

Determination of Vibration Effect on Removal of Volatile Aromatic Hydrocarbons (VAHs) from Groundwater Using Steam Injection

OLADEJO A. O.¹, ADEGBOLA A. A.², BADMUS S. A.³, ABIOYE A. I.⁴

^{1, 2, 3, 4} Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria

Abstract- Groundwater contamination by petroleum-derived volatile aromatic hydrocarbons (VAHs) specifically benzene, toluene, ethylbenzene, and xylene isomers, poses severe health and environmental hazards due to their toxicity and mobility. Traditional thermal remediation via static steam injection is often limited by capillary forces that trap non-aqueous phase liquids (NAPLs) within porous media. This study investigated the removal of VAHs from contaminated groundwater using steam injection coupled with mechanical vibration. Contaminated groundwater samples collected from Olopemmarun (Well 1) and Aje-Iya (Well 2) in Ogbomoso South, Nigeria, were treated in a bench-scale sandbox model. Gas Chromatography with Flame Ionization Detection (GC-FID) established baseline total VAH concentrations of 120.36 µg/L in Well 1 and 141.20 µg/L in Well 2. Baseline benzene levels (15.95–18.40 µg/L) exceeded the 10.0 µg/L safety limit set by the World Health Organization (WHO) and Standards Organization of Nigeria (SON). Evaluating steam injection only (140°C, 2.4 bar, 0.01 cm³/s, 60 min, 0 Hz) yielded a low total VAH removal efficiency of approximately 25%, with less than 9% of benzene removed. Conversely, evaluating varying vibration frequencies revealed that applying mechanical vibration ($A = 1.0$ mm) at 3.375 Hz increased total mass removal to 70.18–70.75%, reducing benzene below 10.0 µg/L (7.80–8.90 µg/L). Elevating vibration frequency to 6.750 Hz achieved over 95% total mass removal and reduced residual benzene to highly safe limits of 1.25–1.40 µg/L. These findings demonstrate that varying mechanical vibration frequencies successfully overcome capillary trapping during steam injection, ensuring compliance with potable water standards. The experiment carried out showed that the combined application of steam injection with vibration appreciably enhances groundwater remediation.

Keywords: Benzene, Groundwater remediation, Mechanical vibration, Steam injection, Volatile aromatic hydrocarbons

I. INTRODUCTION

Water is one of the most important natural resources abundant, but not always available in the right place, at the right time, or in the right quality (WHO, 2022). Water contains simple molecules, consisting of two hydrogen atoms attached to an oxygen atom, its simplicity belies the complexity of its properties, and these properties seem to fit the requirements of all life, as no other matter can replace it (Chaplin, 2021). Our planet is covered with about 71% water, of which about 97% is in oceans, leaving only 3% as fresh water. Of this available 3% of freshwater, an estimated 68.7% is locked up in ice caps and glaciers, and almost all the remaining freshwater is below ground (UNESCO, 2022).

Groundwater is of major importance to civilization because it is the largest reserve of drinkable water in regions where humans can live. Groundwater is water below the ground surface that saturates pore space in the subsurface, it may appear at the surface as springs or be tapped by wells, and it is often preferable because it tends to be less contaminated by waste and organisms (Mukherjee *et al.*, 2021). About 40% to 50% of drinking water withdrawn globally comes from groundwater; in many regions, almost the entire rural population depends on it for domestic needs (Pointet, 2022).

Groundwater pollution deteriorates the physical, chemical, and biological properties of water (Lapworth *et al.*, 2022). Groundwater can be contaminated in different ways by different sources, including natural sources, septic systems, improper disposal of hazardous waste, landfills and impoundments, sewers, pipelines, fertilizer use, drainage wells, injection floor drains, mining

activities, and spills from stored chemicals and petroleum products such as Non-Aqueous Phase Liquids (Mukherjee *et al.*, 2021). Non-Aqueous Phase Liquids (NAPLs) are liquid contaminant solutions that do not dissolve easily in or mix with water, and they contaminate soil and groundwater. They are classified into Dense Non-Aqueous Phase Liquids (DNAPLs) and Light Non-Aqueous Phase Liquids (LNAPLs) (Suthersan *et al.*, 2022). LNAPLs are less dense than water; when spilled, they infiltrate the subsurface into the saturated zone where they pool and spread atop the groundwater table. Examples include gasoline, benzene, toluene, ethylbenzene, xylenes, mesitylene, and related fuel hydrocarbons (Chen *et al.*, 2022).

Fuel compounds such as benzene, toluene, ethylbenzene, and xylene are well-known pollutants that may cause serious environmental and health issues if not removed from the water before use. Volatile aromatic hydrocarbons are highly mobile and soluble in groundwater and are strictly regulated at low microgram-per-liter thresholds in drinking water standards (Environment and Climate Change Canada [ECCC], 2024). Over the last few decades, their removal has become a primary focus as they are toxic and carcinogenic even at low concentrations (Chen *et al.*, 2022). The Environmental Protection Agency (EPA) and the International Agency for Research on Cancer (IARC) categorize them as a hazard to humans (Hua *et al.*, 2023). Exposure to toxicant pollution causes immense health impacts such as physical and mental disorders, organ dysfunction, neurological disorders, cancer, reduced life expectancy, weakening of the body's immune system, and, in some cases, death. Benzene, in particular, is categorized as a known Group 1 human carcinogen associated with leukemia, hematological disorders, and aplastic anemia, whereas toluene, ethylbenzene, and the xylene isomers exhibit substantial systemic toxicity (Pratama *et al.*, 2023).

Many remediation technologies can be used to remediate groundwater. Thermally enhanced remediation technologies show promise for removing contaminants at contaminated sites (Helmig *et al.*, 2023). Many researchers have utilized steam injection techniques to separate and recover NAPLs from water, making the method widely adopted (Murugan *et al.*, 2022). Steam Injection (S.I.) involves an injection of

steam into injection wells and the recovery of mobilized groundwater, contaminants, and vapor from the recovery wells. When steam is injected into the subsurface, it gives up its latent heat of vaporization to the soil, groundwater, and the contaminant, thereby sweeping the contaminant vapor from the soil and bringing it to the surface via the extraction well or port (Schmidt *et al.*, 2002). This study aims to address this problem through the following specific objectives: Determine the baseline concentrations of volatile aromatic hydrocarbons in groundwater samples using chromatographic analysis, benchmarking initial contamination levels against national and international (WHO) drinking water standards. Determine the effect of steam injection only on volatile aromatic hydrocarbon removal from groundwater. Determine the effect of varying vibration frequency and amplitude on the removal of volatile aromatic hydrocarbons in groundwater using steam injection.

II. LITERATURE REVIEW

Groundwater can be polluted through landfill seepage, discharge of industrial waste into soil, percolation of contaminated water into soil, rupture of underground storage tanks, and excessive application of pesticides, herbicides, and fertilizers (Masood, 2005). Chemical substances are the major causes of soil and groundwater pollution, including petroleum hydrocarbons, heavy metals, solvents, and Non-Aqueous Phase Liquids (Mukherjee *et al.*, 2021). Non-Aqueous Phase Liquids (NAPLs) are liquid contaminants that do not dissolve easily in or mix with water; they contaminate soil and groundwater and are classified as Dense Non-Aqueous Phase Liquids (DNAPLs) or Light Non-Aqueous Phase Liquids (LNAPLs). Dense non-aqueous phase liquids are denser than water and have limited, variable solubility in water; thus, they occur in separate layers in the subsurface (Suthersan *et al.*, 2022).

Groundwater remediation is the process of treating polluted soil and groundwater by removing pollutants or converting them into harmless substances (Figure 1) (Raza *et al.*, 2022). Over the past few years, several in situ techniques have been developed to clean up soils contaminated by non-aqueous phase liquids (NAPLs) (Kuppusamy *et al.*, 2024). Existing remediation technologies include vapor extraction,

radio frequency heating, steam stripping (steam injection), and biological, chemical, and physical methods (Qin *et al.*, 2021). Thermal technologies are applied to groundwater to increase the recovery efficiency of volatile and semi-volatile contaminants from the aquifer (Jiang *et al.*, 2022). Thermal treatment includes the use of electrical resistance heating, steam-enhanced extraction, conductive heating, radio-frequency heating, and vitrification technologies (Gao *et al.*, 2023; Zheng *et al.*, 2022). The two major remediation techniques are ex-situ and in-situ technologies.

Challenges and Limitations

This research work investigates the vibration effect on the removal of Volatile Aromatic Hydrocarbons (VAHs) in groundwater using steam injection with vibrational effects. A close look at previous studies shows several key weaknesses. Many past researchers, such as Jacob (2003) and Nor (2015), used computer

simulations and single artificial oils instead of real soil and water from polluted sites. Other studies tested vibration or waves only at normal room temperatures with air stripping (Lie, 2013; Sameer, 2016; Rahman and Foong, 2018), completely ignoring how heat from steam works together with vibration to free trapped oil droplets. Furthermore, while Adegbola *et al.*, (2021) did test steam with vibration in a sandbox, they only measured total petrol as one big group, without checking individual toxic chemicals like benzene, toluene, ethylbenzene, and xylene. Most importantly, none of these past works tested whether adding vibration effects to steam injection can actually clean real contaminated well water down to the strict 10.0 µg/L safety limit set by the World Health Organization (WHO) and Nigerian drinking water standard. Also, this work is experimental-based rather than a theoretical simulation, as done by many other authors.

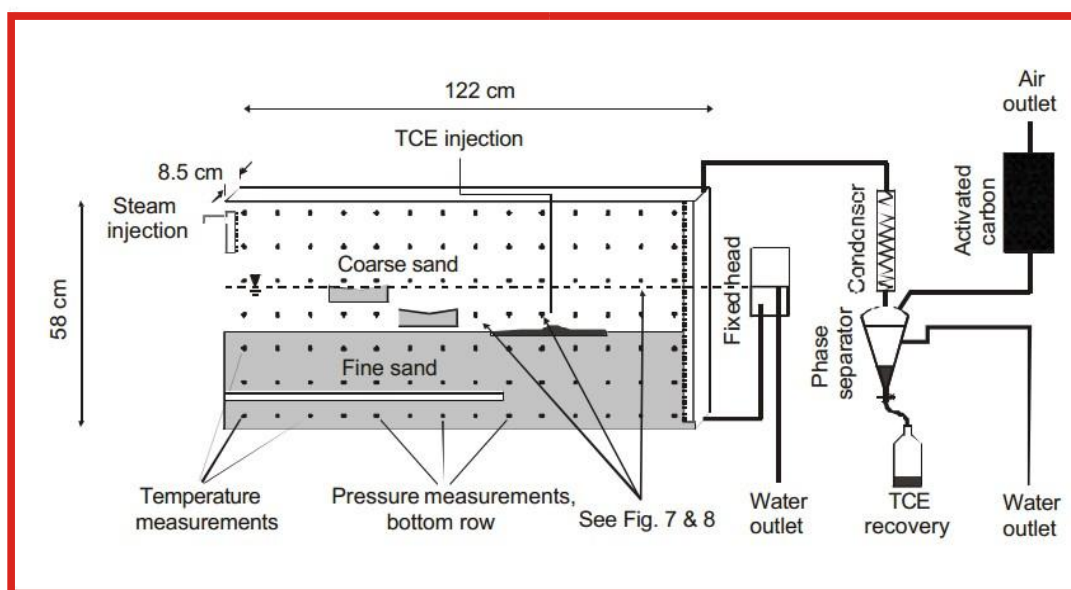


Figure 1: Schematic diagram of experimental setup
Source: Gudbjerg (2003)

III. MATERIALS AND METHODS

The research considered the Ogbomoso South Local Government Area of Oyo State, which is located in southwest Nigeria, West Africa (Bayode *et al.*, 2024). This area is located approximately between latitudes 8° 08' N and 8° 15' N and longitudes 4° 15' E and 4° 19' E (Bayode *et al.*, 2024). The regional climate

yields an average annual precipitation between 1,200 and 1,400 alongside consistent ambient diurnal temperatures ranging from 26°C to 33°C (Ogunkoya *et al.*, 2025). The method of sampling employed is called Discrete Sampling, which was also known as Grab Sampling (Manoj *et al.*, 2018). Samples were collected in an individual container from two existing wells, one at Olopetmarun, latitude 8°07'33" N and

longitude 4°15'48" E, and the other at Aje-Iya, latitude 8°06'55" N and longitude 4°16'12" E. A total of 50 liters of water sample was collected and kept in gallons. These two wells were selected because surface runoff and accidental tank overflow have contributed to persistent fuel hydrocarbon plumes in the shallow aquifer, characterized by a persistent hydrocarbon sheen and volatile aromatic odor. Preservative measures were taken to maintain the integrity of the samples (stored at 4°C) prior to any treatment process. Geotechnical and Soil Testing

The geotechnical test was performed on the soil sample obtained from the study locale in order to determine the identity of the soil samples used in the experiment. Porosity was calculated using macro-porosity and micro-porosity via a volumetric water displacement method (New Jersey Department of Environmental Protection, 2011). Soil permeability was measured by monitoring water flow through a suspended soil core serving as a hydraulic head over a five-minute period to calculate hydraulic conductivity. Moisture content was determined using the oven-drying method of the English Standard Institution (E.S.I), maintaining temperatures at 105°C–110°C for 24 hours (Muhammed *et al.*, 2014). Soil textural determination was done using the hydrometer method (Bouyoucos method), utilizing a 50g oven-dried sample treated with ten percent hydrogen peroxide (Andres *et al.*, 2014). Experimental Setup and Equipment

The bench-scale experiments were conducted using a sandbox model (test chamber of 1180mm × 85mm × 580mm dimension) made of austenitic stainless steel to withstand high heat, and insulated on the outside with fiber materials to prevent heat loss. The chamber was packed evenly with clean sand and granite in 5 cm lifts to achieve a uniform dry bulk density of 1.65 g/cm³ and a porosity of 0.38. A gas-powered steam boiler equipped with a digital temperature measuring device, pressure gauge, and fluid flow-meter was

utilized to supply saturated steam. The extraction port featured a condenser to liquefy the vaporized gas and a phase separator to separate water from non-aqueous materials. For mechanical excitation, an electromechanical vibrational device (1.32W DC electric motor) was mounted on the sandbox, capable of generating variable vibrational frequencies of 3.375 and 6.75 Hz with a controlled peak displacement amplitude of 1.0 mm (Adegbola *et al.*, 2021).

Baseline Concentrations Testing and Standards Comparison

Initial pollution levels were tested for each sample using the collected well water stored at 4°C. 10.0 mL of water was placed into a 20 mL glass vial with 3.0 g of salt to help the gases escape into the air space of the vial. The vials were tightly sealed and heated in an autosampler oven at 80°C for 10 minutes while shaking. The trapped gas was sent into an Agilent 8860 Gas Chromatograph (GC-FID) set at 250°C, utilizing Helium to push the sample through a DB-624 column to separate the chemicals. The initial amounts of benzene, toluene, ethylbenzene, and xylenes (VAHs) were measured from standard curves and compared to the 10 µg/L drinking water limit set by the WHO and SON.

Steam Injection Only Experiment

The effect of steam injection only was tested on each sample in the sandbox model without mechanical vibration and amplitude (0 Hz, A = 0mm) Figure 2. The packed chamber was filled from the top with polluted groundwater, and once fully soaked, it was left to rest for two hours. Steam was heated to 140°C at an operating pressure of 2.4 bar and pumped into the side of the box at a steady flow rate of 0.01 cm³/s. The steam injection ran for 60 minutes, pushing out fluids into a phase separator. Treated water samples were collected and analyzed via GC-FID to establish baseline thermal removal efficiency.

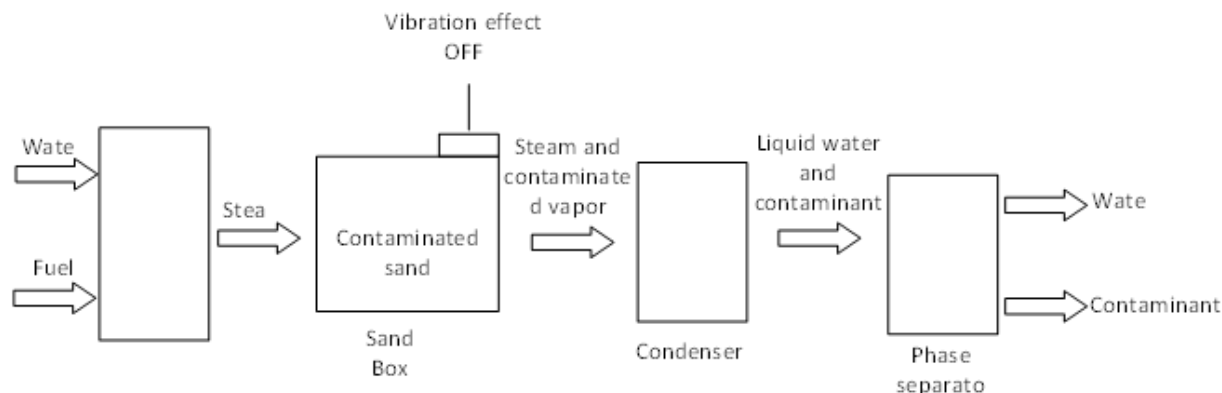


Figure 2: Block Diagram of Experimental Set up of Steam Injection only.

Varying Vibration Frequency and Amplitude Experiment

The combined effect of steam injection and mechanical oscillation was tested using defined vibration frequencies and a calibrated displacement amplitude over the 60-minute injection period. Saturated steam was injected at 140°C, 2.4 bar, and a flow rate of 0.01 cm³/s for 60 minutes across all runs. Vibration was applied at a low frequency of 3.375 Hz with a constant peak displacement amplitude of 1.0

mm ($A = 1.0 \times 10^{-3}$ m), generating a peak oscillatory velocity of 21.2 mm/s. In subsequent runs, the frequency was raised to 6.750 Hz at the same 1.0 mm amplitude, increasing the peak oscillatory velocity to 42.4 mm/s. These settings provided the mechanical shear needed to overcome capillary resistance and trapped hydrocarbon droplets from the pore throats. Post-treatment water samples were collected at the end of each run and analyzed using the GC-FID.

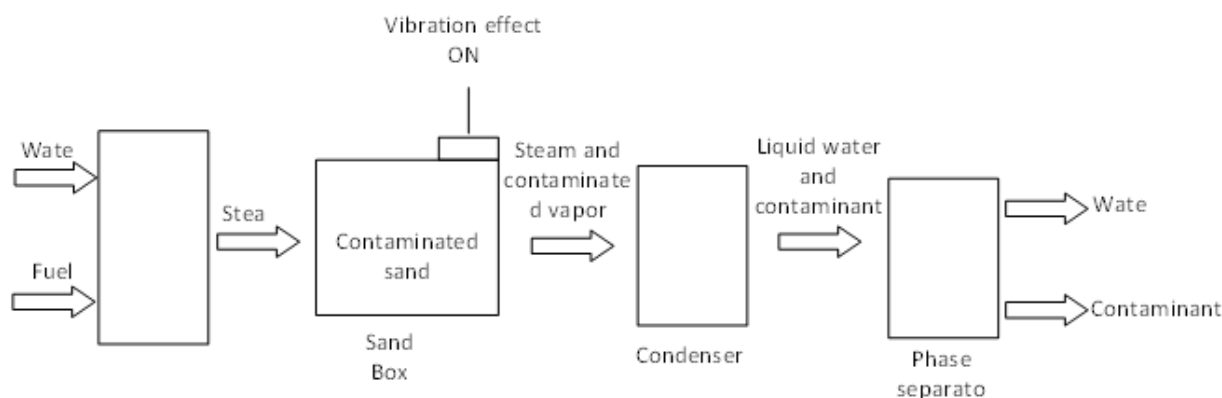


Figure 3: Block Diagram of Experimental Setup of Steam Injection with Vibration Effect.

Procedure for Data Analysis

The following tools, such as effectiveness, process synergy ratio, and relative process effectiveness, will be employed in analyzing the data for this study.

a. Effectiveness of the steam injection

The effectiveness of the steam injection remediation process at pre-treatment and post-treatment, respectively, was evaluated using equation (3.1) Muhibu-din and Ayodele (2021).

$$\eta = \frac{C_o - C_f}{C_o} \times 100\% \quad (3.1)$$

Where;

η is the Effectiveness

C_o is the amount of VAHS in pre-treatment

C_f is the amount of VAHS in post-treatment

$$\eta = (C_o - C_f) / C_o \times 100\%$$

η

=

$$\frac{\text{Amount of BTEX in Pre tretment} - \text{Amount of BTEX in post treatment}}{\text{Amount of BTEX in Pre-treatment}} \times 100\% \quad (3.2)$$

b. Effectiveness of the steam injection with the vibrational and amplitude effect method

The effectiveness of the steam injection remediating process at different frequencies of 3.75 to 6.75 Hz and amplitude of 1mm, respectively were evaluated using the equation (3.1) Muhibu-din and Ayodele (2021).

IV. RESULT AND DISCUSSION

Soil Geophysical Properties

Geotechnical tests carried out on the soil sample collected from Olopemaranun determined its properties for evaluating the vibrational effects on the removal of VAHs. The average moisture content of the soil was 11.54 percent. The textural analysis determined the percentage of sand, silt, and clay content to be 78.00%, 14.00%, and 8.00%, respectively, which makes the soil samples used to be classified as sand and silt. Permeability tests established a hydraulic conductivity (Kt) of 0.000320 cm/s. Other properties of the soil sample used for the experimental investigation were dry density, bulk density, specific gravity, void ratio, and porosity, which were 1.56 g/cm³, 1.74 g/cm³, 2.65, 0.7, and 41.18%, respectively.

Baseline Contaminant Levels in Groundwater

Table 1: Pre-Treatment Quantitative Analysis of VAHs

Contaminant Parameters	RT (min)	Well 1 C _o (µg/L)	Well 2 C _o (µg/L)	WHO /SON (µg/L)	Well 1 Ratio (µg/L)	Well 2 Ratio (µg/L)	Status
Benzene	5.862	15.95	18.40	10	1.60x	1.84x	Non-Compliant
Toluene	8.658	26.23	31.10	700	Bellow limit	Bellow limit	complaint
Ethyl benzene	10.998	5.97	7.20	300	Bellow limit	Bellow limit	complaint
Meta, Para-Xylene	11.191	11.21	14.50	500	Bellow limit	Bellow limit	complaint
Ortho-Xylene	11.84	61.00	70.00	500	Bellow limit	Bellow limit	complaint
TOTAL	----	120.36	141.20	----	----	---	contaminated

Untreated groundwater samples were collected from the two impacted monitoring locations: Well 1 (Olopemaranun) and Well 2 (Aje-Iya). Table 1 shows that the chromatographic fingerprints revealed the total baseline VAHs concentrations were 120.36 µg/L for Well 1 and 141.20 µg/L for Well 2. Within both water sources, the relative mass distribution was dominated by xylenes (72.21 µg/L in Well 1 and 84.50 µg/L in Well 2), followed by toluene (26.23 µg/L and 31.10 µg/L), benzene (15.95 µg/L and 18.40 µg/L), and ethylbenzene (5.97 µg/L and 7.20 µg/L). When benchmarked against the health-based statutory thresholds set by the World Health Organization (WHO) and the Standards Organization of Nigeria (SON), toluene, ethylbenzene, and total xylenes remained well within their permissible limits of 700 µg/L, 300 µg/L, and 500 µg/L, respectively. In contrast, benzene exceeded the legal potable limit of 10.0 µg/L at both sites. Well 1 recorded a baseline concentration of 15.95 µg/L (1.60x the allowable ceiling), while Well 2 recorded a baseline concentration of 18.40 µg/L (1.84x the allowable ceiling). Because benzene is categorized by the International Agency for Research on Cancer (IARC) as a Group 1 human carcinogen without a safe toxicological threshold, its exceedance renders both groundwater sources unfit for domestic consumption without active remediation.

Steam Injection Only Remediation Performance

The baseline remediation performance of steam injection without mechanical agitation (0 Hz, A = 0 mm) was evaluated during Runs S3 (Well 1) and S4 (Well 2). Under steam injection only in Table 2, total VAHs concentrations declined from 120.36 µg/L to 90.49 µg/L in Well 1 (a mass reduction of 24.82%) and from 141.20 µg/L to 105.80 µg/L in Well 2 (a reduction of 25.07%). Although sensible heating effectively mobilized toluene (66.37% and 63.99% removal), parent benzene was barely reduced, showing marginal stripping efficiencies of only 6.14% (C_f = 14.97 µg/L) and 8.70% (C_f = 16.80 µg/L). Similarly, ethylbenzene showed low stripping rates of

7.20% and 8.33%. Chromatographic analysis of Runs S3 and S4 also revealed an apparent concentration increase in the m,p-xylene peak (from 11.21 µg/L to 24.93 µg/L in Well 1, and from 14.50 µg/L to 27.20 µg/L in Well 2). Higher molecular weight alkylbenzenes volatilized and condensed immediately ahead of the thermal condensation boundary, forming a concentrated organic in the cooler downstream sampling zone. This confirmed that the efficacy of steam injection without vibration effect on VAHs polluted groundwater cannot be satisfactorily effective in the remediation process.

Table2: Analytical VAHs Concentrations and Removal Efficiencies under Steam Injection only

Contaminant parameters	Well 1 C _o (µg/L)	Well 1 S3 C _f (µg/L)	Well 1 η (%)	Well 2 C _o (µg/L)	Well 2 S4 C _f (µg/L)	Well 2 η (%)
Benzene	15.95	14.97	6.14	18.40	16.80	8.70
Toluene	26.23	8.82	66.37	31.10	11.20	63.99
Ethyl benzene	5.97	5.54	7.20	7.20	6.60	8.33
Meta, Para-Xylene	11.21	24.93	-	14.50	27.20	--
Ortho-Xylene	61.00	36.23	40.61	70.00	44.00	37.14
TOTAL	120.36	90.49	24.82	141.20	105.80	25.07

Effect of Vibration Frequency on Contaminant Mobilization

To overcome capillary retention, mechanical vibration was coupled with steam injection across two dynamic operations at a constant peak displacement amplitude of 1.0 mm (A = 1.0 x 10⁻³ m) in Table 3. Low Frequency Operation (3.375 Hz): At low frequency (implemented in Run S5 for Well 1 and Run S6 for Well 2), an induced oscillatory velocity of 21.2 mm/s was generated. Mechanical vibration enabled the system to meet drinking water quality targets. Residual benzene concentrations dropped to 7.80 µg/L in Well 1 (51.10% removal) and 8.90 µg/L in Well 2 (51.63% removal). These values met the 10.0 µg/L WHO and SON standards, confirming initial regulatory compliance. The total VAHs removal increased from 25% at baseline steam to 70.75% in Well 1 (C_f = 35.20 µg/L) and 70.18% in Well 2 (C_f = 42.10 µg/L). High Frequency Operation (6.750 Hz):

At high frequency (implemented in Run S7 for Well 1 and Run S8 for Well 2), an induced oscillatory velocity of 42.4 mm/s was generated. Doubling the frequency to 6.750 Hz increased total mass extraction to 95.11% in Well 1 (C_f = 5.88 µg/L) and 95.08% in Well 2 (C_f = 6.94 µg/L). Residual benzene concentrations dropped to 1.25 µg/L in Well 1 (92.16% removal) and 1.40 µg/L in Well 2 (92.39% removal). Both water sources reached concentrations well below the 10.0 µg/L health limit, establishing an order-of-magnitude safety factor. Frequency scaling systematically eliminated residual tailing across every compound. Heavier alkylbenzenes such as o-xylene, which showed high residual retention under steam injection alone (36.23 µg/L in S3), dropped to 16.20 µg/L at 3.375 Hz and 2.80 µg/L at 6.750 Hz (95.41% overall removal). Consequently, 6.750 Hz at 1.0 mm amplitude was determined to be the optimal operational regime for site remediation.

Table 3: Analytical VAHs Concentrations and Removal Efficiencies under Dynamic Vibration Excitation (A = 1.0 mm) Injection (0 Hz)

Contaminant parameters	Well 1 C _o (µg/L)	Well 1 S5 (µg/L)	Well 1 S7 (µg/L)	Well 2 C _o (µg/L)	Well 2 S6 (µg/L)	Well 2 S8 (µg/L)
Benzene	15.95	7.80 (51.10%)	1.25 (92.16%)	18.40	8.90 (51.63%)	1.40 (92.39%)
Toluene	26.23	2.90 (88.94%)	0.45 (98.28%)	31.10	3.60 (88.42%)	0.52 (98.33%)
Ethyl benzene	5.97	2.10 (64.82%)	0.38 (93.63%)	7.20	2.50 (65.28%)	0.42 (94.17%)
Meta, Para-Xylene	11.21	6.20 (44.69%)	1.00 (91.08%)	14.50	7.50 (48.28%)	1.20 (91.72%)
Ortho-Xylene	61.00	16.20 (73.44%)	2.80 (95.41%)	70.00	19.60 (72.00%)	3.40 (95.14%)
TOTAL	120.36	35.20 (70.75%)	5.88 (95.11%)	141.20	42.10 (70.18%)	6.94 (95.08%)

V. CONCLUSION

The results obtained from the study revealed that steam injection with vibration effect can be employed to remediate VAHs polluted groundwater. Based on the results addressing objectives one through three, the following conclusions were drawn: Raw groundwater from Well 1 and Well 2 was heavily contaminated with VAHs, recording baseline levels of 120.36 µg/L and 141.20 µg/L. Baseline benzene levels reached 15.95 µg/L and 18.40 µg/L, exceeding the 10.0 µg/L WHO/SON potable ceiling and confirming the water is unsafe for domestic use. The efficacy of steam injection without vibration effect on VAHs polluted groundwater cannot be satisfactorily effective in the remediation process. Adding mechanical vibration eliminated mass-transfer limitations and accelerated hydrocarbon stripping. Operating at 3.375 Hz elevated VAHs removal to approximately 70%. Increasing frequency to 6.750 Hz achieved over 95% total VAHs recovery and reduced benzene to 1.25–1.40 µg/L, well below the safe drinking standard. The vibration effect brings about higher removal of the pollutants compared to using steam injection only.

REFERENCES

- [1] Adegbola, A. A., Olawale, O. A., Ajao, T. O., Oguindele, K. A., and Raheem, R. A. (2021). Experimental approach for removal of petrol from groundwater using steam injection technique with vibration effect. *International Journal of Engineering Applied Sciences and Technology (IJEAST)*, 6(3), 85–98.
- [2] Andres, N. B., Ana, V. S., Leonardo, P., Deborah, T., Daniel, B., Raquel, M., and Andriana, G. L. (2014). Soil texture analyses using a hydrometer: Modification of Bouyoucos method. *Ciencia e Investigacion Agraria*, 41(2), 263–271.
- [3] Bayode, S., Fajemilo, P. T., Sanusi, S. O., and Ojo, B. T. (2024). Evaluation of groundwater potential of Ogbomoso using stepwise weight assessment ratio analysis (SWARA) model. *Arabian Journal of Geosciences*, 17(8), Article 227.
- [4] Chaplin, M. (2021). *Water structure and science: Physical and chemical properties of liquid water*. London South Bank University.
- [5] Chen, X., Zhang, S., Yi, L., Liu, Z., Ye, X., Yu, B., Shi, S., and Lu, X. (2022). Evaluation of biodegradation of BTEX in the subsurface of a petrochemical site near the Yangtze River, China. *International Journal of Environmental Research and Public Health*, 19(24), Article 16449. [MDPI](#)
- [6] Environment and Climate Change Canada (ECCC). (2024). *Federal water quality*

- guidelines: Benzene, toluene, ethylbenzene, and xylene.* Government of Canada.
- [7] Gao, Y., Wang, F., Li, Y., and Zhao, C. (2023). Thermal conduction heating combined with soil vapor extraction for volatile and semi-volatile organic pollutants: Performance and energy metrics. *Chemosphere*, 318, Article 137951.
- [8] Gudbjerg, J. (2003). *Remediation by steam injection* [Ph.D. Thesis]. Technical University of Denmark.
- [9] Helmig, R., Veyskarami, M., and Michalkowski, C. (2023). Multiphase flow dynamics and thermal stimulation during steam injection in permeable formations. *Transport in Porous Media*, 148(2), 389–419.
- [10] Hua, T., Feng, J., Li, S., and Yan, W. (2023). A general review on the application of adsorption and oxidation combined processes on methyl tertbutyl ether removal. *International Journal of Environmental Science and Technology*.
- [11] Jacob, G. (2003). *Remediation by Steam Injection, PhD Thesis, Environmental and Resources DTU*. Technical University of Denmark. pp 137.
- [12] Jiang, Y., Shen, Z., Gu, F., and Al-Tabbaa, A. (2022). A review of in-situ thermal desorption (ISTD) technologies for contaminated site remediation: Engineering fundamentals and field applications. *Journal of Hazardous Materials*, 424, Article 127607.
- [13] Kuppusamy, S., Venkateswarlu, K., and Megharaj, M. (2024). In situ remediation of non-aqueous phase liquids in complex subsurface environments: Advances and future directions. *Critical Reviews in Environmental Science and Technology*, 54(4), 265–291.
- [14] Lapworth, D. J., Boving, T. B., Brauns, B., and Kebede, S. (2022). Groundwater quality and contamination processes: Emerging issues in vulnerable aquifers. *Science of the Total Environment*, 838, Article 156430.
- [15] Lie, S. H. (2013). *The effect of magnetic field on some physical and chemical properties of tap water, domestic storage tank water and groundwater and its utilization in different fields*.
- [16] Manoj, S., Pankaj, K., Kula, K. S., and Ankit, G. (2018). *Study on magnetic materials for removal of water pollutants*.
- [17] Masood, A. (2005). Groundwater pollution: Sources, mechanisms, and prevention. *Environmental Geology Review*, 14(2), 112–124.
- [18] Muhammed, M. A., Mohammed, S. H., Fariborz, M., Heshmatollah, N., Marzieh, F., and Fazel, M. (2014). Toluene removal from sandy soil via in situ technologies with an emphasis on factors influencing soil vapour extraction. *The Science World Journal*, 2014, Article 6.
- [19] Muhibbu-din, E. I., and Ayodele, I. (2021). Application of steam enhance extraction method on VAHS contaminated soil in a Nigerian petroleum depot and automobile workshop sites in Ilorin metropolis, Nigeria. *Environmental Education and Sustainable Development Journal*, 10, 1–6.
- [20] Mukherjee, A., Scanlon, B. R., Aureli, A., Lancia, M., and Guo, H. (Eds.). (2021). *Global groundwater: Source, scarcity, sustainability, and contamination*. Elsevier.
- [21] Murugan, R., Govindarajan, R., and Sundararajan, M. (2022). Dynamic physical excitation and thermal multiphase displacement for subsurface non-aqueous phase liquid recovery. *Journal of Hazardous Materials Advances*, 6, Article 100068.
- [22] New Jersey Department of Environmental Protection. (2011). *Field sampling procedures manual*. Site Remediation Program.
- [23] Nor, F. N. (2015). *Simulation of LNAPL migration and remediate at a petroleum refinery site* [Unpublished Master's project]. University of Technology Malaysia.
- [24] Ogunkoya, C. O., Adabanija, M. A., and Sunmonu, L. A. (2025). Delineation of depth to some aquifers of Ogbomoso, Southwestern Nigeria. *Dutse Journal of Pure and Applied Sciences*, 11(1d), 343–354.
- [25] Pointet, T. (2022). The United Nations World Water Development Report 2022 on groundwater, a synthesis. *LHB: Hydrosience Journal*, 108(1), 2090867. [Taylor & Francis](#)

- [26] Pratama, A. W., Handayani, D., and Mursid, S. (2023). Health risk analysis of benzene, toluene, ethylbenzene, and xylene in groundwater. *IOP Conference Series: Earth and Environmental Science*, 1263(1), Article 012003.
- [27] Qin, C., Zhou, Y., and Li, M. (2021). Remediation of volatile and semi-volatile organic compound-contaminated groundwater: A review of engineering practices and performance evaluation. *Water Research*, 202, Article 117424.
- [28] Rahman, N. A., and Foong, K. C. (2018). Laboratory investigation of LNAPL migration in double-porosity soil under the influence of vibration. *Transport in Porous Media*, 124(1), 231–249.
- [29] Raza, M., Hussain, F., and Lee, J. (2022). Groundwater contamination and treatment technologies: A global perspective on sustainable remediation. *Science of the Total Environment*, 838, Article 156556.
- [30] Sameer, C. (2016). Effects of application of magnetic field on efficiency of petrol engine. *International Research Journal of Engineering and Technology*, 3(9), 152–161.
- [31] Schmidt, R., Gudberg, J., Sonnenborg, T. O., and Jensen, K. H. (2002). Removal of NAPLs from the unsaturated zone using steam: Prevention of downward migration by injecting mixtures of steam and air. *Journal of Contaminant Hydrology*, 55(3-4), 233–260.
- [32] Standards Organization of Nigeria (SON). (2015). *Nigerian Standard for Drinking Water Quality (NIS 554:2015)*. Abuja, Nigeria.
- [33] Suthersan, S., Horst, J., Schnobrich, M., Welty, N., and Caputi, J. (2022). *Remediation engineering: Design concepts* (2nd edition). CRC Press.
- [34] UNESCO. (2022). *The United Nations world water development report 2022: Groundwater: Making the invisible visible*. Paris, UNESCO. [UNESCO](#)
- [35] World Health Organization (WHO). (2022). *Guidelines for drinking-water quality* (4th ed., incorporating the 1st and 2nd addenda). World Health Organization. [WHO](#)
- [36] Zheng, T., Hou, D., Wang, Y., and Al-Tabbaa, A. (2022). Electro-thermal remediation technologies for persistent organic pollutants in groundwater and soil systems: A review. *Environmental Science and Technology*, 56(16), 11112–11128.