTRACT

This study assessed and classified the phytoremediation potentials of selected plant species around gold mining areas in restoring the environments contaminated by heavy metals. The geographic focuses of the study were the Golden Pride Gold Mine (GPGM) and Geita Gold Mine (GGM) in Tanzania. The shoots and roots of plant species surrounding the mining areas and the samples of associated soils were collected and analysed for total concentrations of lead (Pb), chromium (Cr), cadmium (Cd), copper (Cu), arsenic (As), manganese (Mn) and nickel (Ni) using Atomic Absorption Spectrophotometer (AAS) and UV-VIS spectrophotometry. Results indicated that the soils from study areas were loamy textured and slightly acid (pH 6.1–6.5), soil organic carbon and organic matter were low (0.6–2.0%), total nitrogen was very low (<0.10%), phosphorous ranged from low (6–12 mg kg^{-1} soil) to high (13–25 mg kg^{-1} soil), and cation exchange capacity ranged from low (6.0–12.0 cmol$_{(+)}$ kg^{-1} soil) to medium (12.1–25.0 cmol$_{(+)}$ kg^{-1} soil). In assessing heavy metals using plant parts, the roots of giant rats-tail grass (*Sporobolus pyramidalis*) accumulated highest Pb (757.78 μg g^{-1}), Creeping Blepharis (*Blepharis maderaspatensis*) the Cd (158.11 μg g^{-1}), lantana (*Lantana camara*) the As (68.61 μg g^{-1}), and leuceana (*Leucaena leucocephala*) accumulated higher Mn (2734.61 μg g^{-1}) and Ni (4464.33 μg g^{-1}). In shoots, *L. leucocephala* accumulated higher Cr (1276.67 μg g^{-1}) and higher Cu (2744.44 μg g^{-1}) in *L. camara*. Although *S. pyramidalis, M. repens, L. camara, B. maderaspatensis* and *L. leucocephala* are likely to pose hazards to herbivores (grazing animals) while entering the food chain, they are still potential hyperaccumulators thus can be used to decontaminate metalliferous affected soils. *Blepharis maderaspatensis* has never been reported anywhere as Pb, Cd, Cu, Mn and Ni uptake plant hence this can be regarded as a new finding.

1. Introduction

The mining operation is a significant economic venture in many parts of the world. It is the world's second-oldest and the most important industry after agriculture (Amponsah-Tawiah and Dartey-Baah, 2011). Many countries rely heavily on mining activities to generate wealth for economic development to increase the gross domestic product (GDP) and foreign currency earnings (Andersson et al., 2014; Cao, 2007; Schueler et al., 2011). Apart from contributing to the national economy, increasing GDP and foreign currency earnings, the mining sector alleviates poverty by providing profitable and secure employment and alternative sources of income, particularly for the rural population. For instance, in Tanzania, the annual expansion of the Tanzanian economy was 7% in 2012–13, with mining contributing 3.5% of the GDP and projected to reach 10% by 2025 (URT, 2015). Even though mining activities have aided the economic development of the nations, they have also facilitated a wide range of negative consequences to the environment.

In many parts of the world, mining activity is among the key sources of heavy metals, contributing to contamination in the soil, water, and air. Heavy metals (Pb, Cr, Cd, Cu, As, Mn, Ni, Zn, Hg) are essential environmental pollutants in gold mining areas (Ogundiran and Osibanjo, 2008; Jadia and Fulekar, 2009; Avkopashvili and Avkopashvili, 2017). These metals originate primarily from processing the ores and disposal of tailings and high metal wastewaters around the mines (Mwegoha, 2008; Ogundiran and Osibanjo, 2008; Mkumbo et al., 2012; Petelka et al., 2019). Operations involving mining and ore-processing highly

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contaminate the environment with heavy metals (Gardea-torresdey et al., 2005; Mganga, 2014; Demkova et al., 2017). Heavy metals are of great concern because of their long-term effects on human health and can bio-accumulate in the food chain, predominantly in developing countries, including Tanzania in East Africa, where the techniques to decontaminate the environment are very limited (Mahugija et al., 2020; Mng'ong'o et al., 2021).

The processes and dynamics of heavy metals between soil-to-plant and trophic transfer to food chains are reported widely (Briffa et al., 2020; Liang et al., 2016; Mahmood and Malik, 2014; Nica et al., 2012; Orisakwe et al., 2012). These heavy metals find their sinks through consumption by human beings and other living organisms (animals, ranging from aquatic to terrestrial) from plants along the food chain (Ali et al., 2019a,b; Nica et al., 2012; Wahab et al., 2012). Higher concentrations of these metals were found in grains for cereals (Orisakwe et al., 2012), leaves of vegetables growing along wastewaters (Ali et al., 2019a, b) and in leafy plants than fruit-producing plants (Mahmood and Malik 2014). Pollution by heavy metals has become one of the most severe environmental challenges, requiring continuous monitoring and urgent solution to overcome its negative impacts.

Phytoremediation is one of the significant interventions that can address heavy metal pollution in the soil, as mentioned above. Phytoremediation is an emerging technology of implementing green plants to reduce the toxic effect of heavy metals in the environment, which is cost-effective and an alternative to the conventional remediation approaches (Gardea-torresdey et al., 2005; Nirola et al., 2015; Ashraf et al., 2019). Plants have a selective potential to accumulate heavy metals through phytoremediation (Bhargava et al., 2012). When consumed in the food chain, the phytoremediators impair consumers health (Nedjimi 2021; Sumiahadi and Acar 2018; Tangahu et al., 2011; Yan et al., 2020). Phytoremediator plants can grow in contaminated soils as they have developed mechanisms to minimize the effects of exposure to heavy metals (Mehes-Smith et al., 2013).

Phytoremediator plants have been categorised as hyperaccumulators, excluders or indicators according to their strategy for surviving metalliferous soil (Mganga et al., 2011; Mehes-Smith et al., 2013). Plant species that exclude heavy metals can restrict the translocation of these metals from their roots to the above-ground tissues and maintain a low concentration of heavy metals in their shoots over a wide range of soils (Mehes-Smith et al., 2013; Kutty and Al-Mahaqeri, 2016).

Metal accumulators (hyperaccumulators) are plant species that accumulate metals in their above-ground tissues to levels substantially higher than those found in the rhizosphere soils (Mehes-Smith et al., 2013). Hyperaccumulators have been found in over 400 plant species (Baker et al., 2000). However, many of the discovered species are location and condition-specific, blanket adoption is not feasible (Sangu 2014). Hyperaccumulator plants are commonly employed in phytoremediation. A plant species can be considered as a hyperaccumulator for heavy metals if meet one of the following criteria; (i) levels of heavy metals for instance Pb, Cu, Co, Cr, and Ni > 1000 μg/g or 10.000 μg/g of Fe, Mn, and Zn or Cd > 50 μg g^{-1} in any aboveground tissue in their natural habitat without suffering toxic effects (Kutty and Al-Mahaqeri 2016) (ii) bioaccumulation factor (BAF) and/or a translocation factor (TF) of greater than one (Stewart 1989; Tu and Ma 2003; Mganga et al., 2011; Mehes-Smith et al., 2013; Sangu 2014; Kutty and Al-Mahaqeri 2016) (iii) 10–500 times greater than the same species growing in non-contaminated sites (Kutty and Al-Mahaqeri 2016) (iv) rapid growth, high uptake capacity and large biomass production (Sangu 2014). In this study, therefore, three criteria were used to qualify plant species as phytoremediators. These criteria include the levels of heavy metals, BAF and TF.

Like accumulators, metal indicators plants accumulate metals in their above-ground tissues and may eventually die off for continuously taking up metals. The metal levels of indicator plants usually reflect the metal concentrations in the surrounding environment, i.e., rhizosphere. The determination of metal indicator plants depends on the levels of heavy metals in plant tissues and the surrounding soils (Mganga et al., 2011; Armah et al., 2014; Petelka et al., 2019; Opoku et al., 2020; Tun et al., 2020).

Many pieces of research have been published on the phytoremediation of certain plant species for the removal of heavy metals in the contaminated soils (Kachenga et al., 2020; Mensah, 2015; Mganga et al., 2011; Mganga, 2014; Mkumbo et al., 2012; Mkumbo, 2012; Nkansah and Belford, 2017; Rashed, 2010; Tariq et al., 2016). However, limited studies have assessed the phytoremediation potential of *Sporobolus pyramidalis, Melinis repens, Lantana camara, Leucaena leucocephala* and *Blepharis Maderaspatensis* as among the plant species in the remediation of environment contaminated by heavy metals. Therefore, the overall purpose of this study is to assess the potential of selected plant species for heavy metal accumulation at Golden pride and Geita gold mines by determining the concentration of heavy metals in the roots, shoots and soils of selected plant species and determining the bioaccumulation factor and translocation factor of selected species for specific heavy metals.

2. Materials and methods

2.1. Study areas

The study areas are presented in Figure 1. The Golden Pride Gold Mine (GPGM) is located at latitude 04^0 23′ 31″ S and longitude 032^0 53′ 55″ E in Western Tanzania, but it operated from 1998 to 2013 (Werema et al., 2016). On the other hand, Geita Gold Mine (GGM) is located at latitude 02^0 52′ 03″ S and longitude 032^0 11′ 11″ E in north-western Tanzania (Sibilski and Stephen, 2010). Mining operations at GGM commenced in 2000 and it is expected to close in 2029.

2.2. Data collection on plant and soils

Sampling of soils and plants was conducted in December 2019 during short rains. Three line transects of 160 m long were established along the Tailings Storage Facilities (TSF) of the study areas (at the crest, middle and toe) with a distance between transects of 50 m. Three sampling plots of 20 m × 20 m quadrats were established after every 50 m in each transect. Nine sampling points, i.e., three from each transect, were systematically established and a total of five (5) plant species were collected for laboratory analysis of their heavy metal contents. The plant species sampled were giant rats-tail grass (*Sporobolus pyramidalis*), Natal grass (*Melinis repens*) and lantana (*Lantana camara*) from GGM and leuceana (*Leucaena leucocephala*) and Creeping Blepharis (*Blepharis maderaspatensis*) from GPGM (Table 1).

A stainless-steel knife was used to chop the plant samples and separate shoots from roots. Approximately 10 g of the root and shoot portions were separately taken from each of the sampled plants. The collected samples were labelled, air-dried and preserved in paper bags. Soil samples were collected at a depth of 30 cm using a soil auger at each sampling point where the plants were sampled. The collected soil samples were mixed to constitute composite samples per sampling point. The composite soil samples were kept in air-tight plastic bags. Soil water ratio of 1:2.5 was deployed in determining pH. The OC (and extrapolation to O.M) was determined using the Walkley-Black method, total N was determined using Kjedahl method (Bremner and Mulvaney, 1982) and extractable P was determined using Bray-1 method (Moberg, 2000). The exchangeable bases (Ca and Mg) were determined using atomic absorption spectrophotometer (AAS) while K and Na were determined by Flame Photometer and CEC filtered from the leachate and BS calculated accordingly (Moberg, 2000).

The concentrations of heavy metals in soil and plant samples were measured as described by (Mganga 2014; Molina 2011; Stewart 1989). Before analyzing plant samples, they were thoroughly washed using distilled water to remove firmly attached soil particles in shoots and roots, and then oven-dried to constant weight at 105 °C for 72 h (Molina,

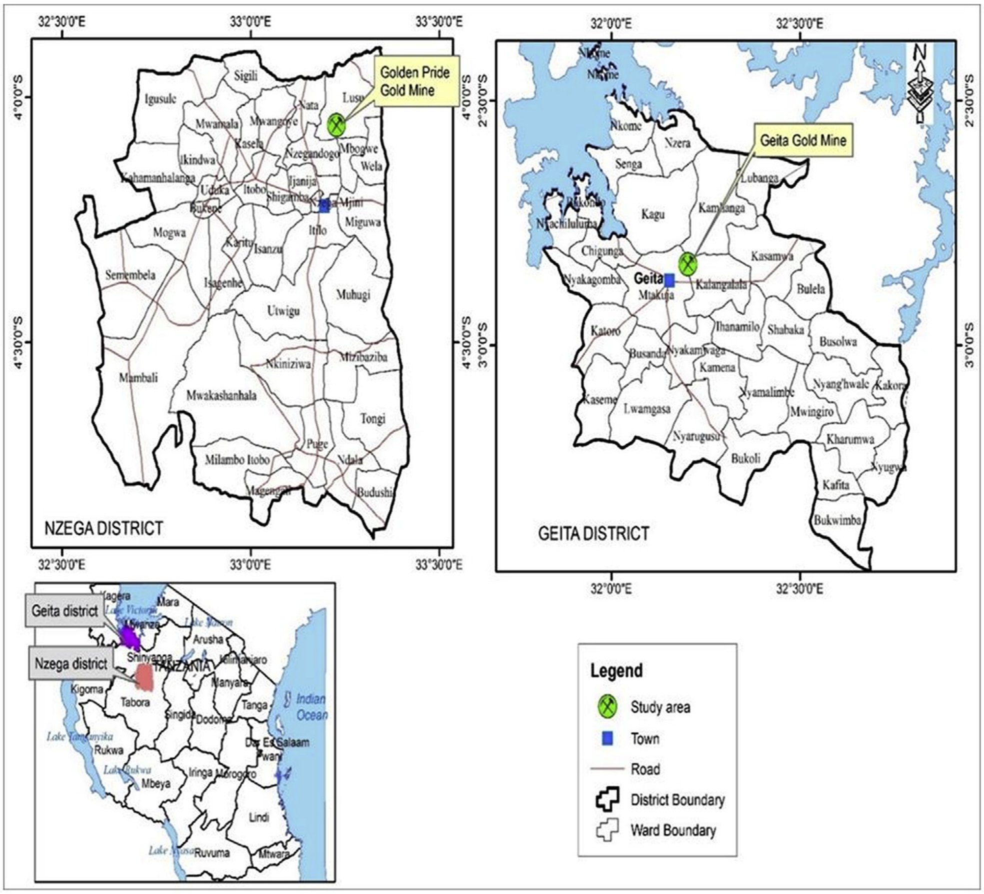

Figure 1. Map of Tanzania showing locations of Golden Pride and Geita Gold Mines (Kahangwa et al., 2020).

Table 1. Family of the studied plant species.

Plant species	Life form	Family
Sporobolus pyramidalis P. Beauv.	Grass	Gramineae/Poaceae
Melinis repens (Willd.) Zizka	Grass	Gramineae/Poaceae
Lantana camara L.	Shrub	Verbenaceae
Leucaena leucocephala (Lam.) De Wit.	Shrub	Mimosoideae
Blepharis maderaspatensis Heine ex Roth	Herb	Acanthaceae

2011). Each dried sample was ground to powder using a wearing blender (Model type A 10 Janke and Kunkel GBH a Co. KG). The ground samples were stored in polyethylene bags to preserve their physical and chemical integrity and labelled clearly for further analysis (Mganga 2014). A mixed acid procedure was used to digest soil and plant materials for determining total Arsenic as described by Stewart (1989) using UV-VIS spectrophotometry. Block digester aluminium was used for heating samples mixed with acid HNO_3, concentrated $HCIO_4$, 70%., HCI, 1:10 and the solutions obtained were used to determine total Pb, Cr, Cd, Cu, Mn, and Ni by Atomic Absorption Spectrometry USA model (AAS 240 Varian).

2.3. Data analysis

2.3.1. Metals analysis

Some of the criteria for selecting hyperaccumulator are bio-accumulation factor (BAF) and translocation factor (TF); which provide an indication on how much the plant bioconcentrate heavy metals in tissues relative to the amount contained in the soils. BAF was calculated based on the concentration's ratio of a metal in plant tissue (shoot and root) to the concentrations in soil (Equation 1). BAF can also show efficiency of the plant in accumulating toxic elements.

$$BAF = \frac{Conc\ of\ metal\ in\ plant}{conc\ of\ metal\ in\ soil} \tag{1}$$

The TF evaluates the ability of a plant to transfer heavy metals from the roots to the above ground parts, thus accounting for the removal from the soils. The TF is the ratio of heavy metal concentration in plant shoot to the concentration in root (Usman et al. 2012) as shown in Eq. (2).

$$TF = \frac{Conc\ of\ metal\ in\ shoot}{conc\ of\ metals\ in\ root} \tag{2}$$

2.3.2. Statistical analyses

The fixed main effects for the concentrations of heavy metals in plant shoots and roots and in soils were the plant species and types of metals while the replicates (sampling transects) were treated as random effect. In assessing sites and heavy metals interactions, A TWO–WAY ANOVA was used for the measurements of soils taken at GGM and/or GPGM sites and the factor effects model was as shown in Eq. (3) and the results were presented in bar charts. Further the differences in concentrations of heavy metals within a plant species (shoots or roots) and/or across plant species (shoots or roots) were compared following Eq. (3) and the results were presented in bar charts. In evaluating the concentrations of heavy metals as affected by only plant species or only sites, ONE-WAY ANOVA was deployed for the measured variables (Equation 4). The effects of significant means were isolated by a *Post-hoc* Tukey's-HSD test at a threshold (Least significant differences of means) of 5% ($P = 0.05$).

$$Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij} \tag{3}$$

where, Yij is the observation in the $ijth$ factors; μ is the overall (grand) mean; α_i, β_j are the main effects of the factors plant species (α) and/or heavy metal types and/or sites (β); $(\alpha\beta)_{ij}$ are the two-way (first factor) interaction effects between the factors α and β; εij is the random error associated with the observation in the $ijth$ factors.

$$Y_i = \mu + \alpha_i + \varepsilon_i \tag{4}$$

where, Yi is the observation in the ith factor; μ is the overall (grand) mean; α_i is the main effect of the factor plant species or sites (α); εi is the random error associated with the observation in the ith factor.

3. Results

3.1. Soil characterization of the two gold mining sites

Soil parameters (not heavy metals) and their quantities measured in the study areas are presented in Table 2. Results indicated that the soils from study areas were loamy textured and slightly acid (pH 6.1–6.5), soil organic carbon and organic matter were low (0.6–2.0%), total nitrogen was very low (<0.10%), phosphorous ranged from low (6–12 mg kg^{-1} soil) to high (13–25 mg kg^{-1} soil), and cation exchange capacity ranged from low (6.0–12.0 $cmol_{(+)}$ kg^{-1} soil) to medium (12.1–25.0 $cmol_{(+)}$ kg^{-1} soil).

3.2. Concentrations of heavy metals in plants and soils

The main effects of plant species and the types of heavy metals on the concentrations of the studied heavy metals in plant shoots and roots and in soils were significant ($P < 0.05$) for the measurements taken at GGM site (Tables 3, 4, and 5). The concentrations of heavy metals as affected by plant species (Table 3) were such that the highest was Ni in shoots of *L. leucocephala* (3126 μg g^{-1} of plant shoot), followed by Ni in shoots of *B. maderaspatensis* (2968 μg g^{-1} of plant shoot). The highest shoot concentrations of Cu and As were recorded in *L. camara* (2744 μg g^{-1} of plant shoot; 45.56 μg g^{-1} of plant shoot) and *L. leucocephala* recorded the highest shoot concentrations of Mn (2346 μg g^{-1} of plant shoot) and Cr (1276.7 μg g^{-1} of plant shoot). The *B. maderaspatensis* recorded the highest shoot concentrations of Cd (144.94 μg g^{-1} of plant shoot), *S. pyramidalis* recorded the highest shoot concentrations of Pb (738.9 μg g^{-1} of plant shoot) and *M. repens* (351 μg g^{-1} of plant root) (Table 3).

These observations were contradicted in roots since the concentrations of heavy metals followed a different trend. The highest root concentrations of Ni (4464 μg g^{-1} of plant root), Mn (2735 μg g^{-1} of plant root), and Cr (1118.4 μg g^{-1} of plant root) were recorded in *L. leucocephala*, As (68.61 μg g^{-1} of plant root) and Cu (2539 μg g^{-1} of plant root) in *L. camara*, Pb (757.8 μg g^{-1} of plant root) in *S. pyramidalis*, and Cd (158.11 μg g^{-1} of plant root) in *B. maderaspatensis* (Table 4). With respect to sites, the highest heavy metal concentrations in soils were Ni (6134 μg g^{-1} of soil), Mn (5211 μg g^{-1} of soil), Pb (3733 μg g^{-1} of soil), Cr (5453 μg g^{-1} of soil), Cd (2197 μg g^{-1} of soil), Cu (4892 μg g^{-1} of soil) in GPGM, and As (4280 μg g^{-1} of soil) in GGM (Table 5).

The interaction effects of plant species and metal types were also significant ($P < 0.05$) on the concentrations of heavy metals measured in shoots, roots, and soils (Figures 2, 3, and 4). As an effect of metal types in the soils, Ni was the highest heavy metal in shoots (>3000 μg g^{-1} of plant shoot; Figure 2) and roots (>4500 μg g^{-1} of plant root; Figure 3) of *L. leucocephala* while Ni was also highest in soil of GPGM site (>6000 μg g^{-1} of soil; Figure 4).

3.3. Bioaccumulation factor and translocation factor

The results of the Bioaccumulation factor (BAF) and translocation factor (TF) are summarized in Table 6. The results indicate that *Sporobolus pyramidalis* is the only species with BAF>1 for Pb. Both *Sporobolus pyramidalis, Melinis repens* and *Lantana camara* recorded BAF>1 for Cu. Furthermore, *Leucaena leucocephala* and *Blepharis maderaspatensis* recorded BAF>1 for Ni. The results also showed that *Leucaena leucocephala* recorded BAF>1 for Mn. There was no individual recorded BAF >1 for Cr, Cd and As.

The same results also showed that *Sporobolus pyramidalis, Lantana camara, Leucaena leucocephala* and *Blepharis maderaspatensis* recorded TF > 1 for Pb. *Sporobolus pyramidalis, Lantana camara* and *Leucaena leucocephala* recorded TF > 1 for Cr. *Sporobolus pyramidalis*, *Melinis repens* and *Lantana camara* recorded TF > 1 for Cd. *Sporobolus pyramidalis*, *Melinis repens*, *Lantana camara*, *Leucaena leucocephala* and *Blepharis maderaspatensis* recorded TF > 1 for Cu. *Sporobolus pyramidalis* recorded TF > 1 for As. *Sporobolus pyramidalis*, *Lantana camara* and *Blepharis maderaspatensis* recorded TF > 1 for Mn. *Sporobolus pyramidalis*, *Melinis repens*, *Lantana camara* and *Blepharis maderaspatensis,* recorded TF > 1 for Ni.

4. Discussion

To our knowledge and through literature synthesis, this is the first study that has assessed the phytoremediation potential of selected plant species in the restored TSF in Golden Pride and Geita gold mining conservation areas of Tanzania. The soils in the studied gold mining areas were loamy textured, a physical characteristic that increases water and nutrient retention of soils, thereby supporting the growth of plants (Petelka et al., 2019; Sheoran et al., 2010). The pH of the soils in the study sites was slightly acid ranging from 6.1 to 6.5. This observation could be attributed to plant root exudates that add hydrogen ion (H^+) to the soil and oxidation of Fe^{2+} to Fe^{3+} whose oxides contribute to soil acidity as acid forming cations (Nassary et al., 2020). Similar to this finding, Mkumbo et al. (2012) reported soil reaction with pH values ranging from 3.5 to 7.3 in gold mining areas of Tanzania. According to Sheoran et al. (2010), the pH ranging between 6.0 and 7.5 is suitable for the growth and development of plants in mining areas. Wide researches acknowledge soil pH to be the main factor governing mobility, solubility and availability of heavy metals to plants (Clemente et al., 2003; Petelka et al., 2019; Rieuwerts et al., 1998). It was not surprising in the present

Table 2. Indication of various soil variables measured in the gold mining areas of Geita and Golden Pride, Tanzania.

Site	pH $_{(H2O)}$ 1:2.5	Ca	Mg	K	Na	CEC	BS	O.M	OC	Total N	C/N Ratio	Bray-1-P
		Exchangeable bases ($cmol_{(+)}$ kg^{-1})					(%)					(mg kg^{-1})
GGM	6.5 ± 0.9	5.6 ± 2.0	1.0 ± 0.2	0.9 ± 0.3	1.7 ± 0.2	22.0 ± 1.7	41.8 ± 6.8	1.8 ± 0.7	1.06 ± 0.39	0.04 ± 0.01	28.5 ± 15.5	11.9 ± 1.3
Rating	Slightly acid	High	Medium	High	High	Medium	Moderate	Low	Low	Very low	Poor quality	Low
GPGM	6.1 ± 0.4	1.6 ± 0.6	0.9 ± 0.2	4.1 ± 1.0	0.1 ± 0.01	10.6 ± 1.0	62.8 ± 8.8	1.6 ± 0.9	0.92 ± 0.53	0.03 ± 0.02	34.1 ± 2.3	23.5 ± 2.4
Rating	Slightly acid	Low	Medium	Very high	Low	Low	High	Low	Low	Very low	Poor quality	High

Key: GGM = Geita Gold Mine; GPGM = Golden Pride Gold Mine; pH = power of hydrogen ion in soil; Ca = calcium; Mg = magnesium; Na = sodium; CEC = cation exchange capacity; BS = base saturation; O.M = organic matter; OC = organic carbon; N = nitrogen; C/N = carbon-to-nitrogen ratio; Bray-1-P = Bray-1- available phosphorus. Ratings of these parameters were based on Landon (2014).

Table 3. Means of heavy metal concentrations in shoots as affected by the plant species.

Plant species	Heavy metals and their concentrations (μg g^{-1})						
	Pb	Cr	Cd	Cu	As	Mn	Ni
S. pyramidalis	738.9^{a}	517.2^{b}	50.39^{ab}	1885^{a}	29.22^{a}	165^{c}	204^{b}
M. repens	224.4^{b}	141.8^{b}	53.17^{ab}	1776^{a}	13.89^{a}	125^{c}	197^{b}
L. camara	701.1^{a}	198.3^{b}	85.11^{ab}	2744^{a}	45.56^{a}	1203^{b}	867^{b}
B. maderaspatensis	63.9^{b}	402.7^{b}	144.94^{a}	139^{b}	22.28^{a}	2294^{a}	2968^{a}
L. leucocephala	163.7^{b}	1276.7^{a}	34.89^{b}	204^{b}	34.39^{a}	2346^{a}	3126^{a}
$LSD_{(0.05)}$	238	443.8	66.11	762.5	32.32	635.9	974.4
s.e.d.	103.2	192.5	28.67	330.7	14.02	275.8	422.6
P – value	<0.001	0.002	0.031	<0.001	0.298	<0.001	<0.001

Means in the same column bearing different letter(s) differ significantly. Otherwise, they are statistically similar based on the Least Significance Difference (LSD) and/or standard errors of differences of means (s.e.d.) detected at 5% error rate.

Table 4. Means of heavy metal concentrations in roots as affected by the plant species.

Plant species	Heavy metals and their concentrations (μg g^{-1})						
	Pb	Cr	Cd	Cu	As	Mn	Ni
S. pyramidalis	757.8^{a}	260^{c}	49.94^{b}	1724^{b}	20.28^{a}	96^{b}	212^{b}
M. repens	272.6^{bc}	223.3^{c}	44.44^{b}	1620^{b}	16.22^{a}	143^{b}	135^{b}
L. camara	561.1^{ab}	202.8^{c}	45.28^{b}	2539^{a}	68.61^{a}	763^{b}	330^{b}
B. maderaspatensis	45.3^{c}	633.2^{b}	158.11^{a}	64^{c}	25.11^{a}	2307^{a}	2984^{a}
L. leucocephala	53.2^{c}	1118.4^{a}	104.34^{ab}	126^{c}	53.11^{a}	2735^{a}	4464^{a}
$LSD_{(0.05)}$	242.7	187.4	64.6	420.6	53.68	779.6	1129.4
s.e.d.	105.2	81.3	28.01	182.4	23.28	338.1	489.8
P – value	<0.001	<0.001	0.013	<0.001	0.196	<0.001	<0.001

Means in the same column bearing different letter(s) differ significantly. Otherwise, they are statistically similar based on the Least Significance Difference (LSD) and/or standard errors of differences of means (s.e.d.) detected at 5% error rate.

Table 5. Means of heavy metal concentrations in soils from two contrasting sites (GGM & GPGM). The comparison is based on concentrations of metals within the same site – the comparison is independent of the site.

Site	Heavy metals and their concentrations (μg g^{-1})							$LSD_{(0.05)}$	s.e.d.	*P – value*
	Pb	Cr	Cd	Cu	As	Mn	Ni			
GGM	1805^{d}	2778^{cd}	2082^{d}	3546^{bc}	4280^{ab}	3677^{bc}	4838^{a}	661.3	303.5	<0.001
GPGM	3733^{bc}	5453^{a}	2197^{d}	4892^{ab}	3278^{cd}	5211^{a}	6134^{a}	815.5	374.3	<0.001

Means in the same row bearing different letter(s) differ significantly. Otherwise, they are statistically similar based on the Least Significance Difference (LSD) and/or standard errors of differences of means (s.e.d.) detected at 5% error rate.

study that the soils in the mined areas were slightly acid as also Mensah et al. (2015) reported this to be a common feature for most soils in mines.

The organic carbon, total nitrogen and phosphorus in the soils of the study areas were generally low, which could be due to the mining activities. Mining activities are reported to have effect of removing vegetation and, consequently loss of plant nutrients (Opoku et al., 2020). Soil organic matter improves nutrient supply to plants and soil physico-chemical properties. Studies have indicated that soil organic matter influences the binding and retention of metals in soils (Liu et al., 2014; Rieuwerts et al., 1998). Based on the findings of the present study, the measures for restoration and mitigation of metal pollution are crucial to improve soil organic matter contents. The variations in soil exchangeable bases and base saturation depended on the gold mining site, which indicated that the pH of soil solution and ionic strength affect the cation exchange capacity (CEC) (Opoku et al., 2020).

Nitrogen and phosphorus are the limiting nutrients of plant growth in soils, including those in mined areas (Opoku et al., 2020; Petelka et al., 2019; Qing-juna et al., 2009). The findings of this study indicated that the contents of total N in the mined areas were very low (<0.1%), which could be attributed to the removal of vegetation cover and associated residues during mining operations. This is a common feature of tropical soils where N values are considerably low when are below 0.2% (Nassary et al., 2020; Landon, 2014). This finding suggests that an introduction of N-fixing plant species could be an efficient measure for the fertilisation of degraded mine areas (Nassary et al., 2020). Phosphorus is the second major growth-limiting nutrient of plants despite its abundant occurrences in soils as organic and inorganic forms (Buta et al., 2019; Gyaneshwar et al., 2002; Reta et al., 2018). The present study indicated that in the post-mining area available P is high but its availability is low in restored areas where mining is still in operation. Similar to these findings are from other studies which reported that available P was deficient in mine degraded or stockpiled soils (Buta et al., 2019; Reta et al., 2018; Sheoran et al., 2010). According to Buta et al. (2019), there is a gradual increase in P fixation by mine soils limiting plant growth and development. The findings of the present study also show that available P in the soil increased with the increase in rehabilitation period (in years).

The extent of heavy metals accumulation in the shoots and roots varied with the type of heavy metals and plant species. The concentrations of Pb, Cr, Cd, Cu, As, Mn and Ni in plant shoots, roots and soils except for Mn in *S. pyramidalis*, *M. repens* and *L. camara* were higher than

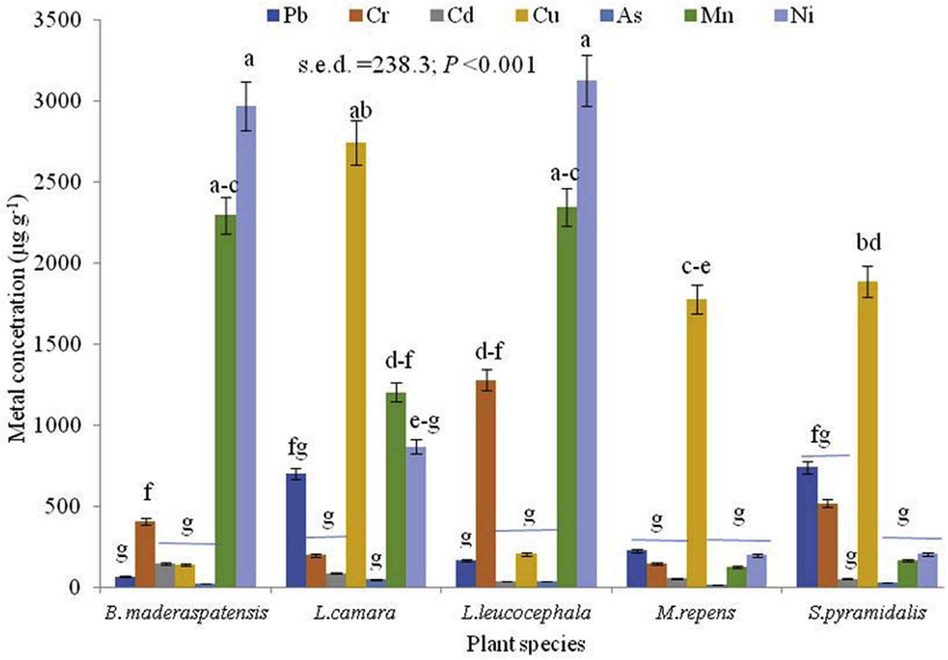

Figure 2. Comparison of mean concentrations of heavy metals in shoots of different plant species. The means are compared within a plant species and across the species.

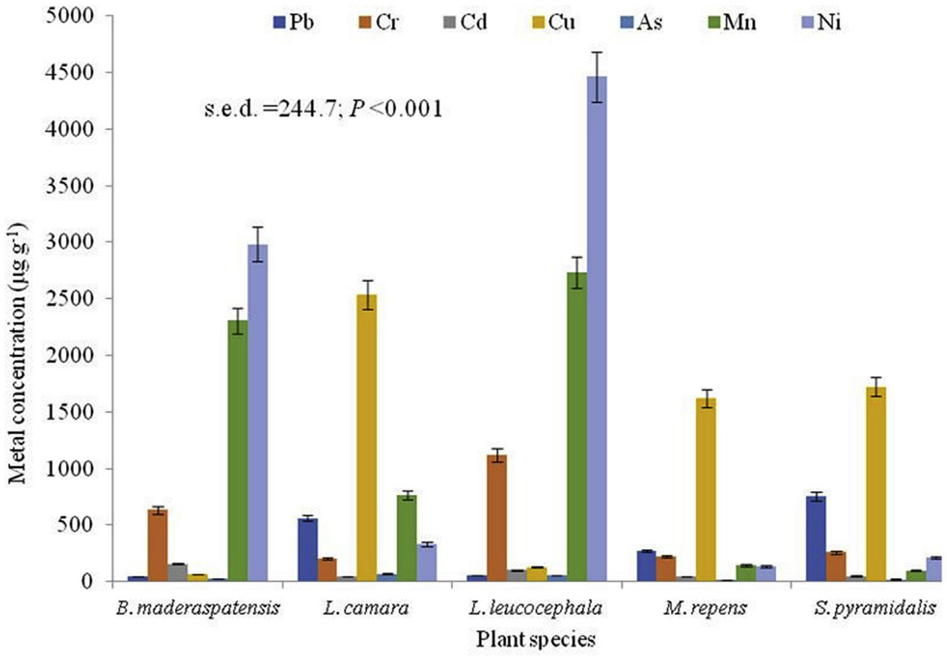

Figure 3. Comparison of mean concentrations of heavy metals in roots of different plant species. The means are compared within a plant species and across the species.

the standard references (Stewart, 1989). Heavy metals in plants vary with the plant species (Mganga et al., 2011; Nkansah and Belford, 2017), and their accumulations depend on the climatic conditions and soil characteristics (Ogundiran and Osibanjo, 2008; Mganga, 2014). The levels of heavy metals for most plant species in the present study exceeded the optima for Pb, Cr, Cd, Cu, As, Mn, and Ni (Stewart, 1989). These findings provide an indication that consumption of plants or parts of plants with higher levels of Pb, Cd, and As by the primary consumers (herbivores) for a long period could lead to exposure through bioaccumulation/biomagnification in omnivores and carnivores such as humans which may pose health risks. These findings corroborated with those of Conesa et al. (2006) who found that total concentrations of Pb, Cu and Zn in mine tailings were above the threshold. Wong (2003) argued that the presence of higher concentration of Pb in the metalliferous soils may restrict the growth of all but the most tolerant plant species.

The present study indicated elevated levels of heavy metals in soils than those in plants. This implies that these heavy metals in soils have not yet been take-up by the plant and/or accumulated in plant tissues. The high retention of these heavy metals in soils could be attributed to the

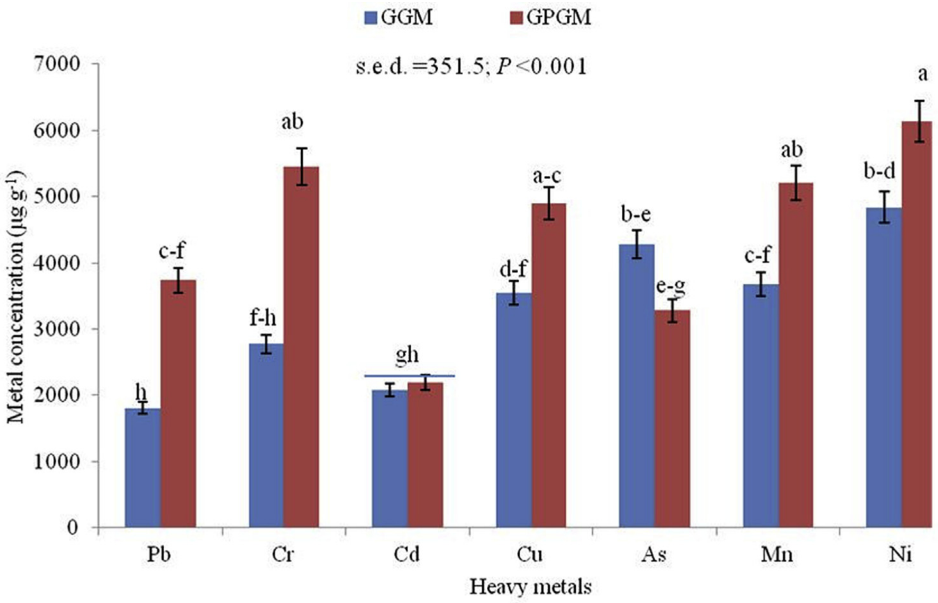

Figure 4. Comparison of mean concentrations of heavy metals in soils from two contrasting sites (GGM & GPGM). The means are compared among metals and across the sites.

low soil pH, increased soil organic matter (SOM), low calcium carbonate and moderate cation-exchange capacity (Mkumbo and Gunno, 2014; Ssenku et al., 2014; Nkansah and Belford, 2017). Sheoran et al. (2010) found that mobility of heavy metals in the soil and their accumulation in plants was reduced by application of limestone ($CaCO_3$) as it also raises soil pH. Similar to the findings of the present study, Kutty and Al-Mahaqeri (2016) also reported that the concentration of heavy metals in soils were higher compared to those in plants. Petelka et al. (2019) reported that the concentration of As was above the international risk thresholds while that of Pb was below the thresholds. However, the overall results of the present study negate those of a study conducted by Nkansah and Belford (2017), which stipulated that the sampling area in gold mines was not polluted with heavy metals. Besides the evidence the soil is polluted with heavy metals and considering their critical or toxic ranges, it was important to select appropriate plant species which can grow and colonize metal contaminated soils (Wong, 2003).

In general, based on the results presented in this study the extent of heavy metal accumulation in the shoots and roots varied with the type of heavy metals and plant species (Mganga et al., 2011; Nkansah and Belford, 2017). Their accumulations depend on the climatic conditions and soil characteristics (Ogundiran and Osibanjo, 2008; Mganga, 2014). Some plants accumulate heavy metals and others exclude heavy metals. Based on the criteria for accumulating heavy metals in the above ground part, Cu was highly accumulated by *Sporobolus pyramidalis, Melinis repens,* and *Lantana camara*. *Leucaena leucocephala* accumulated Cr. *Leucaena leucocephala* and *Blepharis maderaspatensis* accumulated Ni. Cd was accumulated by *Sporobolus pyramidalis, Melinis repens, Lantana camara* and *Blepharis maderaspatensis*. Further, As was accumulated more by the *Lantana camara*.

The process of removing heavy metals from soils and accumulating them in the plant generally requires the bioaccumulation and translocation of heavy metals to easily harvestable plant parts. The studied heavy metals i.e., Pb, Cr, Cd, Cu, As, Mn and Ni recorded both BAF and TF > 1 in some species including *Sporobolus pyramidalis* (Pb and Cu), *Melinis repens* (Cu), *Lantana camara* (Cu) and *Blepharis maderaspatensis* (Ni). This implies that these species effectively accumulated and transferred heavy metals from the soil to the above ground parts. The higher BAF implies that anthropogenic activities in mining areas play a substantial role in the dynamics of heavy metals (Doležalová et al., 2015).

Metal accumulation is characterized by effective metal transfer from roots to shoots, as measured by a translocation factor larger than one (TF > 1). Plant species with TF > 1 are regarded as good phytotranslocators. *Sporobolus pyramidalis* is the best phytotranslocator for Cr, Cd, As, Mn and Ni whereas *Melinis repens* for Cd and Ni, *Lantana camara* for Pb, Cr, Cd, Mn and Ni, *Leucaena leucocephala* for Pb, Cr and Cu, and *Blepharis maderaspatensis* for Pb, Cu and Mn. According to Nkansah and Belford (2017), plants with a BAF value greater than one (BAF$>$1) are suitable for phytoextraction or phytoaccumulation. *Leucaena leucocephala* is the best phytoaccumulator of Mn and Ni into the roots and restricts their transport to the aerial portions. Further, the overall observation is that *Sporobolus pyramidalis, Melinis repens, Lantana camara, Leucaena leucocephala and Blepharis maderaspatensis* are efficient hyperaccumulators of heavy metals.

In this study, *Sporoborus pyramidalis* was classified as a hyperaccumulator for Pb, Cr, Cd, Cu, As, Mn and Ni. In Nigeria, Ogundiran and Osibanjo (2008) reported that *Sporobolus pyramidalis* is one of the species showing a high level of metal tolerance to Pb and Ni. Similarly, in Australia, Nirola et al. (2015) suggested that *Sporobolus pyramidalis* can decontaminate soils polluted with Pb and Ni metals. A study conducted by Mkumbo et al. (2012) found the highest TF (4) of *Sporobolus pyramidalis* for Pb and indicated it to be a good plant for phytoremediation of Pb contaminated soils. Mkumbo (2012) stretched that *Sporobolus pyramidalis* is a hyperaccumulator of Cu. The findings of the present study contradict with those of Petelka et al. (2019) and Mganga (2014), that *Sporobolus pyramidalis* had a smaller bioaccumulation index for Pb and As hence is not preferred for phytoremediating soils contaminated with these metals. Sangu (2014) reported that *Sporobolus pyramidalis* is a hyperaccumulator of As in the metalliferous soils, thus can be used to phytoremediate As contaminated soils.

The present study also classified *Melinis repens* as a potential plant for hyperaccumulating Cd, Cu and Ni hence can potentially be used for phytoremediation of the soils contaminated with these metals. The findings are in line with those of a study conducted by Leteinteinturier et al. (2001) in the Central Province of Zambia, who identified *Melinis repens* to be one of the 39 species recommended for phytoremediation of heavy metal contaminated soils. On the other hand, *Lantana camara* can be used to decontaminate the soils with higher levels of Pb, Cr, Cu, Cd, Mn and Ni but its BAF was less than one for Pb. These results are in line

Table 6. Bioaccumulation factor and translocation factor.

Plant species	Heavy metal	BAF	TF
S. pyramidalis	Lead	**1.0**	**1.0**
	Chromium	0.3	**2.0**
	Cadmium	0.1	**1.0**
	Copper	**1.0**	**1.1**
	Arsenic	0.0	**1.4**
	Manganese	0.1	**1.7**
	Nickel	0.1	**1.0**
M. repens	Lead	0.3	0.8
	Chromium	0.1	0.6
	Cadmium	0.0	**1.2**
	Copper	**1.0**	**1.1**
	Arsenic	0.0	0.9
	Manganese	0.1	0.9
	Nickel	0.1	**1.5**
L. camara	Lead	0.6	**1.2**
	Chromium	0.2	**1.0**
	Cadmium	0.1	**1.9**
	Copper	**1.5**	**1.1**
	Arsenic	0.0	0.7
	Manganese	0.5	**1.6**
	Nickel	0.2	**2.6**
L. leucocephala	Lead	0.1	**3.1**
	Chromium	0.4	**1.1**
	Cadmium	0.1	0.3
	Copper	0.1	**1.6**
	Arsenic	0.0	0.6
	Manganese	**1.0**	0.9
	Nickel	**1.3**	0.7
B. maderaspatensis	Lead	0.0	**1.4**
	Chromium	0.2	0.6
	Cadmium	0.1	0.9
	Copper	0.0	**2.2**
	Arsenic	0.0	0.9
	Manganese	0.9	**1.0**
	Nickel	**1.0**	**1.0**

Values greater or equal to 1 are in bold font.

with those of a study conducted by Petelka et al. (2019) that *Lantana camara* had a bioaccumulation factor of less than one for Pb.

In this study, wood legume *Leucaena leucocephala* accumulated higher quantities of Pb, Cr, Cu, Mn and Ni hence this plant species is potential for phytoremediation of soils contaminated with these metals. This is supported by the study of Yaw (2014) who found that *Leucaena leucocephala* recorded a bioaccumulation factor greater than one for Cr, Mn and Ni. The study conducted by Freitas et al. (2004) indicated that the use of legumes in mine restoration could enrich soil nutrients, and the combined use of perennials and annuals can provide substantial inputs in terms of organic matter and nutrient recycling. Moreover, *Blepharis maderaspatensis* can be used to extract Pb, Cd, Cu, Mn and Ni contaminated soil hence a hyperaccumulator of these metals.

Plants with translocation and bioaccumulation values less than one are excluders and are not suitable for extracting heavy metals from soils (Mganga, 2014). Although excluders are not accumulators, they can tolerate heavy metals in the soils. Wendy et al. (2008) indicated that tolerant plant species are not necessarily hyperaccumulators, as tolerant non-accumulators can exclude metals from entering the root tissue. In this study, Pb excluder was *Melinis repens*, Cr excluders were *Melinis repens* and *Blepharis maderaspatensis*, Cd excluders were *Leucaena leucocephala* and *Blepharis maderaspatensis* and As excluders were *Melinis repens, Lantana camara, Leucaena leucocephala,* and *Blepharis maderaspatensis.* However, there was no plant species found by the present study to exclude Cu. These results contradict Kachenga et al. (2020) that all studied plants excluded Cu from the soils.

5. Conclusions

The present study provides an insight of the ability of *Sporobolus pyramidalis, Melinis repens, Lantana camara,* and *Leucaena leucocephala* to potentially phytoremediate heavy metals contaminated soils. The findings of our study indicated that the studied plants are hyperaccumulators as evidenced from the levels of heavy metals, BAF and TF values. In this case, *Sporobolus pyramidalis* is a hyperaccumulator of Pb, Cr, Cd, Cu, As, Mn and Ni. *Melinis repens* is hyperaccumulator of Cd, Cu and Ni. *Lantana camara* is hyperaccumulator of Pb, Cr, Cu, Cd, Mn and Ni. *Leucaena leucocephala* is hyperaccumulator of Pb, Cr, Cu, As, Mn and Ni. *Blepharis maderaspatensis* is hyperaccumulator of Pb, Cd, Cu, Mn and Ni. It is evidenced that *Blepharis maderaspatensis* has never been reported anywhere as Pb, Cd, Cu, Mn and Ni uptake plant, which can be regarded as a new finding. Further, the synthesis of the findings suggests a need for urgent attention to extend solutions to the problems of exposed contaminated sites. This needs to be accompanied with regular inspections and monitoring of heavy metals in soils and plant tissues to prevent excessive build-up of these metals in the food chain.

5.1. *Limitations of the study*

The concentrations of heavy metals in the selected plant species and associated soils were assessed through analysis of plant and soil samples. In the studied sites, there was no attempt done to collect water samples from surface runoff and/or underground to unravel the dynamics (fate) of these heavy metals in the aquatic environment. In artisanal and small-scale gold (Au) mining areas, mercury (Hg) is mixed with gold-containing materials forming a mercury-gold amalgam which is then heated, vaporizing the mercury to obtain the gold. Excess Hg is usually recovered, but Hg-rich mine tailings are often released directly into the environment. Of the studied heavy metals, some identified Hg-amalgams in the literature are Hg–Cd, Hg–Zn, and Hg–Pb (Esdaile and Chalker, 2018). Therefore, it remains a knowledge gap that needs further investigation of Hg concentrations in the environments and associated implications on the studied heavy metals and/or essential plant nutrients. Furthermore, this research was conducted during the rainy (short) season for which sampling of the study samples from plants and soils was challenging hence requires a complement study to be conducted during dry (summer) season.

Declarations

Author contribution statement

Caren A. Kahangwa: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Cuthbert L. Nahonyo, George Sangu, Eliakira K. Nassary: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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