PERFORMANCE OF ELEPHANT GRASS AND MAIZE PLANT IN ADMIXTURE OF STABILISED/SOLIDIFIED DRILL CUTTINGS WITH LOAMY SAND SOIL

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ABSTRACT

The effectiveness of reuse granulated Stabilised/Solidified (S/S) drill-cuttings in forage production. The background value of total petroleum hydrocarbon (TPH) concentrations was 17,125 mg $kg^{-1}$with low metals concentrations. Drill cuttings were Stabilised/Solidified with varying percentages 5%, 10% and 20% of cementitious binder for 28 day before mixing with soil. There was between 60% reduction in TPH levels after S/S. Three treatment options involved elephant grass (*Pennisetum purpureum*) grown in uncontaminated soil amended S/S cement treated-drill cuttings in a ratio of 3:1. A fourth treatment options involved maize (*Zea mays L*) grown in S/S treated drill cuttings-amended soil with 20% cement dosage. Four controls involved each of the aforementioned forages grown in untreated drill cuttings and uncontaminated soil alone. Fertilizer and Spent Mushroom Substrate (SMS) were employed across all eight options. The growth performance of the forages was assessed for up to 8 - 12 weeks using plant parameters such as plant height, leaf length and leaf width. The physicochemical parameters evaluated were TPH, Metals and total Heterotrophic bacterial (THB) counts. The results showed TPH reduction of 81% - 90% at 8 and 12 weeks period. Two-way ANOVA without replication showed no significant differences (p = 0.14). Elephant grass heights and leaf lengths were higher in soil-amended untreated and treated with granulated S/S drill cuttings than in uncontaminated soil. Maize plant in the drill-cuttings-soil mixture with and without S/S treatment competes favourably with the uncontaminated soil. The results demonstrate that granulated S/S treatment can be reuse for sustainable plant growth.

Keywords: Cement, Drill cuttings, Elephant grass, Maize plant, Spent mushroom substrate**,** Stabilisation/Solidification.

INTRODUCTION

Environmental pollution is a common trend among oil and gas exploration and production companies in the Niger Delta region of Nigeria. Notably, this exploration carries drill cuttings with sizeable rocks and soil pulverized to the surface. They usually contain elevated concentrations of metals emanated from drilling fluids retained within the cuttings and the annulus of the drill bits penetrated through the stream to the surface layer (Ball et al., 2012; Kogbara et al., 2017). These hazardous waste products are heavily laden with some major complex compounds carrying very high molecular weight, which can hinder the biotic level vis-a-viz sustainability of plant growth on soil. Research have shown that polyaromatic hydrocarbon (PAH) carrying drilling mud is still being used for drilling operations in Niger Delta region of Nigeria, especially at greater depth because of its higher performance at these depth compared to either water or synthetic-based mud (Davis, 2016). Therefore, it is of necessity that drill cuttings are been neutralized of harmful effect and recycled into the environment to ameliorate and emend polluted soil for better plant performance (Kogbara *et al.*, 2016a, 2016b).

Clean up technologies and disposal in secure landfills are not easy to come-by with appropriate engineered landfill sites becoming unpopular and very rare to see (Ayotamuno et al., 2010).

LITERATURE REVIEW

The mechanisms for contaminant immobilisation (especially metals) during cement-based S/S include precipitation in insoluble forms such as hydroxides. Contaminants may also be immobilised by inclusion either by physical encapsulation and/or by chemical inclusion through incorporation in binder hydration products (Paria & Yuet, 2006; Falciglia et al., 2014). This was ascertain by Karamalidis and Voudrias (2007) and opined by Leonard and Stegemann (2010) that the solid wastes of hydrocarbons like that of drill cuttings and oily sludge have been immobilised by macro-encapsulation in cement matrices after S/S treatment. The combination of S/S and Phytoremediation is to harness the natural capability of vegetation as economic advantages in restoring contaminated medium with least negative impact to the environment (Glick, 2003; Yuan Peng et al., 2010; Khatibi & Hosseini, 2018). The rationale for using plants in TPH-contaminated soil is essentially for the breakdown of TPHs absorbed by a combination of mechanisms of plant-root and soil interactions. Such mechanisms include the multiplier of microbial activities on the surrounding-soil, recovery of physical and chemical properties of contaminated soil and increase in interaction between rhizosphere microbes and the toxic compounds in a contaminated soil (Aprill & Sims, 1990). The following specific objectives include: (i) to investigate the effect of increasing dosages (5% - 20%) of the stabilizing binder (cement) on total petroleum hydrocarbon (TPH) and metal immobilization in drill cuttings, (ii) to evaluate the phytoremediation potential of the forages in reduction of the TPH content of the soil-amended treated and untreated drill cuttings through assessment of changes in bacteria numbers.

Although several innovative concepts on hydrocarbon treatment techniques have been recorded with emphasis on stabilization/solidification (S/S), thermal, incineration and biological methods have their draw backs (Henner et al., 1997; Khatibi & Hosseini, 2018). For instance, there may be incomplete degradation of hydrocarbons with biological treatment, which is the most environmental-friendly among the aforementioned technologies, due to the presence of possible trace metals in the root and biomass. This was buttressed by Kogbara et al., (2017) that cement-based stabilisation does not remove contamination, it only fixates contaminant migration with fast and efficient physical encapsulation based level by decreasing their toxicity in S/S drill cuttings. It however contained cementitious materials mixed with hazardous wastes to form a highly alkaline mixture that binds contaminants, minimises their rate of migration and alters the physical nature of the waste (Kogbara, 2014; Falciglia et al., 2017). Portland cement-based S/S systems are the most widely used as cement can chemically bind free liquids and encapsulate waste particles surrounding them with an impermeable coating. Cement can also chemically fix contaminants by reducing their solubility and toxicity (Conner, 1997; Paria & Yuet, 2006).

METHODOLOGY

Experimental Materials

The drill cuttings used for this study was obtained from a private treatment, storage, and disposal facility in Onne in Rivers State in the Niger Delta of Nigeria. A multipurpose 42.5R grade Type 1 Ordinary Portland Cement (Dangote Cement Plc, Nigeria) in compliance to BS EN 197-1 (BSI, 2000) was used as the binder for S/S treatment of drill cuttings. Spent mushroom substrate was obtained from Dilomat farm, Rivers State University, Port Harcourt, Nigeria. NPK (20-10-10) fertilizer was gotten from Creek Road in Port Harcourt. Also the uncontaminated soil was obtained from Rivers Institute of Agricultural Research Training (RIART) experimental farm, in Rivers State University Port Harcourt (0.05^{0}IN and longitude 0.06^{0}57E).

Experimental procedure

Sample preparation

Uncontaminated Loamy sand (83% sand, 11.6% silt, 4.8% clay) soil was thoroughly mixed with granulated cement-treated drill cuttings. The soil-cemented-treated drill cuttings mixtures were placed in cylindrical polyvinyl chloride (PVC) plastic containers (reactors) of 30cm diameter and depth respectively. Four parts soil-cemented-treated drill cuttings mixtures (5%, 10%, and 20%) cement dosages and (4000g) drill cuttings to one part (12000g) uncontaminated soil were placed in the reactors. The reactors were nurtured in an exposed region but secured from the rain, such that nutrient level and moisture content could be managed (Kogbara et al., 2017, 2019).

Four treatments and four control options (untreated and uncontaminated soil) were employed. Each option was established in triplicate reactors. Three treatment options contained elephant grass grown on the mixture of soil and granulated cemented – drill cuttings with 5%, 10%, and 20% cement dosages. A fourth treatment option contained maize grown on a mixture of soil and granulated cemented-drill cuttings with 20% cement dosage. 0.5 water/cement ration was adopted during the sample preparation treatment options. The cementatious treatment reactors were incubated in ideal environmental conditions at an ambient temperature of 28°C for 28 days before testing in line with a reviewed work (Kogbara et al., 2016a). After 28 days of curing, the treated samples were crushed into power-like form (i.e. < 2mm) using a crusher (see Figure 1).

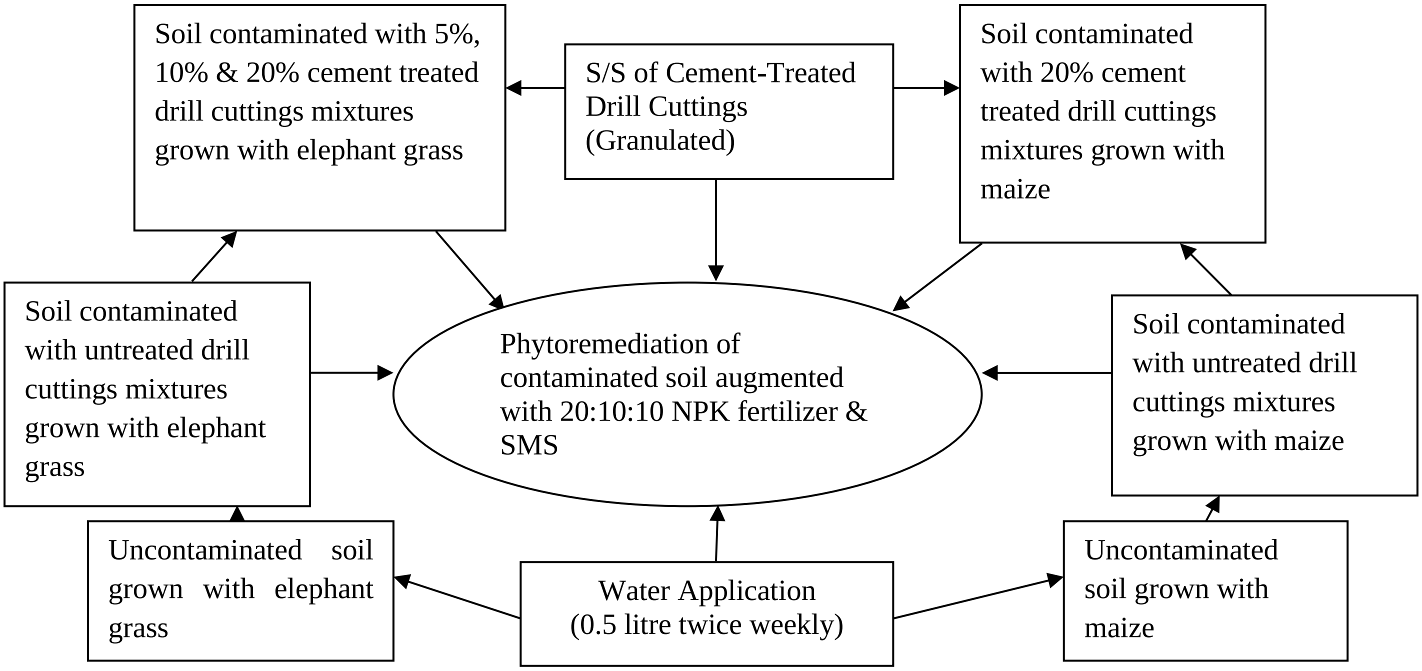

Figure 1: Schematic of reuse S/S treated drill cuttings for forage production

Planting of elephant grass and maize plant

Prior to planting, the granulated S/S cement-treated drill cuttings were thoroughly homogenized with loamy sand, thereafter it was allowed for the interim of 3 days interaction between the soil and the treated drill cuttings before planting. The soil-drill cuttings mix ratio 3:1 was considered and plants were grown on the mixture for 8 and 12 weeks for maize and elephant grass respectively on the medium earlier mentioned. Elephant grass stands were transplanted into the reactors. The grasses in all options were gotten from the same domain with similar rhizomes to ensure they were statistically the same, while maize seeds were sown in the reactors. Five stands each of elephant grass and maize were grown in the reactors. The soil-treated drill cuttings mixtures were augmented with certain amount of 20-10-10 NPK fertilizer of 100g each and SMS compost for three, six and nine weeks to ameliorate nutrient availability for plants achievement. Each reactor received irrigated water of 0.5 L twice a week during the span of the study. The application rates collaborate with a recent published work (Kogbara et al, 2016b, 2017) which contributed to the performance of growth.

Soil sampling

Prior and during treatment, samples were collected from the untreated, uncontaminated soil and soil-cement-stabilised drill cuttings mixtures at prescribed interval were taken to the laboratory for analysis. The samples were augured out from representative options at random spots and depths for background value check, mid-way check and at the end of the study check to evaluate hydrocarbon and metallic concentration in the treatment options.

Laboratory Analysis
The particle size distribution (PSD) of the uncontaminated soil was determined by the Bouyoucos hydrometer method as described in (Bouyoucos, 1962). The pH of the materials (i.e., drill cuttings, soil, and drill cuttings–soil mixture) was then measured using a Hach pH meter calibrated with standardized pH buffer solutions. The total nitrogen was determined by the Kjeldahl method following the procedure described in Bremner & Mulvaney (1982). Hydrocarbon utilizing and heterotrophic bacteria were determined from uncontaminated soil and treated (or untreated) drill cuttings using plate count agar (Oxiod, Hampshire, England) by serially diluting the samples. 1g of soil samples were aseptically transferred into 9ml sterile peptone water to give a 10-fold serial dilution (Madigan et al., 2010). Total petroleum hydrocarbon (TPH) was analysed accordance to US EPA 8015 operating procedure (APHA, 1998). Metals were analysed using flame atomic absorption spectrophotometer in line with APHA (1998).

Determination of plants performance
Plant heights were measured from the soil surface in all the options to the top of the arch uppermost leave that is at least 50% emerged from the whorl (Hager, 2012). The leaf lengths of both plants were determined as the distance of the leaf node to the top of the leaf. The leaf width was measured as the widest region of the leaf blade perpendicular to the length of the leaf (De-Swart *et al*, 2004). The plant stands in a given treatment option were measured before planting, mid-way and at the end of the study period. The leaf of the plants was determined as expressed in equation (1) (Clinton-Brown & Lewandowski, 2000)

$$Leaf\ Area(cm^2) = 0.84 \times leaflength(cm) \times leafwidth(cm) \quad (1)$$

Statistical analysis
Statistical analyses adopted in this study were mean, standard deviation, percentages and analysis of variance (ANOVA) with and without replication was used to compare the TPH data in different treatment option at set period of 4, 6, 8 and 12 weeks. This was used to consider as significant difference at $p \leq 0.05$.

RESULTS

The results of the untreated drill-cuttings before and after S/S treatment and uncontaminated loamy sand applied are shown in Table 1. The drill cuttings preliminary TPH concentration was 17,251mg/kg and the concentrations of the metals were Cu (24mg/kg), Zn (14mg/kg) and Ni (11mg/kg) having the highest concentrations. However, since the TPH of the drill cuttings were above the local permissible regulatory limit as documented in several literatures (TCEQ, 2006; Nicholson & Blakesley, 2011). The TPH and metal levels in the uncontaminated soil results revealed fall within the acceptable allowable threshold (Kabata-Pendias & Mukherjee, 2008; Ideriah et al., 2017). Hence, appropriate treatment of drill cuttings techniques is required to further reduce the contaminants to the lowest possible way as shown in Table 1.

Table 1: Background Values of the Untreated and S/S Treated Drill Cuttings and the Uncontaminated Soil.

Parameter	Untreated Drill Cuttings	Cement-Treated Drill Cuttings			Uncontaminated Soil
		5%	10%	20%	
TPH (mg/kg)	17,251 ± 280	6,601 ± 130	8,664 ± 168	10,985 ± 176	< 0.001
Ph	9.50 ± 0.34	_	_	_	4.90 ± 0.25
Arsenic, As (mg/kg)	< 0.001	_	_	_	< 0.001
Copper, Cu (mg/kg)	24.02 ± 0.44	_	_	_	12.11 ± 0.38
Zinc, Zn (mg/kg)	13.88 ± 0.72	_	_	_	9.22 ± 0.84
Lead, Pb (mg/kg)	1.94 ± 0.16	_	_	_	0.001
Chromium, Cr (mg/kg)	0.94 ± 0.14	_	_	_	0.03 ± 0.001
Nickel, Ni (mg/kg)	10.89 ± 0.26	_	_	_	5.12 ± 0.78
Vanadium, V (mg/kg)	0.24 ± 0.03	_	_	_	0.01 ± 0.001
Sand (%)	_	_	_	_	83.6
Silt (%)	_	_	_	_	11.6
Clay (%)	_	_	_	_	4.8
Moisture content (%)	_	_	_	_	12.78 ±0.38
Total nitrogen (mg/kg)	_	_	_	_	0.97± 0.15
Total organic carbon (mg/kg)	_	_	_	_	0.004
THB Count (x10^4cfu/g)	_	_	_	_	0.98

Results represent the mean ± standard deviation of three replicates. TPH: Total petroleum hydrocarbons. THB: Total heterotrophic bacteria.

Figures 1a and b show TPH concentrations over time in the treatment options with elephant grass and maize plant

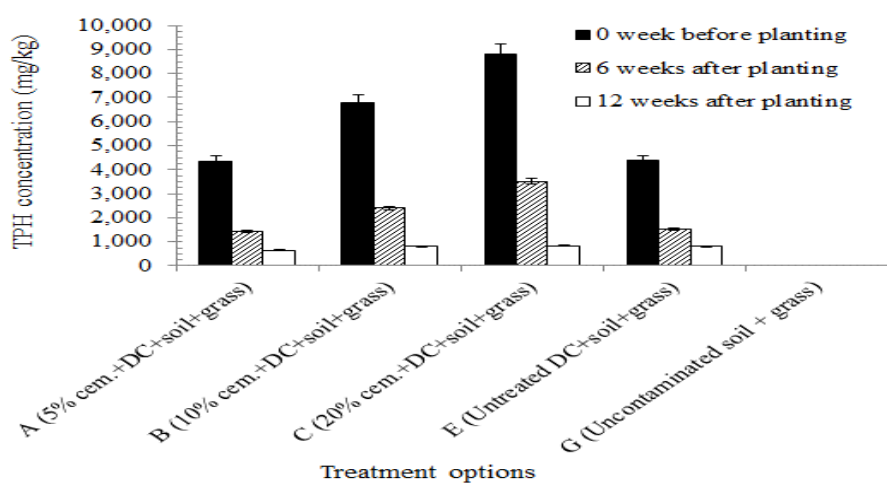

Figure 1a: TPH Concentrations over Time in the Treatment Options with Elephant Grass

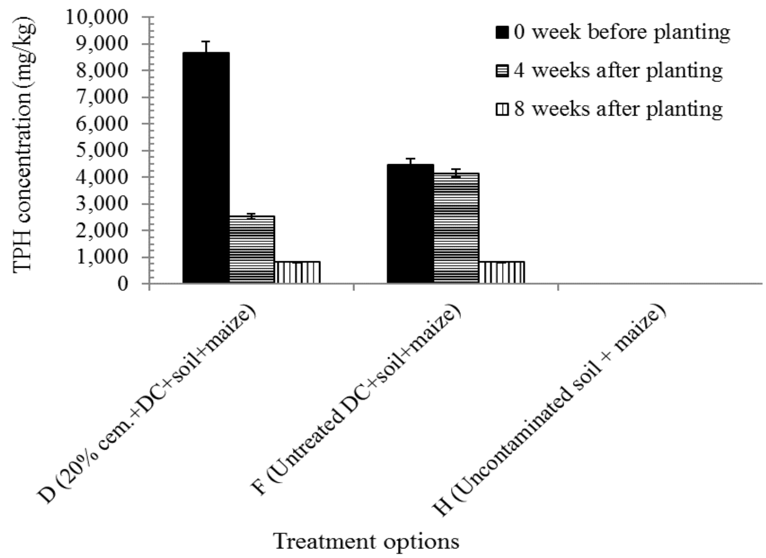

Fig. 1b: TPH Concentrations over Time in the Treatment Options with Maize

Figure 2 shows percentage TPH reduction in the different treatments

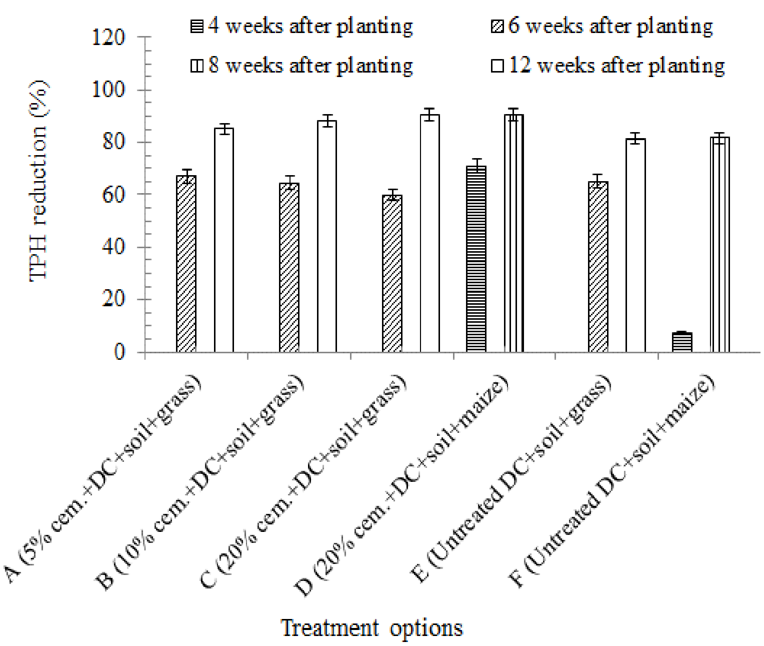

Fig. 2: Percentage TPH Reduction in the Different Treatments

Table 2 shows the supporting chemical and biological parameters in the treatment options.

Table 2: Supporting Chemical and Biological Parameters in the Treatment Options

Option	Description		pH.					Total nitrogen (mg/kg)		
			0	4	6	8	12	0	4	6
A	Drill cuttings with 5% cement treatment, mixed with soil, and elephant grass is grown on it.		5.00	-	640	-	6.90	2.20	-	89.00
B	Drill cuttings with 10% cement treatment, mixed with soil, and elephant grass is grown on it.		5.00	-	6.60	-	7.00	3.20	-	96.00
C	Drill cuttings with 20% cement treatment, mixed with soil and elephant grass is grown on it.		5.20	-	5.88	-	6.10	5.10	-	86.50
D	Drill cuttings with 20% cement treatment, mixed with soil, and maize is grown on it.		5.20	6.10	-	6.50	-	5.10	85.00	-
E	Untreated control with drill cuttings mixed with soil and elephant grass grown on it.		6.00	-	6.89	-	7.10	_	-	88.93
F	Untreated control with drill cuttings mixed with soil and maize grown on it.		6.00	6.30	-	7.20	-	_	99.50	-
G	Uncontaminated soil control used for growing elephant grass.	4.80	4.90	-	6.23	-	6.80	0.004	-	60.00
H	Uncontaminated soil control used for growing maize.	-	4.90	6.15	-	6.80	-	0.004	60.1	-

Note: The total nitrogen was not determined at 8 or 12 weeks after planting as applicable.

Figures 3a and b present the heights of the plants grown in the options with elephant grass and maize plant respectively

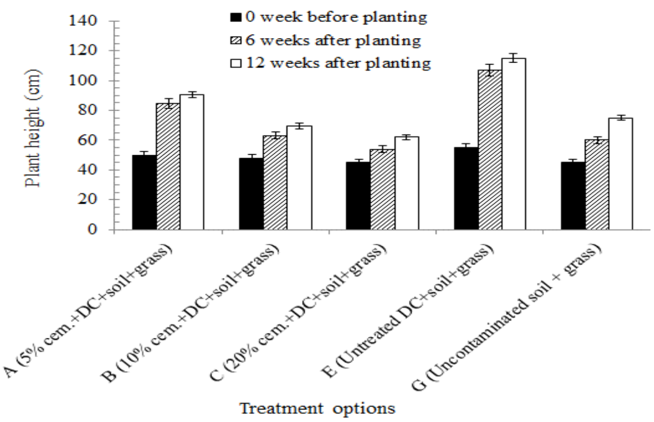

Figure 3a: Heights of the Plants Grown in the Options with Elephant Grass

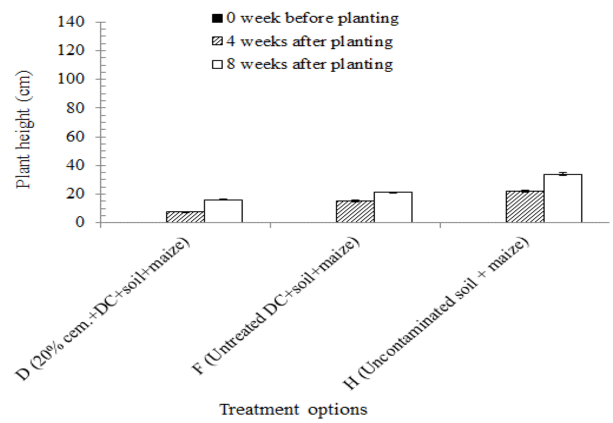

Figure 3b: Heights of the Plants Grown in the Options with Maize

Figures 4a and b presents leaf lengths of the plants grown in the options with elephant grass and maize plants.

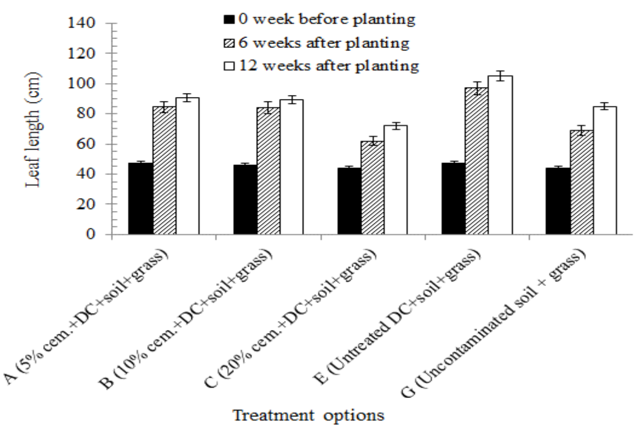

Fig. 4a: Leaf Lengths of the Plants Grown in the Options with Elephant Grass

Fig. 4b: Leaf Lengths of the Plants Grown in the Options with Maize

Figures 5a and b show leaf widths of the plants grown in the options with elephant grass and maize plant.

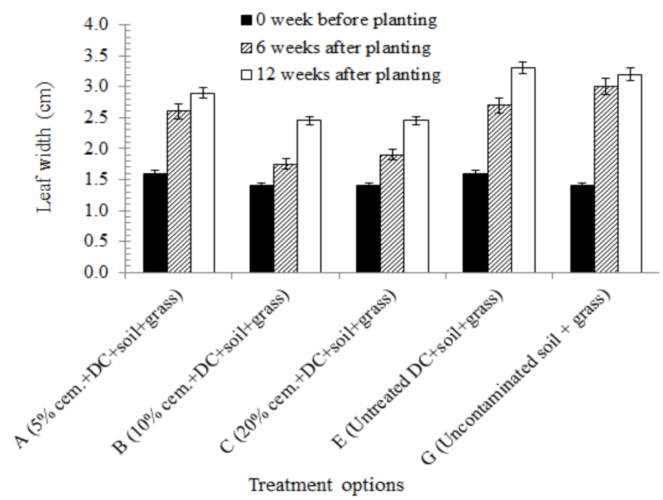

Figure 5a: Leaf Widths of the Plants Grown in the Options with Elephant Grass

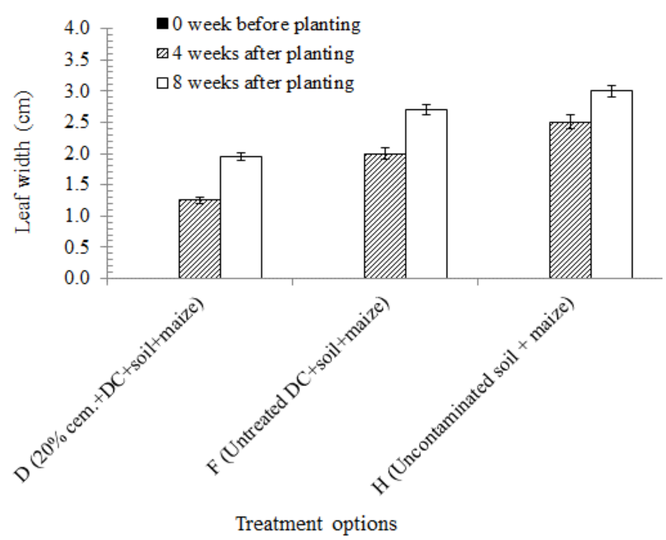

Figure 5b: Leaf Widths of the Plants Grown in the Options with Maize

Figures 6a and b show metal concentrations in the treatment option with elephant grass and maize plant

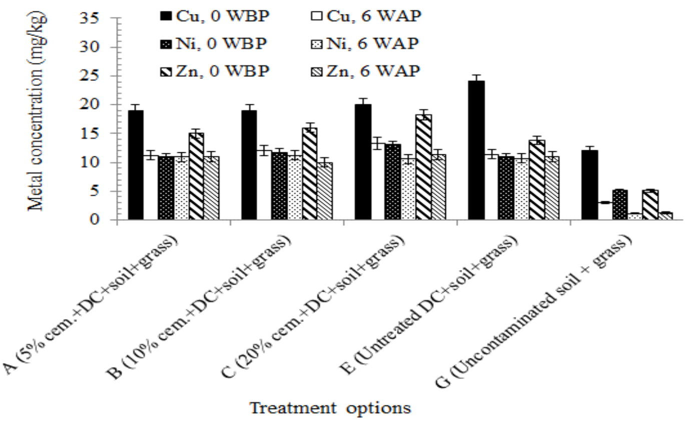

Fig. 6a: Metal Concentrations in the Treatment Option with Elephant Grass

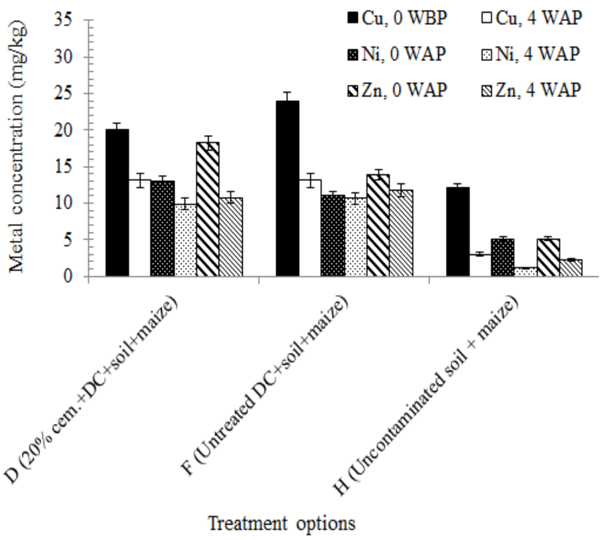

Fig. 6b: Metal Concentrations in the Treatment Option with Maize

DISCUSSION

Effects of admixture stabilised/solidified drill cuttings with loamy sand soil

After 28 days of curing the stabilsed/solidified drill cuttings, there was reduction about 60% reductions in the TPH concentrations. The TPH concentrations of the cement-treated drill cuttings were 6,601 mg/kg, 8,664 mg/kg and 10,985 mg/kg for the 5%, 10% and 20% cement dosages, respectively (Table 1). Although, this is contrary to expectation that the TPH concentration would decrease with increasing cement dosage. A similar observation has been reported for S/S treated drill cuttings and oily sludge evaluated by organic contaminant leachability in a related study (Al-Ansary & Al-Tabbaa 2004) with a lower lechability of paraffin oil with 20% Portland cement dosage than with 30% dosage. This could be that dichloromethane extractable fraction of hydrocarbons from the supernatant leachate (liquid-liquid extraction) as well as in ultrasonic extraction with dichloromethane was responsible with higher pore water alkalinity with higher cement content (Karamalidis & Voudrias, 2007; Leonard & Stegemann, 2010).

Phytoremediation of hydrocarbon treatment options

The soil-amended cement-treated drill cuttings mixed in the ratio of 3 parts uncontaminated soil to 1 part cement-treated drill cuttings 0 week before planting had TPH concentrations ranging from 4,357 mg/kg to 8,795 mg/kg, 3 days after the mixing were presented Figure 1a and 1b (options A , B, C and D). While the untreated drill cuttings amended with uncontaminated soil in the ratio of 3 parts uncontaminated soil to 1 part untreated drill cuttings (options E and F). The relatively lower TPH in the untreated drill cuttings compared to the higher cement dosage mixtures can still be attributed to the aforementioned cement mobilisation of hydrocarbons. Especially, as the 5% and 20% dosage mix (option A and D) has a similar TPH to those of the soil-amended untreated drill cuttings Fig.1a and1b. However, option C and D with 20% cement dosage in the cement-drill cuttings mixture recorded the highest TPH reduction of 90% after 8 and 12 weeks compared to 85% and 88% for options A and B, in Figure 2 which with dilution would have led to the least TPH concentration. Two-way ANOVA without replication executed on the average TPH concentrations of the three options indicated no significant differences ($p \leq 0.01$) in TPH due to the different cement dosages. It however showed significant differences ($p \leq 0.05$) in the TPH of the three options over time.

Furthermore, a two-way ANOVA with replication showed significant differences ($p \leq 0.01$) due to differences in cement dosage and time for the three treatment options. On the one hand, after 12 weeks of elephant grass planting, the differences in TPH between the different cement dosage mixes were quite small. Besides, the 5% dosage mix recorded lower TPH values, which suggests that a smaller cement dosage can be effective for S/S treatment of the drill cuttings before mixing with soil for planting. On the other hand, 8 weeks of maize decontamination level on cement treated-drill cuttings mixture competes favourably to that of (option E) untreated drill-cuttings-soil mixture. Thus, this observation align with the research of Ayotamuno and Kogbara (2007) in which maize was reported to degrade the total hydrocarbon content of an oil-polluted silty-clay better than elephant grass during a 6-week study period. Comparison of options C and D, which had 20% cement dosage in the S/S treated drill cuttings and on which both crops were grown after 4 and 6 weeks of planting. Moreover, the test executed indicates that the different treatment options differ significantly from each other in TPH concentration and TPH percentage reduction (Fig. 1a, b and 2a, b). Nevertheless, at 4 weeks of planting, option F with maize had the lowest percentage TPH reduction as stated in Figure 2b. This is due to the much slower growth rate of maize compared to elephant grass in the contaminated media studied. Moreover, the TPH losses is also corroborated with little or no change in the initial pH after 8 and 12 weeks at the end of study period with hydrocarbon content (A–F) in contrast to the uncontaminated options (G and H), whose pH increased above the initial value after 8 and 12 weeks as described in (Table 2). The increase in total nitrogen 6 weeks after planting due to nutrient application also helped accelerate the hydrocarbon losses recorded.

Growth performance parameters over time

The initial sizes of grasses transplanted in the reactors are shown in figures 3 – 5 as the 0 - week before planting data. The maize seeds planted in the uncontaminated soil sprouted within 2 - 3 days while those in the contaminated soil sprouted within 7 – 8 days. Elephant grass has an advantageous characteristic due to its rapid growth and strong resistance to enhance effective stabilization on petroleum-polluted soils (Ayotamuno *et al,* 2010; Abhilash *et al,* 2009) compared to maize. Bacteria have low tolerance for acidic soil conditions than alkaline soil especially in the Niger Delta where most soils are acidic as determine by the pH. Hence, the elephant grass thrived better in the contaminated soils. The method of propagation (i.e.

seeds versus transplanting) may be possible for the difference between both crops. Hydrocarbon contamination impeded the growth of maize in options D – F with S/S treated and untreated drill cuttings compare to the uncontaminated soil. At the end of study period, the plant height was reduced to 53% and 38% in the S/S treated and untreated options, respectively, compared to the uncontaminated soil (figure 3b). Similarly, the leaf length was reduced by 61% and 54% in options D and F respectively (figure 5b). While the leave width was reduced by up to 23% in the elephant option (compared data in figure 3a, 3b, 4a, 4b and 5a, 5b). Microorganisms during hydrocarbon degradation are higher under slightly alkaline condition than in acidic soil (Bossier & Bertha, 1984).

The perennial rhizomatous grass has the potential to use solar energy, water and nutrients more efficiently compare with many other plants (Heaton *et al*, 2004). Untreated drill cutting-amended soil generally showed marginally better performance than S/S treated drill cuttings-amended soil for most growth parameters with both crops. Vwioko & Fashemi, (2005), in their research discovered that some amounts of hydrocarbons contents improve the growth of crops. Such observation is probably due to the position that nutrients could be more available to plants on the decomposition of the hydrocarbons (Rowell, 1977).

Metal Concentrations in the Different Treatments

The metal concentrations were very low from the background check analysis with Cu (24 mg/kg), Ni (11 mg/kg) and Zn (14 mg/kg) having the highest concentrations in the untreated drill cuttings from the aforementioned Table 1. Hence, only the highest metals were given keen interest in the soil-cemented drill cuttings systems before planting and after 4 or 6 weeks of planting. The concentrations of Cu, Ni and Zn monitored as mentioned above are shown in Figures 6 and 7. Due to the initially low metal levels the amount after 4 or 6 weeks were even lower with maximum concentrations of 13 mg/kg for Cu, 11 mg/kg for Ni and 12 mg/kg for Zn (Figures 6a and b). The formation of strong complexes with the metals by compost derived humid acids (from compost applied to all options) which could result in much lower metal concentration over time (Kogbara *et al*, 2016b, 2017, 2019). The uncontaminated soil controls had the highest percentage metal concentration reduction for all three metals over time.

CONCLUSIONS

The study demonstrates that granulated stabilized/solidified (S/S) treated drill cuttings can be reuse for planting elephant grasses and maize plants. A significant hydrocarbon reduction was achieved by combining S/S and phytoremediation treatment options. Drill cuttings with background value of TPH 17,251 $mgkg^{-1}$ and low concentrations of metals were considered. There was progressive decline in TPH concentration between 81% - 90% reduction of 8 or 12 weeks in soil-amended cement-treated and untreated drill cuttings on which maize and elephant grass were grown. The growth potential of elephant grass in soil-amended treated and untreated drill cuttings generally compared favorably with those in uncontaminated soil. Much higher elephant grass heights and leaf lengths were recorded in soil-amended untreated and treated (especially for 5% cement dosage) drill cuttings than in uncontaminated soil 12 weeks after planting. With maize plant, a better performance was recorded in the uncontaminated soil compared to the mixtures containing drill cuttings for all three growth parameters. There were marginal differences in TPH reduction and growth potential between soil-amended S/S treated drill cuttings and untreated drill cuttings. However, at the end of the study the performance of both forages in terms of TPH reduction was similar. Metal concentrations of 13 mg/kg for Cu, 11 mg/kg for Ni and 12 mg/kg for Zn monitored were even lower after 4 or 6 weeks due to the initially low metal levels. Further studies should be carried out to determine the optimum mixing ratios for a range of contaminant concentrations in drill cuttings to provide the needed clarity for technology uptake. The results suggest that granulated S/S treated drill cuttings and phytoremediation enhance degradation of hydrocarbon for plant growth.

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