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HEAVY METALS TOLERANCE IN OIL-BASED DRILL CUTTINGS CONTAMINATED SOIL PLANTED WITH GRASS SPECIES

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Abstract

The prospect of selected grass species in phytoremediation of oily cuttings contaminated soil was investigated. The grass species were *Panicum maximum*, *Pennisitum purpureum*, *Axonopus compressus*, *Heteropogon contortus*, *Andropogon gayanus*, and *Chloris virgata*. Three levels of contamination were used; 50%, 25%, and 0%. The difference in the day of planting and harvesting was also considered. Furthermore, the growth stages of the grass species were looked at. The parameters assessed were copper, nickel, and zinc concentrations in soils and plant parts (roots and shoots), bioconcentration and translocation factors. The highest decrease of copper concentration in soil was achieved with mature *P. purpureum* and the least was with mature *H. contortus* at 25% contamination. Copper concentration in the shoot of *A. compressus* was significantly higher than the copper concentration in the shoot of the other species of grass. The highest copper concentration in roots was obtained with mature *H. contortus* and mature *P. purpureum* at 25% contamination. The highest reduction in soil nickel concentration was observed in mature and young *P. maximum* and mature *P. purpureum* and the least reduction was seen in young *A. gayanus* and young *H. contortus* at 25% contamination. The highest significant nickel concentration in the shoot was observed in young and mature *A. compressus* at 50% contamination. The lowest nickel concentration in roots was observed in young and mature *P. purpureum*. The highest zinc concentration reduction in soil was achieved with young and mature *A. compressus*, and young and mature *P. purpureum* at 25% contamination and the lowest reduction was obtained with young and mature *C. virgata* and young *P. maximum*. The highest concentration of zinc in the shoot was recorded in mature *A. compressus* at 25% contamination and lowest was observed in young *A. gayanus*, young *P. maximum*, and mature *P. purpureum*. Highest zinc concentration in roots was recorded in mature *A. compressus* and the lowest was observed in mature *C. virgata* at 25% level of treatment

Keywords: Oil-Based Drill Cuttings, Soil Contamination, Grass Species, Phytoremediation, Heavy Metals

Introduction

Heavy metals are defined as metals with an atomic weight that is above twenty and a relative denseness that is above five (Li et al., 2019). But biologically, handling of heavy metals is mostly in connection with harm and risk and are therefore defined in biological terms as a group of metals, including in some instances metalloids, that are harmful to life forms of animals and plants even when occurring in concentrations that would be considered small (Rascio & Navari-Izzo, 2011). Unlike organic contaminants, heavy metal pollution occurs invisibly, persistently, and irreversibly causing deterioration of soil, quality of water bodies and the atmosphere, consequentially having a significant risk to the comfort and existence of life forms via deposition in the ecological chain of ascending dependency for food and energy, which is a major cause of death worldwide (Kankia & Abdulhamid, 2014). Fouling of soil with heavy metals impacts indices of the quality of soil like organic matter, clay content, and pH, which have significant implications for the amount to which metals impact the biochemical and biological

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properties of soils (Singh & Kalamdhad, 2011). Metals such as lead and zinc have a circuitous effect on soil enzyme activity by alteration of the population of microbes that synthesise biochemical catalysts. Different metals impact enzyme activity in different ways, which is related to the fact that enzymes in distinct soil systems have different chemical affinities for different metals. For instance, copper has a greater inhibitory effect on b-glucosidase activity than it does on cellulose activity. Microbe diversity and activity, which constitute plant growth communities, play an important part in nutrient recycling in plants, maintaining the structure of the soil, reducing the toxicity of hazardous chemicals, and controlling pests of plants. Thus, the state of communities of microorganisms that are straight or circuitously linked with the growth of plants makes up a key yardstick for assessing the quality of the soil. Generally, a rise in the content of heavy metals harms soil microbial features including respiration rate and enzymatic activities.

When considering the consequences on the food chain, absorption, in high quantities, of heavy metals from soils that are contaminated might provide a significant health concern (Singh & Kalamdhad, 2011). The toxicity of the metals takes effect in indigestion leading to deposition in organs of the body. Therefore, continuously taking in hazardous heavy metals could result in unfavourable effects on people, which are only noticeable after many years of exposure to the metals. Consumption of copper can result in stomach discomfort, anaemia, diarrhoea, headaches, liver damage, renal damage, metabolic abnormalities, and nausea. Nickel is linked to cardiovascular illness, chest discomfort, dermatitis, dizziness, dry cough, shortness of breath, and headaches, among other things. Zinc may induce dyssynergia, clinical depression, irritation of the gastrointestinal tract, disease in the urinary tract, jaundice, impotency, metal fume fever, failure in kidneys, failure in the liver, fatigue, breakdown in the macula, cancer of the prostate gland, seizure-inducing renal illnesses, lung and nasal cancer, and nausea-inducing vomiting.

During drilling operations, fragments of the rock that is being drilled fall to the bore bottom due to the pressure used to access oil and gas reserves. If not transported out of the well, these bits, known as drill cuttings, block the well. Fluid for drilling, frequently called drilling mud as a result of its appearance and viscosity (Epelle & Gerogiorgis, 2020), circulates in the well to carry cuttings to the surface. The drilling fluid's constitution allows it to fulfil these and other functions like chilling and lubing the bit for drilling, thereby reducing rubbing that could arise amongst the wellbore and drill pipe, and managing the pressure of formation (Neff et al., 2000). Cuttings from drilling are therefore suspended by fluids during drilling operations. Cuttings are contaminated by oil in the fluids and must be rid of harmful substances by treatment to comply with rules for dumping and reusing mud and accompanying cuttings. Drill cuttings are rock particles taken from the well by the drill bit. To sustain fluid pressure and sanitise the hole, fluids are pumped downhole via drill string and up via the wellbore annulus during drilling. Dependent upon the nature of the rock drilled, cuttings have different physical and chemical properties. The size of the cuttings varies from clay to gravel (Reddoch, 2008), and are classified according to the mud in which they are spread. Oil-based, water-based, and synthetic-based cuttings are available. Drill cuttings are analysed during exploratory drilling to ascertain reservoir depth, saturations of water and oil, permeability and porosity, cutting morphology, and mineralogy of the formation being drilled. In the unavailability of cores, they give critical petrophysical data that aid reservoir characterisation. Permeability, porosity, transverse relaxation, and nuclear magnetic resonance are among them (Mahmoud et al., 2021). Operators must find a balance between minimising effects on the environment, maintaining the stability of the borehole, and boosting the efficiency of a drilling operation. The drilling mud being used is usually the most environmentally problematic, not minding its benefit to drilling, avoidance of cracking, and creation of an unchanging well with a secure and dirt-free bore. Nevertheless, the occurrence of discharges, inadvertent spills, the petroleum and gas sector's operating discharges, and inadequately discarded wastes have major adverse effects on the health of humans and the environment. Therefore, used muds, cuttings, and sticky oils are the central target source of contamination handled in drilling waste management procedures (Arce-Ortega et al., 2004).

Oil-based drill cuttings contain certain amounts of heavy metals and including nickel, copper, chromium, arsenic, vanadium, lead, zinc, manganese, iron, and cadmium (Kogbara et al., 2019; Imarhiagbe et al., 2015). But they vary in concentration according to the associated drilling fluid – oil-based, water-based, and synthetic-based drilling fluid and the depth of the formation rock materials - top hole, mid hole and bottom hole drill cuttings. For example, a higher concentration of iron was observed in Ologbo Oilfield Wells at the bottom hole, less concentration at the mid hole and much less concentration at the top hole of the wells (Imarhiagbe et al., 2015).

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Similarly, Kogbara et al. (2019) observed copper, zinc, and nickel in oil-based drill cuttings. Therefore, treatment of these cuttings is carried out to remove or reduce, below regulatory limits, heavy metals found in the cuttings. Several methods can be used to rid oil-based drill cuttings of heavy metals but thermal desorption, cuttings reinjection and offshore disposal (away from no discharge areas) after treatment are the choice methods for handling oil-based drill cuttings in the Nigeria oil and gas sector (EGASPIN, 2018; Mkpaoro et al., 2015). Thermal desorption is a heat-based physical system of separation in which volatile and organic components of oil-based drill cuttings are vaporised and treated before release into the atmosphere (CR 98.008-ENV, 1998; Fernández Rodríguez et al., 2014). Thus, heavy metals, which are non-volatile and inorganic components of oil-based drill cuttings may not be vaporised by thermal desorption. Cuttings are clarified during reinjection by breakage into smaller particles and mixing with a fluid having water as a primary constituent (Hu et al., 2021; Samy, 2021). Thereafter the slurried cuttings are pumped with intense pressure into appropriate wells, which may be new or abandoned, approved by regulatory bodies. The pumping of cuttings with intense pressure however creates a possibility of leakage and loss of worthful oil constituents. Thermal desorption and cuttings reinjection are bedevilled by resultant cost-intensive equipment and procedure and adverse environmental impact including soil degradation, loss of biodiversity, piling of cuttings on the sea bottom, destruction of coral reefs, and pollution of groundwater. But phytoremediation is a low-cost, simple, and plant-based technology for cleaning up contaminated soils. In addition, the technology is well disposed to the environment. Thus, possibleness of phytoremediation of soil contaminated with oil-based cuttings using grass species was investigated by examining the reduction of copper, nickel, and zinc in the contaminated soil.

Materials and Methods

Six species of grass were chosen by their ability to grow fast, establish and be maintained easily, have sturdiness, possess previous reports of potential in phytoremediation, and occur in the Niger Delta. The species of grass are; *Axonopus compressus* (Sw.) P. Beauv. (carpet grass), *Pennisitum purpureum* Schumach. (elephant grass), *Panicum maximum* Jacq. (guinea grass), *Heteropogon contortus* (L.) P. Beauv. ex Roem. & Schult. (black speargrass), *Andropogon gayanus* Kunth (gamba grass), and *Chloris virgata* Sw. (feather finger grass).

The cuttings treated and untreated soil samples were analysed for physical and chemical properties such as level of nitrogen, size of soil particles, pH, level of petroleum hydrocarbons (TPH), and concentration of nickel, zinc, and copper. In addition, the oil-based drill cuttings were analysed for the level of pH, petroleum hydrocarbon (TPH), and concentrations of nickel, zinc, and copper. Determination of nitrogen level was by the Kjedahl method (Bremner, 1996), the size of soil particles was ascertained by using the hydrometer method (Bouyoucos, 1962), pH was measured with Hanna Professional Benchtop pH meter that was standardised with solutions of buffer, analysis for TPH was determined with sixteen (16) hour soxhlet extraction of 95% n-hexane solvent and HP5890 series II Gas Chromatograph-Flame Ionization Detection (GC-FID), and nickel, zinc, and copper concentrations were obtained by acid digestion involving the use of concentrated 1ml nitric acid and 10ml muriatic acid and GBC 908PBMT model of Flame Atomic Absorption Spectrophotometer (FAAS). Bacterial load was carried out by following standard microbiological laboratory procedures such as serial dilution, pour plate, incubation and colony count. The count of bacteria was noted in units of colony formation per gram, cfug^{-1} and calculated by this formula

$$\text{Bacterial count} = \frac{\text{number of colonies x dilution factor}}{\text{volume of aliquot}}$$

The experiments were performed inside a screen house in the Department of Biological Sciences, Niger Delta University, Nigeria. A randomised complete block design of 6 x 3 x 2 x 2 for grass species, treatments (0%, 25%, and 50% oil-based drill cuttings contamination), time (3 days and 105 days after transplanting), and growth stage (young and mature). The 0% treatment level was 5000 g of uncontaminated soil, which was sourced from a horticulturist in Yenagoa, Bayelsa State, Nigeria. The 25% and 50% treatment levels were prepared by three-to-one and one-to-one soil drill cuttings mixture with a total mixture of 5000 g. Each treatment level had unplanted soils that served as negative control and the positive control was planted soils at 0% treatment level. The grass species, sourced from the University campus, were nursed for a month and transferred to the cuttings-treated and cuttings-untreated soils contained in 6 litres of polyvinyl chloride buckets. The plants were allowed to acclimatise in the soils for three days before measurements and soil samples were taken for analyses. The plants were watered with 1.5 litres of water once every day.

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The magnitude of zinc, nickel, and copper reduction in oil-based drill cuttings contaminated soil was ascertained by AAS analyses at 105 days after transplanting by following the method used in obtaining primary soil and cuttings analysis for the heavy metals. Thus, enabling the computation of percentage reduction of the metals by plugging the values in the expression below.

$$\text{Percent reduction}=\frac{(\text{Heavy metal conc. at 3 days - Heavy metal conc. at 105 days})}{\text{Heavy metal conc. at 3 days}}\text{x 100}$$

The same method of determination was used to analyse zinc, copper, and nickel concentrations in roots and shoots of the plant species, separately, after 105 days of plant exposure to oil-based drill cuttings. Bioconcentration and translocation factors of the metals were computed by applying this relationship.

$$\text{Bioconcentration factor (BCF)} = \frac{\text{Heavy metal conc. in parts of plants (root or shoot)}}{\text{Heavy metal conc. in soil}}$$

$$\text{Translocation factor (TF)} = \frac{\text{Heavy metal conc. in shoot}}{\text{Heavy metal conc. in roots}}$$

Consequently, mechanisms of phytoremediation of soil contaminated with oil-based drill cuttings concerning copper, nickel, and zinc concentrations were drawn from these benchmarks
Phytoaccumulation/phytoextraction: $TF > 1$; $BCF > 1$
Phytostabilisation/exclusion: $TF < 1$; $BCF < 1$

Statistical significance of the difference in mean among species, time, growth stages, and treatments was obtained by performing analysis of variance (ANOVA) and turkeyHSD tests at a 5% probability level with the use of aov and turkeyHSD functions in R version 4.1.2 for Windows personal computer (R Core Team, 2021) on R Studio, which is an Integrated Development Environment (IDE) designed for R (RStudio Team, 2021). The mean of the data, standard error, and standard error bar were obtained with mean_se and errorbar functions and plotted with geom_point function in ggplot2 package (Wickham, 2016) in R version 4.1.2 for Windows personal computers.

Results

The 11.84% level of clay in 25% oil-based drill cuttings was significantly different from the 12.76% amount of clay in uncontaminated soil and 12.96% clay in 50% of the cuttings contaminated soil (Figure 1). But the level of clay in uncontaminated soil was not significantly different from the level of clay in 50% oil-based drill cuttings contaminated soil. The 85.52% amount of sand in 25% and 85.52% sand in 50% contaminated soils were not significantly different. However, the 83.62% level of sand in uncontaminated soil was significantly different from the amount of sand in contaminated soil. The contaminated and uncontaminated soils showed a significant difference in the amount of silt. The highest level of clay was seen in both uncontaminated soil at 12.76% and 50% oil-based drill cuttings contaminated soil at 12.96%, and the lowest was recorded in 25% oil-based drill cuttings contaminated soil at 11.84%. The highest level of sand was observed in contaminated soils at 85.52% and the lowest was in uncontaminated soil at 83.62%. The highest amount of silt was present in uncontaminated soil at 3.76% and the lowest occurred in 50% oil-based drill cuttings contaminated soil at 1.52%. There was a significant difference in the pH of the different soils. The highest pH value of 9.64 was observed in drill cuttings and the lowest value of 6.85 was seen in uncontaminated soil.

The nitrogen level of 83.43% in uncontaminated soil was significantly different from the levels (that is, 85.52%) in contaminated soils. However, there was no significant difference among the contaminated soils. The highest nitrogen level of 85.52% was recorded in the contaminated soils and the lowest level of 83.43% was observed in the uncontaminated soils. The contaminated and uncontaminated soils as well as drill cuttings showed significant differences in concentrations of petroleum hydrocarbons. The highest concentration of TPH of 1622.67 mg/kg was seen in the drill cuttings and the lowest TPH of < 0.001 mg/kg was in the uncontaminated soils. There was a significant difference in copper, nickel, and zinc concentrations between soils (contaminated and uncontaminated soils) and drill cuttings. The highest copper concentration of 11.69 mg/kg was found in the drill cuttings and the lowest concentration of 1.33 mg/kg was observed in uncontaminated soil. Similarly, the highest nickel concentration of 4.49 mg/kg was noticed in the drill cuttings and the lowest nickel concentration of < 0.001 mg/kg was seen in uncontaminated soil. The highest zinc concentration of 31.62 mg/kg occurred in drill cuttings and the lowest value of 12.79 mg/kg was in 25% oil-based drill cuttings contaminated soil. The drill cuttings and

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soils (contaminated and uncontaminated soils) showed significant differences in bacterial load. The highest bacterial load occurred in 50% oil-based drill cuttings contaminated soil and the lowest was noticed in uncontaminated soils.

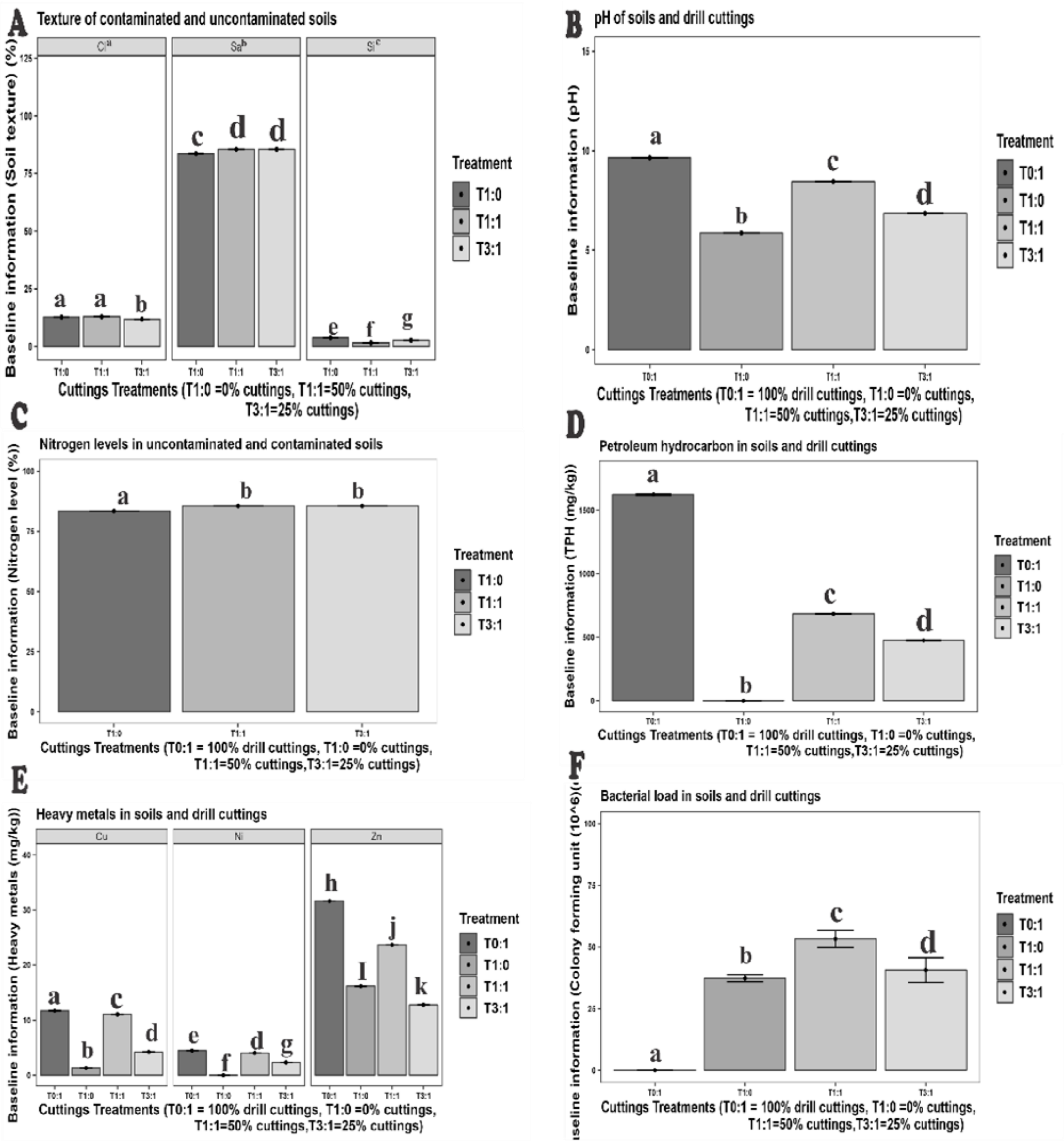

Figure 1: Soil and drill cuttings characteristics

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

There was a significant decrease in copper concentration in the soils planted with grass species but there was no significant reduction in the concentration of copper in soils that were left unplanted (Figure 2). A significant mean difference was seen in copper concentrations amongst levels of treatment at 105 days after transplanting. Thus, there was also a significant difference in copper concentration amongst grass species. The highest decrease in copper concentration was observed in 0% drill cuttings treatment level in planted soils as shown in Figure 3. The decrease in copper concentration in the 25% treatment level was higher than the decrease in the 50% treatment level over the time of the experiment. The highest decrease was achieved with mature *P. purpureum* and the lowest was with mature *H. contortus* at 25% oil-based drill cuttings treatment.

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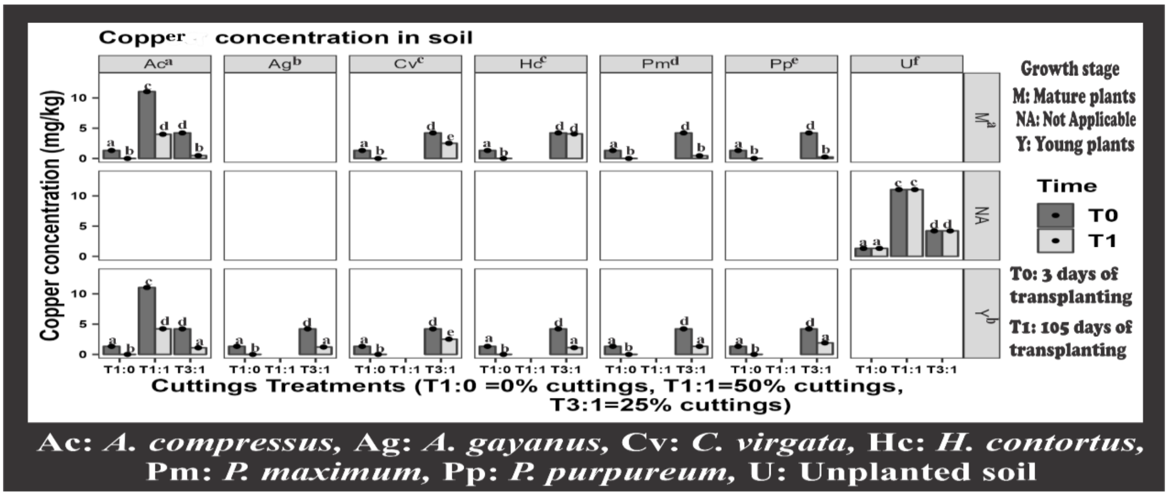

Figure 2: Copper concentration in soils

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

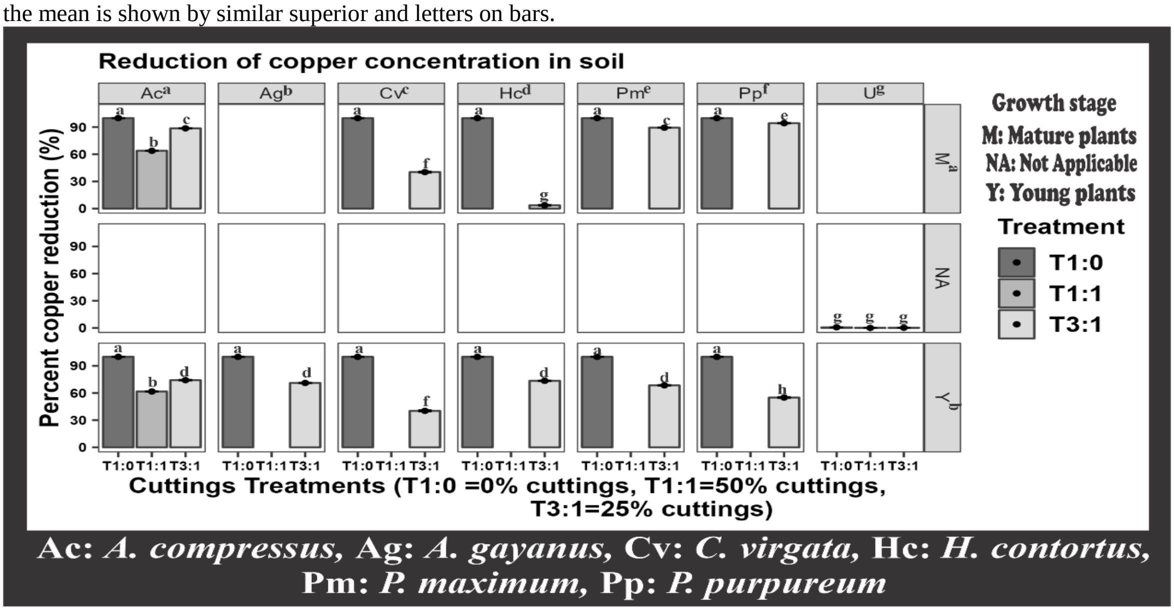

Figure 3: Percent copper concentration reduction in soils

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

Results for copper concentration in the shoot of species of grasses planted in oil-based drill cuttings contaminated soils are presented in Figure 4. The concentration of copper in the shoot of *A. compressus* at 50% oil-based drill cuttings contamination was significantly higher than the copper concentration at 0% and 25% treatment levels. This was also significantly higher than the copper concentration in the shoot of the other grass species. The lowest copper concentration in the shoot was noticed in *A. gayanus*, mature *H. contortus*, *P. maximum*, and mature *P. purpureum*. The result in Figure 5 shows that was a significant difference in treatment levels, grass species, and growth stages in the concentration of copper in the roots of the grass species. The highest concentration was achieved in the roots of mature *H. contortus* and mature *P. purpureum* at 25% oil-based drill cuttings contamination. The lowest concentration occurred in *A. gayanus* at 0% oil-based drill cuttings treatment level.

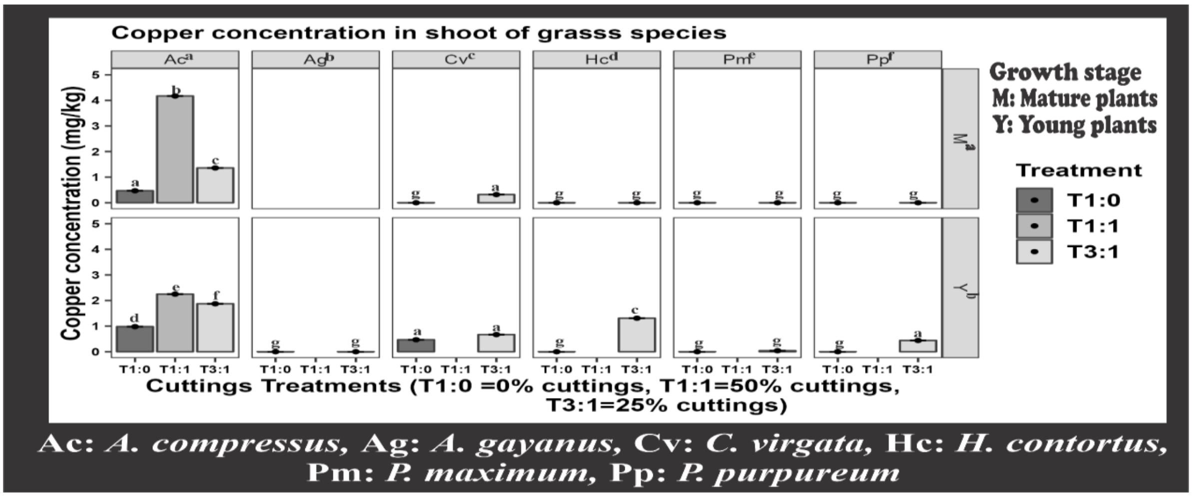

Figure 4: Copper concentration in the shoot of grass species

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

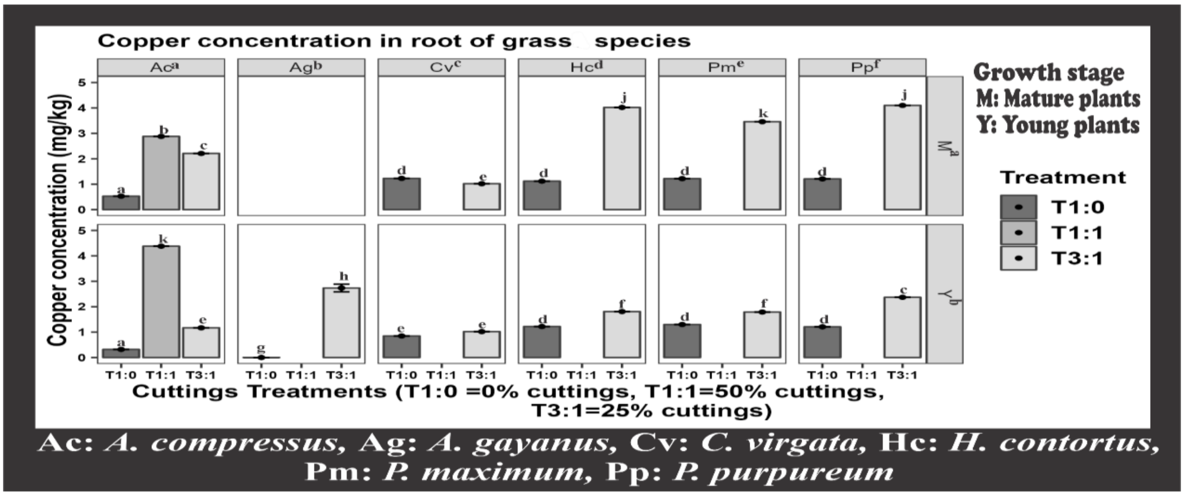

Figure 5: Copper concentration in roots of grass species

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The bioconcentration of copper in the shoot of the grass species is shown in Figure 6. there was no significance in the difference in mean of copper concentration as regards levels of cuttings treatment except in *A. compressus* and young *C. virgata* in which 0% was significantly different from 25% treatment levels. A bioconcentration factor greater than 1 was recorded in young *H. contortus, and* young and mature *A. compressus* at 25% oil-based drill cuttings contamination. The bioconcentration factor in mature *A. compressus* at 50% treatment level was also above one. The factor for bioconcentration was below one in mature *H. contortus*, young and mature *P. purpureum*, *A. gayanus,* young and mature *P. maximum,* and young and mature *C. virgata* at 25% treatment level. The bioconcentration factor was also lower than 1 in young *A. compressus* at 50% oil-based drill cuttings treatment level.

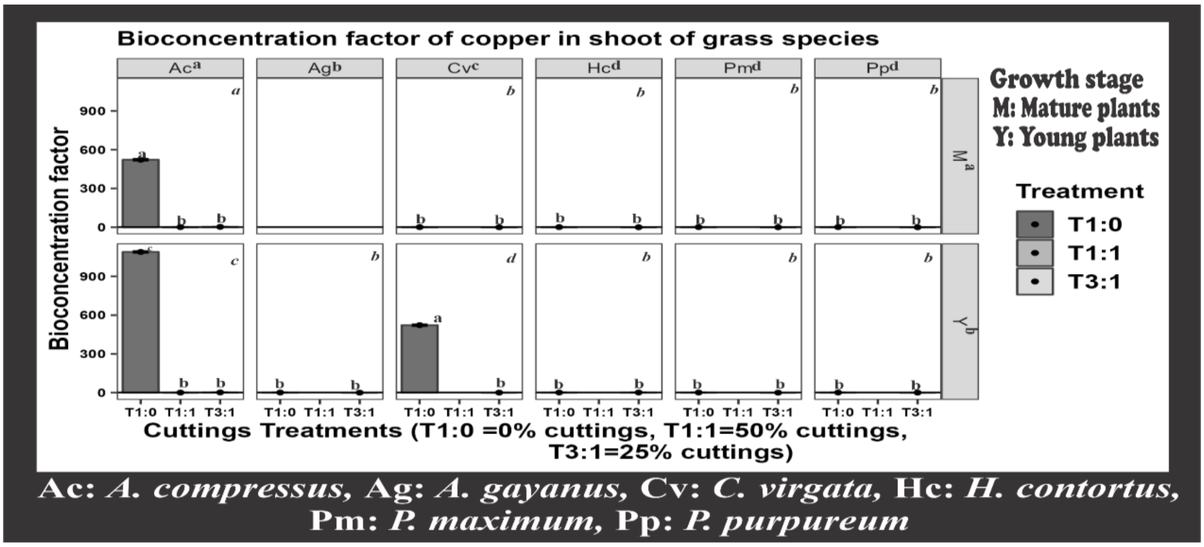

Figure 6: Bioconcentration factor of copper in shoots of grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The bioconcentration factor of copper in the roots of grass species is presented in Figure 7. It was observed that there was no significant difference between 25% and 50% levels of treatment in *A. compressus* and between 0% and 25% levels in *A. gayanus*. But there was a significant difference between 0% and 25% oil-based drill cuttings contamination. The bioconcentration factor was greater than 1 in young and mature *H. contortus*, young and mature *P. purpureum, A. gayanus*, and young and mature *P. maximum* at 25% oil-based drill cuttings contamination. The bioconcentration factor was also greater than 1 in young *A. compressus* at 25% and 50% treatment levels as well as mature *A. compressus* at 25% treatment level. The bioconcentration factor was less than 1 in mature *A. compressus* at 50% treatment level and young and mature *C. virgata* at 25% treatment level.

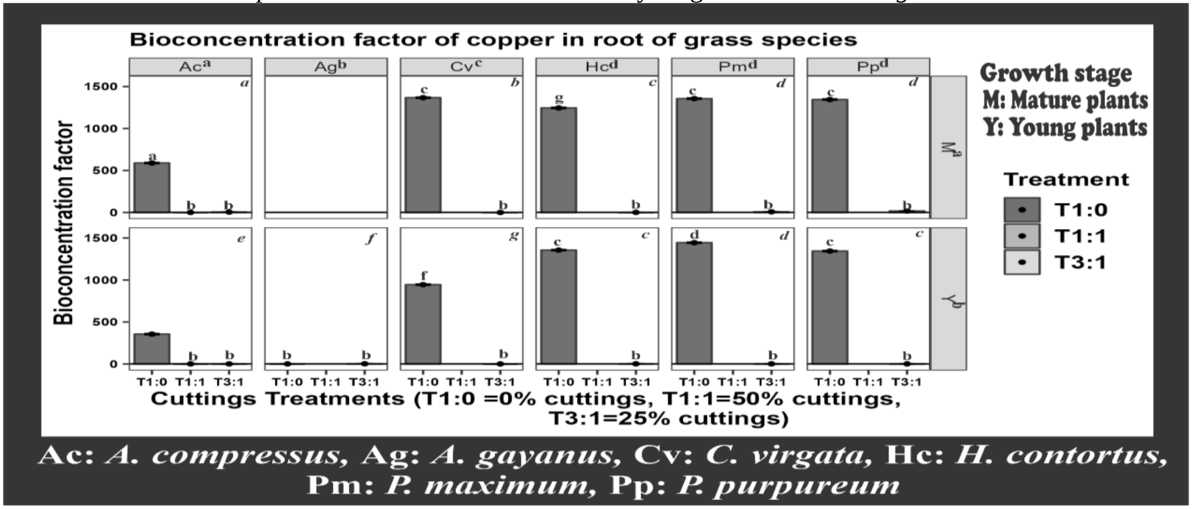

Figure 7: Bioconcentration factor of copper in roots of grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The result for the translocation factor of copper in the grass species is presented in Figure 8 which shows that there was a significant difference in grass species, growth stage, and treatment levels. But there was no significant difference in treatment levels in mature *H. contortus, P. maximum,* and *P. purpureum.* There was additionally no significant difference amongst 0% and 25% treatments of oil-based drill cuttings contamination in young *P. maximum*. The translocation factor was greater than 1 in young *A. compressus* at 25% treatment level and mature

A. compressus at 50% treatment level. The translocation factor was less than 1 in young and mature *H. contortus*, young and mature *P. purpureum*, young *A. gayanus*, young and mature *P. maximum*, young and mature *C. virgata*. The translocation factor was also less than 1 in young and mature *A. compressus* at 50% and 25% treatment levels, respectively.

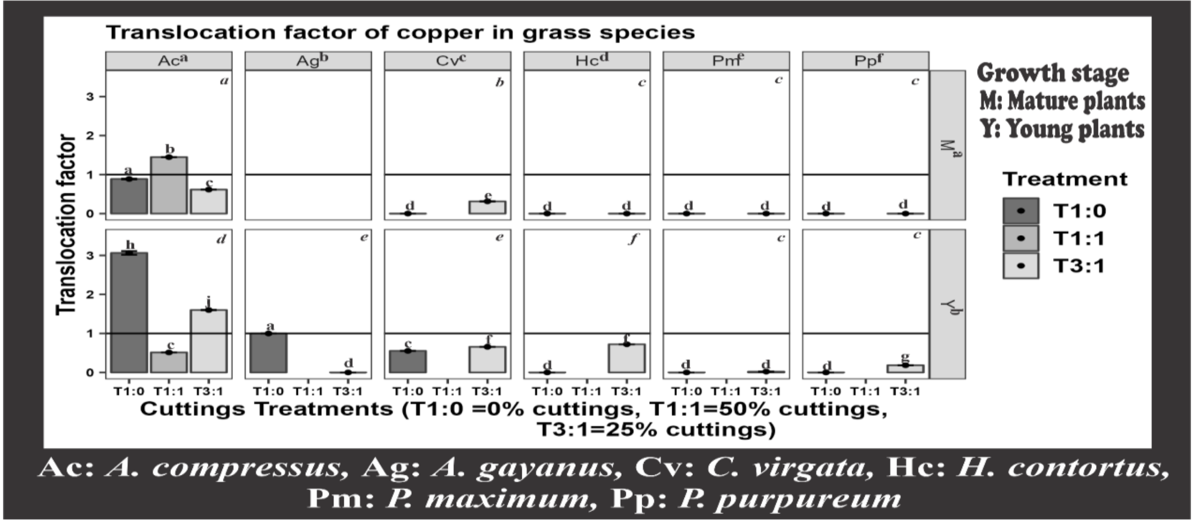

Figure 8: Translocation factor of copper in grass species

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

There was a significant difference in soil nickel concentration on treatment levels, time, growth stages, and species (see Figure 9). But there was no significant difference in nickel concentration on time at 0% oil-based drill cuttings treatment level. The highest reduction in soil nickel concentration was obtained with young and mature *P. maximum* and mature *P. purpureum* at a 25% treatment level as shown in Figure 10. The lowest reduction was seen in young *A. gayanus* and young *H. contortus*. Results for concentration of nickel in the shoot of species of grasses are shown in Figure 11. There was no significant difference in treatments except in young and mature *P. maximum* and young *P. purpureum*. The highest nickel concentration in the shoot was seen in mature *P. maximum* followed by young *P. maximum* and *P. purpureum.*

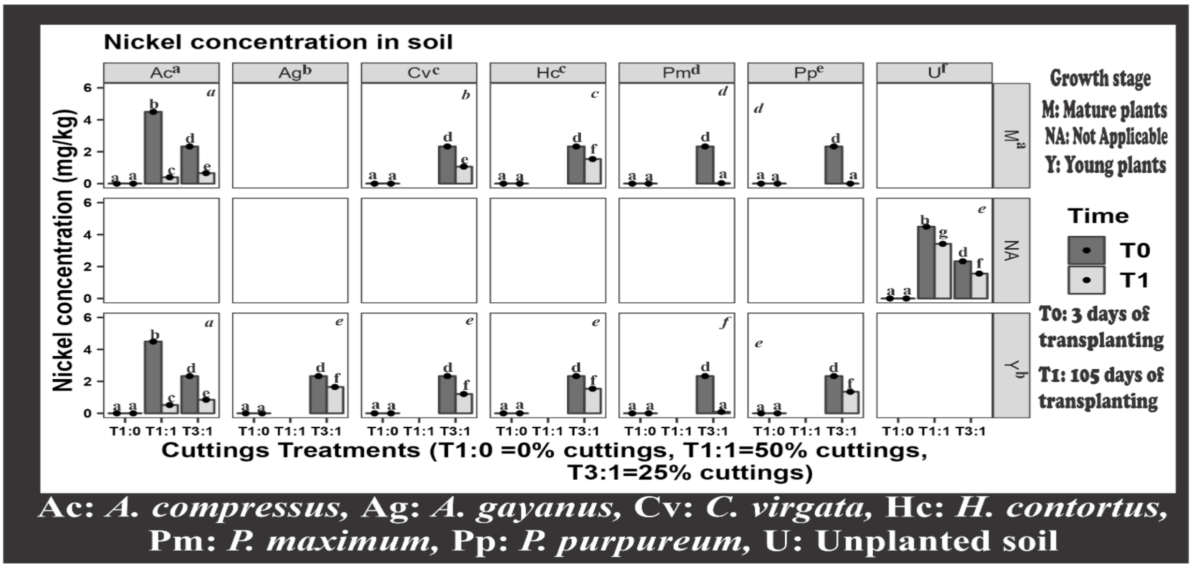

Figure 9: Nickel concentration in soils

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

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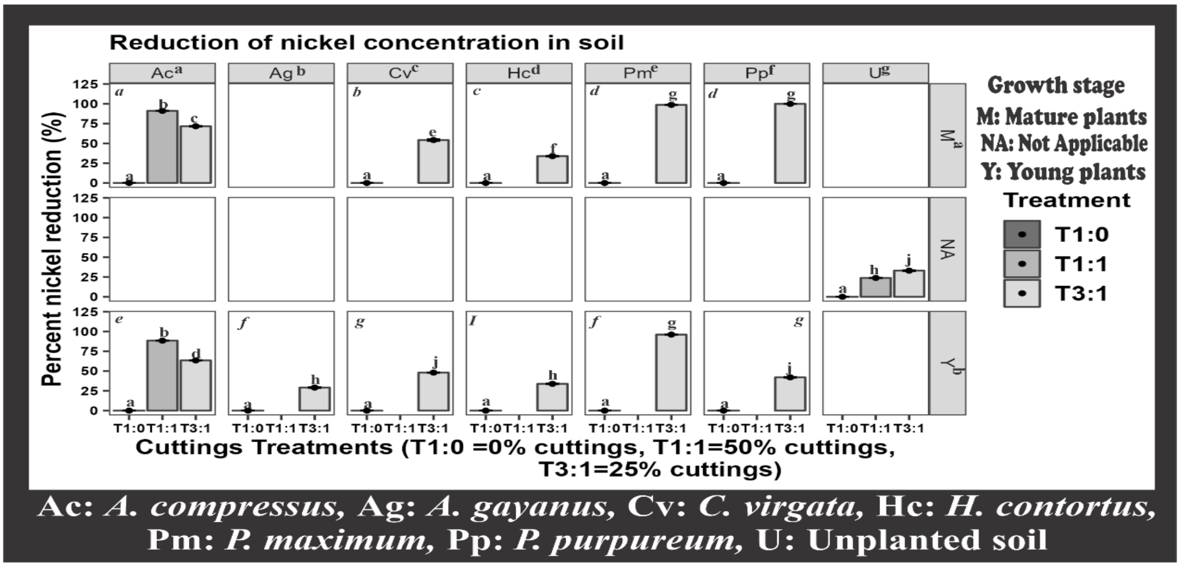

Figure 10: Percent nickel concentration reduction in soils
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

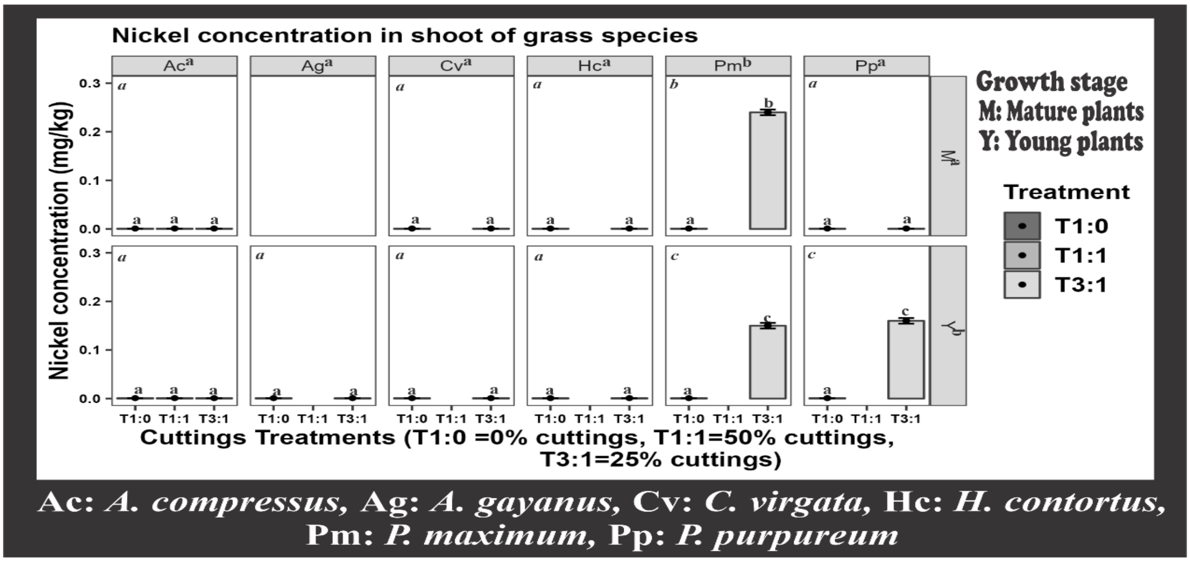

Figure 11: Nickel concentration in the shoot of grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The concentration of nickel in the roots of the grass species is depicted in Figure 12. There was a significant difference between treatment levels. The highest significant nickel concentration was observed in young and mature *A. compressus* in soils contaminated with 50% oil-based drill cuttings. This was followed by young and mature *P. maximum* at 25% oil-based drill cuttings contamination level. The lowest nickel concentration in roots was observed in young and mature *P. purpureum*.

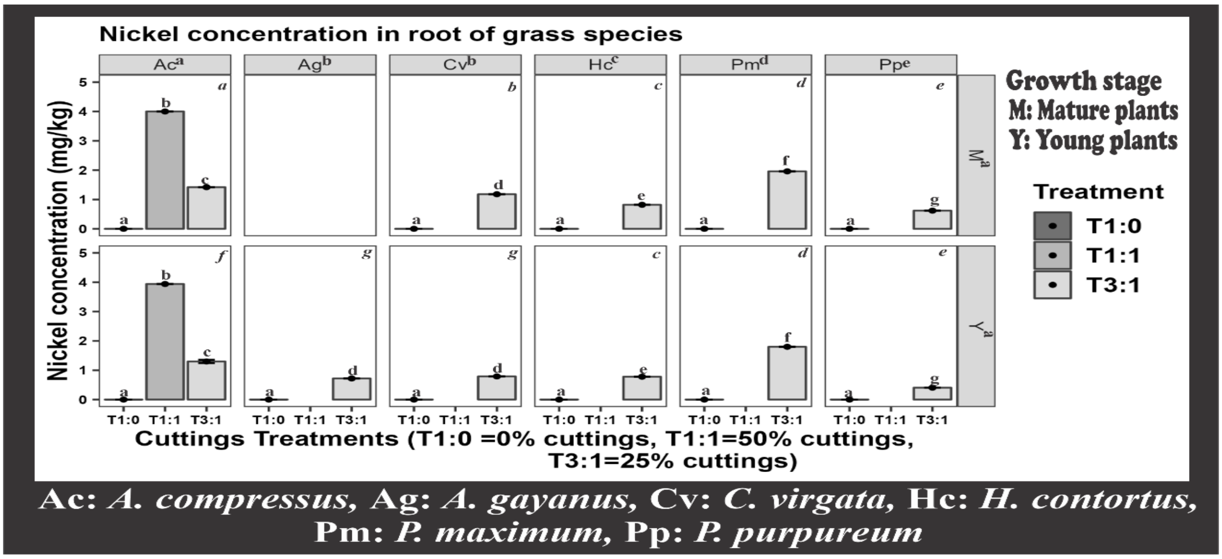

Figure 12: Nickel concentration in roots of grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The bioconcentration factor of nickel in the shoot of the grass species is shown in Figure 13. There was a significant difference between treatment levels except in *A. compressus* and mature *P. purpureum* in which 25% and 50% levels and 0% and 25% levels, respectively, were not significantly different. The bioconcentration factor was less than 1 in young and mature *H. contortus,* young *P. purpureum*, young *A. gayanus,* young and mature *A. compressus,* young and mature *C. virgata* at 25% and 50% oil-based drill cuttings contamination level. The bioconcentration factor was greater than 1 in young and mature *P. maximum.* A bioconcentration factor of 1 was obtained in mature *P. purpureum* planted in a 25% oil-based drill cuttings contamination level.

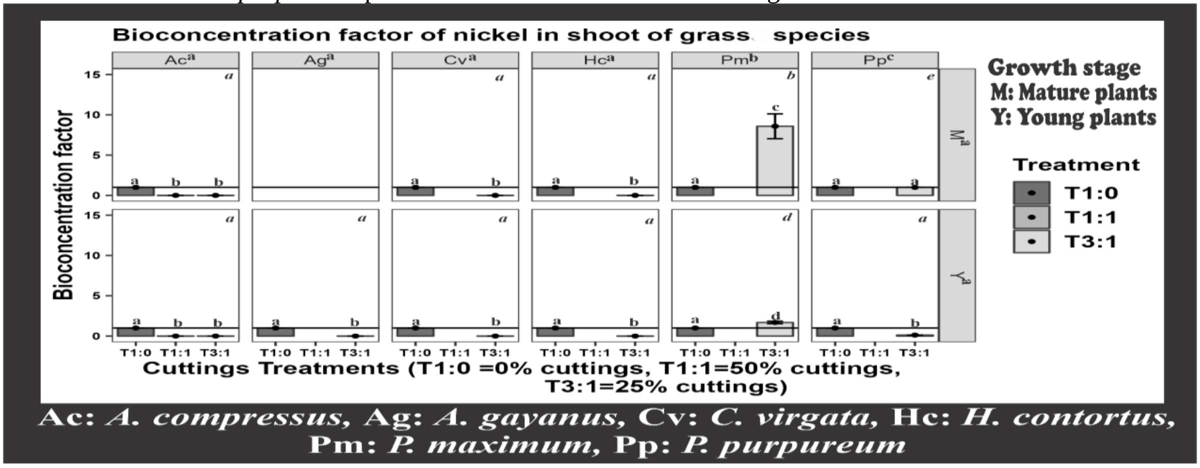

Figure 13: Bioconcentration factor of nickel in the shoot of grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The significant difference in treatment levels in bioconcentration factor was noticed in mature *P. maximum* and *P. purpureum* as presented in Figure 14. There was no significant variation in treatments in *A. compressus, A. gayanus, C. virgata, H. contortus,* young *P. maximum,* and young *P. purpureum.* But the bioconcentration factor was less than 1 in young and mature *H. contortus*, young *P. purpureum*, young *A. gayanus,* and young *C. virgata* at 25% level of oil-based drill cuttings treatment. The values were greater than 1 in mature *P. purpureum,* young and mature *A. compressus,* young and mature *P. maximum* at 25% and 50% treatment levels.

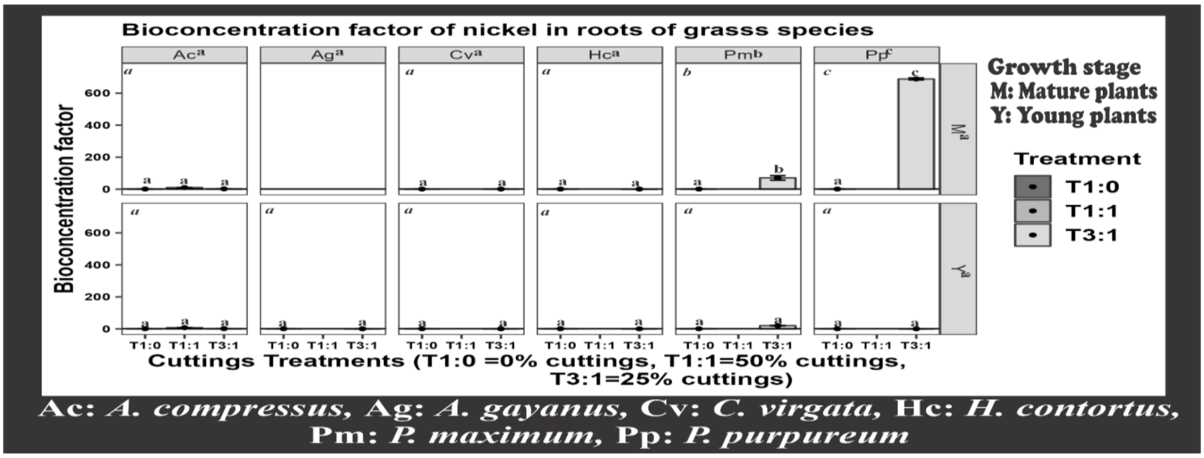

Figure 14: Bioconcentration factor of nickel in roots of grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The result for the translocation factor of nickel in the grass species is illustrated in Figure 15. There was a significant difference in treatment levels with exception of 25% and 50% oil-based drill cuttings treatment levels in young and mature *A. compressus.* A translocation factor less than 1 was obtained in young and mature *H. contortus*, young and mature *P. purpureum*, young *A. gayanus*, young and mature *A. compressus*, young and mature *P. maximum*, and young and mature *C. virgata* at 25% and 50% treatment levels.

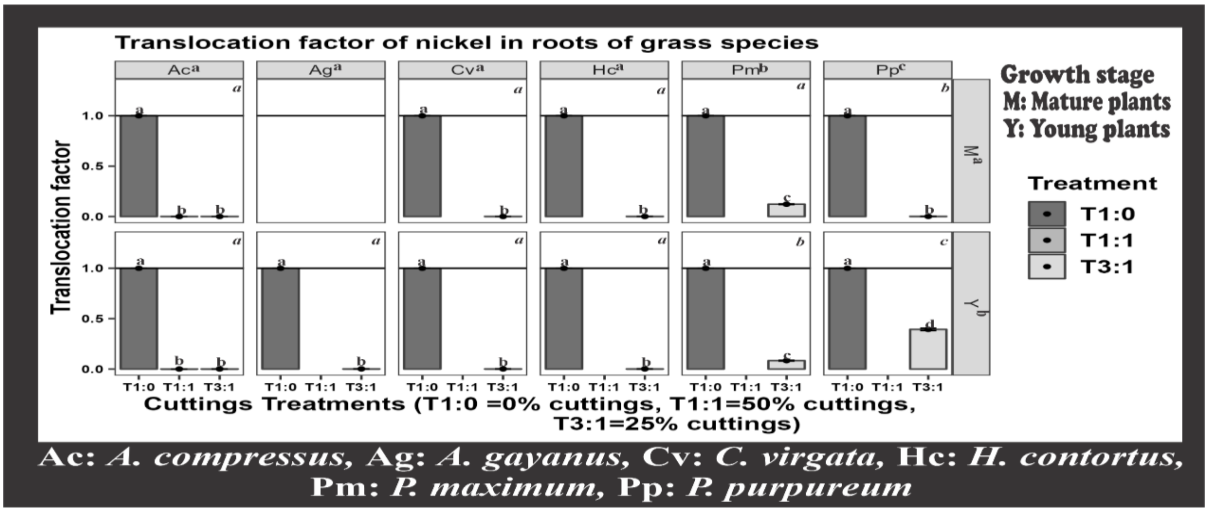

Figure 15: Translocation factor of nickel in grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The result for the concentration of zinc in contaminated and uncontaminated soils is presented in Figure 16. There was a significant difference between a day of transplanting and a day of harvesting in planted soils. But no significant variation in concentration of zinc was seen during a day of transplanting and harvesting in unplanted soils. Thus, the lowest reduction in zinc concentration was seen in unplanted soils as shown in Figure 17. The highest reduction was seen in 0% oil-based drill cuttings contamination. The highest zinc concentration reduction in contaminated soils was achieved with young and mature *A. compressus*, and young and mature *P. purpureum* at a 25% treatment level. The lowest reduction amongst the contaminated soils was obtained with young and mature *C. virgata* and young *P. maximum*.

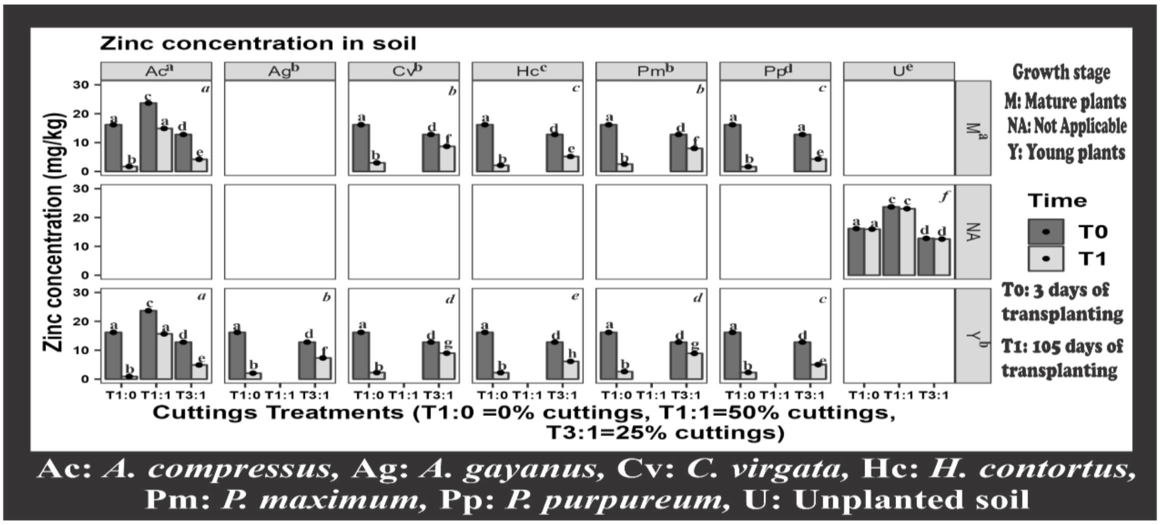

Figure 16: Zinc concentration in soils

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

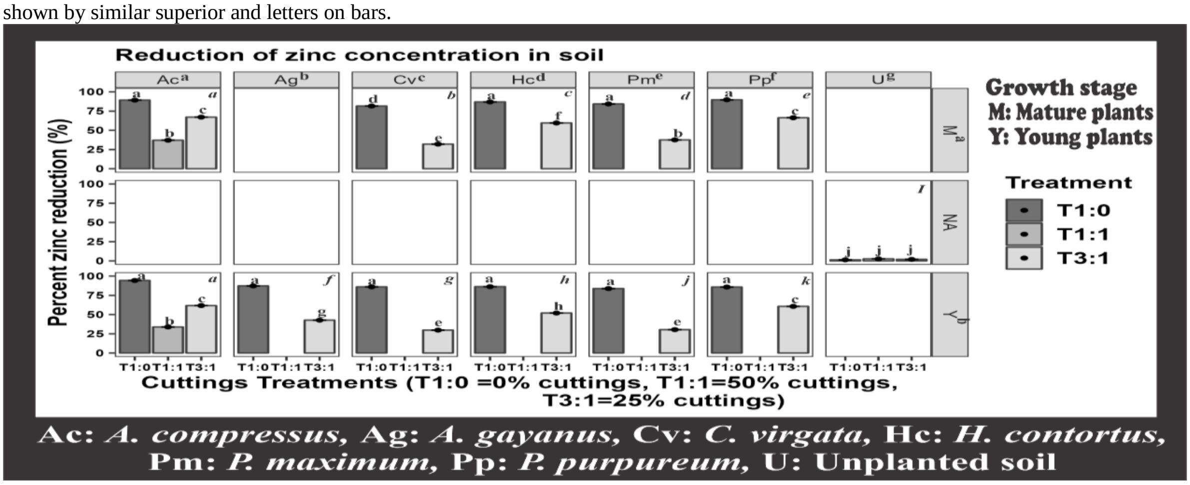

Figure 17: Percent zinc concentration reduction in soils

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

Results for the concentration of zinc in the shoot of species of grasses presented in Figure 18 show that there was a significant difference in grass species, growth stages, and treatment levels. The highest concentration of zinc in the shoot was recorded in mature *A. compressus* at 25% oil-based drill cuttings contamination level. The lowest zinc concentration in the shoot of the grass species was noticed in young *A. gayanus*, young *P. maximum*, and mature *P. purpureum*.

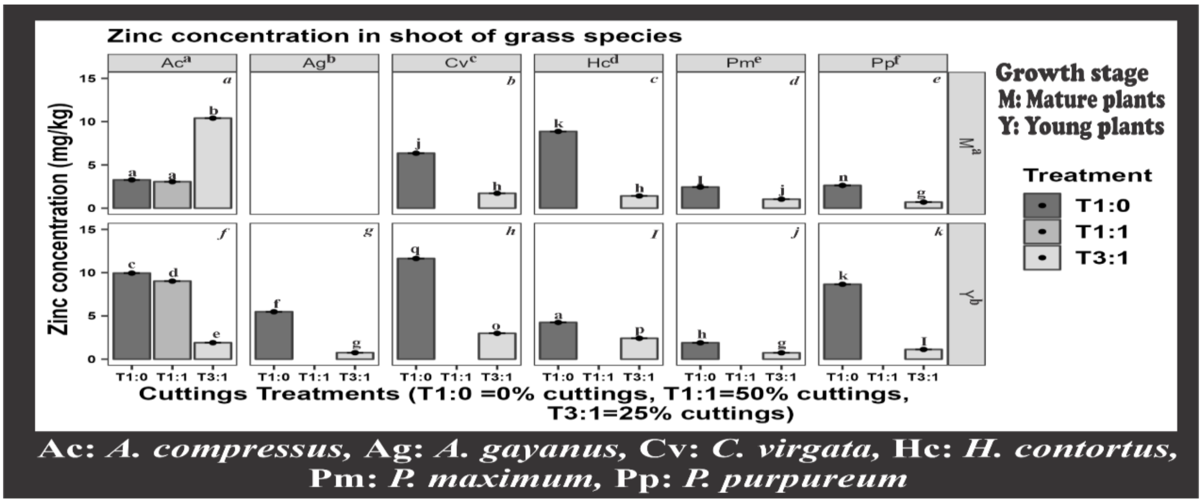

Figure 18: Zinc concentration in the shoot of grass species

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The concentration of zinc analysed in the roots of the grass species is depicted in Figure 19. There was a meaningful difference in levels of oil-based drill cuttings treatment and the growth stage of grass species. But 0% and 50% levels in mature *A. compressus* were not significantly different. The highest zinc concentration was recorded in mature *A. compressus* at 25% oil-based drill cuttings treatment level. The lowest significant zinc concentration was observed in mature *C. virgata* at a 25% treatment level.

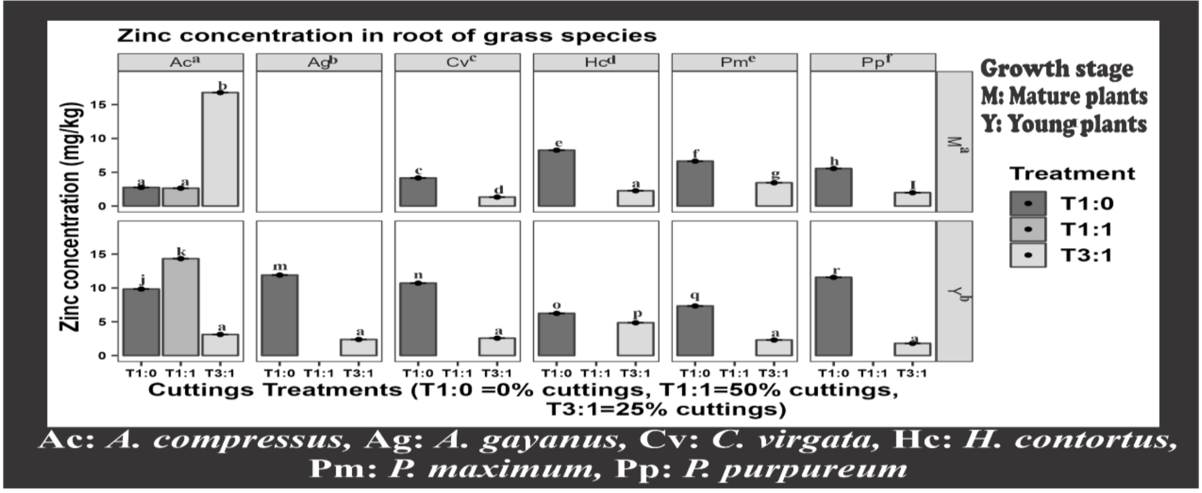

Figure 19: Zinc concentration in the root of grass species

A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The concentration of zinc in the shoot of the grass species concerning concentration in the soils is shown in Figure 20. There was a significant difference between grass species, growth stages, and oil-based drill cuttings treatment levels. The bioconcentration factor was less than 1 in young and mature *H. contortus*, young and mature *P. purpureum*, young *A. gayanus*, young and mature *P. maximum*, young and mature *C. virgata* at 25% oily cuttings treatment. The bioconcentration factor of the heavy metal was also less than 1 in shoots of young *A. compressus* at 25% treatment level and mature *A. compressus* at 50% oil-based drill cuttings contamination. The bioconcentration factor in mature *A. compressus* planted in soil containing 25% oil-based drill cuttings was greater than 1.

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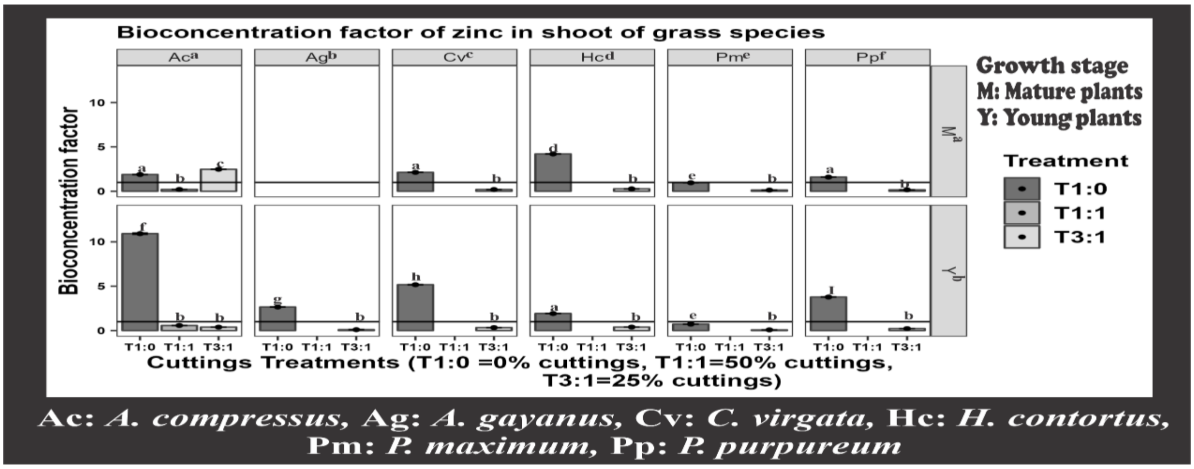

Figure 20: Bioconcentration factor of zinc in the shoot of grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The bioconcentration factor of zinc in the root of the grass species is presented in Figure 21. There was a significant difference in grass species, growth stages, and treatment levels. A bioconcentration factor value less than one was obtained in young and mature *H. contortus*, young and mature *P. purpureum,* young *A. gayanus,* young *A. compressus,* young *P. maximum,* and, young and mature *C. virgata* planted in 25% oil-based drill cuttings contaminated soils. A bioconcentration factor less than 1 was also gotten in mature *A. compressus* planted in 50% oil-based drill cuttings contaminated soils. The bioconcentration factor in mature *A. compressus* planted in 25% oil-based drill cuttings contaminated soils was greater than 1.

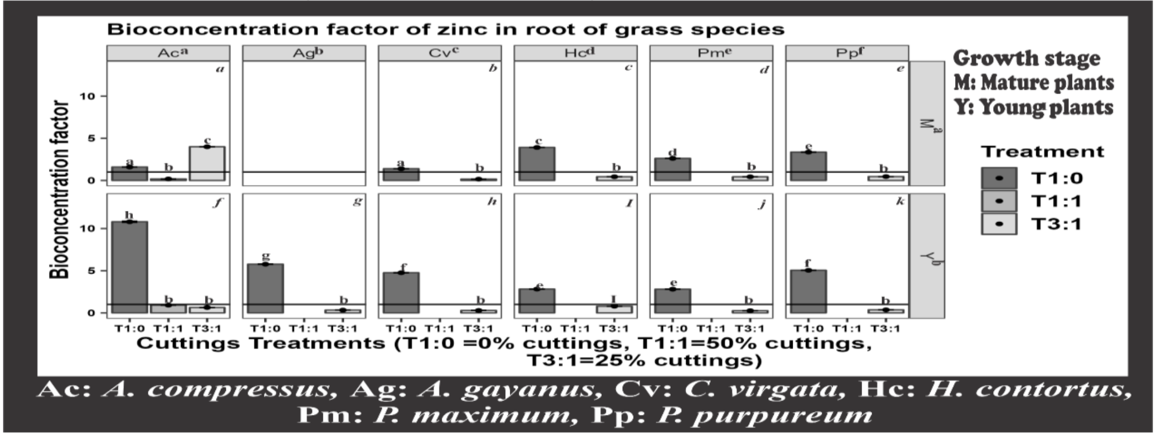

Figure 21: Bioconcentration factor of zinc in roots of grass species
A significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The results for the translocation factor of zinc in the grass species is depicted in Figure 22 below. There was a significant difference in grass species, growth stages, and treatment levels. However, a variation that was not significant amongst 0% and 50% levels in mature *A. compressus* and amongst 25% and 50% levels in young *A. compressus* was recorded. Translocation factor less than 1 was gotten with young and mature *H. contortus*, young and mature *P. purpureum*, young *A. gayansus*, young *A. compressus*, and young and mature *P. maximum* planted in 25% and 50% oil-based drill cuttings contaminated soils. In addition, the translocation factor of zinc in mature *A. compresus* planted in 25% oil-based drill cuttings contaminated soils was less than 1. A translocation factor greater than 1 was obtained with mature *A. compressus* planted in 50% oil-based drill cuttings contaminated soils.

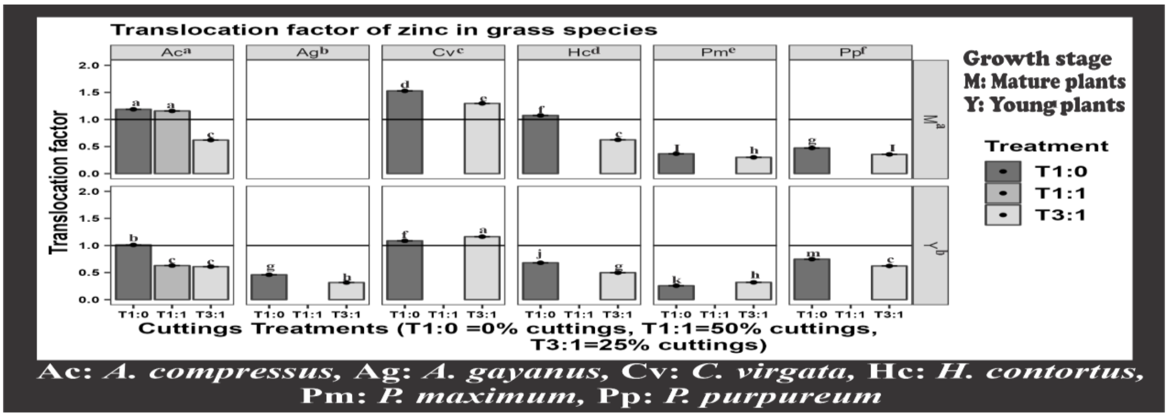

Figure 22: Translocation factor of zinc in grass species
Significant difference in mean at 0.05 level is shown by dissimilar superior and letters on bars. No significant difference in the mean is shown by similar superior and letters on bars.

The significantly highest decrease in copper concentration achieved with mature *P. purpureum* means that the species is most suitable, of those studied herein, for purpose of reducing the concentration of copper in soils contaminated with oil-based drill cuttings. The least suitable for this purpose would be mature *H. contortus* as its planting in the oil-based drill cuttings contaminated soils resulted in the lowest copper reduction throughout the experiment. *P. purpureum* is a hardy grass species that produce large biomass with minimal nutrient requirements and has usefulness in bioenergy and forage production (Ohimain et al., 2014). Its ability to take up copper in oil-based drill cuttings contaminated soils has been recorded in other studies (Dumkhana & Ekemube, 2020; Kogbara et al., 2017, 2019). The other grass species studied herein that can be used to significantly reduce copper concentration in oil-based drill cuttings contaminated soils are *A. compressus*, *A. gayanus*, *P. maximum*, *H. contortus*, and *C. virgata*. But the young growth stage of *H. contortus* is more suitable for reducing copper concentration in oil-based drill cuttings contaminated soils as the mature growth stage of the species resulted in higher copper concentration at the end of the experiment. In like manner, mature *P. purpureum,* young and mature *P. maximum*, and young and mature *A. compressus* would be preferred plant materials for nickel and zinc reduction in oil-based drill cuttings contaminated soils. Nevertheless, considerable nickel and zinc reduction was obtained with *A. gayanus, H. contortus, P. maximum,* and *C. virgata.*

Mechanisms of phytoremediation of soils for heavy metal removal are phytoaccumulation and phytostabilisation (Abdel-Shafy & Mansour, 2018). The bioconcentration factor of copper greater than 1 in shoots of young *H. contortus,* young and mature *A. compressus* concerning the oil-based drill cuttings contaminated soils indicates that the metal was reduced by accumulation into the shoot. The less than 1 bioconcentration factor of copper in shoots of mature *H. contortus*, young and mature *P. purpureum, A. gayanus,* young and mature *P. maximum,* young and mature *C. virgata*, *A. compressus* means that the mechanism of phytostabilisation was used by the grasses to tolerate the presence of oil-based drill cuttings. The relation of roots of young and mature *H. contortus,* young and mature *P. purpureum,* young *A. gayanus,* young and mature *A. compressus* and young and mature *P. maximum* in tolerance to copper in oil-based cuttings and phytoremediation of the contaminated soils resulted in accumulation into the root tissues as the bioconcentration factor was greater than 1. But exclusion mechanism was also employed by *A. compressus* and young and mature *C. virgata* at the root-contaminant interphase because the bioconcentration factor was less than 1.

Young and mature *H. contortus,* young *P. purpureum,* young *A. gayanus,* young and mature *A. compressus,* young and mature *C. virgata* excluded nickel from their shoots as a bioconcentration factor less than 1 was obtained. But young and mature *P. purpureum* extracted nickel into its shoots as the bioconcentration factor was greater than 1. A bioconcentration factor of nickel in roots greater than 1 in mature *P. purpureum,* young and mature *A. compressus,* young and mature *P. maximum* means that these plant materials reduced nickel concentration in oil-based drill cuttings contaminated soils by accumulation in their roots. In contrast, young and mature *H. contortus*, young *P. purpureum,* young *A. gayanus,* and young *C. virgata* used stabilisation to tolerate and phytoremediate oil-based contaminated soil.

The mechanism of phytostabilisation, as regards zinc concentration in shoots of grass species planted in oil-based drill cuttings contaminated soils, can be inferred from the bioconcentration factor less than 1 in young and mature *H. contortus*, young and mature *P. purpureum*, young *A. gayanus*, young and mature *P. maximum*, young and mature *A. compressus*, young and mature *C. virgata*. While the mechanism of phytoaccumulationor or phytoextraction, as regards zinc concentration in shoots of grass species planted in oil-based drill cuttings contaminated soils, can be inferred in mature *A. compressus*. Similarly, phytoextraction was used by roots of mature *A. compressus* to phytoremediate the contaminated soil and reduce zinc concentration. In contrast, phytoexclusion mechanism was employed in the roots of young and mature *H. contortus*, young and mature *P. purpureum*, young *A. gayanus*, young and mature *A. compressus*, young *P. maximum*, and, young and mature *C. virgata*. Furthermore, from the translocation factor results, it can be inferred that young and mature *A. compressus* phytoaccumulated copper and zinc in 50% oil-based drill cuttings treated soils as the values were greater than 1. The TF values of copper, nickel, and zinc less than 1 in mature *A. compressus*, young and mature *H. contortus*, young and mature *P. purpureum*, young *A. gayanus*, young and mature *P. maximum*, young and mature *C. virgata* is a pointer that exclusion mechanism was used by the grass species.

Conclusion

The baseline concentration of copper, zinc, and nickel in the oil-based drill cuttings contaminated soils was below permissible limits. Be that as it may, the analysis showed that the grass species can phytoaccumulate/phytoextract and phytostabilise/exclude the heavy metals. The grass species are therefore capable of tolerating heavy metals occurring in the drill cuttings, and reducing them to even lower concentrations. The take from this is that the grass species can be used as phytoaccumulators or phystabilisers when aiming at copper, zinc, and nickel tolerance.

Contribution of authors

IO Agbagwa and FBG Tanee conceptualised the project, IO Agbagwa, FBG Tanee and CG Ologidi designed the project, CG Ologidi and A Otele did the experiment, analysed and interpreted the data, CG Ologidi wrote the manuscript. All authors read and approved the manuscript.

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