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Optimization and Pilot Scale Study of Soil Column Air Stripper Device for Volatile Organic Chemicals (VOCs) Separation

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Abstract
The stripping of volatile organic compounds (VOCs) plays an important role in the remediation of petroleum contaminated soils and with a mild air blower that gives increased soil column air stripper (SCAS) performance. An experimental study using SCAS for heated and unheated air was simulated to determine its effectiveness and performance for VOCs removal efficiency by counter-current flow. The studies were carried out in a 0.1 m (10 cm) diameter of unpacked column to a depth of 1.1 m (1100cm) and a safety factor of 10% (0.1m) with the gas flow varying from 2.4 l/min to 12 l/min and the soil flow rate from 0.088 Kg/m^2.h to 52.50 Kg/m^2.h while the air flow rate from 0.17 Kg/m^2.h to 101.79 Kg/m^2.h. Temperature was varied from 20 °C to 50 °C. The effects of increasing temperature on the removal efficiency were more significant at temperature of 50^{O}C than at 20 ^{O}C when air flow rate was constant at 4.8 l/min. The concentration of the VOCs in the petroleum contaminated soils was measured by gas chromatography fitted with flame ionization detector (GC-FID) method. The initial concentration measured by GC-FID is 211.95 mg/kg while effluent concentration drops to an average of 39.77 mg/kg of petroleum contaminated soil PCS at 293K, 16.17 mg/kg of PCS at 323K and 8.20mg/kg of waste contaminated soil (WCS) at 323K. The effects of increasing airflow rate, temperature and air-to-soil ratio on the removal efficiency were found to be more significant at air flow rate of 2.0 to 10 l/min., as temperatures rises from 293K to 323K. The results indicate that a high removal of VOCs can be achieved by operating the SCAS at high temperature conditions even at relatively low airflow rate and air-to-soil ratios. The removal efficiency was observed to be very high in PCS with 82.13% in clay, 78.45% loamy, 52.50% sandy and 53.60% coarse-grain soils. This indicates a positive progression in an observable reduction from 211.95 mg/kg to 16.17mg/kg in PCS when temperature was elevated to 323K representing average of 92.37% reduction of VOCs in soil at pressure drop of 10 - 200 N/m^2 with column height of 1.1m and safety factor of 0.1 m (10% column height). The mass transfer processes were achieved using MATLAB and a surface response plot to determine the maximum VOCs recovery using countercurrent SCAS. The VOCs removal efficiency increased from 82.33% to 99.99% while Henry's constant increased from 4.0 x 10^{-3} to 7.3 x 10^{-2} as temperature was elevated from 283 to 323 K. VOCs removal efficiencies of over 99.99% were obtained for all combinations of airflow rate, temperature and air-soil ratio. The result also indicated that air stripping of VOCs from petroleum contaminated soil is most dependent on temperature and moderately air flow rate and air-soil ratio. The study therefore supports the adoption of locally made SCAS device as a practical solution for the treatment of petroleum contaminated soils (PCS) while providing substantial technical and economic benefits over more complex air stripper designs.

Keywords: *Soil column air stripper; volatile organic compounds; removal efficiency; petroleum contaminated soils.*

1.0 Introduction

The treatment of soil contaminated with petroleum distillates are different from other type of contaminated soil treatment, this is due to nonconventional contaminants, high concentration of volatile organic compounds (VOCs) and variability in influent concentration due to soil texture [1]. A major problem in the soil remediation is the removal of VOCs that usually enter the unsaturated zone as discrete liquid phases, which move due to gravitational and capillary forces [1, 2]. They frequently enter groundwater systems after they have been spilled on the surface and pass through the unsaturated zone [2]. The most common source of VOCs presence in soil contamination includes house hold chemicals and petroleum hydrocarbons. The VOCs include aliphatic hydrocarbons (AHCs), polynuclear aromatic hydrocarbons (PAHs), benzene, toluene, ethylbenzene and xylene (BTEX). These compounds are harmful or even toxic to the growth and development of plants and animals, being a source of long-term water and air pollution. The presence of these VOCs in soils has increased their concentrations over time and this is made evident through advanced analytical methods.

High concentration of these VOCs may affect the effectiveness and removal efficiency of air-stripping processes, and therefore this technology will require redevelopment of the convectional air stripping technology. The treatment of VOCs by air stripping processes occurs in two ways, this include destructive

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and nondestructive methods. The nondestructive methods include bioremediation, electro-kinetic, soil washing and air stripping.

Air stripping is a technology uses an air stripper for VOCs removal from soil by increasing the surface area of the contaminated soil that is exposed to air, and this can be used for treatment of petroleum contaminated soils. The types of air stripper include packed column, sieve tray, diffused aeration and tank contactor [1, 2, 3].

The applicability of each technology is based on its performance as reported in literatures and other professional stack holder with the equipment experience [3, 4]. In practice, two methods can be used to achieve contact between phases so that mass transfer can occur, this include continuous or staged contact and the air flow geometry used in practice is counter current, co-current and cross-flow. Counter current flow pattern offer a significant economic advantage over concurrent and cross-current columns when stripping VOCs and this will increase the maximum VOCs removal.

1.1 Air Stripping System

1.1.1 Air strippers and their applications

Air stripping is a treatment technology that uses an air stripper to facilitate the process of VOCs removal and other dissolved gases from contaminated media by transferring them to an air stream. It works by forcing air through contaminated media, increasing the contact area between the solid/liquid and gas phases to encourage VOCs to evaporate from the soil/water and be absorbed by the air stream. Air strippers are used in wastewater treatment, soil and groundwater remediation and other industrial applications [1, 4]. The applicability of each type of air stripper is based on its performance during air stripping process with VOCs removal efficiency as reported in the literature survey. It is important to develop a new treatment technology that will complement the conventional methods in order to improve the VOCs removal efficiency.

1.1.2 Counter-current soil column air stripping overview

The counter-current soil column air stripper (SCAS) consists of a soil column complete with 32mm weirs and filters, air blower unit, conical hopper, pressure gauge, heating coil, thermocouple thermometer, digital thermometer and a mechanical electric motor for a continuous airflow system. The column and the blower unit are the major component units, other equipment and controls are located on a metal frame structure setup as shown in Figure 1.

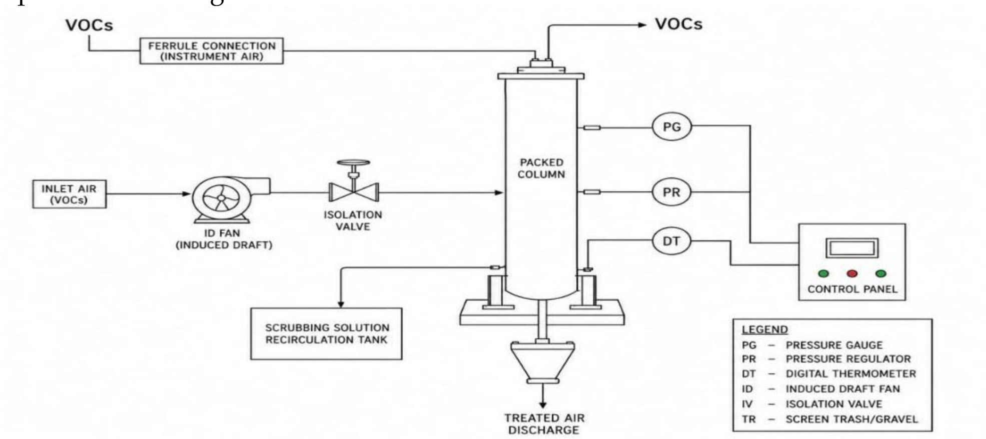

Figure 1: A soil column air stripping system

In SCAS, the soil column is a vertical cylindrical column, whose dimensions are 0.1m in diameter and 1.0m in height. The column has a large surface area for mass transfer of VOCs from the soil to the gaseous phase. The conical hopper is positioned at the top of the column where influent feed stock is introduced over the column. A high-capacity air blower forces air into the bottom of the air stripper where the VOCs are removed from the soils. Filters are arranged at the top of the column to prevent the escape of solid particles with the exiting air [4, 5].

1.1.3 Theory of operation

The SCAS is a gas – solid contactor that uses a counter-current flow with an extended surface area for both soil and fluids in contact. The gas/solid separators, consisting of an upper and lower perforated sieve of uniform diameters (5mm), the filters are positioned at the top (to prevent solids from escaping) and conical hopper is located at the upper part of the column (at 45^0) with an injected air from the blower below (see Figure 1.0). The contaminated soils are distributed via conical hopper and it flows downward under gravity while air flows upward in counter-current with incoming soils. The air carries the removed VOCs to the column outlet into the atmosphere or it can be recycled as fuel to power the reboiler. A schematic diagram of SCAS is shown in Figure 2.0

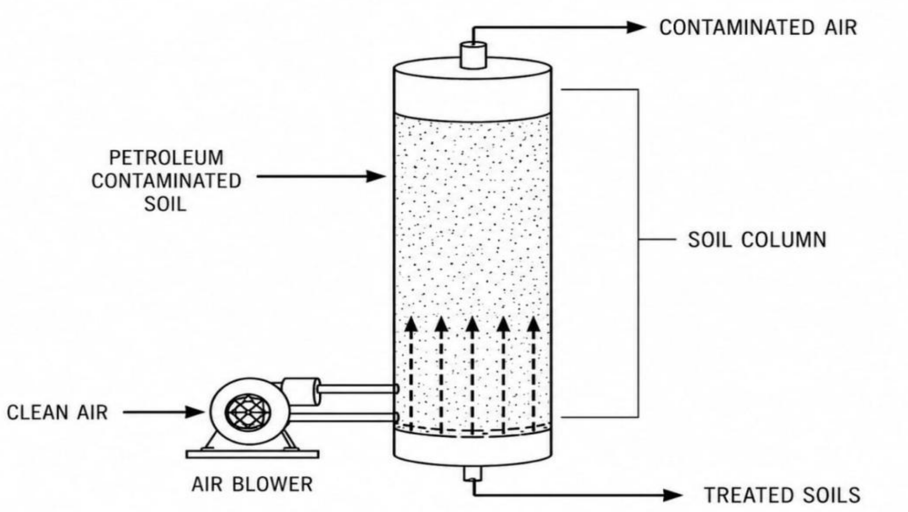

Figure 2: Schematic diagram of soil column air stripper

The VOCs removal efficiency from soil using SCAS is shown in Figure 2 and this depends on several important factors: This includes air temperature, column height, diameter and air to soil ratio. The removal efficiency is highly dependent on temperature and we need to know the true boiling temperature (TBP) of hydrocarbons presence in VOCs. For most VOCs, preheated air 45^{O}C will volatilize VOCs. This is because most hydrocarbons TBP falls within 293K – 323K^{O}C. A temperature of 318K is sufficient to influence VOCs removal efficiency in any stripping facility. The required removal efficiency is directly related to the column height and will result in a taller column. But for structural stability will prevent the use of taller column, the column height can be reduced by increasing the column diameter and maintaining the same removal efficiency. Finally, the air to soil ratio varies depending on the contaminated media. The volatility of the VOCs will determine the required air to soil ratio. A lower air to soil ratio is needed for VOCs that are more volatile. Soil column air strippers will work on petroleum contaminated soils because VOCs can evaporate easily. The key variable in the operation of SCAS systems is Henry's law constant, (K_H) and the VOCs adsorption in soil.

Table 1 presents a recent experimental investigation using air stripping process with different unit operation under controlled conditions. Among recently reported investigations, an experimental study on the application of a packed column air stripper in the removal of VOCs from wastewater was conducted by Evuti et al. (2015), who showed that the packed column air stripper is a proven, effective means of removing VOCs from groundwater and wastewater. They observed that process variables directly influence its performance to 86 %. Michael-Igolima *et al.,* (2022) worked on effectiveness of remediation methods and displayed an observation on the countercurrent flow that causes VOCs removal to 70% by volatilization. They also investigated the air stripping designs and water purification processes for the lunar surface in an effluent wastewater. The VOCs concentration was declined with increasing time of treatment due to a shift in equilibrium that was caused by the selective removal of more VOCs. More recent research work including the air stripper types, title findings and knowledge gap is presented in Table 1.

Table 1: Performance assessment of different air strippers for VOCs removal efficiencies

Sn	Researcher	Type of air stripper	Title	Findings	Knowledge gap
1	Evuti *et al.*[6]	Packed column air stripping	Application of a packed column air stripper in the removal of VOCs from wastewater	The process variables influence its performance to 86 %	Dependence on packing materials
2	Michael-Igolima *et al.,* [7]	packed, unpacked, tray, or spray	Effectiveness of remediation methods by an air stripper	The countercurrent flow causes VOCs removal 70% by volatilization	Lack of multi-parameters optimization
3	Tao *et al.,* [8]	Drum and tank	The application of surfactant colloidal	Lower power to remove 65% of VOCs	Limited mathematical model on air stripping

		contactor	gas aphrons to remediate contaminated soil	from water	system
4	Saqr [9]	Flushing tank	Soil remediation through washing and flushing: technical review, and future prospects	VOCs recovery were 80 – 90% loamy-clay and less 50% for sandy soils	insufficient performance evaluation and process optimization

Table 1 revealed the significant of air stripping techniques for treatment of contaminants in environmental remediation by different researchers, the application of these air stripper measures the mass transfer efficiency for VOCs removal processes. The knowledge gap identified from literature include over dependence on packing materials, Lack of multi-parameters optimization, Limited mathematical model on air stripping system, insufficient performance evaluation and process optimization and high energy consumption and poor sustainability

This present research work advances the field of soil remediation by introducing an optimized unpacked SCAS that overcomes the inherent limitations of conventional packed air stripping systems. The principal novelties in this study include elimination of packing materials, thereby preventing fouling, clogging, scaling, and excessive maintenance. The development of a comprehensive mathematical model for predicting VOCs removal from petroleum contaminated soils under varying operating conditions. Applying advanced optimization techniques such as Matlab design model and Response Surface Methodology to optimize the stripping facility and its operational variables.

Integrating optimization techniques, mathematical modeling, and experimental validation, the unpacked soil column air stripper will address the engineering challenges associated with conventional packed air strippers. The expected outcome is a robust, cost-effective, energy-efficient, and environmentally sustainable soil remediation system that provides a practical solution for treating petroleum contaminated soils in Nigeria and similar hydrocarbon-polluted environments. The treatment of soils using this new developed technology needs to be verified to ascertain its performance when the suspected VOCs in soils can be stripped conveniently. The concept of unpacking materials, optimization-based operation, and predictive performance modeling represents a significant advancement beyond existing air-stripping technologies and constitutes a strong research novelty suitable for academic learning.

The aim of this research work is to determine the stripping efficiency of SCAS device using the treatment variables under controlled conditions for the removal of VOCs from petroleum contaminated soils. The objective is to make air stripping facilities very effective, cheap, reliable and capable to simulate performance leading to better removal efficiency within the SCAS device. The pilot SCAS facility assesses the effectiveness of countercurrent SCAS in reducing various VOCs contaminant levels to meets the stringent environmental standards across diverse operating scenarios.

2.0 Theoretical Background

Mass transfer of VOCs can occur through volatilization which may be induced by mechanical surface aeration. The process of removal of dissolved gas from solid proceeds through the following consecutive steps including transfer from the bulk solid to the interface, transfer across the interface and transfer away from the interface into the bulk of new phase. The evaluation of the stripping facility follows a standard chemical engineering principle involving mass transfer, fluid dynamics and process efficiency as shown in Figure 2.

2.1 Performance equation for an unpacked air stripper

For an unpacked cylindrical air stripper used in soil remediation, the most important column characteristics are the cross-sectional area, volume, height-to-diameter ratio, and empty bed residence time (EBRT). These parameters are used in sizing the column and evaluating its stripping performance

(a) Column geometry

This is to measure all dimensions within the column setup, the conventional formulas used for the calculation of the volume (V) and cross sectional area (Ac) of a cylindrical column was adopted and verified as expressed in equations below.

i. Column area **(A)**

$$A = \frac{\Pi D^2}{4} \quad (1)$$

ii. Column volume **(V)**

$$V = A \times h \quad (2)$$

Where D – diameter of the column, h- height of the column

2.3 Particle transport across the column

(a) Mass of solid

A clear understanding of the fluid mechanics during stripping process, If ρ_s is the density of the solid particles, A_c the cross-sectional area, h_s the height of the column before the particles start to lift, ε_s and ε are the corresponding porosities of the settled and expanded column, respectively, then the mass of solids in the column, W_s, is

$$W_S = \rho_s A_s h (1-\varepsilon_s) = \rho_s A_s h (1-\varepsilon) \quad (3)$$

(b) Void space (porosity)

The porosity of particle is expressed as;

$$\varepsilon = 1 - \frac{\text{Mass of particle}}{\rho_S \, x \text{ total column volume}} \quad (4)$$

The observables stripping process in soil column is used to calculate fluid pressure drop (ΔP) needed to cause the fluid to flow through the column of solids, the fluid velocity (u), and the density of solids (ρ_s). The Ergun equation [10]

(c) Height-to-diameter ratio (H-to-D)

$$\text{H-to-D} = H/D \quad (5)$$

H-to-D is an important aspect that laboratory stripping column to provide adequate air-to solid contact

2.4 Henry constant

For a dilute VOCs system, the minimum air flow rate is estimated by equilibrium relationship in an unpacked air stripper as

$$y* = mx \quad (6)$$

Where

$$m = \frac{H}{RT} \quad (7)$$

Where y*- equilibrium gas-phase concentration, x - solid (or pore soil) concentration and m - Henry's law constant (dimensionless), H - Henry's Law equilibrium constant (unit less).

2.5 Removal efficiency (η)

$$\eta = \frac{Cs_i - Cs_o}{Cs_i} \times 100\ (\%) \quad (8)$$

Cs_i – Influent concentration in mg/kg, Cs_0 – effluent concentration in mg/kg

2.6 Reynolds number

The particle transportation within the column gives the accurate predictions to measure the values when the particles in the column are suspended then the Reynolds number is used to determine of the two velocities involved in the study. This implies the minimum and the maximum fluidization velocity. For $R_{e,p}$ we can resolve the expression as:

$$Re_{,p} = \frac{124 d_p U_P}{\mu} \quad (9)$$

$R_{e,p}$ in equation 9 represent the usual situation, in which fine particles are fluidized by a gas. Sometimes, higher values of the Reynolds number do exist without needing to guess the velocity; this can help you calculate the superficial air velocity at minimum, fluidizing and terminal.

2.7 Superficial air velocity

Superficial air velocity is the speed at which air flows through a column, when the column is empty.

(a) Minimum fluidization velocity

The Minimum fluidization velocity (U_{mf}) is expressed in terms of fluid and solid, this is the velocity required to begin the fluidization at which the weight of particles' gravitational force equals the drag on the particles from the rising gas. The expressed [10] as presented in equation 10

$$U_{mf} = \frac{(\varphi d_P)^2}{150\mu} \square \frac{{e_{mf}}^3}{1 - e_{mf}} \quad (10)$$

(b) Fluidized velocity

The fluidized velocity (U_f) expressed by Kozeny-Carmen equation is as in equation 11

$$U_f = \frac{(\rho_p - \rho_f) g d_p^2}{150\mu} \cdot \frac{\varepsilon^3}{1 - \varepsilon} \quad (11)$$

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(c) Terminal velocity

The terminal velocity due to gravitational settling in the column to avoid chaotic situation can be applied using stokes law as:

$$U_t = \frac{(\rho_p - \rho_f)dp^2}{18\mu} \quad (12)$$

For proper fluidisation the relationship between the U_{mf} and U_t is given in equation

$$U_{mf} > U_f > U_t \quad (13)$$

If the gas velocity is increased to a sufficiently high value, however, the drag on an individual particle will surpass the gravitational force and then the air-to-soil ratio can be calculated as follows:

2.8 Pressure drop

Measure inlet pressure and the outlet pressure as:

$$\Delta P = \text{Pi} - \text{Po} \quad (14)$$

At low pressure drop indicate efficient airflow in an unpacked column

$$\frac{\Delta P}{h} = \frac{150*(1-\varepsilon)^2}{\varepsilon^3} \cdot \frac{\mu U}{dp^2} + \frac{1.75\,(1-\varepsilon)\,U\rho f}{\varepsilon^3 \quad dp} \quad (15)$$

Where, ΔP = pressure drop, h = Height of the column, μ = fluid viscosity, ρ_F = Fluid density, ε = Porosity of Particle, u = fluid velocity and d_p = Particle diameter. Once the drag exerted on the particles equals the net gravitational force exerted on the particles that is the two forces are equal, the particles begin to move up. The force balance describes this condition [10, 11] is given in equation 16;

$$\frac{\Delta P}{h} = (\rho s - \rho_f)\,(1-\varepsilon)\,g \quad (16)$$

At the point of minimum fluidization the weight of the column is equals the pressure drop across the column ($W_s = \Delta P A_c$)

$$\frac{\Delta P}{h} = (\rho s - \rho_f)\,(1-\varepsilon)g = \frac{150*(1-\varepsilon)^2}{\varepsilon^3} \cdot \frac{\mu U}{dp^2} + \frac{1.75\,(1-\varepsilon)\,U\rho_f}{\varepsilon^3 \quad dp} \quad (17)$$

2.9 Air-to-Soil ratio analysis

For an unpacked air stripper used in soil remediation, the minimum air flow rate is estimated from Henry's Law, the contaminant equilibrium relationship, and the overall contaminant mass balance. The air-to-soil ratio (A/S) represents the volume of stripping air supplied per unit mass of contaminated soil and is a key design parameter affecting contaminant removal efficiency.

(a) Air flow rate

The minimum air flow rate is obtained from the equilibrium operating line:

$$\frac{G}{S}\,min = \frac{x_i - x_o}{y^*_o - y_i} \quad (18)$$

Where G = air flow rate ($m^3\ h^{-1}$), S = equivalent solid (or soil pore-water) flow, X_i = inlet contaminant concentration, X_o = outlet contaminant concentration, y_i= inlet air concentration (≈0) and y_o* = equilibrium outlet gas concentration

.

(b) Air-to-Soil ratio

The air-to-soil ratio (ASR) is the product of the gas loading rate times the ratios of the densities as:

$$\text{ASR} = \frac{Q_a}{M_s} \quad (19)$$

Where Qa airflow rate, Ms - mass rate of soil, the parameter strongly affect stripping efficiency

(c) Mass flow rate

Mass flow rate is the measure of mass moving through a cross-section per unit time, expressed in (kg/s).

$$\frac{G_m}{S_m} = \frac{Q_a}{Q} \times \frac{\rho_g}{\rho_s} \quad (20)$$

The mass flow of incoming air accordingly to stoke law is expressed as:

$$G_m = \rho U \quad (21)$$

The mass flow of incoming solid feed to the column is denoted as S_m. Hence, the flow rate at various velocities was calculated as

$$Q = A \times U \quad (22)$$

For practical operation, the overall contaminant balance
Assuming fresh air, y_i = 0, Then

$$G_m = \frac{S(X_i - X_o)}{y_o} \quad (23)$$

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$$G = (1.5 - 3)G_{min} \quad (24)$$

For practical operation, the air flow is 1.5–3.0 times the theoretical minimum air flow to ensure sufficient driving force for mass transfer

2.10 Mass transfer calculation

For unpacked column, VOCs transfer through volatilization of gas bubbles, the overall gas-phase transfer rate

$$N_A = K_G a\ (y* - y) \quad (25)$$

Where K is overall gas mass transfer coefficient, a is interfacial area per unit volume. K_Ga is volume mass transfer coefficient

2.11 Residence time (t)

$$t = \frac{V}{Q} \quad (26)$$

Where V – column volume and Q – Airflow rate, longer residence time generally improve

2.12 Determine blower performance

(a) Power requirement

The minimum and maximum power requirements of the bed were calculated from equations 27 to 29 respectively below

$$P_{min} = \Delta P \times \emptyset_{min}$$
$$P_{fluidized} = \Delta P \times \emptyset_{fluidized} \quad (27)$$
$$P_{max} = \Delta P \times \emptyset_{max}$$

(b) Air blower power (P)

$$P = \frac{Q\Delta P}{\eta} \quad (28)$$

Where η – blower efficiency

(c) Energy consumption

Specific energy consumption

$$SEC = \frac{Power}{Mass\ removal} \quad (29)$$

Lower SEC indicate better performance

2.13 Overall Transfer Unit

An overall Transfer unit refers to the number of transfer units (NTU) and height of a transfer unit used for performance evaluation and analyzes separation columns (mass transfer).

(a) Number of transfer unit (NTU)

The number of transfer unit is

$$NTU = \int_{y_i}^{y_o} \frac{dy}{y^* - y} \quad (30)$$

For a dilute system

$$NTU = \text{In}\ [(y^* - y_i)/(y^* - y_o)] \quad (31)$$

A design factor termed NTU was introduced by Kavanaugh to characterize the difficulty of removing the contaminant from the solid phase [11]. The NTU is defined using Equation 32

$$NTU = \frac{R}{1-R}\left\{\ln\left[\frac{X_{in}/X_{out}\,(R-1)+1}{R}\right]\right\} \quad (32)$$

Where R - stripping factor, X_{in} - influent mole fraction of contaminant in solid, and X_{out} as effluent mole fraction of contaminant in solid.

(b) Height of transfer unit (HTU)

$$HTU = \frac{G}{K_G a} \quad (33)$$

(c) Height of column

The column height Z is calculated using Equation 34 required for achieving a desired separation.

$$Z = HTU \times NTU \quad (34)$$

The product of the HTU and NTU yields the column height necessary to effect the desired removal of the VOCs. The adsorption factor is a ratio of the soil flow rate to the gas flow rate multiplied by the Henry's constant. It represents the minimum air-to-solid ratio that is required for high treatment efficiency. See equation (8)

(d) Stripping factor

The stripping factor (R) is a dimensionless parameter used in chemical engineering and air stripping technology to evaluate the effectiveness of stripping facility, where a VOCs is removed from a solid phase into a vapor or gas phase

$$R = H \times [G^{\circ}/S^{\circ}] \quad (35)$$

Where: R - stripping factor (unit less) S - Soil flow rate (mol/s) G - Air flow rate (mol/s), R is crucial in determining the ability of soil column air stripper to remove a specific contaminant under the following operating conditions. For R > 1, implies air stripping will occur, R= 1, signifies the process will be at equilibrium and R < 1 meaning absorption will be taking place. It is necessary to have a stripping factor greater than 1. R and H are two parameters to determine mass transfer relative to equilibrium condition to produce high VOCs removal rates, but may not optimize power requirements. Figure 3 showed the AutoCAD drawing for soil column air stripper system used for a pilot scale experiment.

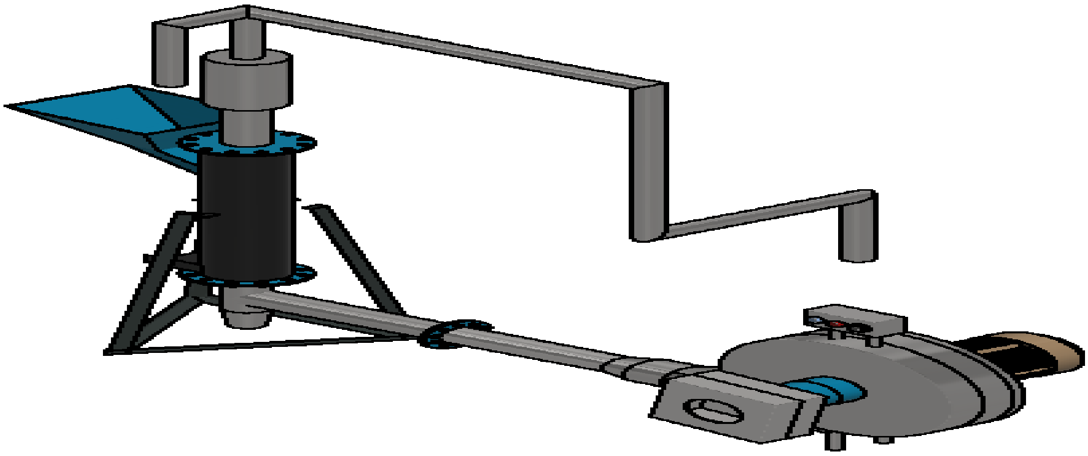

Figure 3: AutoCAD drawing of soil column air stripper system

The AutoCAD drawing of the stripping device directly impact VOCs removal efficiency. The VOCs removal efficiency dependent on temperature, air flow rate, air-to-soil ratio, soil texture and true boiling temperature (TBP) of the VOCs presence in petroleum contaminated soils. For most VOCs, the performance of the air stripper can be enhanced using mass transfer equations and design software such as Aspen hysys or Matlab computational method.

3.0 Material and Methods

3.1 Experimental setup

The air stripping column consists of the soil column, air blower unit; level control, sprue, sampling pipes, heat chamber, electric motor and the control panel. Other system component includes flanged, ware gauze, filters, bolts and nuts, sensor, thermometer, thermocouple, pressure gauge and others**.** The countercurrent soil column air stripper offers greater interfacial surface area for mass transfer of VOCs than do other type of air stripping processes. This method offers significant advantages in efficiency and overall cost when used for the removal of VOCs from soil matrix. Equations have been developed to optimize SCAS system for removal of VOCs. In addition, a pilot study I use to measure the magnitude and sensitivity of VOCs removal requirements of the stripping facility project is recommended to achieve the remediation objectives and overall cost estimates. This technique overcomes the effect of additional treatment unit, increase removal efficiency of air-stripping processes.

3.1.1 Experimental basic and process conditions

The SCAS facility is shown in Figure 3 and operating conditions are presented in Tables 2 and 3

Table 2: Assumption and process conditions

Sn	Variables	S,I Unit	Values
1	Air flow rate	min/l	0.1 – 2.4
2	Soil flow rate	kg/h	0
3	Temperature	^{O}C	20 – 50
4	Soil mass	G	1000
5	Porosity	-	0.3 – 0.55
6	Air-to-soil ratio	-	1 – 2.4
7	Influent concentration	mg/kg	200 – 250

3.1.2 Measurement of VOCs removal using air stripper device

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The performance evaluation of an unpacked is carried out to determine the VOCs removal efficiency from contaminated soil by considering literatures on selected VOCs removal using air stripper types by determining the optimum performance using stripping factor, column height and removal efficiency as shown in Table 3

Table 3: Pilot scale investigation on various VOCs removal using air stripper

Sn	VOCs Types	Stripping Factor	Column Height (m)	Removal efficiency (%)	References
1	AHCs	2.0	1.2	85.00	Ghoreyshi et al, 2014
2	PAHs	1.79	2.10	63.30	Schwarzenbach et al., 2017
3	BTEX	2.0	1.0	85.00	Henrique et al., 2022
4	Ammonia	1.25	1.0	68.20	Zhang et al., 2022
5	Tetrachloroethylene	1.62	0.9	74.80	Wang et al., 2023

Table 3 presents the characteristic of the column material in an air stripper to provide a large surface area for mass transfer of VOCs to the gas phase, or ambient air. Several stripping factor, column height and removal efficiency are considered leading to the selection of trayless or empty column air stripper (soil column air stripper). It is necessary to optimize the soil column with stripping factor greater than 1 to achieve a successful removal rate. The investigation on the treatment variables was compared to bench laboratory scale and used response surface plot to determine the interactive effect of temperature, air flow rate, air-to-soil ratio and Henry constant on the removal efficiency of VOCs using unpacked column air stripper is shown in Tables 2, 3 and Figure 3.

3.2 Methodology

3.2.1 Laboratory analysis

An analytical procedure was established, capable of identifying and quantifying VOCs present in soil source to be treated, in order to assess remedial technique. The maximum contaminant levels (MCLs) for VOCs contaminant in mg/kg have been prescribed by the US Environmental Protection Agency (US EPA), based on continual improvements in detection techniques [16]. US EPA has an established list of VOCs found in air, water and soil [16]. The soil analyses were performed using gas chromatography fitted with flame ionization detector (GC - FID) and a packed column to separate VOCs by increased the resolution of GC - FID detection [16, 17]. The goal of using this analytical method is to assess contaminated soil, particularly where treatment levels and options will be considered. The objectives include setting up an analytical approach to determine the types and concentrations of VOCs present in order to allow the evaluation of various treatment methods. The variability of VOCs level in soil must be considered and a treatment system capable of treating the range of VOCs in soil matrix to acceptable limits. Finally, the concentrations of VOCs in soil before and after remediation must be determined to allow analysis of the efficiency of the system. A pilot-study investigation is used to determine the effects of varying operating parameters based on laboratory analyses of soil.

3.2.2 Experimental methods

The experimental method is as follows:

i. In air stripping, the operating conditions for the stripping facility is VOCs removal by heating and fluidizing into excess air, the VOCs in the contaminated soil is transferred to the gas phase;

ii. Air as the carrier gas, through its carrying VOCs into the SCAS system with injected air tube, heating with electric heating, digital temperature and control panel to control the reaction temperature, in a certain temperature range, the oxygen and VOCs in the air produce oxidation reaction in the column. The concentration of VOCs in the air was measured; the VOCs concentration in the soil samples before and after the air stripping was measured accordingly.

iii. The study on treatment of high concentration VOCs removal by stripping method at constant pressure using heated and unheated air. According to the change of VOCs concentration in the gas phase, the conversion rate of VOCs and the removal rate of VOCs in contaminated soils were calculated according to the change in VOCs concentration from solid phase to gaseous phase. To determine the VOCs concentration in soil, the soils were analyzed using Varian 3700 GC/FID.

iv. The VOCs removal efficiencies (η) of the air stripper were calculated using equation 8

v. The above procedure was repeated for all samples in the petroleum polluted soil samples corresponding to the reduction in VOCs concentration in soil sample.

3.3 Optimization

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The optimization of VOCs recovery system presented in Figure 3 is essential for improving separation efficiency, reducing operational costs, and minimizing energy consumption. The conventional optimization approaches are often limited in handling nonlinear interactions among process variables.

Therefore, Response Surface Methodology (RSM) combined with Matlab simulation provides a powerful computational tool for process modeling, prediction, and optimization. A pilot scale soil column air stripper with the data shown in Table 4 was used in this study. The system was assumed to operate at 212 mg/kg influent concentration of VOCs, air-soil ratio range of 2.4 to 12 and at different temperatures of 20^{O}C, 30^{o}C, 40^{o}C and 50^{o}C referred to as T1, T2, T3, T4 and T5 respectively. The selection of temperature was based on the studies of Yakubu et al. (2023) and Evuti et al. (2014) which outline the performance efficiencies that occur at temperature above 50^{0}C and high air-soil ratios for air stripping of VOCs. The effects of temperature and air-air-to-soil ratio on the η were determined by solving the process equations 3 - 36 using Matlab design program with data obtained from experimental results

Table 4: Soil column air stripper specifications

Sn	Parameters	S.I Unit	Values
1	Column Volume	m^3	0.1551
2	Column area	m^2	0.141
3	Column diameter	m	0.10
4	Column height	m	1.1
5	Safety factor	m	0.1
6	Column thickness	mm	12
7	Column material	-	Galvanize iron

The Matlab response surface plots visualize the variable interactions and identification of optimum operational regions. Previous studies showed a successful application of simulation-assisted optimization and mathematical modeling in VOCs recovery systems involving adsorption and stripping processes.

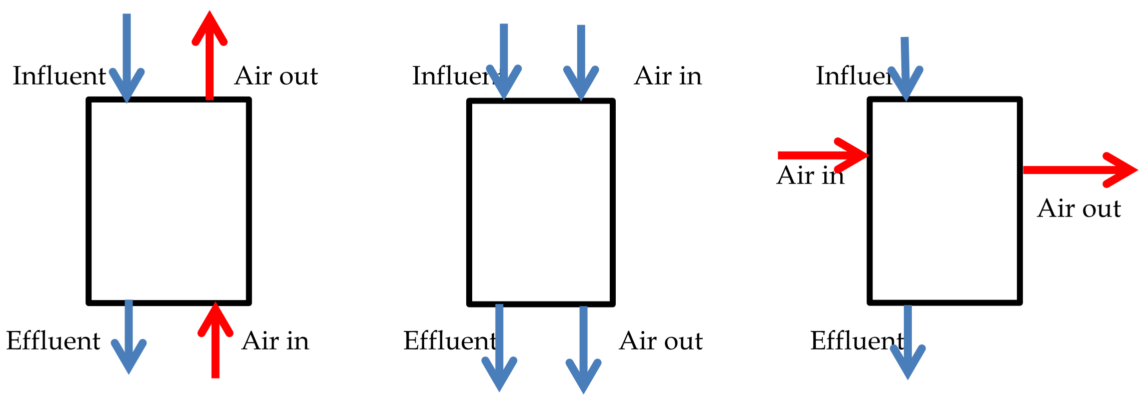
4.0 Results and Discussion

4.1 Technical requirement for soil column air stripper

To assess the performance of SCAS system for VOCs removal efficiency from soil is to investigate the soil column air stripper behaviour during transfer of dissolved VOCs from soil to gas stream and to determine the process conditions. The working conditions of the SCAS system are tested and to evaluate the effectiveness of SCAS system when it is not leaking. The effectiveness of countercurrent soil column air stripper without material for VOCs removal efficiency were considered using air flow geometry, air flow requirement and estimating the soil column air stripper performance for VOCs removal efficiency.

4.1.1 Air flow geometry

The process flow geometry plays an important role in soil remediation and modern unpacked air stripper to give increased column performance. An experimental comparison is made of the performance of the three modern process flow geometry in stripping VOCs from petroleum contaminated soils. The first step is decision whether to use countercurrent, concurrent or countercurrent flow, which are illustrated in Figure 4. The countercurrent flow column offers a significant economic advantage over concurrent and crosscurrent columns when stripping high VOCs such as AHCs, PAHs, BTEX and other VOCs. The gas/solid ratio is selected with a normal value that falls between 2 and 4. For countercurrent column, the gas – soil (G/S) ratio will determine the maximum percentage removal.



(a) Countercurrent **(b) Concurrent** **(c) Crosscurrent**

Figure 4: Airflow geometry in countercurrent, concurrent and crosscurrent

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Furthermore, the column diameter must be considered by the researcher, wider column has a lesser efficiency during stripping operation for the crosscurrent column. However, for the countercurrent column, the effectiveness is independent of the column width [17, 18]. Both the VOCs concentration and the flow are likely to vary periodically. The mechanical configuration depends on the nature of material selected, their propertied and the air flow requirement.

4.1.2 Air flow requirement

Air flow requirement in an air stripping process is a parameter that quantified by the gas-to-solid (G/S) volumetric ratio**.** It is the most critical operating parameter determining mass transfer, directly driving the evaporation and transfer of VOCs from the solid phase to the gas phase as shown in Table 5**.**

Table 5: Air requirement in soil column air stripper

Sn	Parameters	Symbols	Values/Unit	Volumetric flow rate @ STP (l/min)	Volumetric flow rate @ NTP (l/min)
1	Theoretical molar flow of air	$n_{Air-theo}$	576 mol air	774,627.84	845,510.40
2	Molar flow rate of air	n_{Air}	12, 00 mol/min	26,896.80	29,358.00
3	Molar flow rate of VOCs	n_{VOCs}	0.003 mol/min	215.17	234.86
4	Feed composition rate	$n_{feed} = n_1 + n_2$	11.27 mol/min	909,111.84	992,300.40
5	Gas Loading	G_{nVOCs}	0.8521	NA	NA
6	Percentage recovery	(% n_{VOCs})	85.21 %	NA	NA

Table 5 present a system that is mathematically consistent when operating at 0.8521 gas-to-feed loading ratios achieves the required 85.21% VOC recovery. However, the air supply input must be fixed at 72,000 mol/h to maintain reasonable hydrodynamics, manageable pressure drops, and realistic equipment sizing in an unpacked stripping column [19, 20].

4.1.3 Selection of an air blower

For practical operation, the air velocities at minimum fluidizing, fluidizing and terminal depends on the pressure drop and power requirement to ensure sufficient driving force for mass transfer is tabulated in Tables 6 and 7.

Table 6: Energy requirement data

Sn	Velocity, U (m/s)	Mass flow, G_m (Kg/m^2.h)	Mass flow, S_m (Kg/m^2.h)	Pressure Drop ΔP (KN/m^2)	Flow rate, ϕ (m^3/h)	Power, P (W)
1	0.14	0.17	0.088	158.23	0.007	4.47
2	2.40	2.94	1.52	2712.60	0.120	76.60
3	89.09	101.79	52.50	93912.50	4.150	2651.99

Table 7: Energy requirement and selection criteria for an air blower

Sn	Type of flow	Power requirement (HP) (1hp = 746watt)	Types of operations	Remark
1	Mild	0.5 – 2.0	Mixing, blending	Not recommended
2	Medium	2.0 – 5.0	Heat transfer, suspension, gas absorption	Recommended
3	Violent	5.0 – 10	Reactions, Emulsification	Not recommended

The characteristics of the electric motors vary widely with the nature, application and the type of duty it is expected to perform. It can be observed from Table 6, the power of 2.7kw was required to operate the air blower with the highest speed of 89.09m/s. The speed of an air blower was a factor that enhances air stripping operation and this can be used to select the right air blower using Table 7. Various speeds were considered from minimum fluidizing speed, fluidizing speed and terminal speed corresponding to 0.14m/s, 2.40m/s and 89.09m/s respectively. The application of the electric motor speed whether constant speed,

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variable speed, continuous/intermittent flow, sudden starts and frequent start/stops was be taken into consideration carefully when deciding the choice of a mild air blower to operate the SCAS using batch mode operation with power rating of approximately 2652w (2.7kw) [17, 22].

4.1.4 Pressure drop

Pressure drop is an important factor that indicates resistance to airflow through an air stripper, affecting gas–solid contact, mass transfer efficiency, energy consumption, and overall VOCs removal performance as shown in Table 6. Table 8 reconcile the simulation with experimental values when particle acceleration at high superficial velocities.

Table 8: Simulation and experimental pressure drop data

Operating Conditions	Simulation values (N/m^2)	Laboratory values (N/m^2)	Behavior during air stripping
Normal flow	158.23	200	Agrees and fitted within the range
High air flow	2,712.60	250	Agrees at high velocity for an unpacked column
Terminal flow	93,912.50	10,000	Agrees for particles under high drag

It can be observed from Table 8, the simulation and experimental results demonstrate a clear relationship between fluidizing velocity and pressure drop across the stripping column. At the minimum fluidization velocity, the simulated pressure drop was recorded 158.23 kN/m^2, compared with the experimental value of 200 kN/m^2, indicating a good agreement at incipient fluidization. At the operating fluidizing velocity, the simulated pressure drop increased to 2,712.60 kN/m^2, within the experimental range of 250 kN/m^2. Terminal velocity simulated value reached 93,912.50 kN/m^2 while the experimental range was 10,000 kN/m^2, showing a substantial deviation. The simulation predicted pressure-drop behavior at low operating velocities, and this may requires a little calibration at terminal conditions for improved accuracy.

4.1.5 Evaluating pilot scale and experimental soil column air stripper

The first stage to verify the performance of soil column air stripper is to compare the theoretical calculation data against pilot-scale experimental data. The difference between the two will show the gap between thermodynamic assumptions and the real world industrial challenges. To verify an air stripper require a comparison between pilot scale and theoretical calculation data as shown in Tables 9 and 10.

Table 9: Soil column air stripper pilot scale data

Sn	Parameters	Symbols	Values/units
1	Diameter	Dc	0.1 m
2	Height	Hc	1.1 m
3	Cross-sectional area	Ac	0.10 m^2
4	Volume	Vc	0.10 m^3
5	Height to diameter ratio	H/D	11
6	Air flow ratio	Qa	12 l/min
7	Superficial velocity	U	0.14 m/s
8	Stripping factor	R	1.41
9	VOCs removal efficiency	η	92.02 %
10	Air-to-soil ratio	ASR	0.35
11	Temperature effect	T	45 ^{O}C
12	Pressure drop	ΔP	200 N/m^2

Table 10: Soil column air stripper calculation data

Sn	Parameters	Symbols	Values/units
1	Diameter	Dc	0.1 m
2	Height	Hc	1.1 m
3	Cross-sectional area	Ac	0.007855 m^2
4	Volume	Vc	0.008641m^3
5	Height to diameter ratio	H/D	11
6	Air flow ratio	Qa	12 l/min
7	Superficial velocity	U	0.14 m/s
8	Stripping factor	R	1.41
9	VOCs removal efficiency	η	88.76%
10	Air-to-soil ratio	ASR	2.4

11	Temperature effect	T	323K
12	Pressure drop	ΔP	12.03 N/m²

The percentage removal of the VOCs contaminant is used to evaluate the efficiency of the SCAS device. Tables 2, 3 and Figure 3 represent the pilot scale and calculation results which showed high performance removal efficiencies of VOCs at the temperature range of 293K – 323K and air-soil ratios of 0.1 – 2.4.

The results show that for pilot scale and calculation data using the combinations of temperature and air-soil ratio, removal efficiencies of between 43.70 to 88.76% for calculation while 85–92% were obtained for VOCs respectively. The high removal efficiencies favour air stripping system. Other studies have reported similar results of high VOCs removal efficiencies using air stripping is shown in Table 5. It can be observed that the laboratory optimization carried out on SCAS device compared other air strippers in literature was responsible for high performance in the air stripper device for the removal of VOCs from petroleum contaminated soils. The average variations of removal efficiencies for air stripper with temperature, surfactant and combination (temperature and surfactant) in soil samples were, 79 and 87% respectively [11, 12, 23]. This result shows that soil column air stripper is more effective in VOCs removal coupled with some technical requirement. The technical requirement determines the effectiveness of unpacked air stripper through a proper selection and optimization of treatment process.

4.1.6 Operating parameters

This session describe the process conditions and equipment characteristics of stripping column and this determine airflow, solid flow, temperature, pressure, column dimensions, and gas–solid contact, influencing VOCs removal efficiency and the operational stability as presented in Table 11 and the effect of temperature on VOCs removal for heated and unheated soil is probably due to the larger dependency of the Henry's law constant and the characteristic of individual VOCs in AHCs, PAHs, BTEX and others.

Table 11: Process condition and equipment characteristics

Sn	Process parameters	Symbols	Values/Units
I	Height of transfer unit	HTU	1.4 m
Ii	Column height	Z	NTU = 0.714, HTU = 0.714
Iii	Safety factor	Z	Z = 1.0m, Z′=1.1 m
Iv	Effluent concentration	C_e	4.2027 mg/kg
V	VOCs removal efficiency	η	98.02 %
Vi	Gas loading	$(Qa/Q)_{min}$	0.978
Vi	Air-to soil ratio	$\frac{G_m}{S_m}$ =	G_m/S_m= 0.42, G_m= 1.26kg, S_m= 2.5kg
Vii	Henry's Constant	H	0.73
viii	Stripping factor	R	1.41
2 I	Column capacity Molar flow rate	% Excess Air	n_{Air} = 72, 000 mol/s, n_{VOCs} = 0.16 mol/s, n_{VOCs}= 0.8521, % n_{VOCs}= 85.21%
3	Minimum air-to-soil ratio	(Gm/Sm)	Q_G/Q_S = 1.93, Q_G = 0.23 m³/s, Qs = 0.12 m³/s
4	Cross-sectional area	Ac	A_{Strip} = 0.01m², D_C = 0.11m, A_{design} = 0.0095 m²
	Pressure Drop across the Column	$\frac{\Delta P}{H}$	ΔP/H = 10.48 Pa/m

Table 11 present the approach in accessing the performance of soil column air stripper using the operating parameters for high VOCs removal efficiencies at a fixed gas flow rates were investigated respectively. The performance of soil column air stripper depends on several operating parameters that influence the mass transfer of VOCs from the solid to the air phase. Proper optimization of these parameters improves stripping efficiency, reduces treatment time, and enhances the overall performance of the system. It can be observed that the stripping equipment, characteristic and process parameters are used as a factor to determine the VOCs stripping efficiency. This indicates that at low airflow rate, the residual VOCs concentration in soil was very high but as the airflow rate increases, the performance of the soil column air stripper increases to 98.02% and the residual VOCs concentration becomes very low. Interestingly the SCAS

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behaviour at a low pressure drops for the same air stripping facility revealing that the application of a medium blower and motor will reduce electrical operating costs [1, 24].

This implies that SCAS will be less expensive and easier to remove VOCs at low air-to-soil ratio. The removal efficiency is an important factor that needs to be verified when using stripping facility as shown in Tables 9, 10 and Figure 3. The analysis of VOCs in soil quality prompted the selection of SCAS over other type of air strippers for treatment of petroleum contaminated soil. The countercurrent soil column air stripper provides a good medium of air-soil contact for desorption of VOCs. The pilot air stripping experiment evaluate the performance of Figure 3 under a controlled operating conditions. The optimal performance of the stripping facility can be achieved through the treatment of the soil sample by analyzing the VOCs before and after equipment operation. The variation in the VOCs treatment efficiency with time for heated and unheated soil samples need to be verified. This implies that the remedial strategy needs to be developed to address the VOCs contamination. This can be achieved using atmospheric air for the treatment investigation using soil column air stripper. Similarly as in the case of air stripping, mass transfer rate and mass transfer area for each of air stripper is needed to determine the reduction in the MCLs [25].

4.2 Preliminary testing for temperature and pressure

The performance analysis of the soil column air stripper was first carried out by taking time at an even temperature distribution when atmospheric air pressure was injected and the VOCs removal rate was determined using column test. The results are shown in Figures 5 and 6.

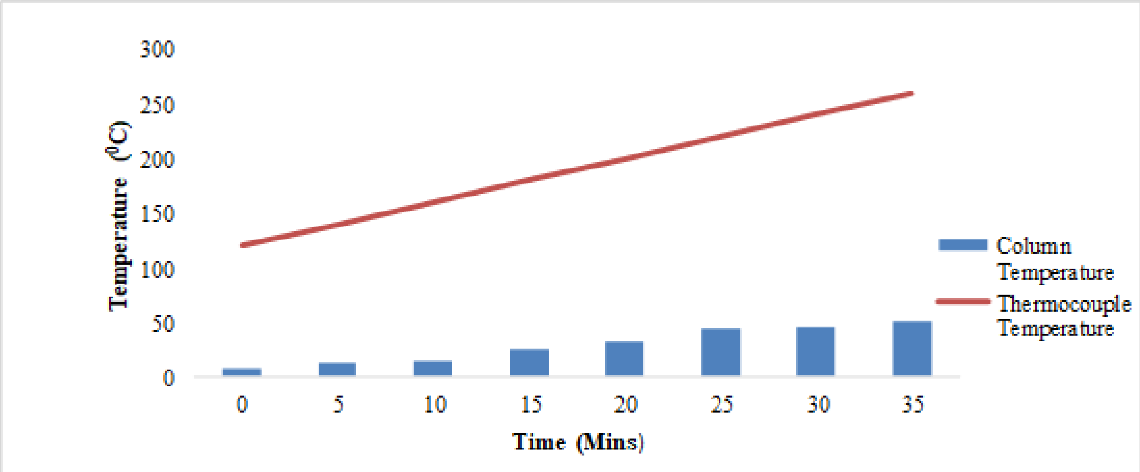

Figure 5: Temperature distributed profile

Figure 5 present the readings of the thermocouple and the timer were observed and recorded as a regular interval. The soil column air stripper was operated by injecting atmospheric air, the time taken to complete soil treatment and the corresponding temperatures were taken for each run. It can be observed that the inlet air temperature increases from 30°C to 50°C while the particles get heated up much faster than observed temperature at 20°C. This is because the rate of heat transfer is directly proportional to temperature difference between air and particles. This shows a progressive linear increment as the temperature increases for both digital thermometer in the soil column and thermocouple obtained from the hot plate over a period of time. Furthermore, this validates the effectiveness and performance of the soil column for VOCs removal rate [2, 10, 26]. In order to investigate the effect of air-flow rate on mass transfer rate of VOCs from the immiscible and soil phase to gas phase, experiments were conducted at different air-flow rates assuming that the air supply pressure was at a steady state. Seven experimental runs were carried out to observe the conditions required for air and VOCs movement inside the SCAS facility.

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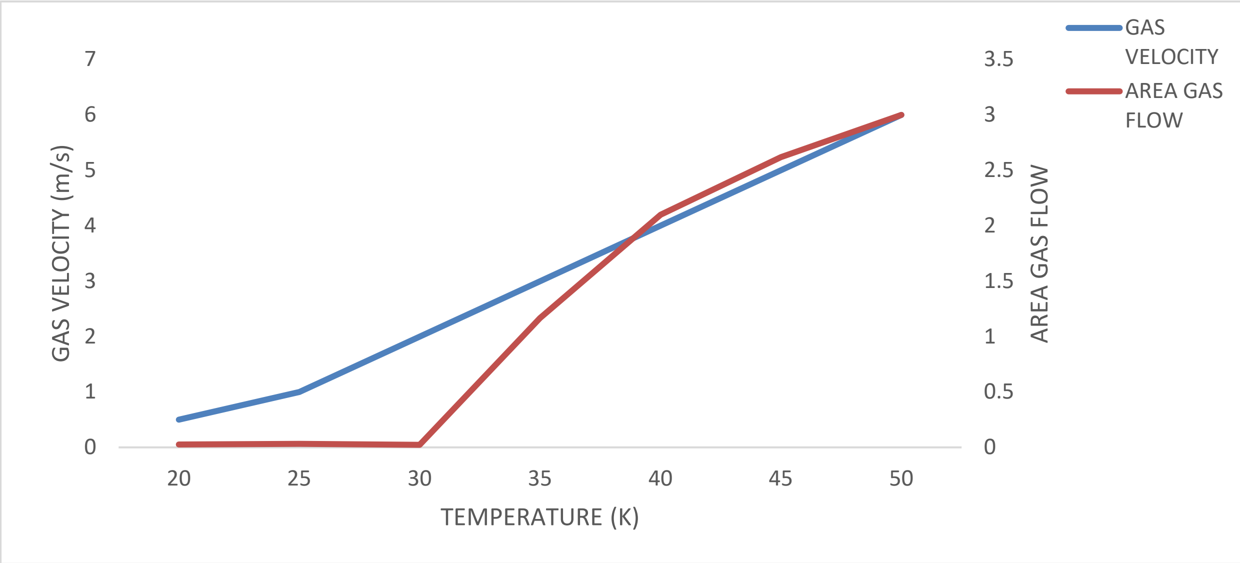

Figure 6: Effect of air flow on design soil column air stripper

Figure 6 showed the experimental run for gas velocity that increased from 0.5m/s to 3m/s and the period for remediation were then varied correspondingly from 5 to 30 minutes. Beyond 3m/s, it was found that the gas velocity increases, this changes the condition for which the fluidization occur and this does not agree with the behaviour of the gas velocity when it was between 0.5 to 3.0 m/s. It can be observed from Figure 5, the heat-carrying air moves upward as the air velocity gradually increases from 0.5 to 3.0m/s corresponding to the pressure exerted on the column, the particle material layer suddenly changes to complete fluidization state [5, 27]. As the air velocity increases beyond 3m/s, pressure appears to have negative effect of the gravitational force acting on the particles. At this point, the oxygen level increases and begin to cause expansion of particle layers in volume (entrainment). It can be recommended in optimizing soil column air stripper; entrainment rate should be measured so as to measure the VOCs removal efficiency during air stripping operation.

4.3 Estimation of VOCs removal efficiency

The experiments were performed in order to correlate the effects of air stripping for VOCs recovery efficiency in petroleum contaminated soils (PCS) at 293K and 323K and waste oil (used oil) contaminated soils (WCS) at 323K. The application of air stripping technique can be extended by injecting hot air into the soil column air stripper because the vapor pressure of VOCs increases with increasing temperature, leading to a higher volatilization. Total VOCs in the selected soil samples are given in Table 12 and a comparison with the experimental investigations are listed in Table 13.

Table 12: Total VOCs concentration presence in the selected sites

Soil samples	ΣVOCs conc. of PCS (mg/Kg)	ΣVOCs conc. of WCS (mg/Kg)
Clay	114.95	26.90
Loamy	86.57	25.05
Sand	27.79	20.06
Coarse-grain	26.42	15.28

Table 13: Residual VOCs concentrations in soil after air stripping of soil samples

Soil samples	Residual VOCs conc. of PCS @ 293K (mg/kg)	Residual VOCs conc. of PCS @ 323K (mg/kg)	Residual VOCs conc. of WCS @ 323K (mg/kg)
Clay	65.53	20.53	09.07
Loamy	51.66	18.66	08.85
Sandy	21.53	13.20	08.24
Coarse-grain	20.37	12.30	06.63

Tables 12 and 13 investigate the effect of air stripping technique on the soil sample results obtained from the two sources; petroleum contaminated soils and waste oil contaminated soils respectively. The

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stripping of VOCs and the mechanism of air stripping needs to be verified to ascertain the consequences of VOCs in the residual soil as shown in Table 10. The VOCs concentrations presence in the selected soil samples was 26.42 to 114.97 mg/kg of PCS and 15.28 to 26.90 mg/kg of waste oil contaminated soils. The GC-FID investigation revealed the distribution of VOCs among the two sample sources was observed to be very high [1, 5, 24, 28]. The results indicate the consequence of these VOCs in the environment and human health; this will require a proactive treatment technology such as soil column air stripper to clean up the entire environment.

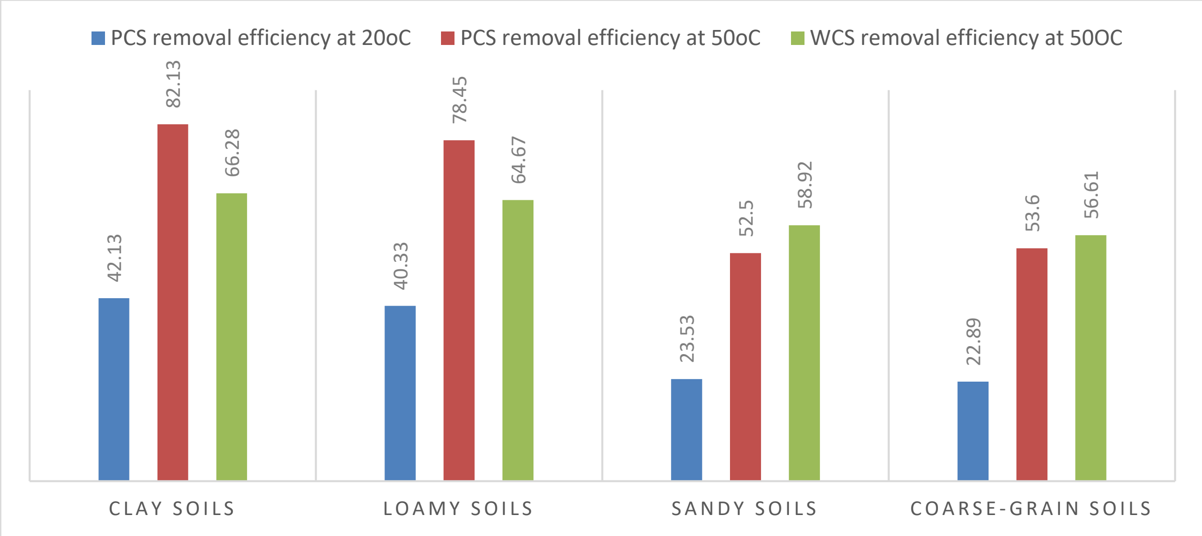

Figure 7: Comparison between PCS and WCS removal efficiency on air stripping process

During air stripping, removal of contaminated air causes an equilibrium shift as fresh air replaces the contaminated vapors. The VOCs remaining as residual liquid volatilizes into the fresh air, seeking to establish a balanced. As the process continues, more and more VOCs in the residual liquid is "mobilized" into the air phase and removed by soil column air stripper system. It can observe that the VOCs in the soil pore were transported with the air to the exit of the soil column air stripper for all soil samples. There were inconsistence reductions in concentration level with 90.53 mg/kg clay, 51.66 mg/kg loamy, 21.53 mg/kg sandy and 20.37 mg/kg coarse-grain samples when air was injected at ambient temperature. Beyond the initial stages of air injection, the temperature was elevated to 50^{O}C and recorded a further reduction in VOCs concentration of 20.53mg/kg clay, 18.66mg/kg, 13.20mg/kg and 12.30 mg/kg for all PCS. This result was compared to WCS that observed 09.07mg/kg clay, 08.85 mg/kg loamy, 08.24mg/kg sandy and 06.63mg/kg coarse-grain soils when air was injected at the same 323K. After treatment exercise, the experimental results were compared and against the EPA standard to ascertain the MCLs and the residual VOCs concentrations after air stripping of soil samples.

After 1 hour of air stripping, the VOCs concentration in the effluent air significantly increases, this is because the removal rate is proportional to the air-flow rate [28] and a relatively larger amount of VOCs were recovered. This can be observed in recovery efficiency of 82.13% clay, 78.45% loamy, 52.50% sandy and 53.44% coarse-grain for PCS corresponding to 66.28% clay, 64.67% loamy, 58.97% sandy and 56.60% coarse-grain soils for WCS respectively. The application of soil column air stripper for the removal; of VOCs in the two soil sources for both heated and unheated condition showed that air stripping program is a promising technology that will boost soil remediation technique. The results from Figure 5 revealed the removal efficiencies in each samples enhanced by air stripping oil and have important implications for the residual VOCs presence in the soil samples.

Analyzing the results from Figure 12, it can be observed that the VOCs removal efficiencies for PCS at 293K (42.13 % clay, 40.33 loamy, 23.53% sandy and 22.89 % coarse-grain) and 323K (82.13% clay, 78.45% loamy, 52.50% sandy and 53.60% coarse-grain) compared to WCS at 323K (66.28% clay, 64.67% loamy, 58.92% sandy and 56.61% coarse-grain) using the same air stripping technique. The result identifies the extent which remediation objectives were achieved for PCS and WCS using soil column air stripper. The VOCs removal efficiency for the experiment records the highest with 82.13% followed by 78.45% of PCS and least with 22.89%. The VOCs removal efficiencies were higher in PCS at 50^{O}C and WCS at 50^{O}C because the VOCs have similar physicochemical properties while WCS increase in temperature causes a decrease in the solubility of VOCs in soil and increases Henry's coefficient and hence improves removal efficiency [20, 29]. The decrease in the solubility of VOCs in soil as the temperature increases can be explained using the second law of thermodynamics. Heating the soil enables the particles of gas to move more freely between the soil

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and the gas phase. The second law predicts that they will shift to the more disordered; more highly dispersed, and therefore more probably gas state. This leads to an increase in Henry's coefficient and hence improves removal efficiency as indicated in PCS and WCS respectively. The results presented in Figure 5 was successfully used to investigate the performance of SCAS during air stripping process as the most promising and preferred method currently for remediating VOCs and petroleum hydrocarbons from soils. To predict soil treatment cost, the best type of air stripper that can be used to evaluate the cost and performance of SCAS facility.

4.4 Optimization of soil column air stripper

4.4.1 Matlab experimental analysis

The simulation of SCAS device investigate the effects of varying: airflow rate, air-to-soil rate temperature, column height, column diameter, Henry's constant and the surface response plot for VOCs removal efficiency against each variable. This study focuses on the interactive effect of air flow rate, air-soil ratio and temperature on VOCs removal from PCS. The VOCs removal is used to evaluate the efficiency of the stripping device at the temperature range of 283 - 323K, air-to-soil ratios of 0.2 – 1.0 and airflow rate of 2.0 -10 l/min for various combinations that affect VOCs removal and indicates that soil column air stripper is more effective in VOCs removal (Tables 15, 16 and 17)

a). VOCs removal efficiency

For a pilot air stripping operation, the air flow is two times the theoretical minimum air flow to ensure sufficient driving force for mass transfer. The assumptions and process conditions is shown in Figure 14

Table 14: Effect of different temperatures and air-to-soil flow rates on removal efficiencies

G/S	0.2	0.3	0.4	0.5	0.6	0.7	0/8	0.9	1.0
283K	99.0051	99.0112	99.0218	99.0325	99.0455	99.0567	99.0672	99.0785	99.0833
293K	99.0974	99.3612	99.5219	99.6253	99.6953	99.7447	99.7808	99.8078	99.8287
303K	99.9357	99.9505	99.9600	99.9664	99.9709	99.9742	99.9767	99.9787	99.9802
313K	99.9948	99.9956	99.9962	99.9966	99.9969	99.9971	99.9973	99.9974	99.9976
323K	99.9995	99.9996	99.9996	99.9996	99.9996	99.9997	99.9997	99.9997	99.9997

The performance and accuracy of this model depends on how close the predicted results are to the practical results. The optimization data showed a good prediction of VOCs removal efficiency. The results in Table 13 showed that over 99% VOCs removal efficiencies were obtained for all the combinations of temperature and air-to-soil ratios.

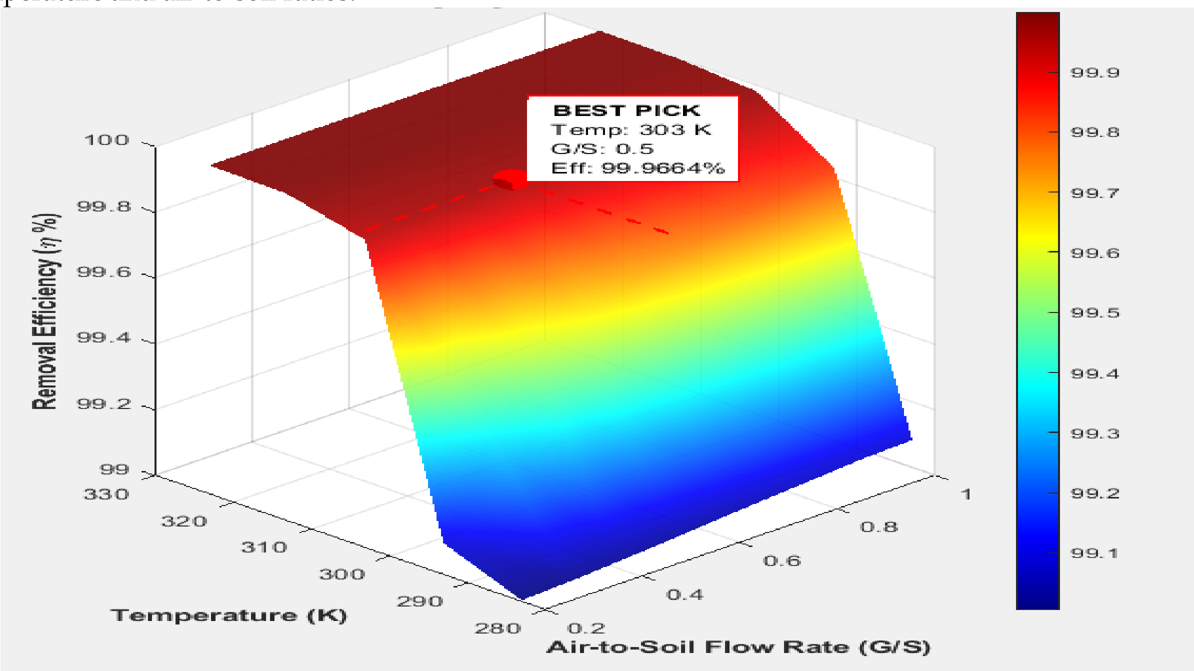

Figure 8: VOCs removal efficiency surface plot as temperature and air-to-soil ratios increases

Figure 8 shows that the removal efficiency of 99.0051% and 99.9997 % were obtained for G/S ratio of 0.2 at 283K and 1.0 at 323K respectively. More also, a very high VOCs removal efficiencies of over 99% were obtained for VOCs removal using soil column air stripper device as shown in Figure 8. The results demonstrated that VOCs removal efficiency increases with increase in temperature for all air-to-soil ratios [30, 31]. The effectiveness of soil column air stripper was evaluated by progressive increase in the VOCs removal efficiency for all combination of temperature and air-to-soil ratios. The temperature change at higher temperature range in the VOCs stripping but it does not significantly influence the stripping efficiency. This situation occurred because the optimum removal efficiency is reached due to the combined effect of high temperature and high air-to-soil ratio [31].

b). Influence of air-to-soil ratio

The effects of air-to-soil on VOCs removal efficiency were studied at air-to-soil ratio at all temperatures. The increase in air-to-soil ratio causes a decrease in partial pressure of the solute in the gas phase, decreases its solubility and improves its removal efficiency as shown in Table 15 and Figure 9

Table 15: Effect of air-to-soil ratios and temperature on stripping factor of VOCs

G/S	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
283K	1.01	1.13	1.25	1.36	1.47	1.56	1.61	1.65	1.69
293K	1.71	1.88	2.06	2.23	2.40	2.57	2.74	2.91	3.08
303K	2.77	3.05	3.32	3.60	3.88	4.16	4.43	4.71	4.99
313K	4.34	4.78	5.21	5.65	6.08	6.52	6.95	7.38	7.82
323K	6.62	7.28	7.95	8.61	9.27	9.93	10.60	11.26	11.92

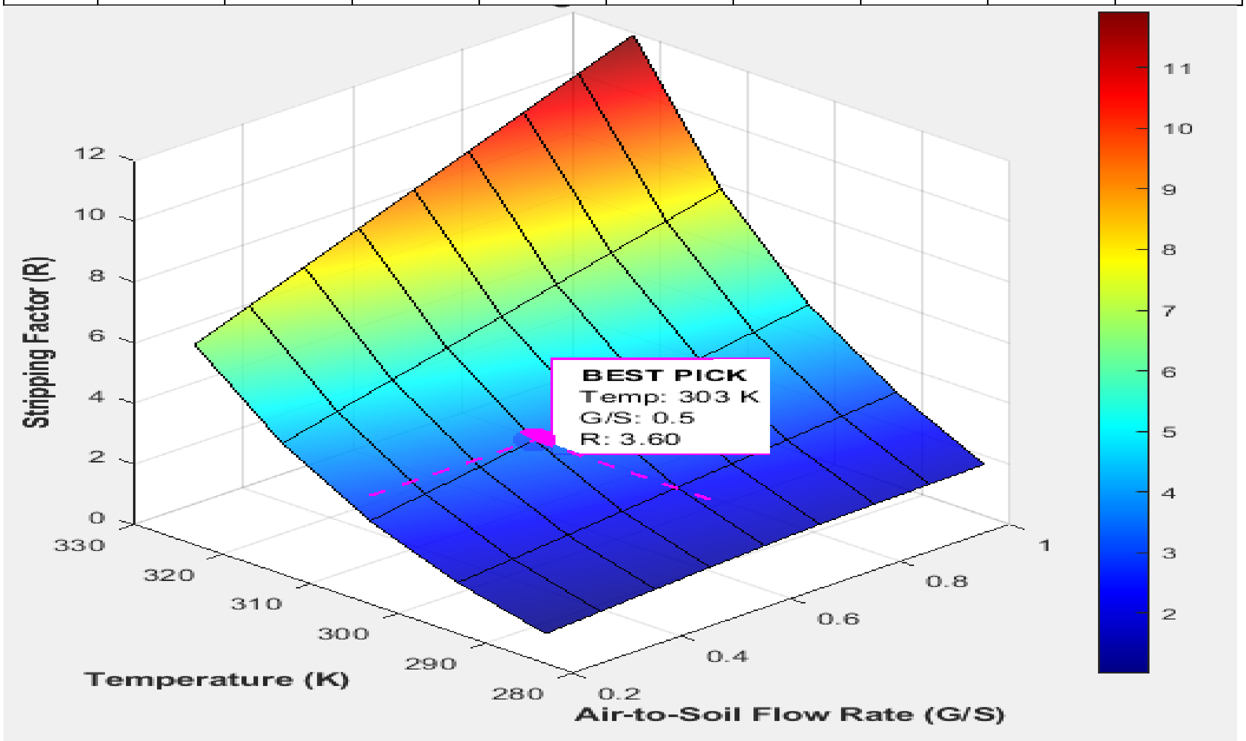

Figure 9: Stripping factor response plot on VOCs removal efficiency for air-to-soil ratio and temperature

Figure 9 shows the trend of removal efficiencies of VOCs at different air-to-soil ratios and temperatures. At any given temperature, increase in air-to-soil ratios results in higher VOCs removal efficiency. This is because, increase in air flow rate increases the interfacial area, decreases gases phase resistance and hence increase the mass transfer efficiency [32]. The result shows the trend that becomes less significant at high temperatures that falls at 303K to 323K where the difference in VOCs removal rate under different air-to-soil ratios becomes smaller. At these conditions, the maximum VOCs removal efficiency is reached because the combined effect of high temperature and high air-to-soil ratio which accelerate the mass transfer of VOCs between the solid and the gas phase [31, 32].

c) Influence of Henry constant

The percentages of VOCs removed during the experiments were verified and the trend shows a decrease in the influent VOCs concentrations over time, which is most likely a result of the treatment in petroleum contaminated soils and the off gases discharged at the exist point. The VOCs concentrations for subsequent trials were tested to determine the VOCs removals level as a function of their Henry's constant despite increase in airflow rate for all combination and hence the removal efficiency as temperature is elevated from 283K to 323K is presented in Table 16 while the surface response plot in Figure 10

Table 16: Effect of Henry constant and air flow rate on VOCs Removal efficiencies

Henry constant	0.01	0.15	0.30	0.45	0.60	0.75	0.90	1.05	1.20
283K	98.9061	98.9129	98.9229	98.9466	99.0455	98.9577	98.9682	98.9795	98.9843

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293K	98.9984	99.2619	99.4224	99.5258	99.5957	99.6451	99.6811	99.7081	99.7290
303K	99.8359	99.8506	99.8601	99.8663	99.8669	99.8742	99.8767	99.8787	99.8802
313K	99.8948	99.8956	99.8962	99.8966	99.8974	99.8971	99.8973	99.8974	99.8976
323K	99.8995	99.8996	99.8996	99.8996	99.8996	99.8997	99.8997	99.8974	99.8997

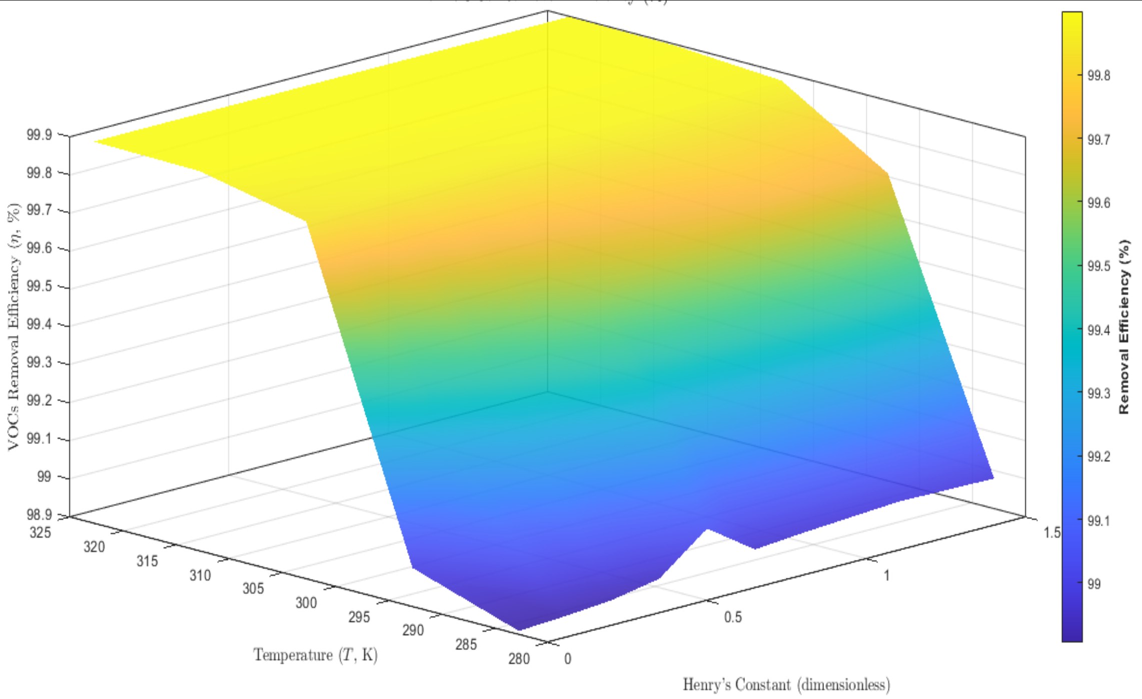

Figure 10: Henry's constant response plot on VOCs removal efficiency for air-to-soil ratio and temperature

Table 16 showed the influence of temperature on VOCs concentration and Henry's constant on VOCs removal efficiency was considered within a temperature range of 283-323K at a fixed airflow rate. This indicates that a high removal of VOCs can be achieved by operating the SCAS at high temperature condition even at a relatively lower air-to-soil ratio. This applies to high percentage removal that can also be achieved by stripping at high air-to-soil ratio even at a relatively lower temperature.

d) Influence of temperature

From Table 18, increasing the operating temperature from 283 to 323 K resulted in a steady increase in both the VOCs concentration and Henry's constant respectively. The VOCs concentration decreased from 211.95 mg/kg at 283 K to 52.06 mg/kg at 323 K, representing a decrease of approximately 75.44%. This improvement indicates that higher temperatures enhance the rate at which VOCs are transferred from the contaminated soil (aqueous phase) into the stripping air [33]. The increase is primarily due to enhanced molecular diffusion, reduced liquid viscosity, and greater kinetic energy of the VOCs molecules, all of which reduce resistance to mass transfer. Furthermore, Henry's constant increased substantially from 0.004 at 283 K to 0.74 at 323 K, corresponding to an increase of approximately 99.46%. This trend indicates that VOCs becomes increasingly volatile as temperature rises. This implies that elevated temperatures improve the stripping efficiency by facilitating VOCs desorption from soil matrix (Table 17)

Table 17: Change in VOCs concentration and Henry's constant with temperature

Temperature (K)	283	293	303	313	323
VOCs concentration mg/kg	211.95	167.04	116.53	72.03	52.06
Henry's constant (dimensionless)	0.004	0.22	0.38	0.55	0.74

The results also showed that at high temperature, an equilibrium removal efficiency of over 99% is reached and further increase in temperature gives no significant change in removal efficiency. The removal efficiency increases with increase in temperature at all Henry's constant. This is because an increase in temperature causes a decrease in the solubility of VOCs in soil spore and increases Henry's coefficient as shown in Table 11 and hence improves removal efficiency [31].

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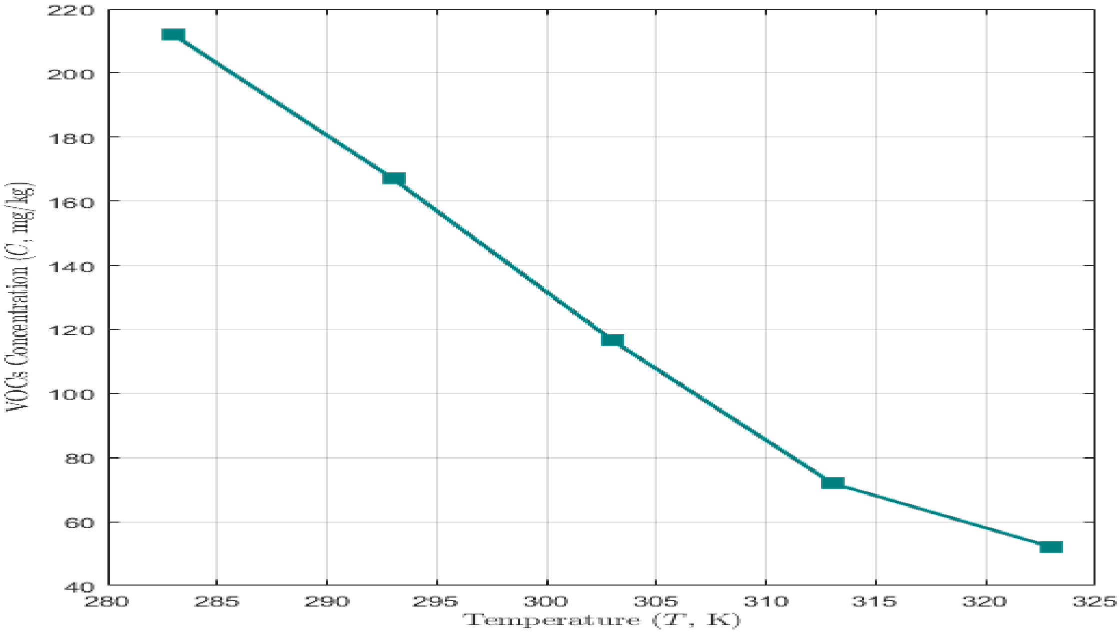

Figure 11: Effect of temperature on VOCs concentration

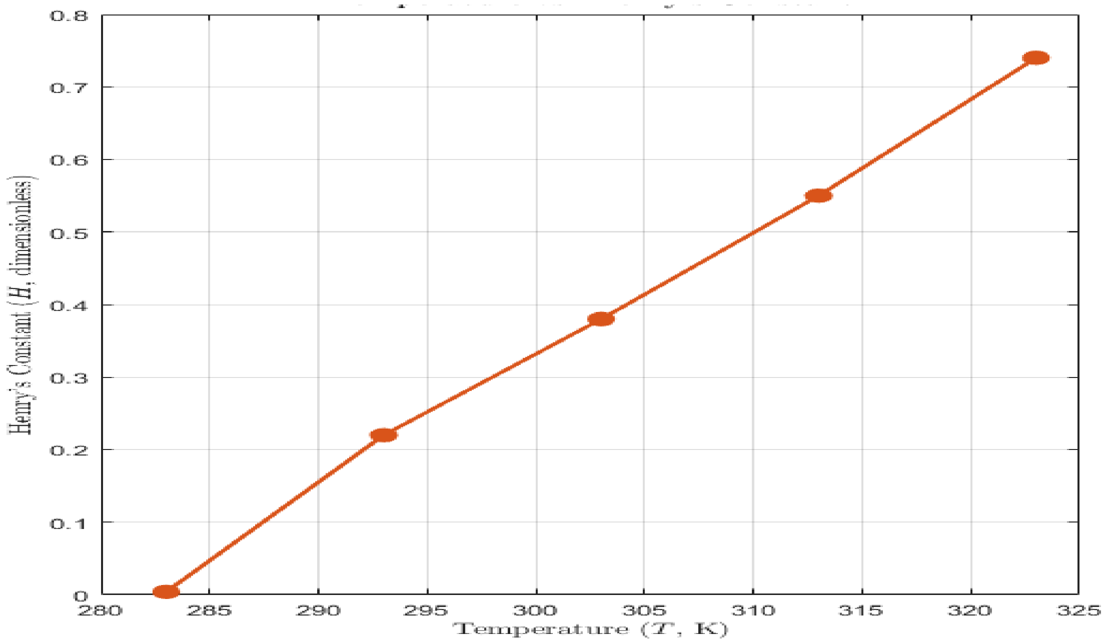

Figure 12: Effect of temperature on Henry's constant for VOCs

Figure 11 shows the relationship between temperature and Henry's constant. The results show a continuously increasing curve, confirming a strong positive correlation between these two variables. The increase is not perfectly linear but becomes steeper at higher temperatures, suggesting that the volatility of VOCs increases more rapidly as temperature rises. This behaviour agrees with thermodynamic principles, where increasing temperature raises the vapour pressure of VOCs, thereby increasing their Henry's constants [31, 33]. The observed trend confirms that temperature is one of the most influential operating parameters governing air-stripping performance.

Figure 12 predicts the effect of influent concentration in petroleum contaminated soil during treatment. As the VOCs concentration decreases progressively, elevating the temperature enhances VOCs removal by accelerating the transport of VOCs molecule from soil phase into the air phase. This implies, increasing the temperature from 283 to 323K leads to shorter treatment times and higher overall removal efficiencies. However, higher temperatures improve process performance, practical operation required additional energy consumption and operating costs associated with heating the contaminated soil. Therefore, selecting an optimum operating temperature is essential to balance removal efficiency with economic feasibility. It can be observed that Figures 11 and 12 represents the effect of temperature on VOCs concentrations and Henry's constant for treatment of petroleum contaminated soil under operating

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conditions. The result indicates that air stripping of VOCs from soil is most dependent on temperature and moderately on airflow rate and air-to-soil ratio.

4.4.2 Comparison between experimental and predictive design results

When comparing the experimental to predictive design models, shows a deviations in the application of the operating parameters, this demonstrate a real operational challenges in the removal efficiency, residual VOCs concentrations, air-to-soil ratio and temperature. Table 18 is the summary presentation of experimental results to predictive model.

Table 18: Variation in results obtained from experimental and predictive design

Sn	Parameters variables	Experimental results	Predictive design model
1	Removal efficiency	22.89 – 82.13%	> 99%
2	Residual VOCs concentrations	12.30 - 65.53 mg/kg (>5.00mg/kg)	< 1.0 mg/kg (<5.00mg/kg)
3	Air-to-soil ratio	High air-to-soil ratio can cause pressure drops, channeling and alters the matrix	Linear increase in VOCs recovery as air-to-soil ratio rises
4	Temperature effects	Preheated air at 45°C can boost the VOCs recovery up to 90%.	This predicts an exponential increase in Henry's constant with temperature increase

Table 18 provides a highlight experimental to predictive results as its affect the operation of soil column air stripper. The air stripper device determines the optimal VOCs removal efficiency, air-to-soil ratio and blower capacity needed to transfer VOCs from soil to air under a prescript process condition. This prevents flooding within the column and ensures compliance with soil treatment condition and off-gas regulations [31, 33].

4.5 Cost estimate

The financial capital required to execute this pilot project was originally planned for treatment of petroleum contaminated soils using soil column air stripper. The pilot scale test used in evaluating the stripping facility in Table 19 showed a bill of engineering, measurement and evaluation (BEME) for soil column air stripper facility. The viability of this project is verify using the unit cost to ascertain whether the project is a good investment and this will make a good profit margin with BEM

Table 19: BEME for design and fabrication of SCAS system

S/N	Items	Specifications	Quantity	Rate (N)	Cost (N)
1	Carbon steel	300 mm x 400 mm	1	35, 000	35, 000
2	Pipe	100 × 4 m	2	5, 000	10, 000
3	Valves		1	600	600
4	Air blower/		1	75, 000	75, 000
5	Bolts and nuts		30	60	1, 800
6	Digital thermometer		1	8,000	8, 000
7	Thermocouple		1	10, 000	10, 000
8	Pressure gauge		1	5, 000	5, 000
9	Hot coil plate		1	3, 000	3, 000
10	Electrical cable		25 yards	1400	35,000
11	Switches		1	500	500
12	Fuse		2	500	1,000
13	Paints		1	2,000	2, 000
14	Labour cost		5 Months	8,000	80,000
15	Miscellaneous				30,000
	Total				296,900.00

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Table 20: Estimated cost for selling SCAS facility

Cost Element	Itemization	Cost (₦)
Estimated cost for assembling SCAS and auxiliary equipment	-	296,900
Contingency	10%	29,690
Contractor's fees and startup	25%	74,230
Total capital cost		400,820.00

Table 21: Estimated annual cost for operating SCAS system

Sn	Category	Estimated Units	Estimated Cost (₦)
1.	Cost of surfactant	1g commercial grade (SDS)	25,500/yr
2.	Labour	-	
I	Operator	< 8 hours/wk	-
Ii	Engineering startup	32 hours/yr	180,000/yr
3	Electricity	5 HP	60,000/yr
I	Chemical analysis	-	-
Ii	Before remediation	12 samples	240,000/yr
Iii	After remediation	16 samples	320,000/yr
	Maintenance	Varies	60,000/yr
	Total Annual Cost		885,000/yr

Table 22: Estimated life-cycle costs for SCAS system

Sn	Category	Estimated Cost (₦)
1	Estimated capital cost	400,820.00
2	Annual cost (30 years)	26,550,000
3	30-year life-cycle costs	26,550,000
4	30-year life-cycle costs (discounted at 5%)	1, 327,500

Tables 19 to 22 revealed that air stripping technique is considered as relatively inexpensive remedial technology compared to other options. The cumulative sum of ₦ 296,900.00 used to develop SCAS system while the selling price of ₦ 400,820.00 which include contingency, contractor's fees and startup were incorporated prior to installation. The annual operational cost of ₦ 885,000/year was achieved without stress, because of availability of manpower. The result provides the basis for this study and it is expected to be fully recovered at the end of the project life. Furthermore, the economic implication provides clear picture about the cost of producing locally made SCAS system at ₦400, 820. 00. The internal rate of return is greater than the hurdle rate while the profitability index is greater 1; this implies that the project is accepted and economically viable. The addition of 25% margin to the total design cost is expected to generate a total sum of ₦ 101, 245. 67 as an annual profit for a period of 12 years, 7 months. When comparing soil column air stripper with other soil remediation technique, the technology is considered to be cheaper and reliable with the best performance when it comes to VOCs removal from soil. The comparison between soil column and other types of air strippers is shown in Table 23.

Table 23: Cost estimates of the locally made soil column over other types of air strippers

Types of air stripper	Estimated cost (N)	Total cost (N)	Selling cost (N)	Duration
Soil column air stripper	296, 900	400, 800	450, 000	Short
Packed column air stripper	1, 652, 800	2, 205, 000	2, 425, 000	Short
Fluidized bed reactor	2, 262, 500	3, 011, 700	4, 116, 700	Short
Excavator	9, 337, 500	12, 450, 000	17,950, 000	Short
Bioremediation	1, 687, 500	2, 250, 000	2, 500, 000	Long

The SCAS was found to be a very economical and efficient for VOCs removal. The new technology is simple, inexpensive to install and has low maintenance requirements based on the economic standpoint. The cost price for selling soil column air stripper is about ₦450,000.00 which is still cheaper compared to other commercial air stripper sold at ₦ 30, 000,000 ($60,000) [34]. The expect payoff provide a cost-effective

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way of dealing with petroleum contaminated soil using SCAS device which employed some treatment parameters to enhance the performance of SCAS device for soil remediation project. Large savings will accrue from the use of this locally SCAS device. Table 22 revealed the economic benefits the locally made SCAS device offers including high operational reliability. The absence of packing and internal components minimizes the likelihood of process interruptions caused by clogging or fouling, allowing the system to maintain consistent VOCs removal performance under varying operating conditions. This study evaluated the performance of SCAS device for the removal of VOCs from PCS and WCS, with emphasis on process optimization, VOCs removal efficiency, operational reliability, and economic feasibility. The SCAS facility offers significant financial advantages over packed column, fluidized bed, tray column, spray column and other convectional air strippers. The elimination of packing materials substantially reduces the costs of selling SCAS at the international market at N 30, 000,000 ($60,000) to N450, 000 ($900) , resulting in capital cost savings of approximately 98.5% compared with conventional air stripper sold at the market (assumed N500/dollar). The operating costs reduced to N 885,000/yr at lower pressure drops of 12.3 N/m2 (93.85%) and this requires less maintenance and consumes less energy during operation. These reductions in locally made SCAS device observed in Tables 19 to 23 can translate into lifetime savings in several thousand of US dollars. The lower overall life-cycle cost observed in Table 21 with SCAS device become economical and attractive option, for developing country like Nigeria that require small-medium scale remediation projects with low finance.

5.0 Conclusions

This study successfully evaluated the performance of locally made SCAS device for the remediation of hydrocarbons contaminant from petroleum contaminated soils through process simulation and optimization. The results demonstrated that the stripping performance of the unpacked air stripper is significantly influenced by elevating the temperature from 283 K to 323 K after 1 hour of air stripping. However, as the temperature increases, the performance of SCAS increases with VOCs removal efficiency from 40.33 to 82.13% while the treatment times was reduced, this enhances VOCs volatilization and reduce VOCs concentration level within the treatment system. The simulation findings using MATLAB design model indicate that SCAS device achieved over 99% VOCs removal efficiencies for all combinations of temperature, airflow rate and air-to-soil ratio while maintaining stable and consistent operation across a range of operating conditions. Temperature effect is more dominant than the effect of airflow rate and air-to-soil ratio resulting in improved removal efficiency by SCAS device. The modification of SCAS device with preheated air can be introduced as a promising approach that promote greater gas–solid contact, thereby improving stripping efficiency and overall process performance.

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