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Modelling for the phytoremediation of crude oil polluted soil using Cassava and Yam waste peels

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A B S T R A C T

The objective of this study is to investigate the extent of degradation of soil contaminated with petroleum hydrocarbons by utilizing the remedial potential of cassava peels and yam peels as amendment additives. To achieve this, a baseline study was conducted to assess the physicochemical properties of the contaminated soil, using appropriate analytical methods. For the experimental phase, homogenized soil samples (1000 g each) were amended with 10.53g of cassava peels and 107.48g of yam peels to achieve a concentration of 0.2%. Additionally, to establish a concentration of 0.4% nitrogen, 23.87g of cassava peels and 243.54g of yam peels were added. Different microorganism experiments (labeled A, B, C, and D) were set up, alongside a control group (lacking the aforementioned additives). Throughout a six-week incubation period, the microorganism experiments were aerated three times a week. Samples from each microorganism were collected at two-week intervals for subsequent analysis. The results revealed a rapid decrease in TPH concentration within the first two weeks of incubation, which continued to decrease progressively over subsequent sampling periods. This reduction in TPH concentration corresponded to an increased rate of removal of hydrocarbon compounds. Notably, Sample D exhibited the highest rate of TPH removal, while the control group (Ct1) displayed the lowest. Furthermore, microbes established with a nitrogen concentration of 0.4% demonstrated a greater rate of nitrogen consumption compared to those with a 0.2% nitrogen concentration. The combined approach of bio-stimulation appears to be an effective method for facilitating the removal of TPH components from contaminated soil.

Capsule Summary: This study evaluates soil hydrocarbon degradation using cassava and yam peels. Synergistic use of these additives, along with homogenization and moisture, effectively removes TPH from contaminated soil.

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INTRODUCTION

Bioremediation refers to the use of biological mechanisms to destroy, transform, or immobilize environmental contaminants so as to protect potential sensitive receptors. (Amadi et al., 1993). Two remediation techniques are; Ex *situ* and *in situ* remediation techniques. Ex *situ* remediation techniques involve taking out the soil from the subsurface in order to treat it (Amadi and Antal, 1991). *In situ* remediation techniques encompass leaving the soil in its original place and bringing the biological mechanisms to the soil. Earlier thermal, chemical and physical treatment methods have been unsuccessful in eliminating the pollution problem because those approaches only move the pollution to a new phase such as air pollution (Bertrand et al., 1993). Bioremediation technology, which leads to degradation of pollutants, may be a worthwhile and environmentally beneficial substitute that could produce an economic profit (Lendlem, 2002).

In Niger Delta, Nigeria, increased petroleum exploration has led to an unprecedented accidental release of crude oil polluting the land and water sources of the area. Furthermore, illegal tampering of well heads, flow lines, pipelines, manifolds and flow stations have added to the total amount of crude oil entering the environment. With recurrent reports of oil spillage in Niger Delta, there is a need for a cost-effective method for remediation of crude oil contaminated soil. Crude oil affects the physicochemical properties of the soil such as temperature, structure, nutrient status and pH when spilled on land (Luizer, 1992; Tabarabaci et al., 2010; Magnusson, 1998; Murphyt and Brouwer, 1995; Octave and Levienspiel, 2004; Ogoni, 2001).

In Nigeria, contamination of soil and water by crude petroleum and refinery products is a rising problem as oil mining and refining activities increase steadily. This problem results particularly in the loss of fertility of agricultural lands and death of plants, including crops, in the oil producing areas of Nigeria. Soil contamination by crude oil spills is a widespread environmental problem requiring cleaning up of the contaminated sites (Prince, 1999). The most common sources of petroleum contamination are the disposal of oil-based wastes, oil spills from well blowouts and pipeline ruptures (Ukpaka, 2011; Ukpaka, 2006). Crude oil spills adversely affect plants by creating conditions which make essential nutrients like nitrogen and oxygen required for plant growth unavailable to them. It has been noted that oil contamination results in a slow rate of germination in plants. It has been stated that this effect might be due to the oil which acts as a physical barrier preventing or reducing the access of seeds to water and oxygen. It has been reported that oil pollution thwarts crop growth and yield in those areas for changing periods of time (Ukpaka et al., 2009). Crude oil adversely affects the germination, shoot growth and yield of most plant species including seashore plants (Ukpaka and Farrow, 2009) and field grasses (Ukpaka, 2006b). Crude oil and its products are made up of aliphatic, oleic, naphthenic and aromatic hydrocarbons, which change the chemical and physical properties of soil and its structure (Ukpaka, 2006c). These compounds are mainly responsible for the altered fertility of soil. It is noted that oil in soil has deleterious effects on the biological, chemical and physical properties of the soil depending on the dose, type of the oil and other factors [20]. Crude oil impedes proper soil aeration as an oil film on the soil surface acts as a physical barrier between air and soil thereby causing a breakdown of soil texture followed by soil dispersion. Crude oil alters the soil's redox potential ratio and also increases the soil's pH. Hence, as crude oil pollution levels increase, soil pH also increases. It has been found that the microbiological components of soil are usually adversely affected when oil is applied to soil (Van-Hamme et al., 2000). The alteration in the physical and chemical nature of the soil is one of the environmental challenges posed by oil pollution which consequently affects the growth of plants (Wami, 1997). Petroleum hydrocarbon contamination may affect plants by retarding seed germination and reducing height, stem density, photosynthetic rate, and biomass or causing complete mortality (Mene and Iwuoha, 2021).

Certain plants can render harmless, extract or stabilize a contaminant in soil, therefore making it unavailable for other organisms and reducing environmental hazards in a process termed as phytoremediation (Chokor, 2021). Recent phytoremediation techniques require that plants live in the zone of contamination. Subsequently, plant viability is a critical issue in the successful application of phytoremediation. Cultivation of plants can be a valuable tool in soil remediation if the contaminant in its present concentration is not phytotoxic (Ukpaka and Ugiri, 2022). The efficiency and mechanism of this technology called phytoremediation depends on the type of contaminant, bioavailability and soil properties. The stimulation of growth and activity of degrading microorganisms in the rhizosphere are the mechanisms believed to be responsible for most of the degradation of petroleum hydrocarbons in vegetated soil . Several approaches to selecting candidate plants for phytoremediation of soils contaminated with organic pollutants exist and these approaches have been based on the occurrence of plants under specific climatic conditions, their resistance to pollutant phytotoxicity, the presence of phenolic compounds in the plant root exudates or their ability to reduce the pollutant concentration in soil (Chokor, 2021).

Cassava peels and yam peels belongs to the family of *Fabaceae*. The tubers are edible as they contain carbohydrates. It is commonly grown in crop rotation to replenish lost fertility especially nitrogen in the soil. The capacity of *Vigna unguiculata* to fix nitrogen in the soil which is always a limiting factor in crude oil polluted soil makes it important in farming systems, thus warranting its use in the remediation of crude oil polluted soil as oil spillage is one of the challenges in the agricultural lands of the Niger Delta Regions. This possibility needs to be scientifically evaluated (Mene and Iwuoha, 2021).

Nigeria has experienced environmental pollution of different forms (land, water, air) and efforts have been made by both governmental and non-governmental organizations in finding a lasting solution to this menace. Across the length and breadth of the country, the influx of companies (locals and multinationals) engaged in all manner of activities impact negatively on our environment. The management of hydrocarbon is an essential environmental management tool especially in mining companies that deal with large volumes of hydrocarbons and hydrocarbon-related wastes. Soil contamination with petroleum hydrocarbons is as a result of oil excavation and shipping and is a possible threat to agriculture production. Soil contaminated with oil is a concern because the contaminated soils are not suitable for agricultural and industrial uses and are possible sources of water contamination (Ukpaka and Ugiri, 2022).

Agriculture which happens to be the major source of food in Nigeria and all over the world is hindered because of this contamination. Through the expanding population of the country, shortages of food could lead to poor health and poor standards of living. Current public concern and rising costs regarding the conventional clean-up procedures demonstrates the need for a less expensive bioremediation option such as phytoremediation. Phytoremediation is largely considered a promising technology for the tropics because climatic conditions favor microbial growth and activity. One of the first steps in the selection of species for phytoremediation in the tropics is the screening of plant species for their capability to grow and establish in contaminated soil, followed by the evaluation of their influence on the degradation of petroleum hydrocarbons in soil (Abbas et al., 2021). Thus, this research was aimed at evaluating one of the crops that has the potential for phytoremediation namely cowpea.

Soils contaminated with petroleum crude oil are of no benefit to the agriculturist and other uses of land due to nutrient depletion (Mene and Iwuoha, 2021). There is therefore the need to redeem the soil for use in agriculture. However, cassava peel can be applied to the soil as a remediating factor. This is because Cassava Peel leaf does not only enrich the soil it also ameliorates the crude oil pollution effect on the soil. The aim of this research is the remediation of petroleum crude oil in contaminated soil using cassava peel. To determine the efficacy of remediating petroleum crude oil contaminated soil using cassava peel in a period of three months. To determine the rate of remediation in the various soil samples, observing and comparing these changes with respect to the control soil sample (uncontaminated soil without treatment) to ascertain the level of remediation. To determine some physiochemical parameters of uncontaminated soil without treatment and contaminated soil with treatment after three months.

MATERIAL AND METHODS

Crude oil and soil sample

The crude oil sample was collected from Ogoni Local Government Area in Rivers State. And the color of the petroleum crude is black. The type of soil used for this research was a loamy soil which was dogged with shovel from the farm land at the Federal University Otuoke.

Development of the model

A general reaction is presented in Eq. 1.

Crude oil + soil + cassava peel + microorganisms → CO_2 + New biomass (1)

Simplified into the following

$$A + E \rightarrow E + P \quad (2)$$

We can also represent the rate equation of the bioremediation having an nth order and a rate constant k as

$$\int_{C0}^{C} \frac{dC}{dt} = -KC^n \quad (3)$$

Equation 3 can be rearranged to obtain

$$\int_{C0}^{C} \frac{dC}{C^n} = \int_0^t -Kdt \quad (4)$$

Integrating equation 4 and taking its limits

$$\frac{C^{1-n}}{1-n} - \frac{Co^{1-n}}{1-n} = -Kt \quad (5)$$

$$\frac{C^{1-n} - Co^{1-n}}{1-n} = -Kt \quad (6)$$

Equation (6) can then be written as

$$C^{1-n} = Co^{1-n} - (1-n)Kt \quad (7)$$

The above equation can be used to predict the concentration of crude oil present in the soil at any time t as the remediation proceeds. In order to obtain the K and n of the reaction we make use of the fractional conversion method. As stated in chemical reaction engineering by octave and levienspiel.

$$T_F = \frac{F^{1-n}-1}{K(n-1)} Co^{1-n} \quad (8)$$

Where, Tf = time needed for fractional conversion, F = fractional conversion, K= rate constant of reaction, n = order of the reaction. Taking the logarithm of both sides of the equation to obtain

$$logT_F = log(\frac{F^{1-n}-1}{K(n-1)}) + (n-1)logCo \quad (9)$$

In order to obtain the value of n, we plot a graph of logTf versus log Co in which has slop as depicted in Eq. 10.

$$\text{Slope} = (n-1) \quad (10)$$

From which the value of n was obtained. To obtain the value of k we substitute the value of n and the other known values we are left with only k as the unknown from which we can solve to obtain the value of k. Further model was developed to relates specific rate of the bioremediation reaction, the initial concentration of the cassava peel and the rate constant by means of the Monod's equation.

Table 1: Concentration of TPH of the samples as recorded on a 2-day interval for 16 days

Reactor Time(days)	A_wC (ppm)	D_dC (ppm)	H_w12 (ppm)	F_d12 (ppm)	B_w9 (ppm)	U_d9 (ppm)	C_w6 (ppm)	G_d6 (ppm)
0	0.062	0.06	0.059	0.058	0.057	0.063	0.059	0.062
2	0.061	0.06	0.054	0.057	0.051	0.057	0.056	0.06
4	0.060	0.059	0.047	0.049	0.049	0.051	0.05	0.058
6	0.061	0.06	0.041	0.045	0.048	0.046	0.049	0.054
8	0.059	0.06	0.039	0.04	0.047	0.045	0.049	0.053
10	0.060	0.059	0.031	0.039	0.044	0.044	0.048	0.053
12	0.058	0.06	0.028	0.038	0.043	0.043	0.048	0.052
14	0.058	0.059	0.027	0.037	0.039	0.041	0.047	0.051
16	0.057	0.059	0.025	0.035	0.038	0.041	0.045	0.05

$$V = \frac{V_{max}[S]}{K+[S]} \quad (11)$$

Where S = initial concentration of cassava peel [M], K =specific rate constant of the bioremediation reaction stimulated by cassava peel, Vmax= maximum attainable rate of crude disappearance. Equation (10) can be re-written as:

$$V = \frac{V_{max}[M]}{K+[M]} \quad (12)$$

Model of the pH as an inhibitor or activator. The Monod's equation for the mechanism of inhibition is stated as

$$V = \frac{V_{max}[M]}{K+[M]} \times I \quad (13)$$

In a situation where the pH is an activator that is the increment in pH favours the bioremediation reaction the inhibitor is represented as

$$I = P^H \quad (14)$$

Therefore, Equation (12) becomes

$$V = \frac{V_{max}[M]}{K+[M]} \times P^H \quad (15)$$

This only holds if an increase in the pH favors the bioremediation reaction. In a situation where an increase in pH acts as an inhibitor to the bioremediation reaction the inhibition is represented as

$$I = \frac{1}{p^H} \quad (16)$$

Equation (12) theoretically becomes

$$V = \frac{V_{\max}[M]}{K+[M]} \times \frac{1}{p^H} \quad (17)$$

Equation (16) is only valid in a bioremediation reaction in which the increment in the pH inhibits. Equation (7) can also be related to equation (11) this can help us establish the concentration of the crude oil in the soil undergoing bioremediation at any time T knowing the initial concentration of cassava peel introduced into the soil. Defining equation (11) in terms of michealis Menten terms it becomes

$$C = \frac{C_{max}[M]}{K+[M]} \quad (18)$$

But from equation (7)

$$C^{1-n} = Co^{1-n} - (1-n)kt$$

Therefore equation (17) becomes

$$C_0^{1-n} - (1-n)kt = \frac{[C_0^{1-n} - (1-n)kt]_{max} \times [M]}{K+[M]} \quad (19)$$

The above equation can be written in terms of the line waver burke plot just like The Monod's equation is expressed in Eq. 20.

$$\frac{1}{V} = \frac{K}{V_{max}[S]} + \frac{1}{V_{max}} \quad (20)$$

Equation (19) can be express in the line waver burke plot as:

$$\frac{1}{Co^{1-n} - (1-n)kt} = \frac{K}{[Co^{1-n} - (1-n)kt]_{max}[S]} + \frac{1}{[Co^{1-n} - (1-n)kt]_{max}} \quad (21)$$

The specific bioremediation rate constant and the maximum rate of bioremediation can be obtained by plotting the line weaver burke plot of

$$\frac{1}{V} = \frac{K}{V_{max}[Co]} + \frac{1}{V_{max}}\text{; -V=kCn} \quad (22)$$

Where, V= rate of reaction, K = specific rate of bioremediation, C=concentration of crude present in the soil K= rate constant of reaction

The cassava peel sample preparation

Table 2: Log T_f vs Log Co for Reactor C

Co	0.8 Co	Time needed to decompose from Co to 0.8Co	Log T_f	Log Co
0.059	0.0472	5.8 days	0.763	-1.229
0.058	0.0464	12.4 days	1.073	-1.3365
0.057	0.0456	14. 5days	1.161	-1.4441

Table 3: Log T_f vs Log Co for Reactor B

Co	0.8Co	Time needed to decompose from Co to 0.8Co	Log T_f	Log Co
0.057	0.0456	8.7 days	0.9395	-1.2441
0.046	0.0346	10.7 days	1.0294	-1.3372
0.037	0.0296	12.8 days	1.1072	-1.4317

Table 4: Log T_f vs Log Co for Reactor H

Co	0.8Co	Time needed to decompose from Co to 0.8Co	Log T_f	Log Co
0.059	0.0472	3.9 days	0.5910	-1.2291
0.047	0.0372	4.6 days	0.6622	-1.3279
0.032	0.0250	5.6 days	0.7481	-1.4948

Table 5: Log T_f vs Log Co for Reactor F

Co	0.8Co	Time needed to decompose from Co to 0.8Co	Log T_f	Log Co
0.058	0.0404	4.81	0.6821	-1.2365
0.048	0.044	5.5	0.7345	-1.3596
0.033	0.0424	6.053	0.782	-1.4757

Table 6: Log T_f vs Log Co for reactor U

Co	0.8Co	Time Needed to decompose from Co to 0.8Co	Log T_f	Log Co
0.063	0.0504	4.2 days	0.6232	-1.2
0.054	0.0456	5.4 days	0.7323	-1.2376
0.044	0.0424	6.5 days	0.8129	-1.3565

Table 7: Log T_f vs Log Co for reactor G

Co	0.8Co	Time Needed to decompose from Co to 0.8Co	Log T_f	Log Co
0.062	0.0496	16.4 days	1.2148	-1.2076
0.05	0.0400	35.6	1.3136	-1.3010

The cassava peel Sample was gotten from Agudama Epie community in Yenagoa local government area of Bayelsa State Nigeria.

A juice extractor was used to extract the Cassava Peel juice from the Cassava Peel leaf immediately they were harvested and then, the Cassava Peel and the left-over chaff were refrigerated immediately. Two different kinds of analysis were carried out on the cassava peel namely, microbial analysis; to find out if the extract can support microorganisms. Chemical analysis; to find out the presence and composition of certain chemical species in the extract used in the study.

Determination of total petroleum hydrocarbon (TPH)

A 5 g of oven dried soil, after which acidify soil with HCl to minimize contaminants and kill microbes. Pipette in 60 ml of CCl_4 and combine it with the soil to extract the TPH materials, after which filter solution containing the extract from the suspension. Transfer filtrate into cuvette and place into the Buck Model HC-404 with standard 10 mm IR Quartz Cuvette instruments, cell holder the ppm of TPH present in sample will be displayed in the visual display unit of the instrument.

RESULTS AND DISCUSSION

Based on the experiment conducted it was observed that the rate of disappearance of the TPH increased as the amount of the bio-stimulant cassava peel increased notice that reactor H its concentration reaches d lowest value by a

Table 8: The N and K values

Amount of Cassava Peel	Reactor	Order (N)	Rate constant (k)
12 ml	H_w12	1.5829	0. 3254
12 ml	F_d12	1.4177	0.1606
6 ml	C_w6	2.8501	3.8168
6 ml	G_d6	1.9453	0.2098
9 ml	B_w9	1.8937	0.3176
9 ml	U_d9	2.0832	1.1445

Table 9: Reactors and equations of reaction

Reactor	Equation of Reaction
H12	$C^{0\ 5829}\quad Co^{0\ 5829} + 0\ 1894t$
F_w12	$C^{0\ 4177}\quad Co^{0\ 4177} + 0\ 06708t$
B_w9	$C^{0\ 8937}\quad Co^{0\ 8937} + 0\ 2838t$
U_d9	$C^{1\ 0832}\quad Co^{1\ 0832} + 1\ 2383t$
C_w6	$C^{1\ 8501}\quad Co^{1\ 8501} + 7\ 06146t$
G_d6	$C^{0\ 9453}\quad Co^{0\ 9453} + 0\ 1983t$

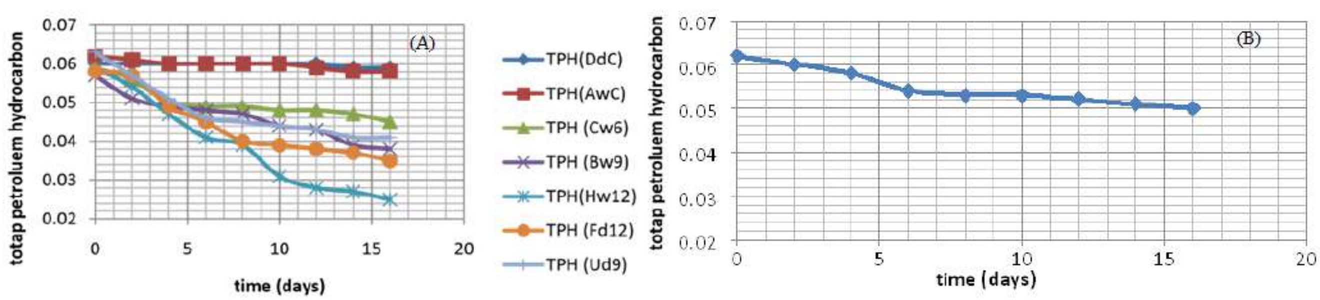

Fig. 1: (A) Graph of TPH (ppm) versus time showing the reduction rate of the TPH for reactors (A, B, C, D) and (B) Graph of TPH (ppm) versus time showing the reduction rate of the TPH for reactor G

lot of margin and in reactor C, its TPH reduced but it isn't as much as it is in reactor H, this is as a result of the fact that the cassava peel contains in it certain nutrients in the form of phosphates and nitrates that are very important in bioremediation process because the help to supply nutrients to the soil and in so doing the microbes responsible for the bioremediation feed on this nutrient and as they do that the reproduce and thus their population increases as the population increases more microbes become available to breakdown the crude oil in the soil thus the crude oil present in the soil experiences a continual decrease. Thus, an increase in the quantity of cassava peels brings about an increment in the nutrients supplied to the soil this in turn stimulates the bioremediation. The results of the crude oil degradation is illustrated in Table 1 and Figure 1 for various reactor studied as well as upon the influence of cassava peel.

In Figure 1 and 2 furthermore notice that the crude oil in the control reactors A and C never experienced any appreciable decrease in their concentration over the 16 day period, even though some of the crude present in these reactors disappeared its quantity and its rate of disappearance becomes negligible when compared to that of the reactors that were stimulated this is simply because naturally bioremediation occurs in the environment but this natural bioremediation is slow and it may take hundreds of years before a soil polluted with crude oil and that was left to nature to remedy will return to a TPH free state. Thus, the natural process of bioremediation was stimulated that is its speed was increased by the cassava peel. Figure 2 illustrate the degradation of hydrocarbon upon the influence of time.

Order (N) and the specific reaction rate constant (K)

From the graphs given we can attempt to deduce the order and rate constant of the equation by using the formula presented in equation (8) and (8i) stated as shown in Eqs. 23-24.

$$T_F = \frac{F^{1-n}-1}{K(n-1)} Co^{1-n} \tag{23}$$

$$logT_F = log(\frac{F^{1-n}-1}{K(n-1)}) + (n-1)logCo \tag{24}$$

To obtain the n and k of all the batch reactors using F = 0.8 where f stands for fractional conversion Reactor C6w (Table 8).

Reactors performance

Reactor Bw9: From slope n and k is obtained from equation (8) and (9) K= 0.3176 and n= 1.8937. Reactor Hw12: From slope n and k is obtained from equation (8) and (9) n= 1.5829 k= 0.3254. Reactor Fd12: From the graph n can be obtained as 1.4177 and k as 0.1606. Reactor U_d9: From the graph n= 2.0832 and the value of k is obtained from equation 3.8 to be 1.1445. Reactor Gd6: From the graph n=1.9453 and k= 0.20948863 (Table 9).

The results presented in Table 2, 3, 4, 5, 6 and 7 illustrates the relationship of log T_f against log C_n for various day of degradation of crude upon the influence of time for reactor C_6w, B_w9, H_w12, F_d12, U_d9 and G_d6 respectively. The variation on the functional parameters can be attributed to variation on the degradation time. The results presented in Figure 3, 4, 5, 6 and 7) illustrates the relationship of log T_f against log C_n for various day of degradation of crude upon the influence of time for reactor C_6w, B_w9, H_w12, F_d12, U_d9 and G_d6 respectively. The variation on the functional parameters can be attributed to variation on the degradation time. Relationship of log T_f against log C_n shows an increase in both dimensions with equations of best fit established in each curve as presented in this paper.

It was also observed that of the reactions, the reactors that were operated under wet condition experienced a much higher bioremediation rate than those under dry conditions, this is due to the fact that the water supplied to the microorganism under wet conditions weren't supplied to those that were operated under dry conditions and water is of paramount importance to both micro and macro life because it is part of the metabolic pathway by which microorganism feed, produce energy and grow thus as a result of that the moist reactors experienced a faster bioremediation rate than those done under dry conditions.

Thus, we can conveniently say that they higher they cassava peel they faster they bioremediation process this statement only olds to the extent of inhibition of bioremediation caused by excessive supply of nutrients to the soil to be bioremediated. Bioremediation is a process that uses living organisms, such as bacteria, fungi, or plants, to degrade, remove, or neutralize pollutants from contaminated environments. It offers several advantages compared to traditional methods of pollution cleanup. Some of the key advantages of bioremediation include, Bioremediation is often considered a more sustainable and environmentally friendly approach to pollution cleanup. It relies on natural processes and organisms, reducing the need for harsh chemicals or disruptive techniques. In many cases, bioremediation can be more cost-effective than traditional methods. Once the necessary conditions are established, the microorganisms or plants can continue to work over time, requiring minimal human intervention. Bioremediation can be tailored to specific pollutants and contaminants. Different microorganisms or plants can be chosen or engineered to target particular substances, allowing for a more precise cleanup (Wang and Guo, 2023; Wang et al., 2023; Xu et al., 2023).

Traditional methods of pollution cleanup, such as excavation or chemical treatment, can be disruptive to ecosystems and communities. Bioremediation is less invasive, minimizing disruption to the surrounding environment. Bioremediation can provide a long-term and sustainable solution to pollution problems. Once established, the natural processes can continue to work over extended periods, ensuring ongoing remediation. Bioremediation can be applied to various types of pollution, including hydrocarbons, heavy metals, pesticides, and more. This versatility makes it suitable for a wide range of contaminated sites. Some traditional cleanup methods can generate secondary pollutants or waste streams. Bioremediation processes typically generate fewer byproducts and have a lower risk of creating additional pollution. Bioremediation is often perceived more positively by the public and stakeholders due to its natural and non-invasive nature. Bioremediation can be performed in situ, meaning the cleanup occurs directly at the contaminated site. This eliminates the need for transporting contaminated materials elsewhere, reducing associated risks. Ongoing research and advancements in biotechnology continue to improve the effectiveness and efficiency of bioremediation methods, expanding its potential applications. It is important to note that the effectiveness of bioremediation can depend on various factors, including the type of contaminants, the specific site conditions, and the choice of organisms or plants used. In some cases, a combination of bioremediation with other techniques may be necessary to achieve the desired results (Behera and Das, 2023; C et al., 2023; Kong et al., 2023).

CONCLUSIONS

This study showed addition of cassava peel had significantly enhanced the growth of microbial consortium, leading to the highest total petroleum hydrocarbon removal of 100% after 30 days incubation. Assemblages of mixed population with overall broad enzymatic capacities are required to increase the rate and extent of TPH biodegradation. Therefore, bioaugmentation and biostimulation has a great effect in enhancing biodegradation of crude oil in real environmental condition Although the experiment was conducted in soil restrained in a bucket, conclusions can be extrapolated to actual field soil contaminated with crude oil. Thus, it is concluded that when a farm is contaminated by crude oil, it can be recovered by cassava peel and yam peels several times.

DECLARATION OF COMPETING INTEREST

The authors declare no competing financial interest.

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