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Article

Influence of Biostimulants (Spent Mushroom Substrate and *Costus Afer* Bagasse) in the Remediation of Heavy Metals in Oil Field Drill Cuttings

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Abstract: *Costus afer* and spent mushroom substrate (SMS) are abundantly available in the Niger Delta region of Nigeria. Their successful application in the remediation of heavy metal-contaminated sites would further demonstrate the effectiveness of organic amendments in removing harmful contaminants from the environment and improving both environmental quality and human health. This study investigated the remediation potential of *Costus afer* bagasse (CAB) and spent mushroom substrate (SMS) for the treatment of heavy metal-contaminated soil. Different amendment application rates of 0.5 kg, 1.0 kg, and 1.5 kg were evaluated for both CAB and SMS treatments (T_2-T_7) over a 120-day experimental period. To achieve this, 10 kg of oilfield drill cuttings-contaminated sandy loam soil was placed in plastic reactors and treated with the amendments in triplicate under three contamination scenarios representing low (C_1), medium (C_2), and high (C_3) contamination levels. Additional untreated reactors at each contamination level served as controls (T_1). Physicochemical parameters assessed included pH, moisture content (MC), organic matter (OM), organic carbon (OC), electrical conductivity (EC), particle size distribution (PSD), and the concentrations of barium (Ba), zinc (Zn), lead (Pb), copper (Cu), chromium (Cr), cadmium (Cd), and nickel (Ni). Sample collection, handling, and analysis were conducted in accordance with the standards of the Nigerian Upstream Petroleum Regulatory Commission (NUPRC). Multiple linear regression analyses for Ba, Zn, Pb, Cu, Cr, Cd, and Ni were performed using Minitab v.19. The results showed substantial reductions in heavy metal concentrations across all treated samples. Treatment T_7 reduced Ba concentrations from initial values of 160.24, 159.59, and 156.51 mg/kg to 21.00, 25.77, and 17.69 mg/kg under C_1, C_2, and C_3 contamination levels, representing reductions of 86.88%, 88.70%, and 88.70%, respectively. Similarly, treatments T_3 and T_4 demonstrated enhanced barium removal with increasing amendment application rates, reducing Ba concentrations from 157.42 to 24.08 mg/kg and from 156.51 to 17.69 mg/kg, corresponding to reductions of approximately 84.7% and 88.7%, respectively. All final concentrations remained below the intervention regulatory target value of 625 mg/kg and the target value of 200 mg/kg. Similar reduction patterns were observed for Zn, Pb, Cu, Cr, Cd, and Ni. Overall, the remediation effectiveness of the treatments was ranked as follows: 1.5 kg SMS (T_4) > 1.0 kg SMS (T_3) > 1.5 kg CAB (T_7) > 0.5 kg SMS (T_2) > 1.0 kg of SMS (T_6) > 0.5 kg CAB (T_5) > control (T_1). Analysis of variance (ANOVA) using a completely randomized design (CRD) revealed statistically significant differences ($P < 0.05$) among treatments for Ba, Zn, Pb, Cu, Cr, Cd, and Ni. These findings demonstrate the effectiveness of both SMS and CAB as sustainable remediation amendments for heavy metal-contaminated sandy loam soils across low, medium, and high contamination levels. The adoption of these bioremediation strategies could substantially reduce both the cost and duration of remediation projects.

Keywords: Heavy Metals, Bioremediation, Spent Mushroom Substrate, *Costus afer*, Bagasse, Oilfield Drill Cuttings, Niger Delta

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1. Introduction

Heavy metal contamination of soil is a global concern with regards to human health and agriculture. Except for uncommon geogenic origins, heavy metal contaminants are inadvertently introduced to soils through anthropogenic activities such as mining, smelting, warfare and military training, electronic industries, fossil fuel consumption, waste disposal, agrochemical use, and irrigation. For example, the common fossil fuel coal contains an array of heavy metals including Ba, Hg, Pb, Cd, Cr, Cu, Co, Zn, and Ni in the concentration range of 0.1 to 18 mg kg^{-1}. These heavy metals are discharged into the environment in vapor, flue gases, particulate matter, fly ash, and bottom ash upon coal combustion [9, 20]. Inappropriate soil disposal of mine spoils, industrial waste, and construction waste frequently causes heavy metal contamination [21]. Land application of phosphorus (P) fertilizers, Cu-based pesticides, biosolids, and animal manure and crop irrigation with sewage water and poorly treated industrial wastewater are major pathways for heavy metals to enter agricultural soils [4, 9].

Globally there are >5 million sites covering 20 million ha of land in which the soils are contaminated by different heavy metalloids [9]. The heavy metals in contaminated soils impair the natural ecosystem services and eventually damage human health via the food chain [20]. Heavy metal contamination is detrimental to agricultural soil and ultimately affects the health of the soils [22]. Therefore, contaminated soil is largely liable to environmental deterioration and human health problems. Crop production may be affected by exposure to heavy metals in soils. Different analysis (e.g., contamination factor and potential ecological risk) demonstrated that metals were below the pollution level. Ingestion, inhalation and dermal contact of the metals in adult and children have no possibility of posing a cancer risk [1, 2], but the concern is that long-term exposure of these metals can pose cancer risk both to a child and an adult [27].

When exposed to heavy metals in soil by means of ingestion, dermal contact, and inward breath pathways were lower than the acceptable limit but can cause cancer [20]. Crops, cultivated in contaminated agricultural soils may cause serious health hazards in humans when consumed [25]. Exposure to contamination from heavy metals is extremely alarming for children in their first developmental stages and for adults [28]. Chromium, copper, arsenic, cadmium, and lead are of particular concern because a lot is now known for their detrimental health effects on humans through food consumption [29]. Intake of toxic substances from soils is through food, which is a recognized pathway for pollutant exposure for children [13]. Chronic heavy metal exposure has a harmful effect on humans and other animals [15]. Cr and Cu can be responsible for non-carcinogenic health hazards such as neurological disorder, headache, and liver disease if they exceed their safe threshold values [22].

It has been reported in the literature that the co-occurrence of heavy metals in contaminated soils is an issue of great concern affecting human health and ecosystem in the world today [14, 15, 24]. In recent times, government, Industry and the public are much more aware of the potential dangers that the complex mixtures of xenobiotics such as heavy metals – mercury (Hg), cadmium (Cd), lead (Pb), nickel (Ni), copper (Cu), zinc (Zn), chromium (Cr), arsenic (As) and organic compounds – total petroleum hydrocarbons (TPH), polychlorobiphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans (PCDD/FS), phthalic acid esters (PACS), chlorinated solvents, pesticides, antibiotics, and detergents pose to human health and environment [26, 31].

Over the years various in-situ and ex-situ remediation techniques have been developed to contain, clean up, or restore heavy metal-contaminated soils, such as surface capping, soil flushing, electrokinetic extraction, solidification, vitrification, and phytoremediation. These techniques can be classified into five categories: physical, chemical, electrical, thermal, and biological remediation or three divisions: containment-based (e.g., capping/encapsulation), transformation-based (e.g.,

stabilization/immobilization), and transport-based (e.g., extraction/removal) methods. In general, these soil remediation methods employ different working mechanisms and demonstrate specific application advantages and limitations. More importantly, these techniques vary significantly in effectiveness and cost in field practices [21]. There are several literature documents overviewing the soil heavy metal remediation technologies [9]. Yet few are comprehensive to compare all the existing technologies and provide instructive evaluations on the practical feasibility of the technologies 16, 17, 30].

Although there are multiple methods of remediating contaminated soil such as biological, physical and chemical, the biological method (Bioremediation) seems to be the most preferred because of its eco-friendliness and cost effectiveness, given that other methods are either too expensive or present secondary negative impact on the environment due to the materials used. Spent mushroom substrate (SMS) and *Costus afer*, both in abundance in the region could simply pass as wastes, but they fit perfectly as natural, organic and locally sourced amendments for contaminated soils. Their potential usefulness in tackling a localized pollution problem could be considered as a breakthrough for remediation in Nigeria [8, 9]. However, when the studies in the literature were examined, there were several studies conducted on the degradation of contaminant level in soil treated with spent mushroom substrate but the use of *costus afer* bagasse in the soil are rather limited, hence this research investigated the effects of spent mushroom substrate and *costus afer* bagasse on heavy metals (Ba, Zn, Cu, Pb, Cd, Cr, Ni) in oil field drill cuttings [10, 11, 13].

2. Material and Methods

2.1. Study Area

The Niger Delta region, located in the southern part of Nigeria, is bordered to the south by the Atlantic Ocean and to the east by Cameroon.

It encompasses nine states in Nigeria, categorized politically, including Abia, Akwa-Ibom, Cross River, Edo, Imo, and Ondo States, which are part of the Niger Delta region alongside the core Niger Delta states of Rivers, Bayelsa, and Delta. However, the heart of the Niger Delta is Delta. [3, 4] detailed the research conducted by the Niger Delta Development Commission (NDDC), indicating that the region covers a surface area of approximately 112,110 square kilometers. Furthermore, [20] noted that the region features approximately 450 km² of coastlines, serves as the world's second-largest delta, and ends at the Imo Rivers. Spanning 20,000 km², this area is Africa's largest wetland and ranks third in size worldwide [5, 6, 21]. The Niger Delta region is characterized by three primary types of vegetation: mangrove forests, freshwater swamp forests, and the savanna and stunted rain forests found on the sand ridges and mainland margins. Its ecological zone is categorized into four types: lowland rain forest, freshwater zone, mangrove swamp, and coastal inland zones. [6, 9] indicated that the area is designated as a tropical rainforest, hosting an ecosystem that includes countless species of both aquatic and terrestrial flora and fauna. The Niger Delta region is home to approximately 23% of Nigeria's total population, which exceeds 140 million.

The region is a primary provider of timber and forest products, and it houses crucial habitats for wildlife at great risk of extinction, alongside areas with significant agricultural and fishery prospects. Nigeria, as a producer of oil and gas, relies heavily on the Niger Delta, home to the majority of its oil and gas operations [7, 9]. *Costus afer* is typically an unbranched tropical plant regarded as a herb with a creeping rhizome. This is a relatively small monocot shrub that is commonly found in humid rainforests as well as along riversides [3, 23]. This is a perennial plant that can reach a height of 4 m and produces white and yellow flowers. The plant is abundant in the area and is treated as waste.

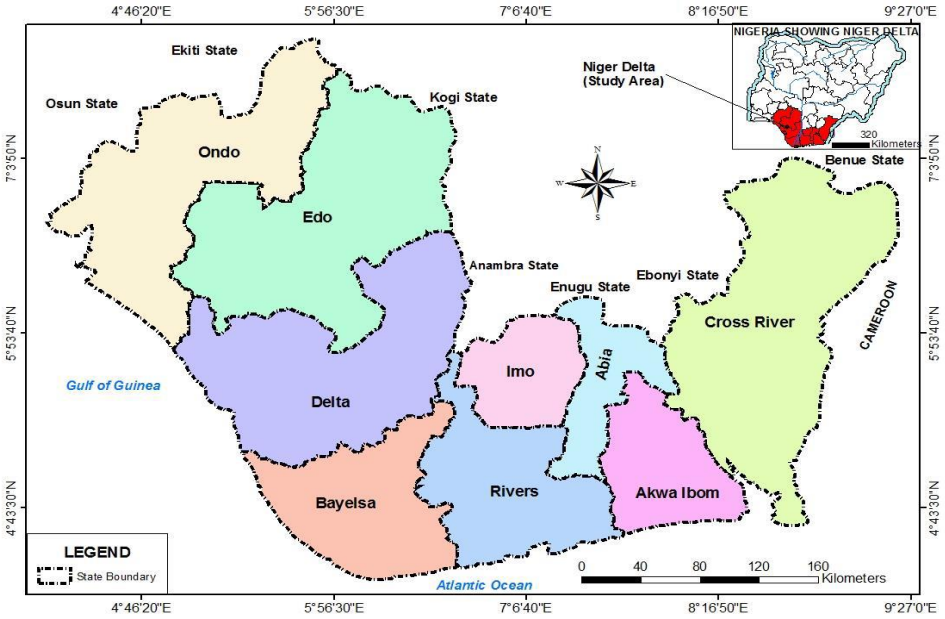


Figure 1. Map of Niger Delta Region of Nigeria. [9]

2.2. Sources of Materials

Soil samples for this study were gathered from the Teaching and Research Farm of the Rivers Institute of Agricultural Research and Training (RIART) at Rivers State University in Port Harcourt.

Drill cuttings from the oil field were obtained from a waste management company located in the same area. The waste management company did not subject the drill cuttings used to any form of pre-treatment process. Samples of drill cuttings from the oil field were handled per the directives of the Nigerian Upstream Petroleum Regulatory Commission [19]. The spent mushroom substrate was gathered from Dilomat Farm, located at Rivers State University in Port Harcourt. Additionally, the *Costus afer* bagasse was sourced from an agricultural land in the area.

2.3. Sample Preparation

Approximately 10 kg of uncontaminated agricultural soil was blended with different amounts of oil field drill cuttings.

All samples were placed in individual reactors and incubated for 72 hours. After this period, the samples were taken immediately for baseline analysis, including a sample of uncontaminated agricultural soil. In the laboratory, the samples were examined for heavy metals in oil field drill cuttings.

2.4. Experimental Design

This study employed a 2 × 7 factorial experiment with a complete randomized design (CRD). This experiment features a design comprising 7 reactors labeled T2, T3, T4, T5, T6, and T7, along with the control reactor T1, and includes two replications. The draw lot method, as outlined in various sources, was used to accomplish randomization. The plastic reactors utilized in the study each have a diameter of 30 cm, a depth of 35 cm, and contain 10 kg of soil.

2.5. Statistical Analysis

The significance of the difference in mean values of each treatment for heavy metals was determined using one-way analysis of variance (ANOVA). The ANOVA for a completely randomized design was performed with the ANOVA data analysis toolbox in

Microsoft Excel 2019 (Microsoft Inc., USA). At a significance level of 5% ($p \leq 0.05$), differences were deemed significant if F Computed exceeded FTabulated [12].

3. Results and Discussion

3.1. Effect of Biostimulants (SMS and Costus afer bagasse) in the Remediation of Heavy Metals in Drill Cuttings

The concentrations of Barium, Zinc, Lead, Copper, Chromium, Cadmium, and Nickel in untreated drill cuttings, including the control, were as follows: 156.51–160.07 mg/kg for Barium, 185.96–187.73 mg/kg for Zinc, 23.16–24.13 mg/kg for Lead, 119.305–122.13 mg/kg for Copper, 0.047–0.051 mg/kg for Chromium, 0.090–0.0945 mg/kg for Cadmium, and 186.205–188.375 mg/kg for Nickel on treatments (T1 - T7), This indicates that the contents of Ba, Zn, Pb, Cu, Cr, Cd, and Ni are below the intervention values of 625 mg/kg, 720 mg/kg, 530 mg/kg, 190 mg/kg, 300 mg/kg, 12 mg/kg, and 210 mg/kg, as well as the target values of 200 mg/kg, 140 mg/kg, 85 mg/kg, 36 mg/kg, 100 mg/kg, 0.8 mg/kg, and 35 mg/kg, respectively, as specified by [10, 18]. Nevertheless, it is necessary to reclaim or reuse the waste. The level of Barium in drill cuttings treated with varying amounts of spent mushroom substrate (SMS) over 120 days is shown in Figure 2-8. Additionally, Table 1-7 illustrates the changes in concentrations of Ba, Zn, Pb, Cu, Cr, Cd, and Ni in drill cuttings at different Drill/SMS mixing ratios (5:0.5, 5:1, 5:1.5). The reduction of Ba, Zn, Pb, Cu, Cr, Cd, and Ni after thirty (30) days of remediation in drill cuttings treated with different quantities of SMS is presented in Table 1-7. Over time, the degradation of Ba, Zn, Pb, Cu, Cr, Cd, and Ni intensified. In the first 30 days, there was a significant increase in degradation, but it slowed down afterward [7, 9].

Table 1. Mean Results of Barium Concentration in Drill Cuttings

Period (days)	Barium Concentration (mg/kg)						
	T_1	T_2	T_3	T_4	T_5	T_6	T_7
3	159.44	158.3	157.415	156.505	157.315	159.59	160.07
30	147.55	80.733	89.20345	91.57745	82.58395	91.08675	94.1225
60	139.495	64.91343	60.38359	53.64528	69.35162	64.78854	58.68608
90	131.52	48.66825	42.55356	36.63098	55.27993	51.03749	42.25326
120	123.835	27.93575	24.0845	17.68507	32.00145	25.7652	21.00835

Table 2. Mean Results of Zinc Concentration in Drill Cuttings

Period (days)	Zinc Concentration (mg/kg)						
	T_1	T_2	T_3	T_4	T_5	T_6	T_7
3	187.56	186.9	186.765	185.96	187.73	187.7	186.98
30	162.42	94.66535	106.3481	109.7164	100.785	107.1302	109.477
60	152.105	76.64319	71.63118	63.72889	82.74568	76.19829	68.5439
90	131.52	57.46425	48.39685	43.51496	65.96877	60.02676	50.28415
120	123.835	32.98435	27.83413	21.39437	36.8532	30.3093	29.63041

Table 3. Mean Results of Lead Concentration in Drill Cuttings

Period (days)	Lead Concentration (mg/kg)						
	T_1	T_2	T_3	T_4	T_5	T_6	T_7
3	23.155	24.125	23.305	22.96	23.765	23.88	23.445
30	21.97	12.31908	13.3153	13.51204	12.79633	13.7009	13.59583
60	21.685	9.8904	8.93813	7.868517	10.47563	9.694411	8.591934
90	20.495	7.5124	6.153835	5.37274	8.307064	7.63689	6.32527
120	19.36	4.097625	3.635885	2.641446	4.697191	3.855685	3.77441

Table 4. Mean Results of Copper Concentration in Drill Cuttings

Period (days)	Copper Concentration (mg/kg)						
	T_1	T_2	T_3	T_4	T_5	T_6	T_7
3	120.67	120.46	119.305	119.445	120.535	121.075	122.125
30	109.555	61.49002	67.63946	69.99559	65.51876	69.46515	70.82963
60	101.8	49.69797	45.75876	40.57587	53.13588	49.15254	44.76723
90	93	37.52704	31.51152	27.9485	42.13466	38.72022	32.96296
120	81.24	20.48355	19.20649	18.52162	23.83189	20.76545	23.55671

Table 5. Mean Results of Chromium Concentration in Drill Cuttings

Period (days)	Chromium Concentration (mg/kg)						
	T_1	T_2	T_3	T_4	T_5	T_6	T_7
3	0.0505	0.047	0.0485	0.047	0.048	0.048	0.049
30	0.0475	0.023998	0.027492	0.027543	0.026096	0.02754	0.028425
60	0.0445	0.019388	0.018601	0.015966	0.021162	0.019486	0.01797
90	0.0425	0.014637	0.012808	0.010996	0.01678	0.01535	0.013236
120	0.039	0.007985	0.007807	0.007289	0.009495	0.008232	0.009454

Table 6. Mean Results of Cadmium Concentration in Drill Cuttings

Period (days)	Cadmium Concentration (mg/kg)						
	T_1	T_2	T_3	T_4	T_5	T_6	T_7
3	0.09	0.0935	0.0925	0.0935	0.092	0.092	0.0945
30	0.088	0.047725	0.052858	0.055029	0.049525	0.052965	0.054808
60	0.0865	0.038351	0.035478	0.032049	0.041114	0.037805	0.03464
90	0.0825	0.029131	0.024802	0.021884	0.032157	0.029422	0.025506
120	0.0805	0.016547	0.014431	0.011289	0.018763	0.01485	0.015643

Table 7. Mean Results of Nickel Concentration in Drill Cuttings

Period (days)	Nickel Concentration (mg/kg)						
	T_1	T_2	T_3	T_4	T_5	T_6	T_7
3	188.375	187.815	187.5	186.83	185.955	186.205	186.8
30	174.475	96.80453	106.786	110.323	100.4954	107.8327	107.4845
60	165.4	77.02961	71.91645	64.02734	81.96754	75.58937	68.47692
90	152	58.50957	49.5317	43.71878	64.99999	59.54825	50.42177
120	139	31.93598	29.2495	21.49422	36.75114	30.07368	29.98096

Table 8. Heavy Metals Percentage Reduction in Drill Cuttings (%)

Heavy Metals	Period (Days)	T1	T2	T3	T4	T5	T6	T7
Barium	0	0	0	0	0	0	0	0
	30	7.46	49	43.33	41.49	47.50	42.92	41.20
	60	12.51	58.99	61.64	65.72	55.92	59.40	63.34
	90	17.51	69.26	72.97	76.59	64.86	68.02	73.60
	120	22.33	82.35	84.7	88.7	79.66	83.86	86.88
Zinc	0	0	0	0	0	0	0	0
	30	13.40	49.35	43.06	41	46.31	42.92	41.45
	60	18.90	58.99	61.65	65.73	55.92	59.40	63.34
	90	29.88	69.25	74.09	76.60	64.86	68.02	73.11
	120	33.98	82.35	85.10	88.50	80.37	83.85	84.15
Lead	0	0	0	0	0	0	0	0
	30	5.12	48.94	42.87	41.15	46.15	42.63	42.01
	60	6.35	59.00	61.65	65.73	55.92	59.40	63.35
	90	11.49	68.86	73.59	76.60	65.04	68.02	73.02
	120	16.39	83.02	84.40	88.50	80.23	83.85	84.93
Copper	3	0	0	0	0	0	0	0
	30	9.21	48.95	43.31	41.40	45.64	42.63	42.00
	60	15.64	58.74	61.65	66.03	55.92	59.40	63.34
	90	22.93	68.85	73.59	76.60	65.04	68.02	73.01
	120	32.68	83	83.90	84.49	80.23	82.85	83.71
Chromium	3	0	0	0	0	0	0	0
	30	5.94	48.94	43.32	41.40	45.63	42.62	41.99
	60	11.88	58.75	61.65	66.03	55.91	59.40	63.33
	90	15.84	68.86	73.59	76.60	65.04	68.02	72.99
	120	22.77	83.01	83.90	84.49	80.22	82.85	80.71
Nickel	3	0	0	0	0	0	0	0
	30	7.38	48.46	43.05	40.95	45.96	42.09	42.46
	60	12.20	58.99	61.64	65.73	55.92	59.40	63.34
	90	19.31	68.85	73.58	76.60	65.05	68.02	73.01
	120	26.21	83	84.40	88.50	80.24	83.85	83.95

As illustrated in Figure 2-8, the concentrations of Ba, Zn, Pb, Cu, Cr, Cd, and Ni diminished as the amount of SMS applied to drill cuttings and the duration in days increased. Additionally, an increase in the quantity of SMS applied correlates with a greater reduction in the levels of Ba, Zn, Pb, Cu, Cr, Cd, and Ni in the drill cuttings [11, 31]. At 30 days post-treatment application, the drill cuttings were observed. The 5:1.5 mix ratio DC/SMS showed a reduction in Ba, Zn, Pb, Cu, Cr, Cd, and Ni content compared to other treatments. As indicated in Table 8, the greatest reduction occurred in the DC/SMS ratio of 5:1.5 (T4), followed by the 5:1 DC/SMS ratio (T2), while the smallest reduction was in the soil/SMS ratio of 5:0 (T1). The trend persisted until the conclusion of the 120-day remediation period, as shown in Figure 2-8. However, as shown in Figure 2-8, the remediation of drill cuttings using SMS was quite effective in reducing the levels of Ba, Zn, Pb, Cu, Cr, Cd, and Ni to lower values. The highest percentage reductions of 88.7%,

88.5%, 88.5%, 84.9%, 76.6%, and 88.5% were observed with a 5:1.5 soil/SMS mixed ratio (T4), followed by T3 and T2, while the control (T1) had percentage reductions of 22.33%, 33.98%, 16.39%, 32.68%, 16.84%, and 26.21% [9, 16]. Thus, it demonstrates that the DC/SMS ratio of 5:1.5 (T4) resulted in the most significant reduction of total Ba, Zn, Pb, Cu, Cr, Cd, and Ni in the remediation of drill cuttings. Nonetheless, it fell significantly short of the target value set by NUPRC (2018) for soil and sediment [10, 14]. This could be attributed to SMS's potential for remediation. The ANOVA result for the impact of varying soil/SMS mixed ratios on the concentrations of Ba, Zn, Pb, Cu, Cr, Cd, and Ni was significant. It was observed that the treatment means differed significantly at the 5% significance level. This indicates that, with 95% confidence, the difference in treatment means was attributable to the variation in soil/SMS mixed ratios applied [17, 30]

The content of Barium, Zinc, Lead, Copper, Chromium, Cadmium, and Nickel in the drill cutting treated with 5, 10, and 15 kg of *Costus afer* bagasse over a period of 120 days (Figure 2). Table 1-7 illustrates the changes in the concentrations of Ba, Zn, Pb, Cu, Cr, Cd, and Ni in drill cuttings at various DC/Costus afer bagasse mix ratios (5:0.5, 5:1, 5:1.5). The reduction of Ba, Zn, Pb, Cu, Cr, Cd, and Ni after thirty (30) days of remediation in drill cuttings treated with varying amounts of *Costus afer* bagasse. With time, the degradation of Ba, Zn, Pb, Cu, Cr, Cd, and Ni also escalate; there was a significant rise in the initial 30 days, but it slowed down afterwards. On the other hand, in the control sample [18, 29]. Figure 2-8 showed that the Ba, Zn, Pb, Cu, Cr, Cd and Ni concentrations decreased with increase in the quantity of *Costus afer* bagasse administered to the drill cuttings and number of days.

Drill cuttings were observed 30 days post-treatment application. Content of Ba, Zn, Pb, Cu, Cr, Cd, and Ni decreased across all treatments. The reduction was greatest in the DC/Costus afer bagasse ratio of 5:1.5 (T7), as indicated in Table 8. Following this was the 5:1 drill cuttings/Costus afer bagasse ratio (T2), and the smallest reduction occurred in the DC/Costus afer bagasse ratio of 5:0 (T1). This trend persisted until the conclusion of the 120-day remediation period, as shown in Figure 2-8. Figure 2-8 demonstrates that the remediation of drill cuttings using Costus afer bagasse was effective in reducing the levels of Ba, Zn, Pb, Cu, Cr, Cd, and Ni to much lower concentrations of 21.01 mg/kg, 29.63 mg/kg, 29.63 mg/kg, 23.56 mg/kg, 0.0094 mg/kg, 0.0094 mg/kg, and 29.98 mg/kg from initial concentrations of 160.07 mg/kg, 186.98 mg/kg, 186.98 mg/kg, 122.13 mg/kg, 0.049 mg/kg, 0.049 mg/kg, and 186.8 mg/kg, representing reductions of 88.55%, 86.25%, 84.93%, 83.71%, 83.71%, 83.71%, and 82.3% (Table 8). The outcome was significantly lower than the local regulatory target values of 200mg/kg, 140mg/kg, 85mg/kg, 85mg/kg, 100mg/kg, 100mg/kg, and 35mg/kg as per the Nigerian regulatory framework [9, 18]. Thus, it is evident that the Drill cuttings/Costus afer bagasse ratio of 5:1.5 (T7) resulted in the greatest reduction of Ba, Zn, Pb, Cu, Cr, Cd, and Ni during remediation, and the other treatments (T6, T5, T4) exhibited the same trend. This could be attributed to the remediation potential of Costus afer bagasse. The ANOVA results regarding the impact of varying DC/Costus afer Bagasse mixed ratios on the concentrations of Ba, Zn, Pb, Cu, Cr, Cd, and Ni indicate that these concentrations were elevated. It is clear that the treatment means differed significantly at the 5% significance level. This indicates that there is a 95% confidence level that the difference in treatment means was caused by the variation in the mixed ratios of DC/Costus afer Bagasse used [9, 29].

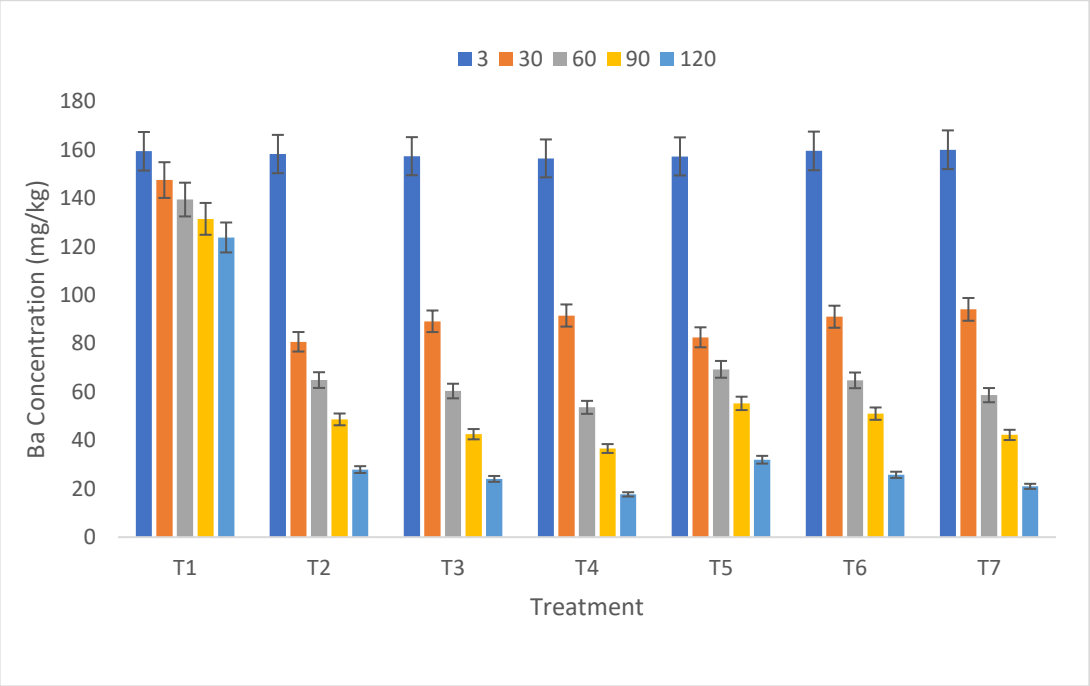


Figure 2. Effects of different SMS and *Costus afer* Bagasse on Barium Concentration in Drill Cuttings. Error Bar (Percentage)

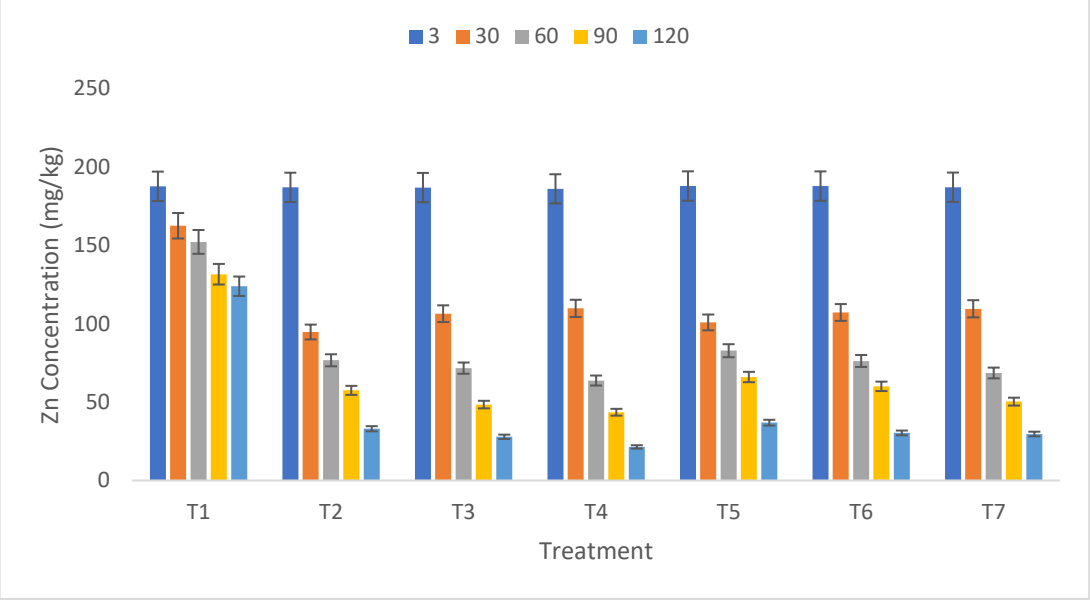


Figure 3. Effects of different SMS and *Costus afer* Bagasse on Zinc Concentration in Drill Cuttings. Error Bar (Percentage)

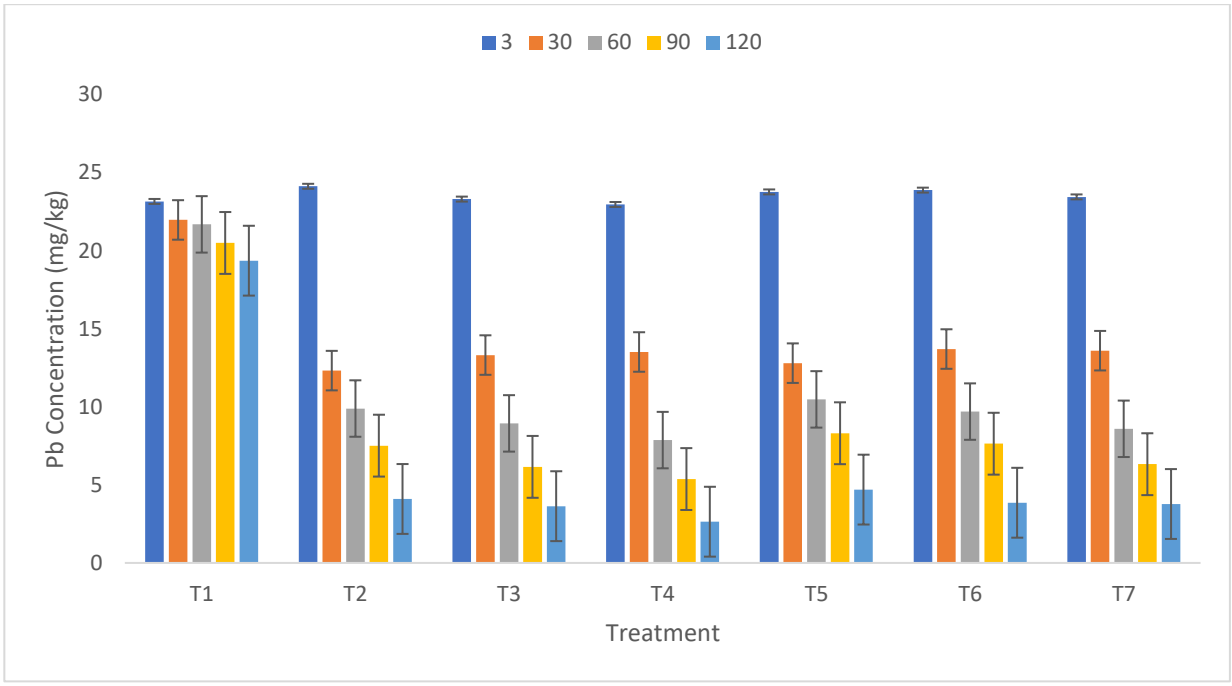


Figure 4. Effects of different SMS and *Costus afer* Bagasse on Lead Concentration in Drill Cuttings. Error Bar (Percentage)

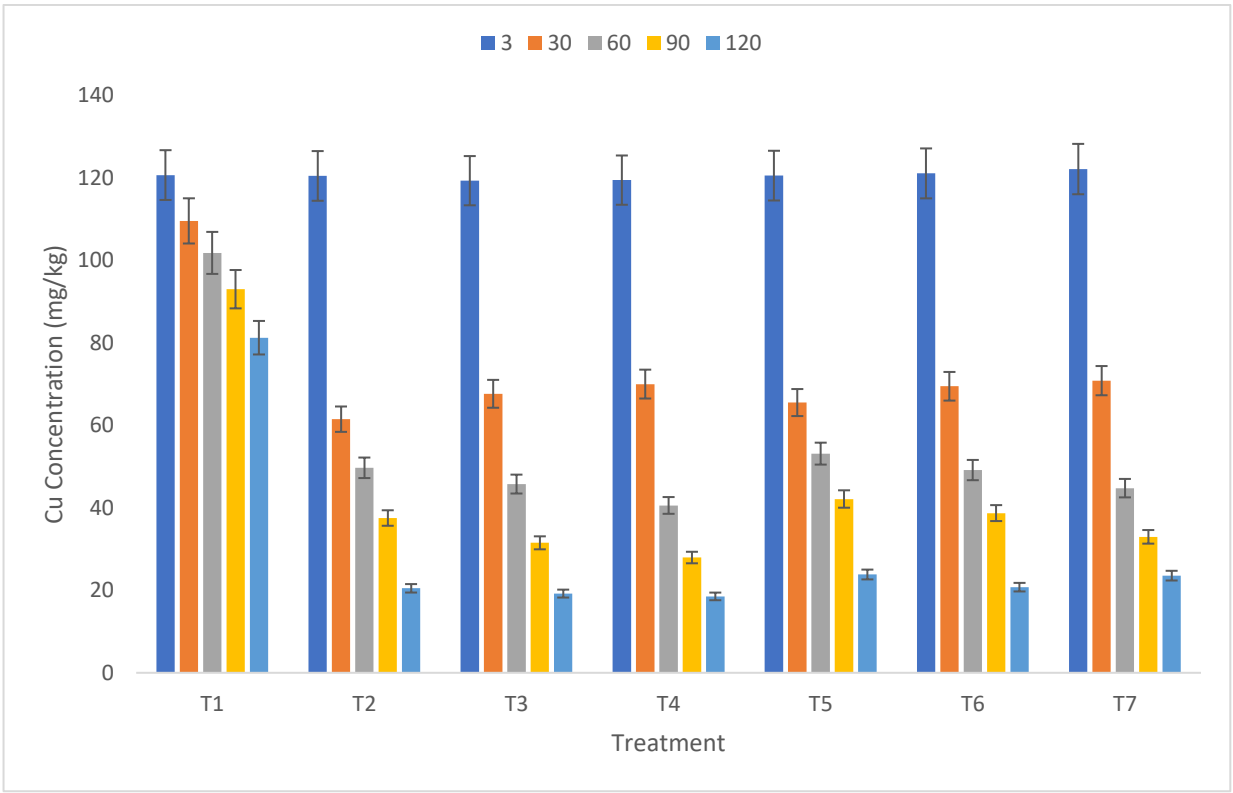


Figure 5. Effects of different SMS and *Costus afer* Bagasse on Copper Concentration in Drill Cuttings. Error Bar (Percentage)

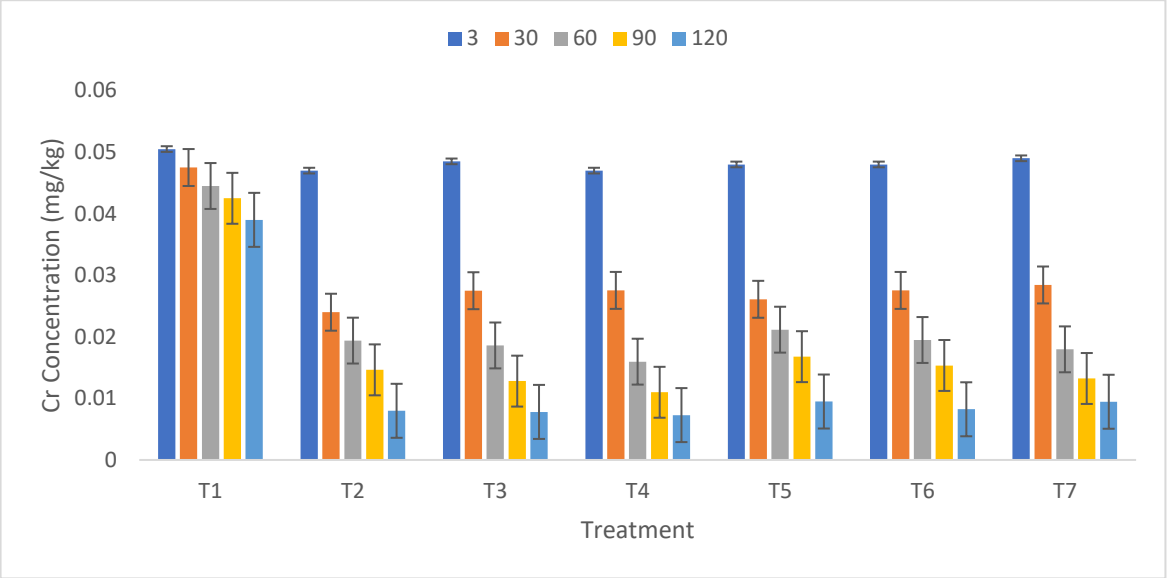


Figure 6. Effects of different SMS and *Costus afer* Bagasse on Chromium Concentration in Drill Cuttings. Error Bar (Percentage)

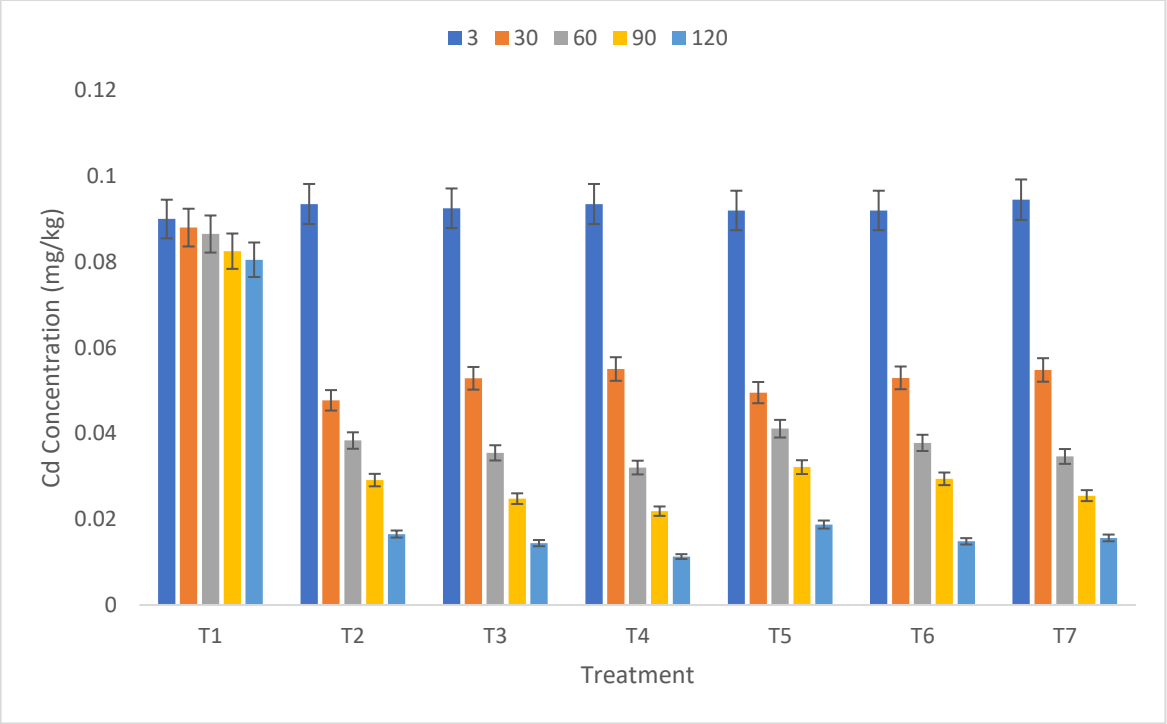


Figure 7. Effects of different SMS and *Costus afer* Bagasse on Cadmium Concentration in Drill Cuttings. Error Bar (Percentage)

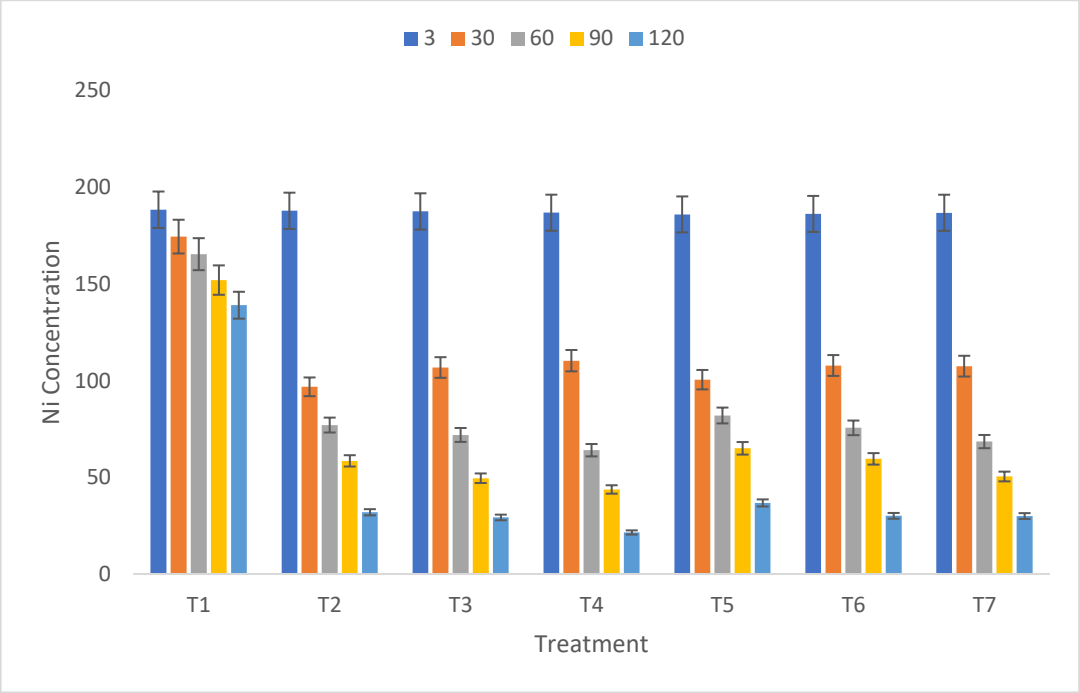


Figure 8. Effects of different SMS and *Costus afer* Bagasse on Nickel Concentration in Drill Cuttings. Error Bar (Percentage).

4. Conclusion

Spent mushroom substrate and *Costus afer* bagasse engineered the biodegradation of heavy metals (Ba, Zn, Pb, Cu, Cr, Cd, and Ni) in the drill cuttings. The SMS degraded Ba, Zn, Pb, Cu, Cr, Cd, and Ni up to 88.50,88.50, 88.49, 84.49, and 88.50% respectively after 120 days of remediation. In addition, *Costus afer* bagasse degraded Ba, Zn, Pb, Cu, Cr, Cd, and Ni up to 86.88, 84.15, 84.93, 83.71, 80.71, and 83.95% respectively %, after 120 days of remediation. ANOVA results showed that there was significant difference among the treatments.

4.1. Limitations

The interpretation of the results should consider several study limitations. The oilfield drill cuttings used in this investigation were obtained from a licensed waste management company, and access to the material was subject to regulatory and contractual requirements that constrained experimental design and operational flexibility. These limitations restricted the ability to evaluate multiple waste sources and a broader range of treatment conditions. Furthermore, the study focused on specific remediation performance parameters over the duration of the experimental period. Future investigations involving diverse drill-cutting waste streams, extended monitoring periods, and fewer operational constraints would strengthen understanding of treatment effectiveness under varying field conditions.

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