International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 12, Issue 11 [November. 2023] PP: 109-116

Developing A Bioremediation Model For Crude Oil Contaminated Soil Using The Buckingham's Pi Theorem

Ndantiobong Peter Akpan, Prof. Ify. L. Nwagozie and Engr. Victor Amah
Centre for Occupational Health, Safety and Environment (COHSE)
Institute of Petroleum Studies (IPS)
School of Graduate Studies,
University of Port Harcourt, Port Harcourt, Nigeria.

ABSTRACT
The study focused on the development of bioremediation model for crude oil contaminated soil using Buckingham Pi theorem. The need for the development of models for predicting the bioremediation of crude oil contaminated soil came as a result of cost ineffectiveness and time-consuming nature of the traditional bioremediation techniques. in this study, the researcher developed a bioremediation mathematical model using the Buckingham Pi theorem using moisture content, pollutant concentration, soil density, pollutant volume, mass of remediating agent and contact time as variables. These variables were used for the model development in their dimensionless units. Data used for validating the model was gotten from the experimental setup used to generate data for the study. The pollutant was light crude oil with 0.85kg/l specific gravity, 35.4API and 2.90P in viscosity. The remediating agent was goat droppings. The soil was contaminated with the crude oil and then mixed with a hand shovel to ensure homogeneity of the mixture. The contaminated soil and goat droppings were taken to the laboratory for analysis. The model was used to predict the THC removal from experimental data. The predicted THC was then compared to the THC gotten from the experiment to establish the accuracy of the model in predicting the removal of THC. Findings showed that the development mathematical model predicted about 79.12% THC removal compared to 76.32% THC removal from the experimental set up after 35 days of exposure to the remediating agent. The researcher concluded that, the establish the reliability of the developed model, a multiple regression analysis was performed between the predicted THC and experimental THC, a regression coefficient of 0.94 was gotten which established the reliability of the developed mathematical model.
Keywords: *Bioremediation, Buckingham Pi Theorem, Total Hydrocarbon Content (THC), Contaminant.*

Date of Submission: 10-11-2023 Date of acceptance: 26-11-2023

I. Introduction

Hydrocarbon contamination of soil has become one of the most important environmental concerns. Accidental spills, improper disposal of oily sludge, vandalism, sabotage of oil facility sites and installations, corrosion of old oil facilities due to uncontrolled spillage in oil refineries, and leakage from storage tanks are all sources of soil contamination that have irreversible consequences for our immediate environment (Agarry, 2010). This is owing to rising demand for petroleum hydrocarbons and products generated from them, as well as increased industrial activity and rapid industrialisation. Hydrocarbons in the soil have detrimental consequences for the ecology (Ugwoha & Okechukwu, 2020). Furthermore, transporting hydrocarbons into the environment via tankers and barges does not limit crude oil leakage to only oil-producing areas, but also to surrounding places that are prone to oil spills due to transportation accidents and the ruptured pipeline network that runs through such areas. Oil spill contamination could occur as a result of sales and uses of petroleum products, pipeline overflow, breakage, and storage tank spills (Obire & Wemedo, 1996).

Traditional soil remediation methods are based on the removal or containment of hydrocarbons, but they often come at a high cost and pose a risk to the environment due to soil excavation and removal, application of chemicals such as solvents or surfactants, application of hot water or air at high pressure, and other factors (Pilon-Smits, 2005). Due to these disadvantages, researchers developed "environmentally friendly" repair technologies that are less expensive and have a lesser environmental impact. Before a bioremediation technique is adopted, an experimental design must be carried out in the lab to ensure its appropriateness for the soil it is intended to remediate. While this technique is both costly and time consuming, it is only effective if laboratory conditions are maintained at the contaminated site, which has not always been possible. The failure of the bioremediation process is hampered by the inability to maintain laboratory conditions at the contamination site. As a result of this constraint, scientists began to seek a way to support experimental approaches for predicting the parameters required for effective contaminated soil regeneration. As a result, environmental modeling was established.

Statement of the Problem

Although there are currently a number of physical and chemical remediation technologies available (such as physical removal, soil washing, and oxidation/reduction via chemical agents), the use of less aggressive and more environmentally friendly techniques, like bioremediation, is becoming more and more popular (Ali et al., 2020). The accessible supply of necessary nutrients and electron-accepting substances (oxygen, nitrate, iron (III), sulfate), along with the presence of microbial catabolic activity towards hydrocarbons, are crucial elements in bioremediation (Zhang, et al., 2019). Since hydrocarbon interactions with the soil's organic carbon content might hinder microorganisms' or their enzymes' access to the compounds, the bioavailability of the pollutants also affects microbial activity (Koshlaf and Ball, 2017).

There is still much to learn about the biodegradation of hydrocarbons in soils, thus more research is needed. Furthermore, the process outcomes prediction and bioremediation technique selection and implementation are quite difficult. Within this paradigm, modeling shows promise as a tool to help decision makers deal with the challenges of cleaning and repairing contaminated sites in an efficient manner (Alridha, et al., 2022). As a result, the purpose of this study is to develop a bioremediation model using the Buckingham Pi theorem.

Aim of the Study

The aim of this research is to develop a bioremediation model for crude oil contaminated soil using Buckingham Pi's theorem.

Buckingham Pi theorem

Numerous scholars have utilized dimensional analysis based on the Buckingham pi theorem (Reddy and Reddy, 2014; Izady et al., 2016; Polverino et al., 2019; Misic, Najdanovic-lukic and Nesic, 2010). It is possible for a physical quantity to have dimensions or not. Physical quantities can be classified as dimensionless, meaning they lack dimensions, or as dimensional, meaning they have dimensions. The quantity's numerical value is determined by the system's measurement units. Physical quantities can be converted from the International System of Units (SI) to their dimensions using the Buckingham pi theorem. For instance, the length per time (L/T) and meter per second (m/s) are the SI units for the speed of light. It is important to select the elements that affect the experimental data you are examining because dimensional analysis helps you to reduce the dependence of a complicated physical quantity to its most basic form. The physical quantity of a system is represented by its dimensions, which are written in square brackets []. For instance, the dimensions of the speed of light (m/s) might be given as [L/T].

II. Materials and Method

Greenish yellow in color, the light crude oil had a specific gravity of 0.85 kg/l, an API of 35.4 and a viscosity of 2.90 P. It was obtained from the Ogu refinery located in the Bolo Local Government Area of Rivers State. For the purpose of this experiment, uncontaminated loamy soil was obtained from Choba Community, Obio-Akpor Local Government Area, Rivers State. Using a shovel, the loamy soil was removed from the top layer up to five inches down and was filled in a bucket. It was sundried for 48 hours. The soil was sieved using a 5 mm sieve to remove big stones and debris.

The remediating agent (goat droppings) was gotten from a local goat herding farm in Emuoha LGA. The researcher wore hand gloves to pick the goat droppings, sundried them for 14 days before grinding and sieving it with a 2mm screen. The filtered product was brought to the laboratory for analysis.

Determination of parameters

Moisture content

In the laboratory, the moisture content (MC) of the uncontaminated loamy soil was evaluated by weighing the container. The soil was weighed after it was placed in the container. The sample container was then cooked for 24 hours in a 105ºC oven before being cooled for sixty minutes before being weighed. The MC of the control and treatments was determined using the same method. The MC was determined using Equation (1). where w_1 is the container's mass, w_2 is the container's mass plus moist soil, and w_3 is the container's mass plus oven-dried dirt.

$$MC = \frac{w_2 - w_3}{w_3 - w_1} \times 100 \qquad - \qquad (1)$$

Total Hydrocarbon Content (THC)

Through the use of a 1L separatory funnel, the 0.5kg soil sample was extracted from the plastic container. It was loaded with precisely 50ml of methylene chloride and shook for 30 seconds. After two minutes of shaking the funnel and intermittently releasing excess pressure, the sample was extracted. After letting the organic and water phases distinct for at least ten minutes, the methylene chloride solution was extracted in a 250 ml flask. After the extraction process was done twice more, the extracts were mixed in an Erlenmeyer flask. The combined extract was put in a vial after going through a drying tube made of silica, anhydrous sodium sulfate, and packed cotton wool. It was then concentrated to 1 ml using a Bunsen burner. To determine the amount of THC, 1ml of the mixture and 1ml of soil sample from the separatory funnel were combined and passed into the flame ionization detector gas chromatography.

Soil density

A sample of the dried soil was put in a container with a known volume. Weighing was done both before and after the container was filled with oven-dried earth. The weight of the dry soil was determined by calculating the difference in weight. Bulk density was calculated using an equation.

$$Soil\ Density = \frac{Mass\ of\ the\ dry\ soil}{Volume\ of\ the\ soil} \quad - \qquad (2)$$

Remediation efficiency

The percentage effectiveness of the remediating agent is represented by the remediation efficiency (RE) calculated using Equation (3). THCci is the total hydrocarbon content in contaminated soil before treatment, and THCti is the total hydrocarbon content after treatment at a specific period (t).

$$RE = \frac{THC_{ci} - THC_{ti}}{THC_{ci}} \times 100 \quad - \qquad (3)$$

Model description

Buckingham's Pi Theorem is a well-known dimensional analysis that helps in focusing on the variables of interest while also grouping them to form a collection of dimensionless variables with variables of interest from several domains. Theoretically, this theorem aids in the prediction of outcomes using just dimensionless variables. A function equation can be constructed by understanding the dependent (denoted as n1) and independent variables with dimensions (denoted as n_2, n_3, n_4, n_5...), as illustrated below.

$$n_1 = f(n_2,\ n_3,\ n_4,\ n_5 \ldots),$$

Thus

$$f(\pi_1, \pi_2, \pi_3, \ldots) = 0$$

Where π is the dimensionless variable that includes both dependent and independent variables, and 0 is the dimensionless result of all variables.

Model assumptions

- The phase of the soil is pseudo-homogeneous.
- Because the soil was regularly mixed, spatial variance is disregarded.
- Free drainage controls the lower boundary condition,
- Evaporation rate controls the higher boundary condition.
- Moisture content, pollutant concentration, soil density, soil pollutant, and mass of remediating agents and contact time are the only elements investigated in this study that affect biodegradation rate.

Model Development

The investigating variables include.

1. Moisture content (MC) measured in /kg.
2. Pollutant concentration (THC) measured in mg/kg.
3. Soil density (σ) measured in kg/m^3
4. Pollutant volume (V) measured in m^3
5. Mass of remediating agent (M_{agent}) measured in kg.
6. Contact time (T) measured in days.

Express each investigating variable in their dimensional units.

$$MC = /kg = M^{-1}$$

$$THC = mg/kg = M^0$$

$$\sigma = kg/M^3 = ML^{-3}$$

$$V = M^3 = L^3$$

$$M_{agent} = kg = M$$
$$T = T$$

Therefor the linearized equation for the variables is;

$$\Delta THC = f(MC, \sigma, V, M_{agent}, T) \qquad (4)$$

Determine the required number of π terms.
n = 6, m = 3
therefore, r = 6 – 3
r = 3
hence, there are 3 pi terms.
Select the repeating variables and they are; (V, M_{agent}, T)

$\pi_1 = (V^a, M^b, T^c, \sigma)$

$$\pi_1 = V^a M^b T^c \sigma$$
$$(L^3)^a M^b T^c M L^{-3} = M^0 L^0 T^0$$
$$L^{3a} M^b T^c M L^{-3} = M^0 L^0 T^0$$
$$L^{(3a-3)} M^{b+1} T^c = M^0 L^0 T^0$$
$$3a - 3 = 0$$
$$3a = 3$$
$$a = \frac{3}{3}$$
$$a = 1$$
$$b + 1 = 0$$
$$b = -1$$
$$c = 0$$

Therefore, the first π term is;

$$\pi_1 = V^1 M^{-1} \sigma$$
$$\pi_1 = \frac{V\sigma}{M} \qquad (5)$$

$\pi_2 = V^a M^b T^c M.C$

$$\pi_2 = L^{3a} M^b T^c M^{-1}$$
$$L^{3a} M^b T^c M^{-1} = M^0 L^0 T^0$$
$$L^{3a} = L^0$$
$$3a = 0$$
$$a = 0$$
$$M^{b-1} = M^0$$
$$b - 1 = 0$$
$$b = 1$$
$$c = 0$$

Therefore, the second π term is;

$$\pi_2 = V^0 M^1 MC$$
$$\pi_2 = M.MC \qquad (6)$$

$\pi_3 = V^a M^b T^c THC$

$$\pi_3 = L^{3a} M^b T^c M$$
$$L^{3a} M^b T^c M = M^0 L^0 T^0$$

Thus;

$$L^{3a} = L^0$$
$$3a = 0$$
$$a = 0$$
$$M^{b+1} = M^0$$
$$b + 1 = 0$$
$$b = -1$$
$$c = 0$$

Therefore,

$$\pi_3 = V^0 M^{-1} THC$$
$$\pi_3 = \frac{THC}{M} \qquad (7)$$

Expressing the final form as a relationship among the π terms;

$$\pi_1 = f(\pi_2, \pi_3)$$

We have;

$$\pi_1 = \frac{V\sigma}{M}, \pi_2 = M.MC, \pi_3 = \frac{THC}{M}$$

$$\frac{THC}{M} = K(\frac{V\sigma}{M})^a (M.MC)^b \qquad (8)$$

Equation 8 can be written as

$$\ln\frac{THC}{M} = lnK + aln\left(\frac{V\sigma}{M}\right) + bln(M.MC) \qquad (9)$$

Write the normal equation for the expression in 9, we have;

$$y = ax + bz + c \qquad (10)$$

The normal equations are;

$$\sum y = ax + b\sum z + c$$
$$\sum yx = a\sum x^2 + b\sum xz + c\sum x$$
$$\sum yz = a\sum zx + b\sum z^2 + c\sum z$$

equation 8 can be written as;

$$\begin{bmatrix} n & \sum x & \sum z \\ \sum x & \sum x^2 & \sum xz \\ \sum z & \sum zx & \sum z^2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum y \\ \sum yx \\ \sum yz \end{bmatrix} \qquad (11)$$

Substituting the values gotten from the first 2 weeks experimental data (see appendix I), we have;

$$\begin{bmatrix} 5 & 1.1394 & 3.8067 \\ 1.1394 & 1.2983 & 4.3375 \\ 3.8067 & 4.3375 & 14.491 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 4.4690 \\ 5.0921 \\ 17.0121 \end{bmatrix}$$

$$\begin{bmatrix} 5 & 1.1394 & 3.8067 \\ 0 & 1.0387 & 2.9392 \\ 0 & 1.0352 & 3.4584 \end{bmatrix} = \begin{bmatrix} 4.4690 \\ 3.4506 \\ 4.0601 \end{bmatrix}$$

$$\begin{bmatrix} 5 & 1.1394 & 3.8067 \\ 0 & 1.0387 & 2.9392 \\ 0 & 0 & 0.0117 \end{bmatrix} = \begin{bmatrix} 4.4690 \\ 3.4506 \\ 0.0140 \end{bmatrix}$$

Therefore,

$$0.0117C = 0.0140$$
$$C = \frac{0.0140}{0.0117}$$
$$C = 1.1966$$
$$1.0387b + 2.9392C = 3.4506$$
$$1.0387b + 2.9392(1.1966) = 3.4506$$
$$1.0387b + 3.5170 = 3.4506$$
$$1.0387b = 3.4506 - 3.5170$$
$$1.0387b = -0.0664$$
$$b = \frac{-0.0664}{1.0387}$$
$$b = -0.0639$$
$$5a + 1.1394b + 3.8067C = 4.496$$
$$5a + 1.1394(-0.0639) + 3.8067(1.1966) = 4.496$$
$$5a - 0.07281 + 4.5551 = 4.496$$
$$5a + 4.4823 = 4.496$$
$$5a = 4.496 - 4.4823$$
$$5a = 0.0137$$
$$a = \frac{0.0137}{5}$$
$$a = 0.00274$$

Therefore,

$$y = ax + bz + c$$

y = THC, x = $ln\frac{V\sigma}{M}$, $x^2 = \ln(M \times MC)$

Calibrating the model, we have.

$$\boldsymbol{THC = 0.00274 + K(\frac{V\sigma}{M})^{-0.0639}(M.MC)^{1.1966}} \qquad (12)$$

Findings

Soil properties

The MC of the loamy soil sample is 11.1 percent, the bulk density is 1.3 grams per cubic centimeter, the particle density is 1.98g/cm^3, the porosity is 37.8%, and the pH is 6.1 (field study, 2022).

Model Verification

Table 1 shows the data for the variables used for the experiment as well as the amount of THC removed from the contaminated soil via the experimental set up. The experimental data was inputted into the mathematical model to predict the THC removal.

Table 1: Computed Data using the Developed Model

Days	x = (vσ/M)	z = (M × MC)	THC (Predicted)	THC (Actual)
0	3.1250	6.0000	7.93715423	11.90573135
14	3.0000	18.0000	29.62178363	52.72677486
21	3.5000	36.0000	67.22384146	70.58503353
28	4.0000	60.0000	122.8213429	147.3856115
35	4.5000	90.0000	198.0214866	178.2193379

Week 2 (14 days)

$$THC = 0.00274 + (3.0)^{-0.0639}(18.0)^{1.1966}$$
= 0.00274 + 0.932206124 * 31.7730627
= 0.00274 + 29.618849
= 29.622

Week 3 (21 days)

$$THC = 0.00274 + (3.5)^{-0.0639}(36.0)^{1.1966}$$
= 0.00274 + 0.923068758 * 72.8235041
= 0.00274 + 67.2211015
= 67.224

Week 4 (28 days)

$$THC = 0.00274 + (4.0)^{-0.0639}(60.0)^{1.1966}$$
= 0.00274 + 0.915226037 * 134.194831
= 0.00274 + 122.818603
= 122.821343

Week 5 (35 days)

$$THC = 0.00274 + (4.5)^{-0.0639}(90.0)^{1.1966}$$
= 0.00274 + 0.908363595 * 217.995027
= 0.00274 + 198.018746
= 198.021486

A plot of THC against Time (in days) is displayed in Figure 1. The plot shows a linear relationship between THC removed and time. From Figure 1, as the time of exposure of the crude oil contaminated soil to the remediating agent increases, the amount of THC removed increases and vice versa. The developed model predicted that about 7.937mg/kg of THC will be removed in less than 14 days after adding the remediating agents while the experimental data showed that 11.906mg/kg of THC was removed within 14 days of adding the remediating agent. At about 35 days of exposure of the crude oil contaminated soil to the remediating agent (goat droppings), THC amount predicted from the mathematical model was 198.021mg/kg while the experimental data showed that about 178.219mg/kg of THC was removed.

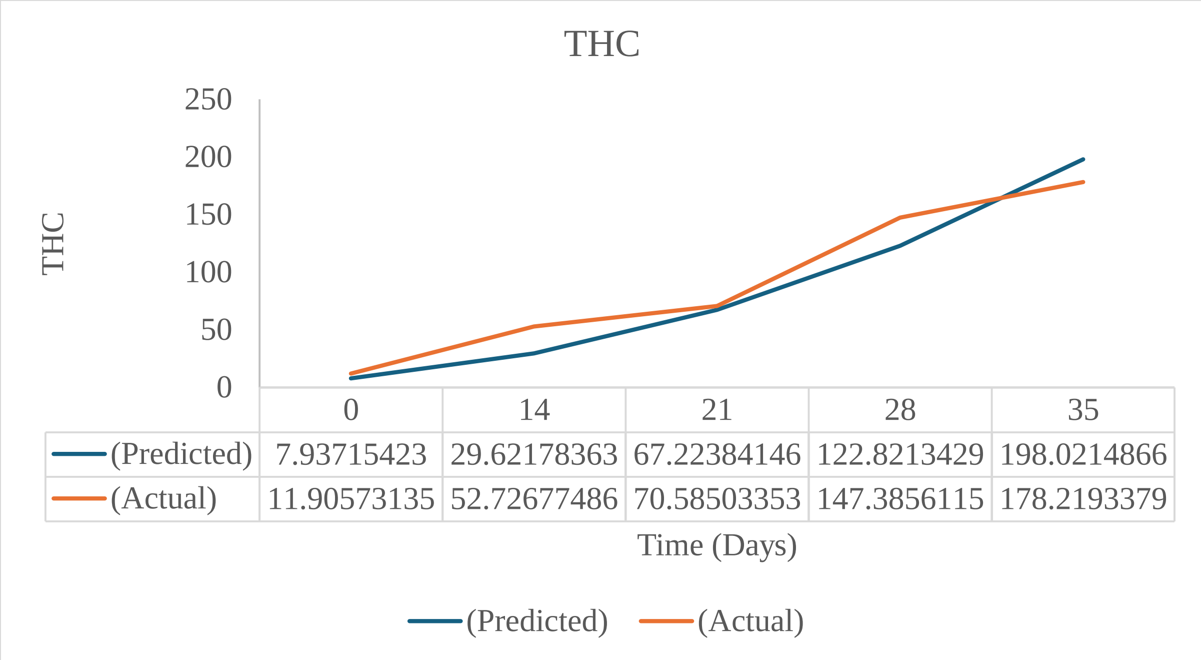

Figure 1: THC Removed

Table 2 shows the regression statistic carried out to compare the THC predicted and THC experimented values to establish a relationship. A regression coefficient of 0.94 was obtained, which confirmed that their similarities were significantly related. The level of significance on the relationship between the THC predicted by the model and THC from the experiment was established with F calculated (32.06) being higher than the f-critical value (0.0298) at 0.05 level of significance. Thus, there is a significant positive relationship between THC predicted by the model and THC from the experiment.

Table 2: Regression Statistics

Multiple R	0.970198
R Square	**0.941284**
Adjusted R Square	0.911926
Standard Error	21.72613
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	15134.13	15134.13	**32.06214**	**0.029802**
Residual	2	944.0495	472.0248		
Total	3	16078.18			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-28.0306	25.79117	-1.08683	0.390652	-139.001	82.9399	-139.001	82.9399
11.90573	1.180198	0.208429	5.662344	0.029802	0.283399	2.076997	0.283399	2.076997

III. Conclusion

Buckingham Pi theorem has been successfully used to develop a mathematical model that can be used to predict the bioremediation of crude oil contaminated soils using goat droppings as a remediating agent. After 35 days, the experimental set up removed about 76.32% of the THC in the crude oil contaminated soil while the developed mathematical model predicted about 79.12% of THC removal from the same crude oil contaminated soil. Thus, the model should be utilized in predicting crude oil contaminated soil at different locations to test its reliability in prediction.

References

[1]. Agarry, S. E. (2010). Bioremediation of soil artificially contaminated with petroleum hydrocarbon mixtures: Evaluation of the use of animal manure and chemical fertilizers. Bioremediation, 14(4), 189-195.

[2]. Ali, N.; Bilal, M.; Khan, A.; Ali, F.; Iqbal, H.M.N. Effective exploitation of anionic, nonionic, and nanoparticle-stabilized surfactant foams for petroleum hydrocarbon contaminated soil remediation. Sci. Total Environ. 2020, 704, 135391.

[3]. Alridha, A.H.; Al-jilawi, A.S.; Alsharify, F.H.A. Review of Mathematical Modelling Techniques with Applications in Biosciences. Iraqi J. Comput. Sci. Math. 2022, 3, 135–144.

[4]. Borsi, I., & Fasano, A. (2009). A general model for bioremediation process of contaminated soils. International Journal of Advances in Engineering and Applied Mathematics, 1(1), 33-42.

[5]. Calman, F. A., Robu, B. M., Smaranda, C., Pavel, V. L., & Gavrilescu, M. (2011). Soil and Groundwater Cleanup: Benefits and Limits of Emerging Technologies. Clean Technology Environment, 13(2), 241-268.

[6]. Ebadi, A.; Khoshkholgh Sima, N.A.; Olamaee, M.; Hashemi, M.; Ghorbani Nasrabadi, R. Remediation of saline soils contaminated with crude oil using the halophyte Salicornia persica in conjunction with hydrocarbon-degrading bacteria. J. Environ. Manag. 2018, 219, 260–268.

[7]. Fernandez, E. L., Merlo, E. M., Mayor, L. R., & Camacho, J. V. (2016). Kinetic modelling of diesel-polluted clayey soil bioremediation process. Science of the Total Environment, 557(558), 276-284.

[8]. Izady, A., Abdalla, O. Sadeghi, M. Majidi, M. Karimi, A. and Chen . (2016) 'A Novel Approach to Modeling Wastewater Evaporation Based on Dimensional Analysis', *Water Resources Management*. Water Resources Management, 30(8), pp. 2801–2814. doi: 10.1007/s11269-016-1324-8.

[9]. Koshlaf, E.; Ball, A.S. Soil bioremediation approaches for petroleum hydrocarbon polluted environments. AIMS Microbiol. 2017, 3, 25–49.

[10]. Misic, T., Najdanovic-lukic, M. and Nesic, L. (2010) 'Dimensional analysis in physics and the Buckingham theorem', *European Journal of Physiscs*, 893(31), pp. 893–906. doi: 10.1088/0143-0807/31/4/019

[11]. Obire, O., & Wemedo, S. A. (1996). Effect of oil field wastewater on the microbial population of a soil in Nigeria. Niger Delta Biologia, 1(1), 77-85.

[12]. Ojewumi, M.E.; Emetere, M.E.; Babatunde, D.E.; Okeniyi, J.O. In Situ Bioremediation of Crude Petroleum Oil Polluted Soil Using Mathematical Experimentation. Int. J. Chem. Eng. 2017, 2017, 5184760.

[13]. Pilon-Smits, E. (2005). Phytoremediation. Annual Review of Plant Biology, 56, 15-39. http://dx.doi.org/10.1146/annurev.arplant.56.032604.144214

[14]. Polverino, P., Bovea, G. Sorrentinoa,M. Pianesea, C. and Berettab, D. (2019) 'Advancements on scaling-up simulation of Proton Exchange Membrane Fuel Cells impedance through Buckingham Pi theorem', *Applied Energy*. Elsevier, 249, pp. 245–252. doi: 10.1016/j.apenergy.2019.04.067.

[15]. Reddy, G. M. and Reddy, V. D. (2014) 'Theoretical Investigations on Dimensional Analysis of Ball Bearing Parameters by using Buckingham Pi-Theorem', *Procedia Engineering*. Elsevier B.V., 97, pp. 1305–1311. doi: 10.1016/j.proeng.2014.12.410.

[16]. Skrdla, P. J. (2007). A simple model for complex dissolution kinetics: A case study of norflxacin. Journal of Pharmaceutical and Biomedical Analysis, 45, 251-256.

[17]. Ugwoha, E. & Okechukwu, L. I. (2020). Modeling the bioremediation of Diesel contaminated soil by Bacteria from Clogged Drainage System. American Journal of Civil and Environmental Engineering, 4(2), 11-21.

[18]. Zhang, B.; Zhang, L.; Zhang, X. Bioremediation of petroleum hydrocarbon-contaminated soil by petroleum-degrading bacteria immobilized on biochar. RSC Adv. 2019, 9, 35304–35311.