

Assessment of Soil Physicochemical Properties and Total Petroleum Hydrocarbon Contamination in Selected Auto-Mechanic Villages in Benin Metropolis

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Research Article

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**ASSESSMENT OF SOIL PHYSICOCHEMICAL PROPERTIES AND TOTAL
PETROLEUM HYDROCARBON CONTAMINATION IN SELECTED AUTO-
MECHANIC VILLAGES IN BENIN METROPOLIS**

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ABSTRACT

Auto-mechanic villages are important sources of petroleum contamination due to the improper disposal of used engine oil, lubricants, fuel residues, and other petroleum-based wastes directly onto surrounding soils. This study evaluated the physicochemical characteristics and total petroleum hydrocarbon (TPH) concentrations of soils from selected auto-mechanic villages in Benin Metropolis. Soil samples were collected at a depth of 0–15 cm from three auto-mechanic locations, Uwelu, Evbareke, and Igun, between February and April 2026. Physicochemical properties were determined using standard analytical methods, while TPH compounds were extracted by Soxhlet extraction and identified and quantified using gas chromatography-mass spectrometry (GC-MS). Mean values of the physicochemical parameters were 27.93 ± 0.404 °C for temperature, 7.48 ± 0.354 for pH, 258.67 ± 57.737 $\mu\text{S}/\text{cm}$ for electrical conductivity, $12.34 \pm 2.414\%$ for moisture, 1705.07 ± 74.481 mg/kg for calcium, 1025.71 ± 159.378 mg/kg for magnesium, $84.10 \pm 5.216\%$ sand, $4.64 \pm 2.578\%$ silt, $11.26 \pm 5.766\%$ clay, 0.93 ± 0.027 g/cm³ bulk density, and $70.57 \pm 3.322\%$ porosity. Significant differences ($p < 0.05$) occurred in pH, sand, and porosity, while silt and clay differed highly significantly ($p < 0.01$) among locations. Sixteen of the 31 investigated TPH congeners were detected, ranging from n-undecane to n-hexacosane. Mean concentrations ranged from 30.990 ± 14.318 to 673.095 ± 34.562 , with n-octadecane recording the highest concentration. Significant spatial differences ($p < 0.05$) occurred for most detected congeners. Principal component analysis extracted six components explaining 96.624% of the total variance, while significant positive correlations among several TPH congeners suggested common lithogenic and anthropogenic sources. Strengthened petroleum waste management, routine monitoring, and appropriate soil remediation are recommended to minimize environmental and health risks.

Keywords: *Auto-mechanic villages; Benin Metropolis; soil contamination; physicochemical properties; total petroleum hydrocarbons; TPH congeners; GC-MS; petroleum waste; principal component analysis; soil pollution.*

INTRODUCTION

Petroleum is a naturally occurring complex mixture of hydrocarbons formed through the decomposition of organic matter under heat and pressure over geological time (Walters, 2017; Liu and Jiang, 2025). It consists mainly of aliphatic and aromatic hydrocarbons, resins, and asphaltenes, which are collectively described as Total Petroleum Hydrocarbons (TPH) (Walters, 2017; Liu and Jiang, 2025). Petroleum products such as gasoline, diesel, kerosene, lubricating and engine oils, hydraulic fluids, and grease are widely used in transportation, energy production, and industrial activities (Aminzadeh and Dasgupta, 2013; Ekejiuba, 2021). Although these products contribute substantially to economic development, their production, transportation, storage, use, and disposal can introduce petroleum-derived contaminants into the environment (Aminzadeh and Dasgupta, 2013; Ekejiuba, 2021).

Nigeria is one of Africa's major petroleum-producing countries and an important crude oil exporter globally (Yakubu, 2017; Melamid, 2018; Oyeranmi and Dube, 2021). Petroleum contributes significantly to national revenue and foreign exchange earnings; however, activities associated with its exploration, refining, transportation, distribution, and consumption have contributed to environmental contamination (Yakubu, 2017; Melamid, 2018; Oyeranmi and Dube, 2021). Oil spills, pipeline leakages, illegal refining, fuel station leakages, and indiscriminate disposal of used lubricants are recognized sources through which petroleum hydrocarbons enter soils and water bodies (Odupitan, 2017; Adeola *et al.*, 2022; Hunter, 2023). Although petroleum pollution has been extensively documented in the Niger Delta, hydrocarbon contamination is also an important concern in urban environments, particularly around areas where automobile repair and maintenance activities are concentrated (Odupitan, 2017; Adeola *et al.*, 2022; Hunter, 2023).

When crude oil or refined petroleum products enter the soil, they can alter its physical, chemical, and biological properties (Udoudo, 2024). Total Petroleum Hydrocarbons comprise several hundred petroleum-derived compounds, including alkanes, cycloalkanes, benzene, toluene, ethylbenzene and xylene (BTEX), as well as polycyclic aromatic hydrocarbons (PAHs) (Odupitan, 2017; Adeola *et al.*, 2022; Hunter, 2023; Udoudo, 2024). The environmental significance of these contaminants varies according to their chemical composition, concentration, persistence, and mobility. Some petroleum constituents are toxic and persistent, with the potential to bioaccumulate and produce adverse ecological effects (Udoudo, 2024).

The rapid expansion of Nigerian cities, increasing vehicle ownership, and growth of informal automobile repair activities have intensified the potential for petroleum contamination of urban soils (Sikakwe *et al.*, 2022; Onyenechere *et al.*, 2022; Oloniyo and Basorun, 2025; Ekwe-Testimony and Chukwura-Osoagba, 2025). Auto-mechanic villages serve as centres for vehicle repairs, servicing, panel beating, battery charging, engine maintenance, and related activities (Lawal, 2022; Ofoezie *et al.*, 2022; Isaiah, 2025). These operations frequently involve the handling of used engine oil, spent lubricants, fuel residues, grease, brake fluids, and transmission oils, which may be discharged directly onto bare ground where adequate waste collection and containment facilities are unavailable (Aliyu and Amadu, 2017; Makanjuola, 2019; Sadiq, 2022). Repeated disposal can result in the accumulation of petroleum hydrocarbons in the soil and prolonged deterioration of environmental quality.

Benin Metropolis has undergone considerable urban expansion accompanied by increasing automobile-related activities and the development of several auto-mechanic villages that provide important employment opportunities while presenting environmental management challenges (John-Abebe and Ajogungbe, 2025; Idebaneria, 2025). The presence of oil-stained soils within

these locations has been associated with prolonged exposure to petroleum-derived substances (Iwuala and Oriaku, 2019; Raji *et al.*, 2021). Continuous discharge of petroleum wastes can facilitate their infiltration into the soil and potentially modify soil structure, nutrient composition, permeability, and microbial activity (John-Abebe and Ajogungbe, 2025; Idebaneria, 2025). Such changes can influence the capacity of soil to support vegetation and maintain essential ecological functions.

Petroleum contamination can increase soil hydrophobicity, reduce porosity and water infiltration, impair fertility, and potentially reduce agricultural productivity where contaminated land is subsequently used for agricultural or residential purposes (Sikakwe *et al.*, 2022; Onyenechere *et al.*, 2022; Oloniyo and Basorun, 2025; Ekwe-Testimony and Chukwura-Osoagba, 2025). Hydrocarbon contamination may also affect microbial diversity and enzymatic activities involved in nutrient cycling, thereby disrupting important soil processes (Yakubu, 2017; Melamid, 2018; Oyeranmi and Dube, 2021). In addition to ecological effects, petroleum-contaminated soils may create exposure pathways for humans through dermal contact, inhalation of contaminated particles, and ingestion of contaminated soil or food crops (Yakubu, 2017; Melamid, 2018; Oyeranmi and Dube, 2021). Benzene exposure has been associated with leukemia and other haematological disorders, while PAHs have been linked to mutagenic and teratogenic effects (Sikakwe *et al.*, 2022; Onyenechere *et al.*, 2022; Oloniyo and Basorun, 2025; Ekwe-Testimony and Chukwura-Osoagba, 2025; John-Abebe and Ajogungbe, 2025; Idebaneria, 2025). Individuals working in auto-mechanic environments may therefore experience prolonged occupational exposure, particularly where appropriate protective equipment and waste management practices are lacking, increasing the potential for respiratory, dermatological, neurological, and systemic health effects (Aliyu and Amadu, 2017; Makanjuola, 2019; Sadiq, 2022).

The consequences of petroleum contamination can extend beyond the immediate soil environment. Hydrocarbons may migrate downward through the soil profile and reach groundwater or be transported by rainfall runoff into drainage channels, rivers, and other surface-water systems, thereby creating additional pathways for environmental exposure (Aliyu and Amadu, 2017; Makanjuola, 2019; Sadiq, 2022; Ayo-Odifiri, 2022; Enuneku *et al.*, 2024). Persistent compounds, particularly PAHs, may remain in contaminated soils for extended periods because of their relatively low biodegradability, contributing to long-term ecological disturbance (Yakubu, 2017; Melamid, 2018; Oyeranmi and Dube, 2021). The proximity of several mechanic workshops to residential areas in Benin Metropolis further increases the potential for interaction between contaminated environments, workers, and nearby communities (John-Abebe and Ajogungbe, 2025; Idebaneria, 2025).

Despite increasing concern regarding petroleum contamination associated with automobile repair activities, localized hydrocarbon pollution in Nigerian urban environments remains less extensively investigated than large-scale petroleum pollution in the Niger Delta (Yakubu, 2017; Melamid, 2018; Oyeranmi and Dube, 2021). In particular, continued disposal of used engine oil and other petroleum wastes within auto-mechanic villages may promote TPH accumulation and deterioration of soil quality, including changes in nutrient availability, microbial activity, and soil pH (John-Abebe and Ajogungbe, 2025; Idebaneria, 2025; Aliyu and Amadu, 2017; Makanjuola, 2019; Sadiq, 2022; Ayo-Odifiri, 2022; Enuneku *et al.*, 2024). Previous studies have also linked petroleum contamination with changes in soil properties and environmental quality (Amadi, Onuoha and Onwuka, 2021; Wang, Zhang and Xu, 2023; Borha and Olujobi, 2026). However, limited systematic information on the concentration and distribution of TPH in soils from selected

auto-mechanic villages in Benin Metropolis restricts effective assessment of contamination levels and associated environmental risks.

Generating reliable information on soil physicochemical characteristics and TPH concentrations is therefore important for understanding the extent of petroleum contamination in these environments and establishing a basis for environmental risk assessment, monitoring, and remediation (Ayo-Odifiri, 2022; Enuneku *et al.*, 2024). Such information can also support improved petroleum waste management, identification of contamination hotspots, and the development of appropriate environmental management strategies for auto-mechanic communities (Odupitan, 2017; Adeola *et al.*, 2022; Hunter, 2023). Accordingly, the present work evaluates the physicochemical properties and TPH concentrations of soils collected from selected auto-mechanic villages in Benin Metropolis, with particular emphasis on the distribution of TPH constituents across the investigated locations.

LITERATURE REVIEW

2.1 PREVIOUS STUDIES ON TOTAL PETROLEUM HYDROCARBONS IN MECHANIC WORKSHOP SOILS

Several studies have investigated the occurrence, distribution, and environmental implications of total petroleum hydrocarbons in soils associated with automobile repair activities. These studies have consistently shown that auto mechanic environments represent significant sources of hydrocarbon contamination due to the frequent handling and improper disposal of petroleum products.

Biose *et al.* (2025) assessed polycyclic aromatic hydrocarbons (PAHs) and total petroleum hydrocarbons (TPHs) in soils from oil-producing communities in the coastal wetlands of Delta State, Nigeria, using indigenous earthworms as bioindicators. The authors collected soil and earthworm samples from Emevor, Effurun, Kwale, Olomoro, and Sapele and analyzed them using Gas Chromatography with Flame Ionization Detection (GC-FID). The study identified sixteen PAHs and twenty-seven TPH compounds in the soil samples, with Emevor recording the highest contamination levels. Earthworms accumulated several PAHs and TPHs, with bioaccumulation factor values greater than one, indicating significant uptake of hydrocarbons from the soil. Biose *et al.* concluded that earthworms serve as effective bioindicators of petroleum hydrocarbon contamination and emphasized the need for remediation of oil-polluted soils. The findings demonstrate the persistence of hydrocarbon pollutants in soil environments and their potential ecological impacts.

Adeniyi and Afolabi (2002) investigated the levels of total petroleum hydrocarbons and heavy metals in soils around facilities handling refined petroleum products in Lagos metropolis. The

researchers collected soil samples from petrol stations, auto mechanic workshops, and a National Electric Power Authority station while control samples were obtained from low density residential areas. Adeniyi and Afolabi (2002) determined total petroleum hydrocarbons using gravimetric analytical methods and heavy metals using atomic absorption spectrophotometry. Their results showed significantly higher concentrations of hydrocarbons and heavy metals in soils from petroleum handling facilities compared with control sites. The study reported mean TPH concentrations of $399.83 \pm 106.19 \mu\text{g g}^{-1}$ and $450.83 \pm 90.58 \mu\text{g g}^{-1}$ in petrol stations, while mechanic workshop soils recorded mean values of $362.60 \pm 185.84 \mu\text{g g}^{-1}$ and $428.55 \pm 119.00 \mu\text{g g}^{-1}$. These values were substantially higher than the control value of $26.63 \pm 4.58 \mu\text{g g}^{-1}$. Adeniyi and Afolabi (2002) concluded that improper handling of petroleum products significantly contributes to soil contamination and recommended bioremediation using microorganisms and plants as potential remediation strategies.

Adebiyi and Afedia (2011) examined the ecological impact of used petrochemical oils on soil properties around automobile repair workshops. The researchers analyzed physicochemical parameters, elemental composition, and total petroleum hydrocarbon concentrations of contaminated soils using standard laboratory methods. Adebiyi and Afedia (2011) detected high concentrations of several metals including manganese, zinc, potassium, sodium, copper, iron, nickel, chromium, vanadium, and lead in the contaminated soils. Their results also revealed elevated hydrocarbon concentrations compared with uncontaminated soils from other locations in Nigeria. The Geoaccumulation Index values indicated that the soils were heavily polluted with most of the analyzed metals. Adebiyi and Afedia (2011) concluded that petroleum hydrocarbon contamination from improper disposal of petrochemical oils significantly altered soil properties and posed serious environmental risks to living organisms.

Khan and Kathi (2014) evaluated total petroleum hydrocarbon and heavy metal contamination in roadside surface soils located near automobile workshops and agricultural fields along major highways in Puducherry, India. The researchers analyzed concentrations of copper, lead, zinc, manganese, cadmium, and chromium in soils collected from different locations. Khan and Kathi (2014) reported that soils collected near automobile workshops contained significantly higher contaminant concentrations compared with soils from nearby agricultural fields. The study also found that total petroleum hydrocarbon concentrations near automobile workshops ranged between 90.72 and 121.79 mg kg⁻¹, whereas agricultural soils contained lower concentrations ranging from 44.94 to 83.4 mg kg⁻¹. Pearson correlation analysis revealed strong positive relationships between total petroleum hydrocarbons and metals such as zinc, copper, and lead. Khan and Kathi (2014) attributed these contaminant levels primarily to anthropogenic activities associated with vehicle repair and maintenance.

Nyarko *et al.* (2019) investigated the effects of petroleum fuels and lubricants on soil properties in auto mechanic workshops in Cape Coast metropolis in Ghana. The researchers collected soil samples from eight automobile mechanical shops and compared them with control samples from uncontaminated sites. Nyarko *et al.* (2019) analyzed several soil characteristics including particle size distribution, pH, electrical conductivity, organic matter, nitrate, and phosphate levels. Their findings indicated that petroleum hydrocarbon contamination altered several soil properties and significantly affected soil chemistry. The researchers also observed correlations between soil temperature, conductivity, organic matter, and nutrient concentrations. Nyarko *et al.* (2019) concluded that petroleum contamination may adversely affect microbial communities and disrupt natural soil processes.

Ikpe *et al.* (2023) investigated petroleum hydrocarbon concentrations in soils from automobile mechanic workshops in Ikot Akpaden, Mkpata Enin Local Government Area of Akwa Ibom State, Nigeria. The researchers collected soil samples from contaminated sites and control locations and analyzed them using Soxhlet extraction and shaking methods followed by column chromatography purification. Ikpe *et al.* (2023) reported measurable concentrations of total petroleum hydrocarbons and total hydrocarbon content in the soils surrounding the mechanic workshops. Their findings confirmed that mechanical repair activities contribute significantly to hydrocarbon contamination in soils and emphasized the need for improved environmental monitoring and management of petroleum related wastes.

Nganje *et al.* (2007) assessed hydrocarbon and heavy metal contamination in groundwater and soils around petrol stations and mechanic workshops in Calabar metropolis, Nigeria. The researchers analyzed samples from sixteen locations to evaluate the impact of these facilities on environmental quality. Nganje *et al.* (2007) found that mean concentrations of petroleum hydrocarbons and polycyclic aromatic hydrocarbons in soils were significantly higher than reference values. The study reported a mean soil TPH concentration of 46.87 mg kg⁻¹ and detected high levels of naphthalene at 340 µg g⁻¹. Nganje *et al.* (2007) also observed that groundwater near petrol stations and mechanic workshops contained hydrocarbon concentrations exceeding recommended environmental standards. The researchers concluded that petroleum related activities can contribute to both soil and groundwater contamination.

Ameh, Mohammed Dabo, Ibrahim, and Ameh (2013) investigated the potential of earthworm assisted bioremediation for petroleum hydrocarbon contaminated soils collected from mechanic workshops. The researchers used the earthworm species *Eudrilus eugenia* to evaluate its effectiveness in enhancing degradation of hydrocarbons in contaminated soils. Ameh *et al.* (2013)

found that earthworm survival depended on the concentration of petroleum hydrocarbons present in the soil. Their results also showed that soils treated with earthworms experienced significant reductions in carbon and nitrogen content as well as notable decreases in total petroleum hydrocarbon concentrations after thirty five days of treatment. Ameh *et al.* (2013) concluded that earthworms can function as biocatalysts that enhance microbial degradation of petroleum hydrocarbons in contaminated soils.

Nneji *et al.* (2016) conducted another study on bioremediation of petroleum hydrocarbon contaminated soils from mechanic workshops in Ibadan, Nigeria. The researchers investigated the combined effects of the earthworm *Alma millisoni* and hydrocarbon degrading bacteria belonging to the genus *Bacillus*. Nneji *et al.* (2016) observed that soils treated with both earthworms and bacteria showed significant reductions in petroleum hydrocarbon concentrations compared with untreated soils. The study also recorded improvements in soil organic carbon and nitrogen levels after treatment. Nneji *et al.* (2016) concluded that the combined use of earthworms and hydrocarbon degrading bacteria can effectively enhance remediation of contaminated soils.

Akomah and Osayande (2018) evaluated hydrocarbon concentrations and microbial populations in soils from Ikokwu auto mechanic village in Port Harcourt, Nigeria. The researchers collected soil samples from different depths and analyzed them for total petroleum hydrocarbons, polycyclic aromatic hydrocarbons, and total hydrocarbon content. Akomah and Osayande (2018) reported TPH concentrations ranging from 34.32 mg kg⁻¹ to 1746.6 mg kg⁻¹ in the upper soil layers. The study also identified several hydrocarbon degrading bacterial genera including *Bacillus*, *Pseudomonas*, *Micrococcus*, *Arthrobacter*, *Proteus*, and *Staphylococcus*. Akomah and Osayande (2018) concluded that microbial populations present in contaminated soils could be utilized in bioremediation strategies.

Alabi *et al.* (2021) investigated hydrocarbon contamination in soil profiles from auto mechanic workshops in Akure metropolis, Nigeria. The researchers analyzed soil samples collected from depths of 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm using gas chromatography mass spectrometry techniques. Alabi *et al.* (2021) detected long chain hydrocarbons ranging from nC8 to nC32 across the soil profiles. The study reported total petroleum hydrocarbon concentrations in top soils ranging from $85.42 \pm 3.42 \text{ mg kg}^{-1}$ to $123.76 \pm 4.37 \text{ mg kg}^{-1}$. Alabi *et al.* (2021) also observed that hydrocarbon concentrations decreased with increasing soil depth but remained detectable across all sampled layers. The researchers concluded that prolonged automobile repair activities can lead to significant hydrocarbon accumulation in soils and may contribute to contamination of surface and groundwater systems.

Ekhaise and Nkwelle (2011) carried out a study on the microbiological and physicochemical characteristics of oil contaminated soils from major motor mechanic workshops in Benin City metropolis. The research examined the ability of microorganisms to utilize used engine oil present in contaminated soils as their sole source of carbon and energy. Soil samples were collected from three major mechanic workshops located at Igun, Evbareke, and Uwelu quarters in Benin City. The analysis of physicochemical properties revealed that soil pH ranged from 5.63 to 6.01, indicating slightly acidic soil conditions. The percentage of carbon ranged from 2.345 to 4.800 while total organic matter ranged from 1.59 to 7.81 percent. The concentration of total petroleum hydrocarbons in the soil samples ranged from 86.10 to 286.50 mg/kg. The study also observed significant differences in the mean values of total heterotrophic bacterial and fungal populations among the different sampling locations. These findings suggest that the presence of petroleum hydrocarbons influences microbial populations and soil chemical characteristics within mechanic workshop environments in Benin City (Ekhaise and Nkwelle, 2011).

Okonokhua and Aghidi (2024) conducted a study to assess soil physicochemical properties and total petroleum hydrocarbon concentrations in a three decade old polluted automobile workshop site located in Evbareke area of Benin City. The study involved the collection of topsoil samples from within the polluted workshop and from a control site. Laboratory analyses were carried out to determine soil fertility parameters, heavy metal concentrations, and total petroleum hydrocarbon levels. The results showed that the soil texture remained relatively unchanged despite long term exposure to contamination. However, the soil pH was altered from strongly acidic to slightly acidic conditions. The study recorded an increase in total petroleum hydrocarbon concentration from 0.22 mg/kg in the control soil to as high as 825 mg/kg in the polluted soil samples. Although this value remained below the regulatory target value of 1000 mg/kg established by the Department of Petroleum Resources, the results indicate a clear accumulation of hydrocarbons within the soil. The study also reported that cadmium concentration exceeded regulatory limits, thereby posing potential health risks to workers and residents in the area (Okonokhua and Aghidi, 2024).

Balogun *et al.* (2023) investigated heavy metal contamination and microbial counts in soils collected from selected auto mechanic workshops within Benin Metropolis in Edo State. The study involved the collection of twenty seven soil samples from Ugbowo and Uwelu auto mechanic sites at three different soil depths of 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm. The soil samples were analyzed for heavy metals including copper, iron, chromium, lead, cadmium, and manganese as well as microbial populations such as total heterotrophic bacteria and fungi. The results showed that most heavy metals were within the permissible limits established by the World Health Organization and the Department of Petroleum Resources. However, cadmium concentration exceeded the acceptable limit in several samples, indicating severe contamination in some locations. The study also found that auto mechanic activities had a greater negative effect on

bacterial populations compared to fungal populations. The researchers concluded that continuous mechanic activities contribute to increased contamination levels in soils within mechanic villages (Balogun *et al.*, 2023).

Abhulimhen (2016) examined the physicochemical properties of soils obtained from automobile mechanic workshops in Ikoku mechanic village located in Port Harcourt, Rivers State. The study investigated several environmental parameters including polycyclic aromatic hydrocarbons, total hydrocarbon content, total organic carbon, soil pH, electrical conductivity, heavy metals, and particle size distribution. Six soil samples were collected from locations close to automobile workshops while control samples were collected from sites that were not influenced by mechanic activities. The results revealed that concentrations of heavy metals, polycyclic aromatic hydrocarbons, and total hydrocarbon content were generally higher in soils affected by automobile mechanic operations compared to the control site. The study also showed that the soil had low permeability which limited the downward movement of contaminants and promoted the accumulation of petroleum hydrocarbons in the topsoil layer. These findings demonstrate that automobile mechanic activities contribute significantly to hydrocarbon contamination of urban soils (Abhulimhen, 2016).

Nneji *et al.* (2016) conducted a study on the remediation of petroleum hydrocarbon contaminated soils obtained from motor mechanic workshops in Ibadan, southwestern Nigeria. The research investigated the effectiveness of earthworm assisted bioremediation using the earthworm species *Alma millisoni* and hydrocarbon degrading bacteria such as *Bacillus* species. Soil samples contaminated with petroleum hydrocarbons were subjected to different treatment conditions in order to evaluate the rate of hydrocarbon degradation. The results showed that the combined treatment involving both earthworms and bacteria produced a significant reduction in total

petroleum hydrocarbon concentration compared to treatments involving either organism alone. The study also reported a reduction in heavy metal concentrations and an increase in soil organic carbon and nitrogen content after treatment. The findings demonstrate that biological remediation techniques can effectively enhance the degradation of petroleum hydrocarbons in contaminated soils (Nneji *et al.*, 2016).

Iloba and Ekrakene (2008) investigated soil microarthropods associated with mechanic workshop soils in Benin City in order to assess the ecological impact of petroleum and carbide wastes present in such environments. The study was conducted over a three month period and involved the collection of soil samples from two stations within a mechanic workshop and a nearby control site. One station was contaminated with petroleum waste while the other station was contaminated with carbide waste. A total of 268 soil microarthropods were identified during the study. However, the petroleum contaminated station recorded only 54 organisms while the carbide contaminated station recorded 27 organisms. The microarthropods collected were classified into two major groups which included Insecta and Acari belonging to eight families. The study found that petroleum contamination significantly reduced soil microarthropod abundance and diversity. The researchers concluded that contamination by petroleum wastes may negatively affect soil biodiversity and ecological balance in mechanic workshop environments (Iloba and Ekrakene, 2008).

Sikakwe *et al.* (2022) carried out a study to assess the presence of polycyclic aromatic hydrocarbons and heavy metal pollutants in soils around semi urban petrol stations and automobile mechanic workshops. Soil samples were collected from the depth range of 0 to 15 cm and analyzed using atomic absorption spectrophotometry and chromatographic techniques. The results indicated that soil pH ranged from 6.12 to 6.81 which represents weakly acidic soil conditions. The heavy metals detected in the soil samples followed the order of lead greater than nickel greater than

vanadium greater than cadmium. Several polycyclic aromatic hydrocarbons were also detected including anthracene, fluorene, pyrene, phenanthrene, and benzo fluoranthene. However, the mean concentrations of these compounds were within permissible standards for agricultural and residential soils. The study concluded that the presence of hydrocarbons in the soils was largely associated with combustion processes from gasoline and kerosene used in vehicles (Sikakwe *et al.*, 2022).

Okolafor and Ekhaise (2021) investigated the biostimulation of waste engine oil polluted soils collected from motor mechanic workshops in Benin City using organic and inorganic amendments. The study examined the effectiveness of different soil amendments including cow dung, sludge, NPK fertilizer, and sawdust compost in enhancing microbial degradation of petroleum hydrocarbons. The contaminated soils were monitored over a period of fourteen weeks to determine the rate of hydrocarbon removal. The results showed that soils treated with organic amendments such as cow dung and sludge exhibited significantly higher microbial activity and faster hydrocarbon degradation compared to soils treated with inorganic fertilizers. The study reported that cow dung and sludge treatments required between nine and seventeen weeks for substantial hydrocarbon removal, while inorganic fertilizer treatments required more than thirty weeks. These results demonstrate the potential of organic amendments in improving the bioremediation of petroleum contaminated soils (Okolafor and Ekhaise, 2021).

Ikhajiagbe *et al.* (2014) carried out a study to evaluate heavy metal contents and microbial diversity in waste engine oil polluted soils within Benin City metropolis. The study involved the collection of soil samples from several locations including mechanic workshops, bakeries, generating plant houses, and spare part shops. Field observations were conducted to assess the extent of contamination based on vegetation health and the presence of soil organisms. Soil samples were

collected from the topsoil layer and analyzed for heavy metals and microbial populations. The results revealed that areas affected by waste engine oil spills showed reduced vegetation growth and lower abundance of soil organisms compared to uncontaminated areas. The study also identified several microbial species capable of degrading petroleum hydrocarbons, suggesting that contaminated soils may support specialized microbial communities adapted to hydrocarbon rich environments (Ikhajiagbe *et al.*, 2014).

Overall, these empirical studies demonstrate that automobile mechanic environments represent important sources of petroleum hydrocarbon contamination in soils. The repeated handling and disposal of petroleum products such as engine oil, lubricants, and fuels contribute to the accumulation of hydrocarbons in soil environments. These contaminants can alter soil physicochemical properties, affect microbial populations, and pose environmental and human health risks. Despite the growing body of research in different regions of Nigeria and other countries, limited studies have specifically examined the extent of total petroleum hydrocarbon contamination in soils from auto mechanic villages in Benin Metropolis, Edo State. This knowledge gap highlights the importance of conducting the present study in order to provide updated information on hydrocarbon contamination levels in this urban environment.

METHODOLOGY

Description of the Study Area

This study was conducted in Benin City, the capital of Edo State in southern Nigeria. Benin City lies approximately between latitude 6° 20' N and 6° 25' N and longitude 5° 35' E and 5° 40' E

(Floyd *et al.*, 2016; Ikpe *et al.*, 2020). The city is one of the major urban centers in Nigeria and serves as an important commercial, administrative, and cultural hub in the South South region of the country (Floyd *et al.*, 2016; Ikpe *et al.*, 2020). Benin City has experienced rapid urban growth in recent decades due to population increase, economic activities, and expansion of infrastructure. (Floyd *et al.*, 2016; Ikpe *et al.*, 2020) According to recent population estimates, the city has a population of over 1.8 million people, making it one of the largest metropolitan areas in southern Nigeria (Floyd *et al.*, 2016; Ikpe *et al.*, 2020). The city is strategically located along major transportation routes connecting the western and eastern parts of Nigeria, which has contributed to its rapid urbanization and economic development (Floyd *et al.*, 2016; Ikpe *et al.*, 2020).

The study took place in three automobile mechanic workshop clusters located within Benin Metropolis: Uwelu (Site 1), Evbareke (Site 2), and Igun (Site 3). The researchers selected these sites due to the high level of automobile repair, servicing, and maintenance activities conducted in the areas.

Uwelu (Site 1)

Uwelu mechanic village is located in the Egor Local Government Area of Edo State and is one of the largest automobile repair clusters in Benin City (Ihimekpen *et al.*, 2025). The area hosts numerous mechanic workshops where vehicle servicing, engine repairs, and oil changes are regularly carried out (Ihimekpen *et al.*, 2025).

Sample 1	Sample 2	Sample 3
N – 06° 22.663	N – 06°22.662	N -06° 22.657
E – 005°35.508	E- 005°35.502	E- 005° 35.512

Evbareke (Site 2)

Evbareke mechanic area is another major automobile repair hub located within Oredo Local Government Area (Nworgu *et al.*, 2012; Ihimekpen *et al.*, 2025). This area also accommodates a large number of automobile technicians and spare parts dealers (Balogun *et al.*, 2023; Onaiwu and Okuo, 2023).

Sample 1	Sample 2	Sample 3
N - 06° 21.688	N - 06°21.686	N – 06°21.689
E- 005°36.521	E- 005° 36.524	E – 005°36.524

Igun (Site 3)

Igun mechanic workshop area is located within the central part of Benin City and serves as an important automobile repair center for residents and commercial vehicle operators (Osazuwa *et al.*, 2015; Balogun *et al.*, 2023; Onaiwu and Okuo, 2023).

Sample 1	Sample 2	Sample 3
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N – 06°20.440

N – 06°20.436

N – 06°20.434

E – 005°38.052

E – 005°38.054

E – 005°38.058

Geology and Climate of the study area

Benin City is characterized by a tropical climate with distinct wet and dry seasons. The wet season usually occurs between April and October, while the dry season lasts from November to March (Balogun and Orimoogunje, 2015; Onwuanyi and Ojo, 2021). Annual rainfall in the city ranges between 1500 mm and 2500 mm, with peak rainfall occurring between June and September (Balogun and Orimoogunje, 2015; Onwuanyi and Ojo, 2021). The average annual temperature is approximately 27°C, although temperatures may occasionally rise above 32°C during the dry season (Balogun and Orimoogunje, 2015; Onwuanyi and Ojo, 2021). Relative humidity in the area is generally high, especially during the rainy season, often exceeding 80 percent (Balogun and Orimoogunje, 2015; Onwuanyi and Ojo, 2021). These climatic conditions influence soil formation, microbial activities, and the mobility of pollutants such as petroleum hydrocarbons in the soil environment (Enuneku *et al.*, 2022).

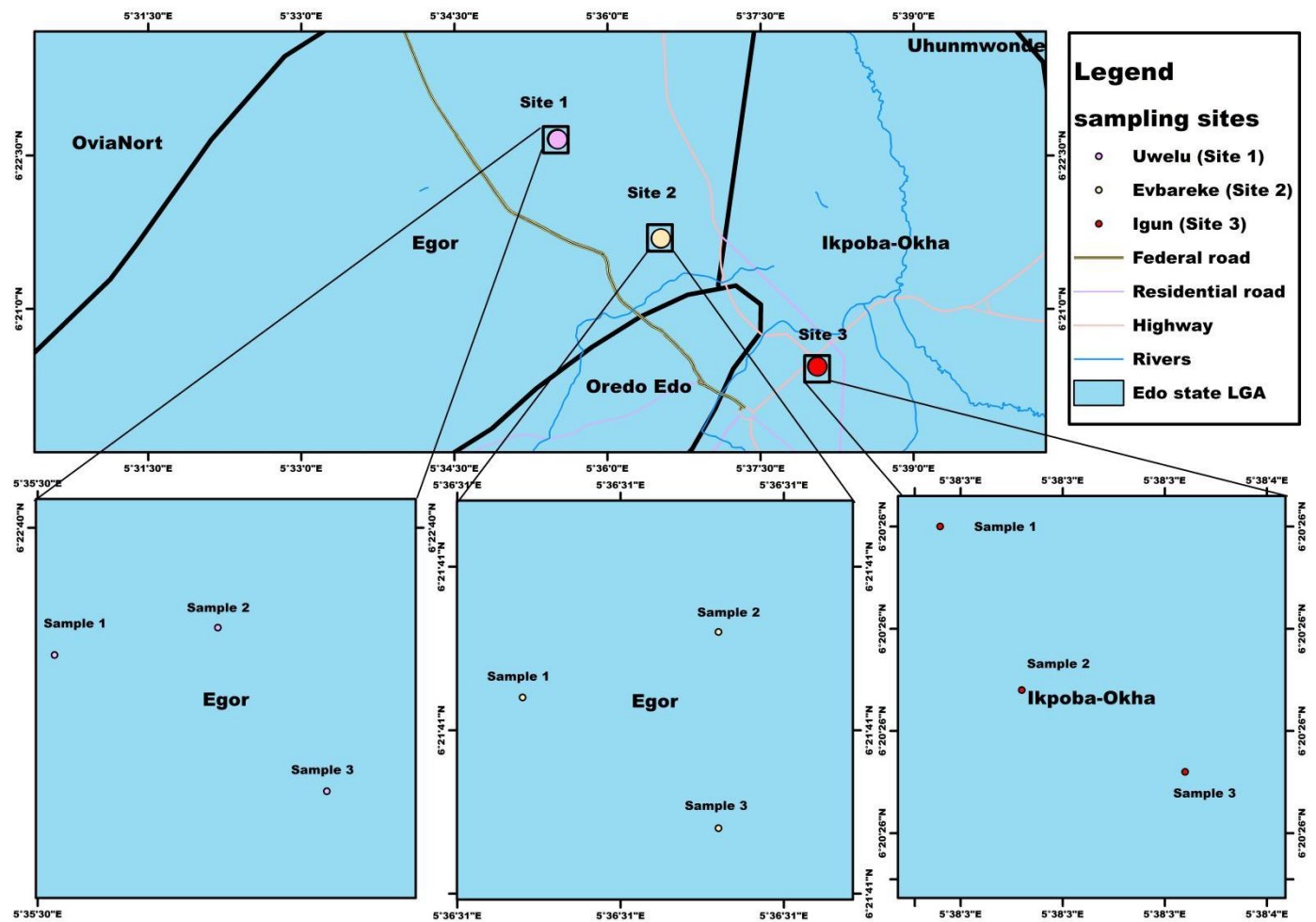


Figure 1 Map of the study area.

Sample Collection

Soil samples were collected from Uwelu, Evbareke and Igun mechanic villages. A T-shaped soil sampling instrument/hand auger was inserted into the ground to collect soil from approximately 0–15 cm depth. Subsamples were obtained from different points and combined to form representative composite samples. Each sample was immediately transferred into a clean nylon/polyethylene bag and properly labelled to prevent mixing and ensure traceability. Three composite samples were collected from each location, giving nine samples in total.

Sample Preparation

Soil samples collected from the selected auto mechanic villages were first air-dried at room temperature to remove excess moisture. The dried soil samples were then ground gently using a mortar and pestle and sieved through a 2 mm mesh sieve to obtain a uniform particle size. This preparation process ensures that the soil samples are suitable for accurate laboratory analysis.

Physiochemical Parameter analysis

The pH of the soil samples was measured using a calibrated digital pH meter. Ten grams of air-dried and sieved soil was mixed with 25 mL of distilled water to prepare a 1:2.5 soil-to-water suspension. The mixture was stirred thoroughly and allowed to stand for 30 minutes to attain equilibrium. The pH meter was calibrated with standard buffer solutions of pH 4.01 and 7.01 before use. The electrode was immersed in the suspension, and the pH value was recorded after the reading stabilized. Measurements were carried out in triplicate, and the mean value was recorded. The same soil suspension was subsequently used for electrical conductivity determination. A digital conductivity meter calibrated with a standard potassium chloride solution

was employed, and the conductivity probe was immersed in the suspension. The conductivity value was recorded after stabilization and expressed in $\mu\text{S}/\text{cm}$.

Soil temperature was measured directly at each sampling location using a calibrated digital soil thermometer. The probe was inserted into the soil to a depth of approximately 10 cm, and the temperature reading was taken after stabilization. Measurements were conducted in triplicate, and the average value was calculated for each sampling point.

Moisture content was determined using the gravimetric oven-drying method. Approximately 10 g of freshly collected soil was weighed into a pre-weighed aluminium crucible and dried in an oven at 105°C for 24 hours until a constant weight was obtained. The crucible was then removed, cooled in a desiccator, and reweighed. The percentage moisture content was calculated from the loss in weight relative to the initial wet soil weight.

The cation exchange capacity (CEC) of the soil samples was determined using the ammonium acetate extraction method. Ten grams of air-dried and sieved soil was treated with 1 M ammonium acetate solution adjusted to pH 7.0. The mixture was thoroughly shaken, allowed to equilibrate, and filtered. The filtrate was analyzed for exchangeable cations, and the CEC was calculated from the total concentration of exchangeable ions present in the soil. Results were expressed in $\text{cmol}(+)/\text{kg}$ of soil.

Particle size distribution analysis was carried out to determine the relative proportions of sand, silt, and clay in the soil samples. The samples were dispersed using an appropriate dispersing agent and mixed thoroughly to separate individual soil particles. The different particle-size fractions were determined through a sedimentation procedure, after which the percentages of sand, silt, and

clay were calculated. These values were subsequently used to classify the soil samples into their respective textural classes.

Determination of Total Petroleum Hydrocarbon

The determination of Total Petroleum Hydrocarbon (TPH) concentrations in the soil samples was carried out according to the standard laboratory test method OAL/AM/S10 for the extraction and gas chromatographic determination of petroleum hydrocarbons. The method covers hydrocarbon compounds ranging from C10 (n-Decane) to C40 (n-Tetracontane) and has a detection capability of approximately $0.025 \mu\text{g g}^{-1}$ dry soil.

Extraction Procedure

Approximately 20 g of the prepared soil sample was weighed and thoroughly mixed with 80 g of anhydrous sodium sulphate. The mixture was transferred into a glass-fibre extraction thimble and placed in a Soxhlet extraction apparatus. Prior to extraction, the extraction thimbles were heated in a muffle furnace at 550°C for one hour to remove organic carbon. A solvent mixture consisting of 150 ml acetone and 150 ml Analar-grade hexane was used for extraction. The samples were subjected to Soxhlet reflux extraction for approximately 18 hours, with the condenser maintained between -10°C and -20°C .

Following extraction, the apparatus was allowed to cool to room temperature and the extract was transferred into a separating funnel. Approximately 300 ml of distilled water was added, and the mixture was thoroughly shaken, with intermittent pressure release, before being allowed to stand for at least five minutes for phase separation. The aqueous layer was discarded and the washing procedure was repeated twice. Approximately 5 g of anhydrous sodium sulphate was subsequently

added to the organic phase to remove residual moisture. The extract was concentrated under a gentle stream of nitrogen to approximately 25 ml and further reduced to approximately 1 ml.

Fractionation

The concentrated extract was fractionated using a glass column packed with silica gel at the bottom and alumina at the top, with the column pre-wetted using hexane. The aliphatic hydrocarbon fraction was eluted with 10 ml of hexane, while the aromatic hydrocarbon fraction was subsequently eluted with 25 ml of benzene. Each fraction was separately concentrated to approximately 1 ml under a gentle stream of nitrogen and sealed to minimize evaporative losses before gas chromatographic analysis.

Gas Chromatographic Analysis

The aliphatic and aromatic fractions were analyzed using a gas chromatograph equipped with a Chrompack CP-Sil-5-CB capillary column measuring 50 m in length, 0.32 mm internal diameter, and 0.12 μm film thickness. Helium was used as the carrier gas and a flame ionization detector (FID) was employed for detection.

For the aliphatic fraction, the temperature programme started at 80°C and was held for 5 minutes, followed by a temperature increase to 300°C at a rate of 5°C min⁻¹ and a final hold at 300°C for 15 minutes. For the aromatic fraction, the initial temperature was 90°C and was maintained for 5 minutes, followed by an increase to 160°C at 5°C min⁻¹ and a subsequent increase to 300°C at 10°C min⁻¹, with a final hold at 300°C for 17 minutes. An injection volume of 2 μl was used for both standards and samples.

The aliphatic hydrocarbons quantified ranged from C10 (n-Decane) to C40 (n-Tetracontane). The aromatic fraction comprised selected polycyclic aromatic hydrocarbons, including acenaphthalene, acenaphthylene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenz(ah)anthracene, indeno(1,2,3-cd)pyrene, benzo(ghi)perylene, and perylene.

Calculation

The concentration of each hydrocarbon component was calculated from the gas chromatographic result using the sample weight, dilution factor, and final extract volume. The concentration in the wet soil was calculated as:

$$X = (a \times z \times v) / w$$

where:

X = concentration in wet soil

a = concentration in 1 µl of extract, obtained as c/2

z = dilution factor

v = final volume of extract (ml)

w = weight of soil sample (g)

The concentration in dry soil was subsequently calculated using the moisture content of the soil:

$$K = X \times ((d \times 100) / 100)$$

where d represents the water content of the soil (%). The resulting values were converted to µg of hydrocarbon per gram of dry soil by dividing by 1000 where applicable and were finally expressed as mg/kg dry soil for comparison with relevant environmental standards.

Statistical Analysis

The data obtained from this study underwent descriptive statistical analysis using Microsoft Excel to determine the mean, standard deviation, minimum, and maximum values of the measured parameters. One-way Analysis of Variance (ANOVA) was applied to evaluate differences in physicochemical properties and total petroleum hydrocarbon concentrations across the three sampling sites, namely Uwelu, Evbareke, and Igun, at a significance level of 5% ($P < 0.05$). Where ANOVA indicated significant variation, Duncan's Multiple Range Test (DMRT) was employed to separate the means. Mean values assigned different superscript letters indicated significant differences, whereas those sharing the same superscript letter showed no significant difference. Pearson's correlation analysis was further conducted to examine the relationships between selected soil physicochemical parameters and heavy metal concentrations. The correlation coefficient (r) was used to determine the strength and direction of the associations between variables, with statistical significance accepted at $P < 0.05$.

RESULTS

Physiochemical Properties and Total Hydrocarbon content of soils from auto mechanic village 4.1

The results of the physiochemical parameters in soil samples obtained from three auto mechanic villages between Benin metropolis are summarized in table 1.

The mean, standard deviation, minimum and maximum value for each parameters analyzed at the sample location are presented in the table. Also shown in table 4.1 are the pvalues of the one way analysis of variance (ANOVA) and the superscript representing posthoc (duncan multiply range-DMR) tests. The super script appears in cases in which the ANOVA presented significant differences. In table 4.1 the following physiochemical properties such as soil, temperature, electrical conductivity, soil moisture, calcium, magnesium and bulk density showed no significant difference ($p > 0.05$) in soils samples obtained between intraspecific variation across three locations, soil, ph, sand and porosity exhibited a significant difference ($p < 0.05$) while silt and clay showed a high significant difference in soil samples across the three locations.

TABLE 1: PHYSICOCHEMICAL PROPERTIES AND TOTAL HYDROCARBON CONTENT OF SOILS												
			Site 1: Uwelu SP			Site 2: Evbareke SP			Site 3: Igun SP			
Parameter s	Units	Methods	$\bar{x}\pm SD$	Min	Max	$\bar{x}\pm SD$	Min	Max	$\bar{x}\pm SD$	Min	Max	P-Value
Temperature	0C	EPA 1979, 170.1	28.37±2.85	25.50	31.20	27.87±2.76	25.00	30.50	27.57±3.21	24.20	30.60	P>0.05
pH		ASTM D4972	7.22±0.09 ^b	7.13	7.30	7.35±0.05 ^b	7.30	7.40	7.89±0.22 ^a	7.67	8.10	P<0.05
EC	uS/cm	USEPA9050 A	237.5±93.50	144.00	331.00	214.5±16.50	198.00	231.00	324±9.00	315.00	333.00	P>0.05
Moisture	%	ASTM D1498	10.78±0.11	10.67	10.88	11.13±3.51	7.62	14.63	15.12±9.40	5.72	24.52	P>0.05
Calcium	mg/kg	ASTM D511	1670.33±3.01	1667.33	1673.34	1654.3±157.31	1496.99	1811.62	1790.57±43.09	1747.49	1833.66	P>0.05
Magnesium	mg/kg	ASTM D511	855.74±272.34	583.40	1128.08	1049.6±88.20	961.40	1137.80	1171.8±199.40	972.40	1371.20	P>0.05
Sand	%	Hydrometer	85.76±1.06 ^a	84.70	86.82	78.26±2.56 ^b	75.70	80.82	88.29±2.41 ^a	85.88	90.70	P<0.05
Silt	%	Hydrometer	7.49±0.67 ^a	6.82	8.15	3.99±0.17 ^b	3.82	4.15	2.46±1.31 ^b	1.15	3.76	P<0.01
Clay	%	Hydrometer	6.76±0.40 ^b	6.36	7.15	17.76±2.39 ^a	15.36	20.15	9.26±1.11 ^b	8.15	10.36	P<0.01
Bulk density	cm-3	ASTM D 7263-21	0.94±0.08	0.86	1.02	0.96±0.13	0.83	1.09	0.9±0.21	0.70	1.11	P>0.05
Porosity	%	Calculation	68.44±1.00 ^b	67.63	69.56	68.87±0.06 ^b	68.81	68.93	74.4±0.92 ^a	73.70	75.44	P<0.05
THC	mg/kg	USEPA 8270	17540.54±3162.16 ^b	14378.38	20702.70	23632.66±3178.15 ^a	20454.50	26810.81	16654.02±1518.88 ^b	15135.14	18172.90	P>0.05

Total petroleum hydrocarbon carbon in soil from automechanic village

The result of the physiochemical parameters in soil samples obtained from there automechanic villages from Benin metropolis are summarized in table 4.2

The mean, standard deviation, minimum and maximum values for each TPH compounds analyzed at the sample locations are shown cased in the table.

Also shown in table 2 are the pvalues of the one way analysis of variance (ANOVA) and the superscript presenting posthoc (Duncan Multiply Range-DMR). The super script appears in cases in which the ANOVA presented significant differences. In table 4.2 the following TPH compounds such as n-Undecane, n-Pentadecane, n-Hexadecane, n-Heptadecane, n-Octadecane, n-Eicosane, n-Heneicosane, showed no significant difference ($p>0.05$) in soils samples obtained between intraspecific variation across three locations. n-Dodecane, n-Tridecane, n-Tetradecane, n-Nonadecane, n-Docosane, n-Tricosane, n-Tetracosane, n-Pentacosane, n-hexacosane exhibited a significant difference ($p<0.05$) in soils samples obtained between intraspecific variation across three locations.

TABLE 2: DISTRIBUTION OF TOTAL PETROLEUM HYDROCARBON											
		Site 1: Uwelu SP			Site 2: Evbareke SP			Site 3: Igung SP			P-Value
Parameters	Units	$\bar{x} \pm SD$	Min	Max	$\bar{x} \pm SD$	Min	Max	$\bar{x} \pm SD$	Min	Max	
n-Decane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	P>0.05
n-Undecane	mg/kg	50.86±7.27	43.59	58.12	46.01±7.53	37.37	51.12	36.42±11.70	24.72	48.12	P<0.05
n-Dodecane	mg/kg	69.23±9.89 ^a	59.34	79.12	52.89±5.23 ^{ab}	47.66	58.13	49.66±9.46 ^b	40.20	59.12	P<0.05
n-Tridecane	mg/kg	165.63±23.66 ^a	141.97	189.29	72.02±7.12 ^b	64.90	79.14	158.92±30.27 ^a	128.65	189.19	P<0.05
n-Tetradecane	mg/kg	189.11±27.02 ^a	162.09	216.12	99.64±9.85 ^b	89.78	109.49	181.63±34.60 ^a	147.03	216.23	P<0.05
n-Pentadecane	mg/kg	302.54±43.22	259.32	345.76	351.37±34.75	316.62	386.13	290.42±55.32	235.10	345.74	P>0.05
n-Hexadecane	mg/kg	432.11±61.73	370.38	493.84	496.53±49.11	447.42	545.64	413.14±78.69	334.45	491.84	P>0.05
n-Heptadecane	mg/kg	617.40±31.06	586.34	648.45	631.41±62.45	568.96	693.86	551.42±105.03	446.39	656.46	P>0.05
n-Octadecane	mg/kg	702.96±43.28	659.68	746.24	681.09±67.36	613.73	748.45	635.23±121.00	514.24	756.23	P>0.05
n-Nonadecane	mg/kg	603.99±29.14 ^b	574.85	633.14	768.26±75.98 ^a	692.28	844.24	531.83±101.30 ^b	430.53	633.14	P<0.05
n-Eicosane	mg/kg	458.92±65.56	393.36	524.48	485.43±48.01	437.42	533.44	415.37±79.12	336.25	494.49	P>0.05
n-Heneicosane	mg/kg	348.50±49.79	298.71	398.29	386.28±38.20	348.08	424.48	334.94±63.80	271.14	398.74	P>0.05
n-Docosane	mg/kg	154.41±22.06 ^b	132.35	176.46	271.41±26.84 ^a	244.57	298.26	150.75±28.71 ^b	122.04	179.47	P<0.05
n-Tricosane	mg/kg	108.70±15.53 ^b	93.17	124.23	242.49±23.98 ^a	218.50	266.47	116.12±22.12 ^b	94.00	138.24	P<0.05

n-Tetracosane	mg/kg	73.61±10.52 ^b	63.09	84.13	167.66±16.58 ^a	151.08	184.24	45.36±18.76 ^b	26.60	64.12	P<0.05
n-Pentacosane	mg/kg	49.21±7.03 ^b	42.18	56.24	67.64±6.69 ^a	60.95	74.33	63.45±6.51 ^a	56.12	68.54	P<0.05
n-hexacosane	mg/kg	21.30±10.65 ^b	10.12	31.33	47.44±4.69 ^a	42.74	52.13	24.23±11.37 ^b	13.86	36.39	P<0.05
n-Heptacosane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Octacosane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Nonacosane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Triacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Hentriacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Dotriacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
Tritracontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-tetratriacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Pentatriacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Hexatriacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Hepatriacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Octatriacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Nonatriacontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d
n-Tetracontane	mg/kg	n.d	0.00	0.00	n.d	0.00	0.00	n.d	0.00	0.00	n.d

Total	mg/kg	4348.47±436.1 3	3911.7 6	4784.0 3	4867.56±483. 75	4382.05	5349.5 3	3998.91±759.1 6	3243.8 5	4762.1 0	P>0.05
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n-Undecane

Figure 4.1 shows the spatial and temporal variations recorded for n-Undecane concentrations in the soil samples obtained from the three sampling stations. The concentration of n-Undecane decreased consistently across all stations throughout the sampling period. Site 1 (Uwelu SP) declined from 58.124 mg/kg in February to 50.859 mg/kg in March and 43.593 mg/kg in April. Likewise, Site 2 (Evbareke SP) decreased from 51.124 mg/kg to 49.543 mg/kg and 37.366 mg/kg, while Site 3 (Igun SP) recorded the greatest reduction from 48.124 mg/kg in February to 36.424 mg/kg in March before reaching 24.724 mg/kg in April. The highest concentration (58.124 mg/kg) occurred at Site 1 during February, whereas the lowest value (24.724 mg/kg) was recorded at Site 3 during April, indicating a general decline in n-Undecane across all sampling stations.

n-Dodecane

Figure 4.2 shows the spatial and temporal variations recorded for n-Dodecane concentrations in the soil samples from the three sampling stations. A gradual decline was observed at all locations throughout the study period. Site 1 (Uwelu SP) decreased from 79.123 mg/kg in February to 69.233 mg/kg in March and 59.342 mg/kg in April. Site 2 (Evbareke SP) similarly declined from 58.126 mg/kg to 52.895 mg/kg and 47.663 mg/kg, while Site 3 (Igun SP) recorded values of 59.123 mg/kg, 49.663 mg/kg, and 40.203 mg/kg, respectively. The highest concentration (79.123 mg/kg) was recorded at Site 1 during February, whereas the lowest concentration (40.203 mg/kg) occurred at Site 3 during April. The results indicate a progressive reduction in n-Dodecane concentration with increasing sampling duration.

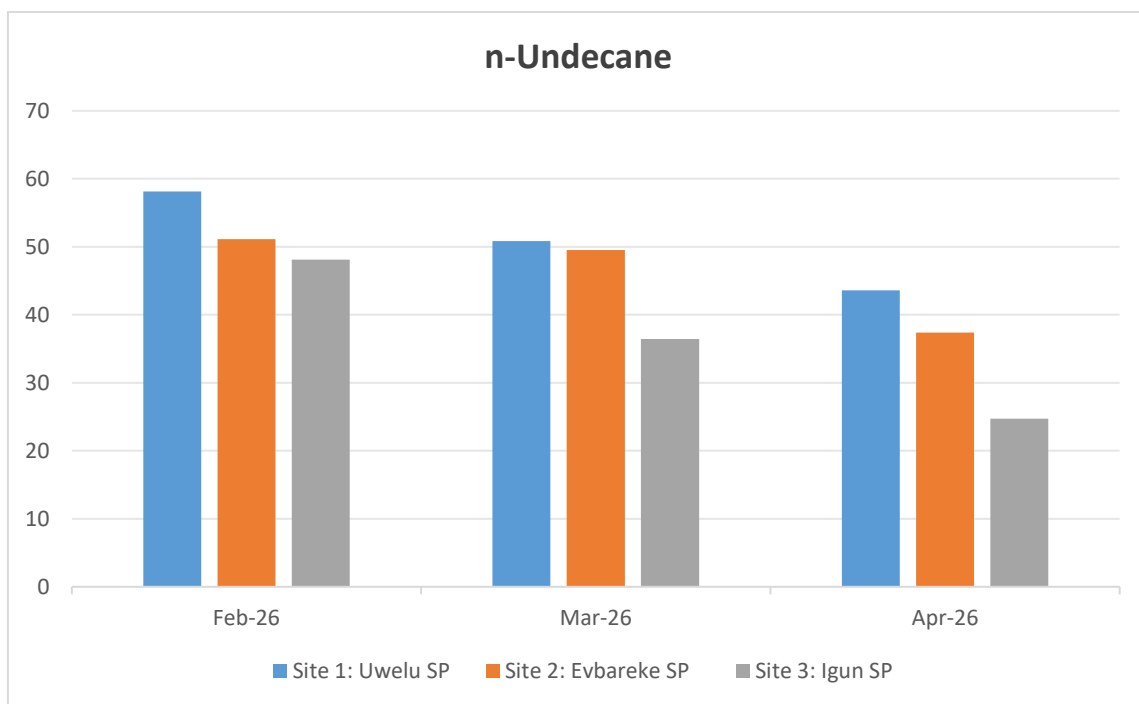


Figure 2: Spatial and temporal variation of n-Undecane in soil during the sampling months

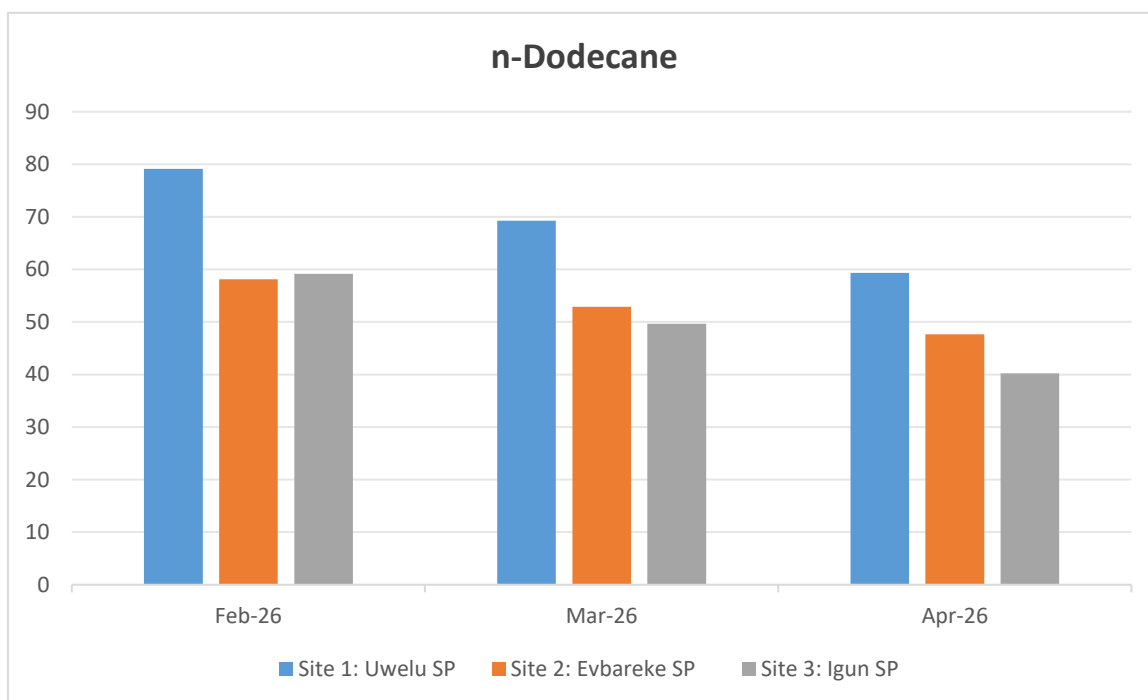


Figure 3: Spatial and temporal variation of n-Dodecane in soil during the sampling months

n-Tridecane

Figure 4.3 shows the spatial and temporal variations recorded for n-Tridecane concentrations in the soil samples collected from the three sampling stations. Concentrations declined steadily throughout the sampling period. Site 1 (Uwelu SP) decreased from 189.289 mg/kg in February to 165.628 mg/kg in March and 141.967 mg/kg in April. Site 2 (Evbareke SP) also exhibited a decline from 79.143 mg/kg to 72.020 mg/kg and 64.897 mg/kg, while Site 3 (Igun SP) decreased from 189.189 mg/kg to 158.919 mg/kg before reaching 128.648 mg/kg in April. The highest concentration (189.289 mg/kg) was observed at Site 1 during February, whereas the lowest value (64.897 mg/kg) occurred at Site 2 during April. Overall, n-Tridecane exhibited a continuous temporal decline across all sampling stations.

n-Tetradecane

Figure 4.4 shows the spatial and temporal variations recorded for n-Tetradecane concentrations in the soil samples obtained from the three sampling stations. Site 1 (Uwelu SP) recorded a steady decline from 216.124 mg/kg in February to 189.109 mg/kg in March and 162.093 mg/kg in April. Similarly, Site 2 (Evbareke SP) decreased from 109.489 mg/kg to 99.635 mg/kg and 89.781 mg/kg, while Site 3 (Igun SP) declined from 216.226 mg/kg in February to 181.630 mg/kg in March before reaching 147.033 mg/kg in April. The highest concentration (216.226 mg/kg) was recorded at Site 3 during February, whereas the lowest value (89.781 mg/kg) occurred at Site 2 during April. These results demonstrate a consistent reduction in n-Tetradecane concentration over the sampling period.

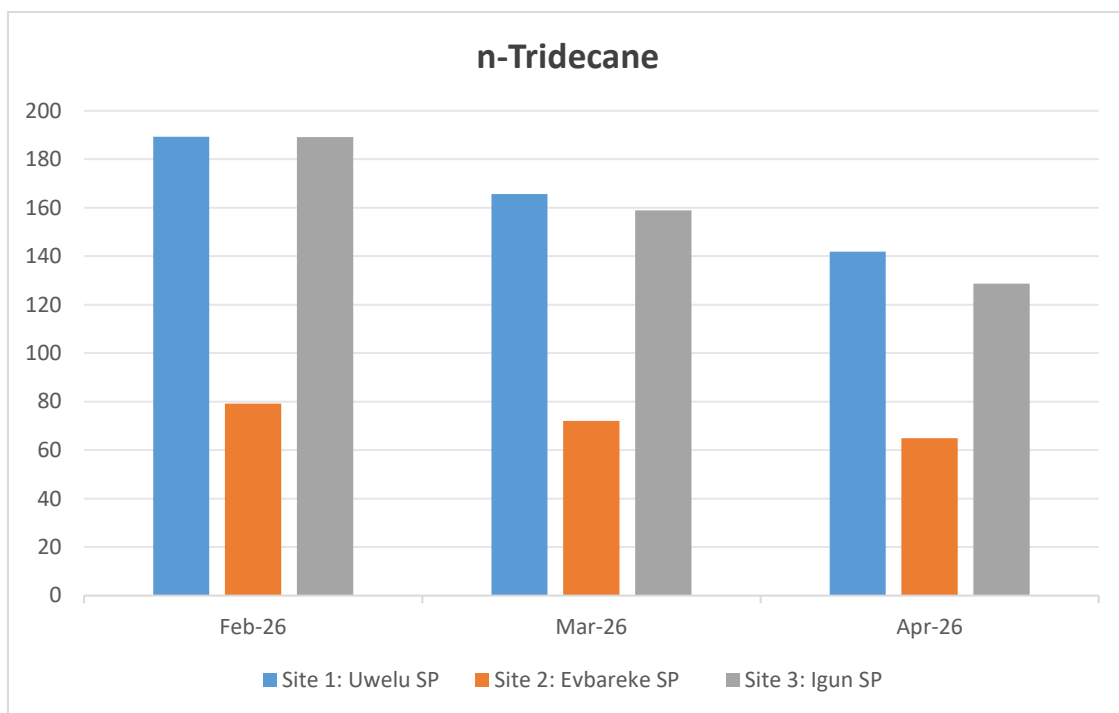


Figure 4: Spatial and temporal variation of n-Tridecane in soil during the sampling months

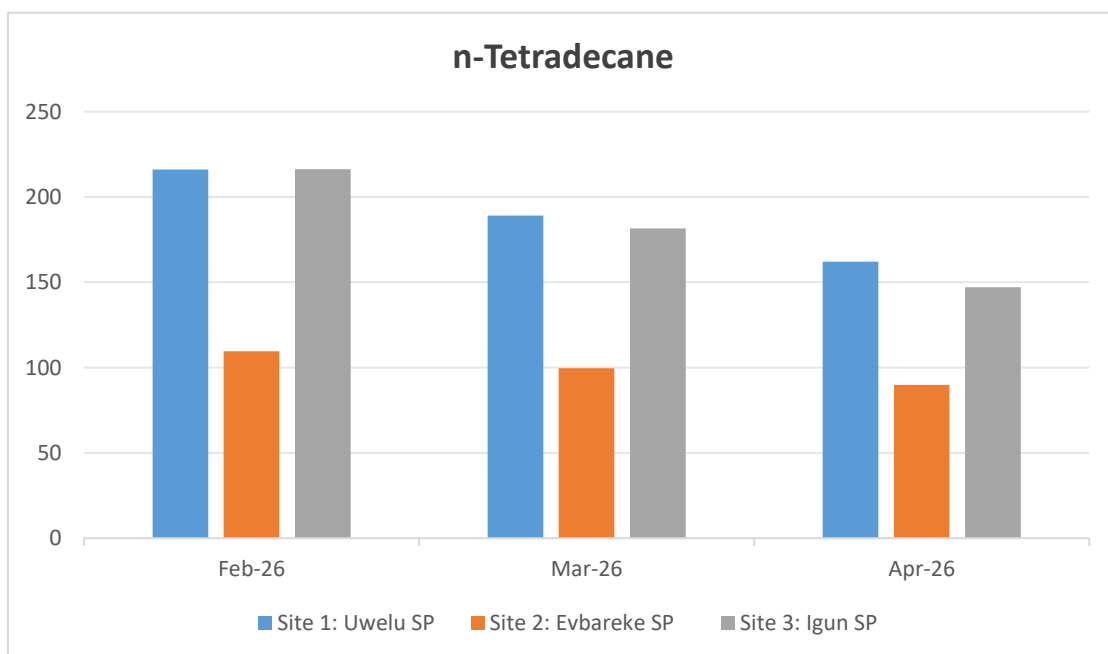


Figure 5: Spatial and temporal variation of n-Tetradecane in soil during the sampling months

n-Pentadecane

Figure 4.5 shows the spatial and temporal variations recorded for n-Pentadecane concentrations in the soil samples from the three sampling stations. At Site 1 (Uwelu SP), concentrations decreased from 345.758 mg/kg in February to 302.538 mg/kg in March and 259.319 mg/kg in April. Site 2 (Evbareke SP) consistently recorded the highest concentrations, declining from 386.126 mg/kg to 351.375 mg/kg and 316.623 mg/kg over the study period. Similarly, Site 3 (Igun SP) exhibited a reduction from 345.738 mg/kg in February to 290.420 mg/kg in March before reaching 235.101 mg/kg in April. The highest concentration (386.126 mg/kg) occurred at Site 2 during February, whereas the lowest value (235.101 mg/kg) was observed at Site 3 during April.

n-Hexadecane

Figure 4.6 shows the spatial and temporal variations recorded for n-Hexadecane concentrations in the soil samples collected from the three sampling stations. Site 1 (Uwelu SP) exhibited a gradual decline from 493.837 mg/kg in February to 432.107 mg/kg in March and 370.378 mg/kg in April. Similarly, Site 2 (Evbareke SP) recorded a decrease from 545.638 mg/kg to 496.531 mg/kg and 447.423 mg/kg, while Site 3 (Igun SP) declined from 491.838 mg/kg in February to 413.144 mg/kg in March before reaching 334.449 mg/kg in April. The highest concentration (545.638 mg/kg) was recorded at Site 2 during February, whereas the lowest value (334.449 mg/kg) occurred at Site 3 during April. Overall, n-Hexadecane displayed a continuous reduction across all sampling stations.

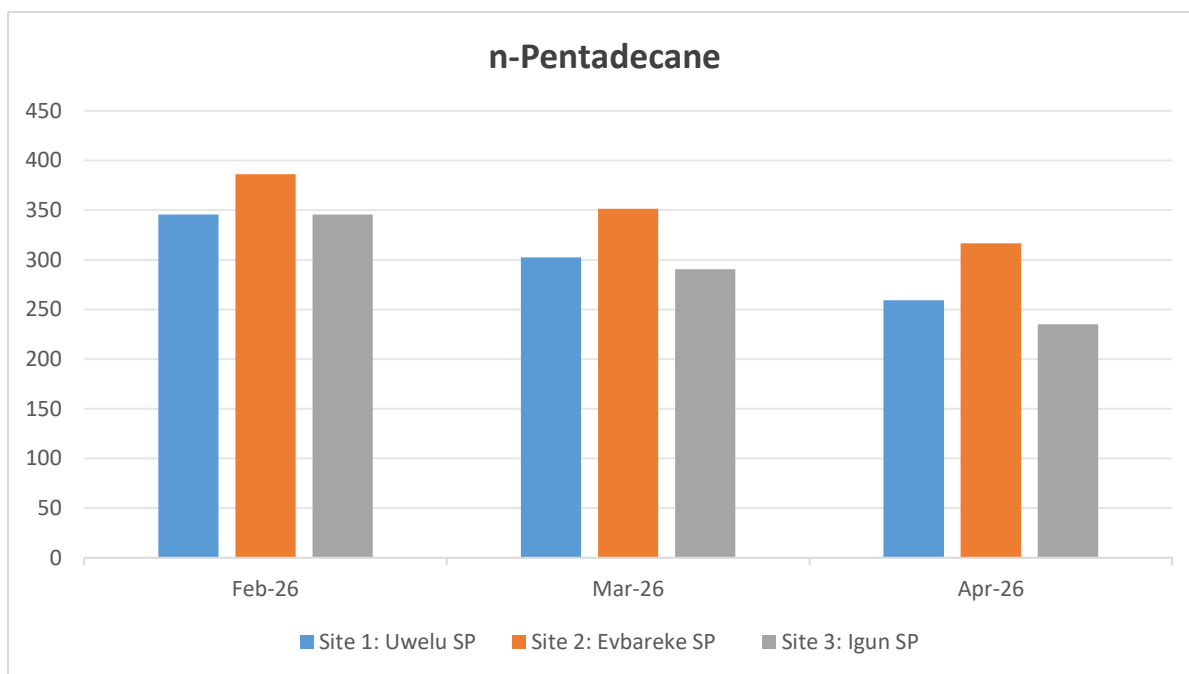


Figure 6: Spatial and temporal variation of n-Pentadecane in soil during the sampling months

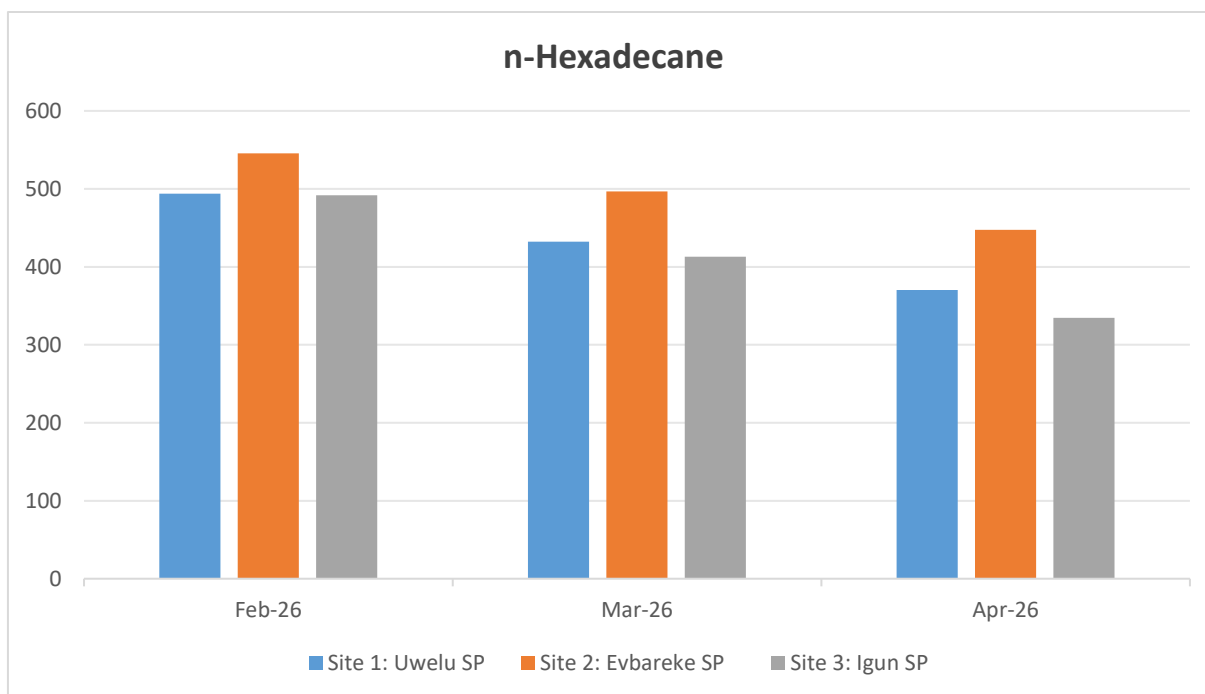


Figure 7: Spatial and temporal variation of n-Hexadecane in soil during the sampling months

n-Heptadecane

Figure 4.7 shows the spatial and temporal variations recorded for n-Heptadecane concentrations in the soil samples obtained from the three sampling stations. Site 1 (Uwelu SP) decreased from 648.454 mg/kg in February to 617.397 mg/kg in March and 586.341 mg/kg in April. Site 2 (Evbareke SP) also showed a progressive decline from 693.858 mg/kg to 631.411 mg/kg and 568.963 mg/kg, while Site 3 (Igun SP) decreased markedly from 656.456 mg/kg to 551.423 mg/kg before reaching 446.390 mg/kg in April. The highest concentration (693.858 mg/kg) was recorded at Site 2 during February, whereas the lowest value (446.390 mg/kg) occurred at Site 3 during April. The results indicate a sustained decrease in n-Heptadecane concentration throughout the sampling period.

n-Octadecane

Figure 4.8 shows the spatial and temporal variations recorded for n-Octadecane concentrations in the soil samples collected from the three sampling stations during the study period. Site 1 (Uwelu SP) recorded concentrations of 746.236 mg/kg, 702.957 mg/kg, and 659.677 mg/kg during February, March and April, respectively. Site 2 (Evbareke SP) exhibited a similar decline from 748.454 mg/kg to 681.093 mg/kg and 613.732 mg/kg, while Site 3 (Igun SP) recorded the highest concentration during February (756.231 mg/kg) before decreasing to 635.234 mg/kg in March and 514.237 mg/kg in April. The highest concentration (756.231 mg/kg) occurred at Site 3 during February, whereas the lowest concentration (514.237 mg/kg) was recorded at the same station during April. Overall, n-Octadecane concentrations declined consistently across all sampling stations throughout the study period.

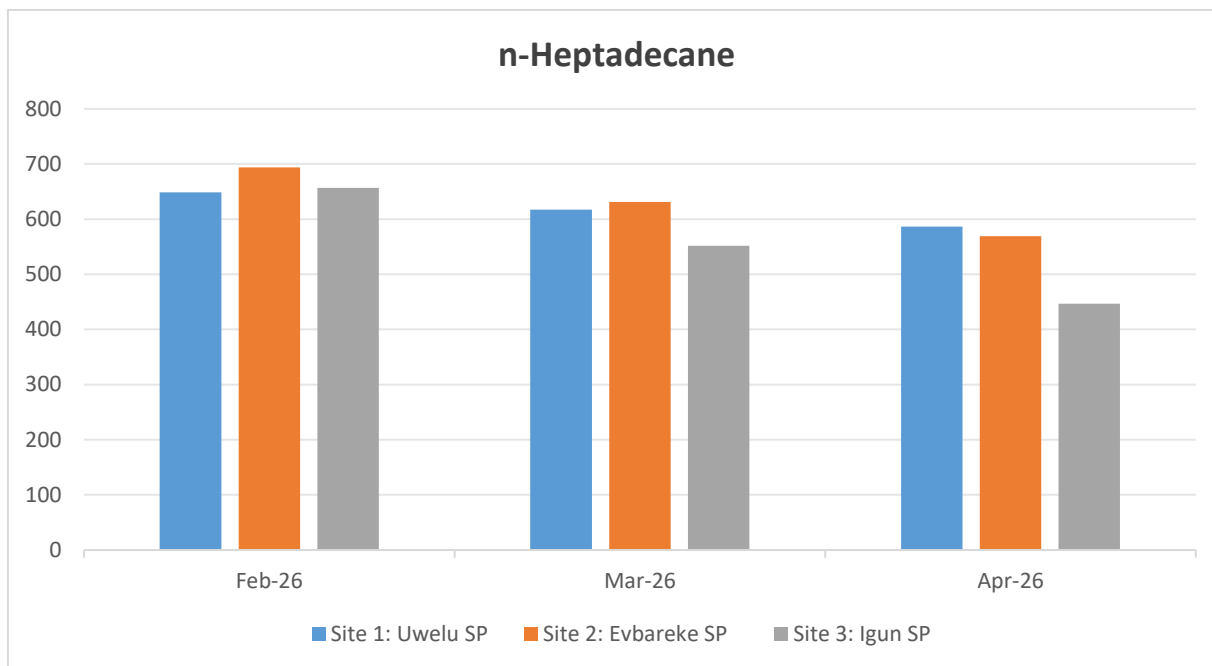


Figure 8: Spatial and temporal variation of n-Heptadecane in soil during the sampling months

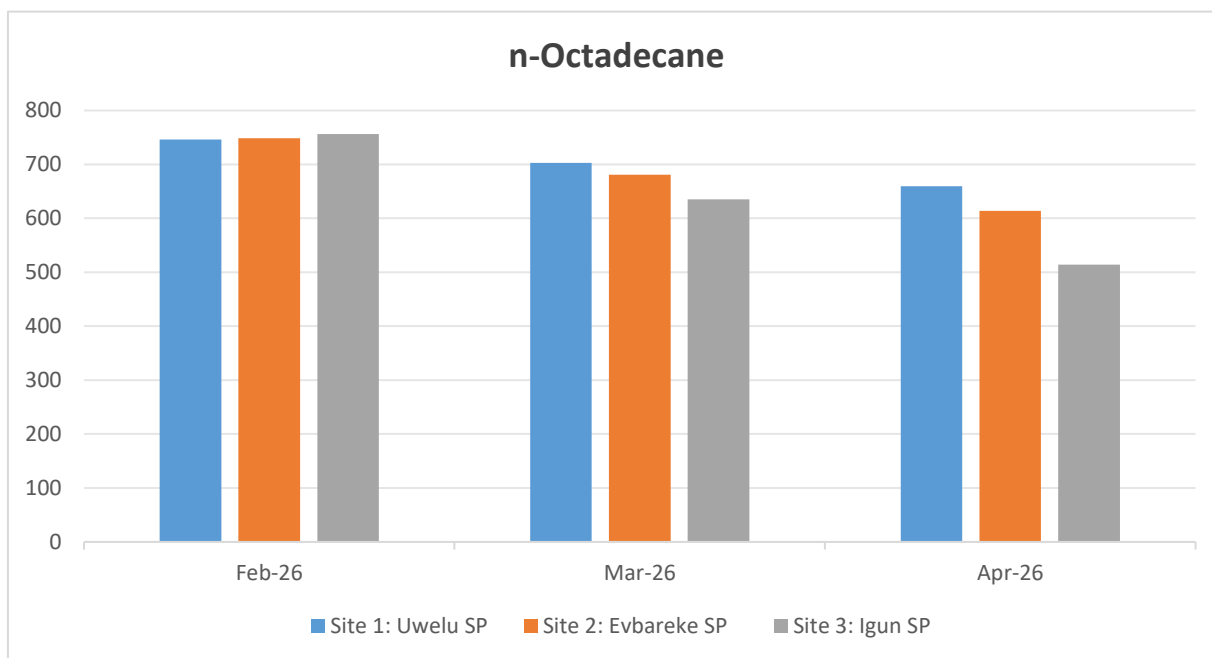


Figure 9: Spatial and temporal variation of n-Octadecane in soil during the sampling months

n-Nonadecane

Figure 4.9 shows the spatial and temporal variations recorded for n-Nonadecane concentrations in the soil samples collected from the three sampling stations during February, March and April 2026. The concentration of n-Nonadecane decreased progressively across all sampling stations throughout the study period. At Site 1 (Uwelu SP), concentrations declined from 633.136 mg/kg in February to 603.994 mg/kg in March and further to 574.852 mg/kg in April. Similarly, Site 2 (Evbareke SP) recorded the highest concentrations throughout the study, decreasing from 844.238 mg/kg in February to 768.257 mg/kg in March and 692.275 mg/kg in April. Site 3 (Igun SP) also exhibited a marked decline from 633.136 mg/kg in February to 531.834 mg/kg in March before reaching 430.532 mg/kg in April. The highest concentration (844.238 mg/kg) was observed at Site 2 during February, whereas the lowest value (430.532 mg/kg) occurred at Site 3 during April. These findings indicate a continuous reduction in n-Nonadecane concentrations across all sampling stations over time.

n-Eicosane

Figure 4.10 shows the spatial and temporal variations recorded for n-Eicosane concentrations in the soil samples obtained from the three sampling stations. Site 1 (Uwelu SP) exhibited a gradual decline from 524.482 mg/kg in February to 458.922 mg/kg in March and 393.362 mg/kg in April. Likewise, Site 2 (Evbareke SP) showed a decrease from 533.436 mg/kg to 485.427 mg/kg and 437.417 mg/kg, while Site 3 (Igun SP) declined from 494.486 mg/kg in February to 415.368 mg/kg in March before reaching 336.250 mg/kg in April. The highest concentration (533.436 mg/kg) was recorded at Site 2 during February, whereas the lowest value (336.250 mg/kg) occurred at Site 3 during April. Overall, n-Eicosane concentrations showed a consistent temporal decline across all sampling stations.

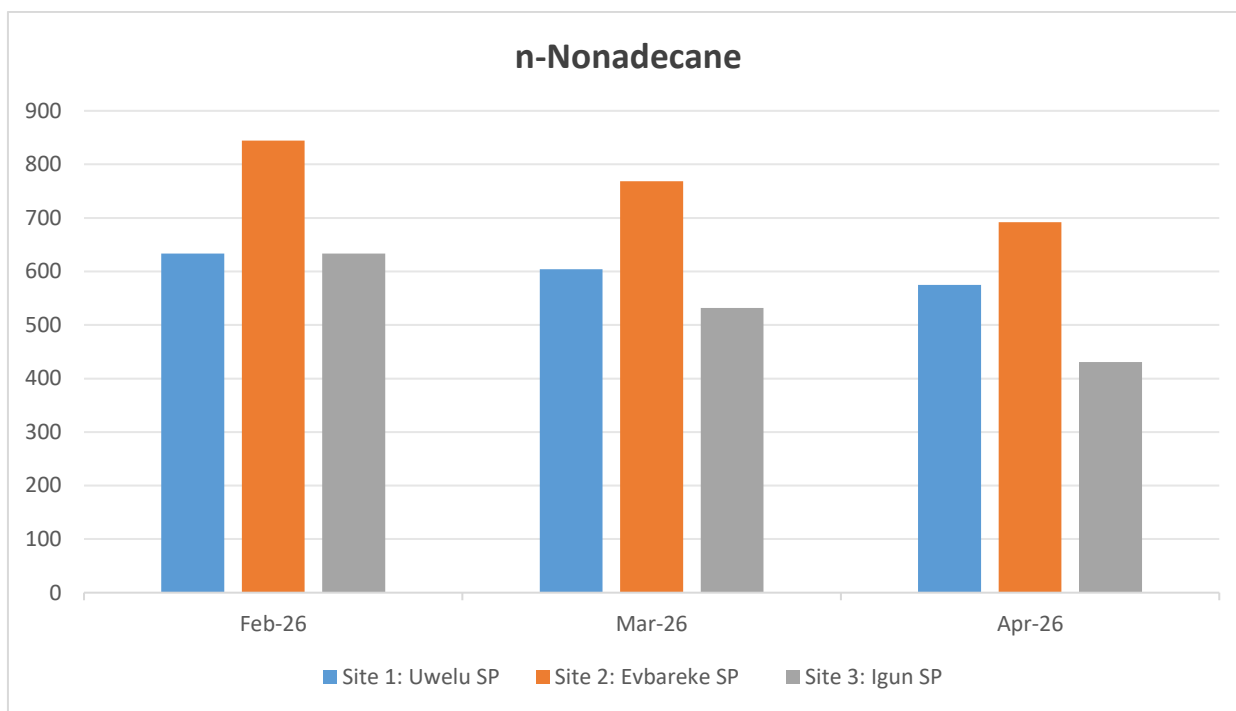


Figure 10: Spatial and temporal variation of n-Nonadecane in soil during the sampling months

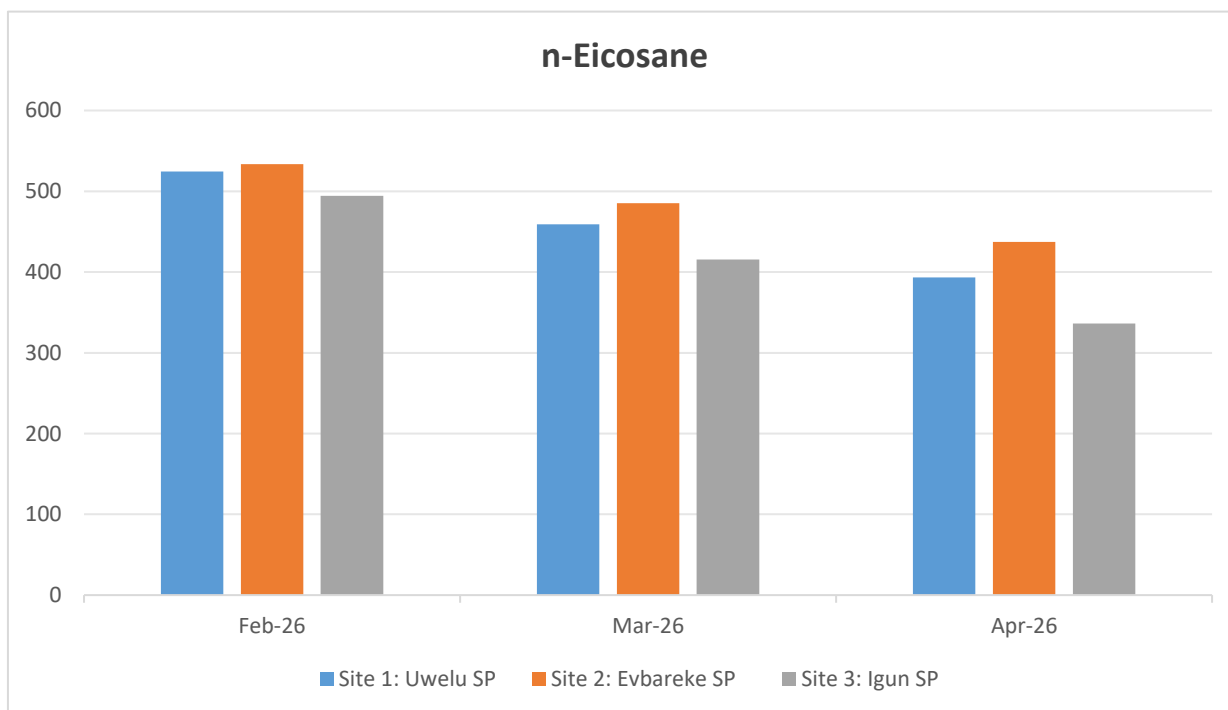


Figure 11: Spatial and temporal variation of n-Eicosane in soil during the sampling months

n-Heneicosane

Figure 4.11 shows the spatial and temporal variations recorded for n-Heneicosane concentrations in the soil samples collected from the three sampling stations. Site 1 (Uwelu SP) recorded concentrations of 398.286 mg/kg, 348.500 mg/kg, and 298.715 mg/kg during February, March and April, respectively. Site 2 (EVBAREKE SP) exhibited the highest concentrations, decreasing from 424.482 mg/kg in February to 386.279 mg/kg in March and 348.075 mg/kg in April. Similarly, Site 3 (IGUN SP) declined from 398.736 mg/kg to 334.938 mg/kg before reaching 271.140 mg/kg in April. The highest concentration (424.482 mg/kg) occurred at Site 2 during February, while the lowest value (271.140 mg/kg) was recorded at Site 3 during April. The overall trend indicates a steady reduction in n-Heneicosane concentrations throughout the sampling period.

n-Docosane

Figure 4.12 shows the spatial and temporal variations recorded for n-Docosane concentrations in the soil samples collected from the three sampling stations during the study period. Site 1 (Uwelu SP) showed a gradual decrease from 176.463 mg/kg in February to 154.405 mg/kg in March and 132.347 mg/kg in April. Site 2 (EVBAREKE SP) consistently recorded the highest concentrations, declining from 298.256 mg/kg in February to 271.413 mg/kg in March and 244.569 mg/kg in April. Site 3 (IGUN SP) also exhibited a reduction from 179.468 mg/kg to 150.753 mg/kg and 122.038 mg/kg over the same period. The highest concentration (298.256 mg/kg) was observed at Site 2 during February, whereas the lowest concentration (122.038 mg/kg) occurred at Site 3 during April. These results indicate a progressive decrease in n-Docosane concentration across all sampling stations.

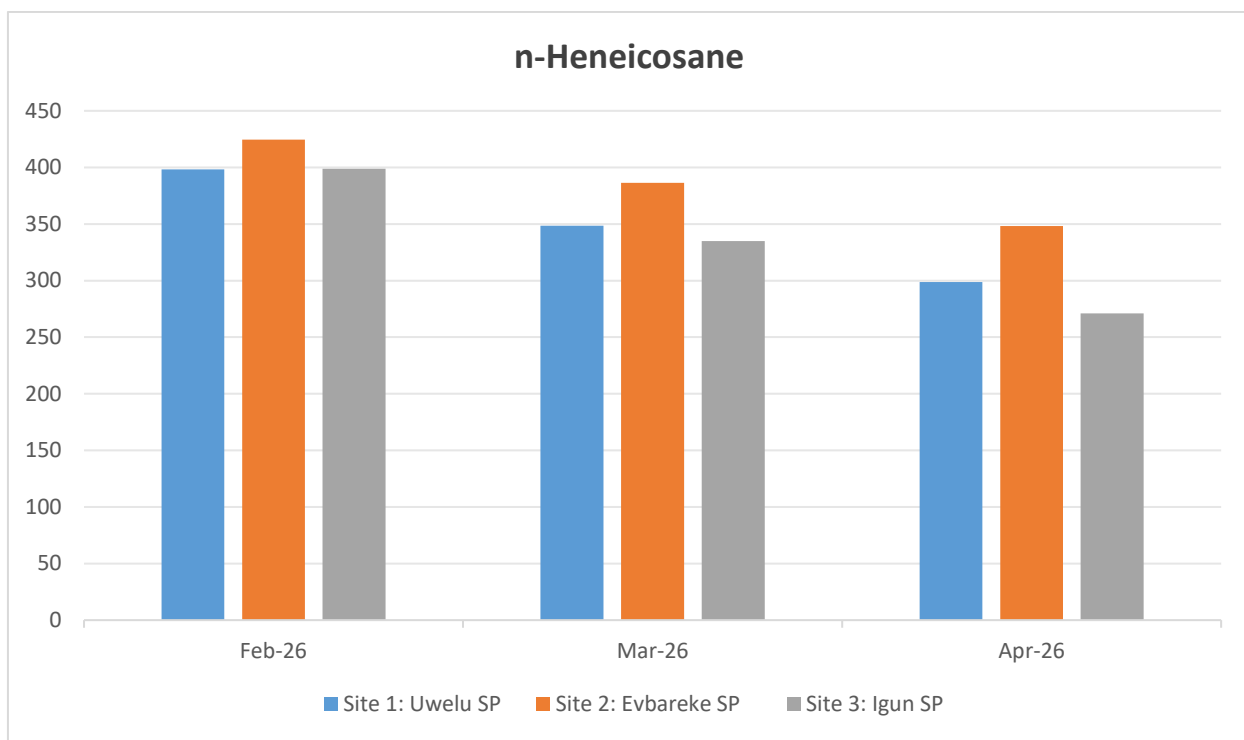


Figure 12: Spatial and temporal variation of n-Heneicosane in soil during the sampling months

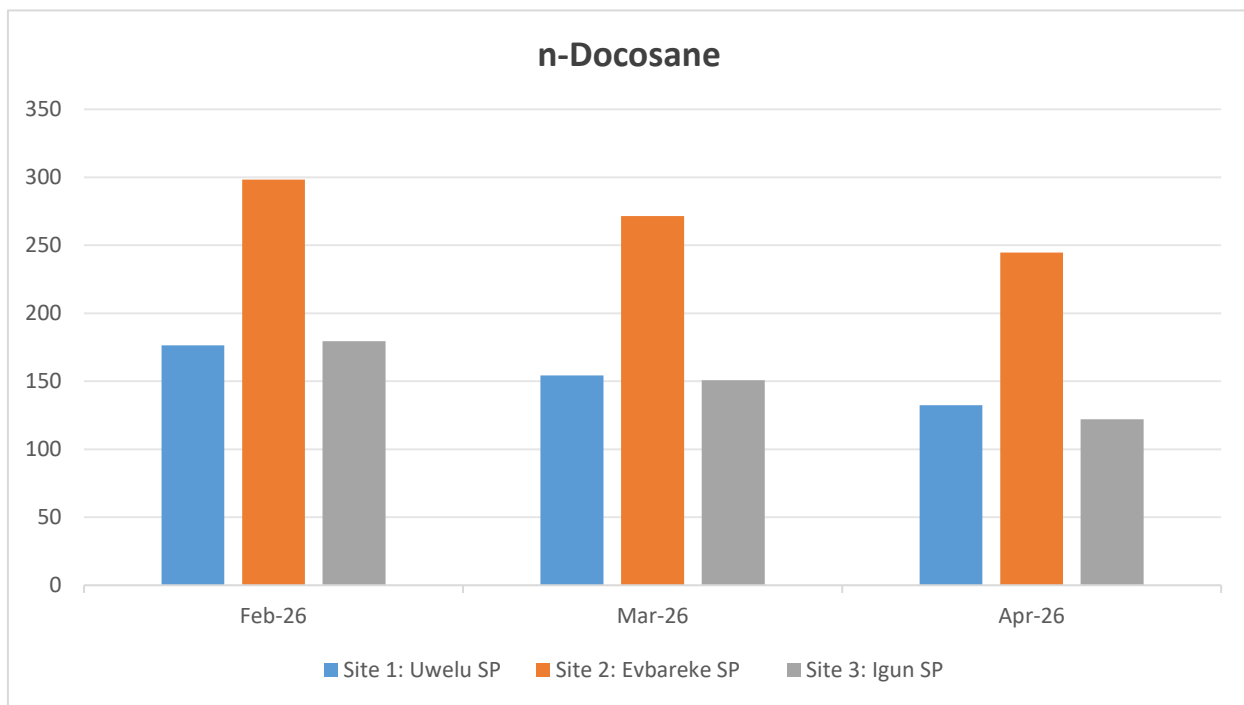


Figure 13: Spatial and temporal variation of n-Docosane in soil during the sampling months

n-Tricosane

Figure 4.13 shows the spatial and temporal variations recorded for n-Tricosane concentrations in the soil samples obtained from the three sampling stations. Site 1 (Uwelu SP) recorded a steady decline from 124.232 mg/kg in February to 108.703 mg/kg in March and 93.174 mg/kg in April. Similarly, Site 2 (Evbareke SP) decreased from 266.468 mg/kg to 242.486 mg/kg and 218.503 mg/kg, while Site 3 (Igun SP) declined from 138.235 mg/kg in February to 116.117 mg/kg in March before reaching 93.999 mg/kg in April. The highest concentration (266.468 mg/kg) was recorded at Site 2 during February, whereas the lowest value (93.174 mg/kg) occurred at Site 1 during April. Overall, n-Tricosane exhibited a consistent decreasing trend throughout the study period.

n-Tetracosane

Figure 4.14 shows the spatial and temporal variations recorded for n-Tetracosane concentrations in the soil samples collected from the three sampling stations. At Site 1 (Uwelu SP), concentrations declined from 84.126 mg/kg in February to 73.610 mg/kg in March and 63.095 mg/kg in April. Site 2 (Evbareke SP) consistently recorded the highest concentrations, decreasing from 184.238 mg/kg to 167.657 mg/kg and 151.075 mg/kg, respectively. Site 3 (Igun SP) exhibited the greatest decline, falling from 64.122 mg/kg in February to 45.362 mg/kg in March before reaching 26.602 mg/kg in April. The highest concentration (184.238 mg/kg) was recorded at Site 2 during February, whereas the lowest value (26.602 mg/kg) occurred at Site 3 during April. These findings demonstrate a pronounced temporal decline in n-Tetracosane concentrations at all sampling stations.

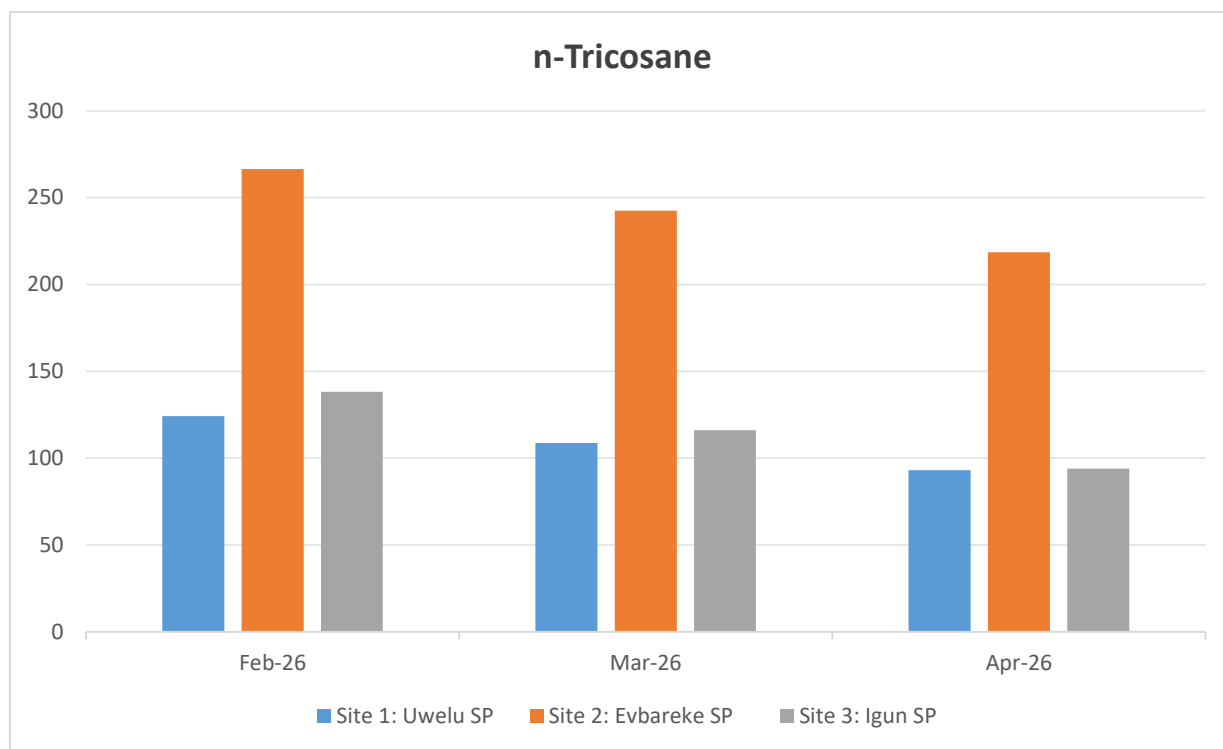


Figure 14: Spatial and temporal variation of n-Tricosane in soil during the sampling months

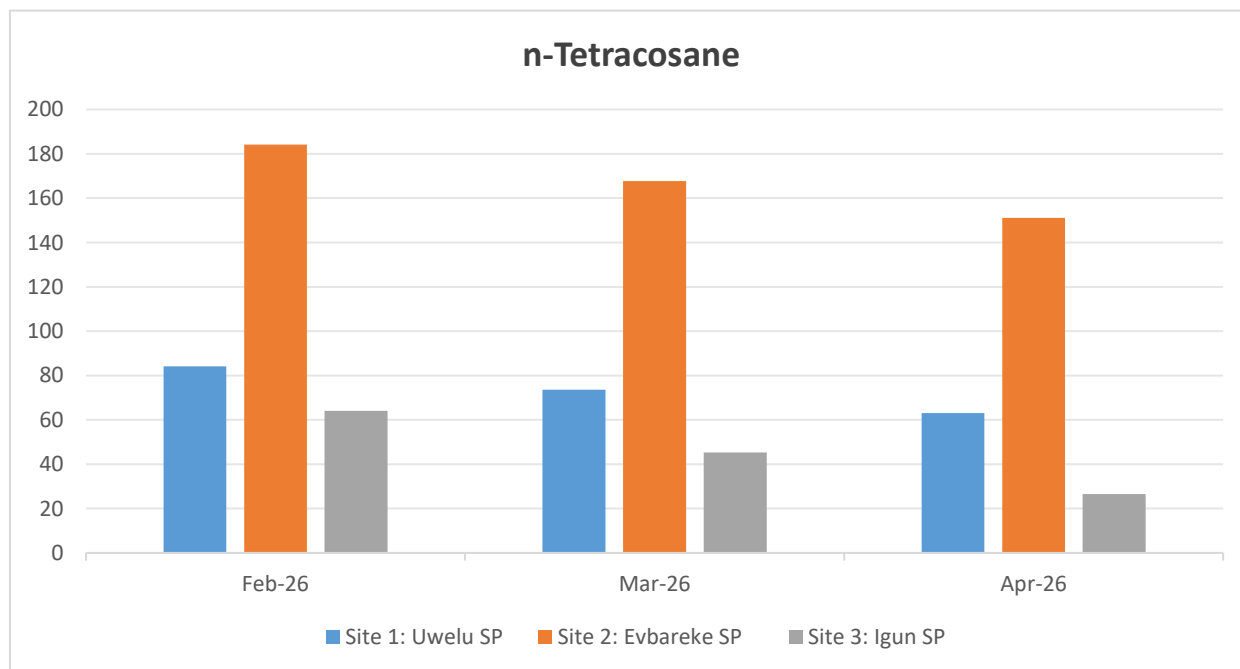


Figure 15: Spatial and temporal variation of n-Tetracosane in soil during the sampling months

n-Pentacosane

Figure 4.15 shows the spatial and temporal variations recorded for n-Pentacosane concentrations in the soil samples collected from the three sampling stations. Concentrations decreased progressively throughout the sampling period. Site 1 (Uwelu SP) declined from 56.235 mg/kg in February to 49.206 mg/kg in March and 42.176 mg/kg in April. Site 2 (EVBAREKE SP) recorded the highest concentrations, decreasing from 74.326 mg/kg in February to 67.637 mg/kg in March and 60.947 mg/kg in April. Site 3 (IGUN SP) also exhibited a gradual decline from 68.542 mg/kg to 65.681 mg/kg before reaching 56.117 mg/kg in April. The highest concentration (74.326 mg/kg) occurred at Site 2 during February, whereas the lowest value (42.176 mg/kg) was recorded at Site 1 during April. Overall, n-Pentacosane concentrations declined steadily across all sampling stations.

n-Hexacosane

Figure 4.16 shows the spatial and temporal variations recorded for n-Hexacosane concentrations in the soil samples collected from the three sampling stations. Unlike most of the hydrocarbon fractions, n-Hexacosane exhibited contrasting temporal trends among the sampling locations. At Site 1 (Uwelu SP), concentrations increased markedly from 10.120 mg/kg in February to 22.450 mg/kg in March and 31.330 mg/kg in April. Site 2 (EVBAREKE SP), however, showed a gradual decline from 52.128 mg/kg in February to 47.436 mg/kg in March and 42.744 mg/kg in April. Site 3 (IGUN SP) exhibited fluctuating concentrations, decreasing from 22.450 mg/kg in February to 13.860 mg/kg in March before increasing sharply to 36.390 mg/kg in April. The highest concentration (52.128 mg/kg) was observed at Site 2 during February, whereas the lowest value (10.120 mg/kg) occurred at Site 1 during February. The results indicate that n-Hexacosane displayed greater temporal variability than the other hydrocarbon fractions.

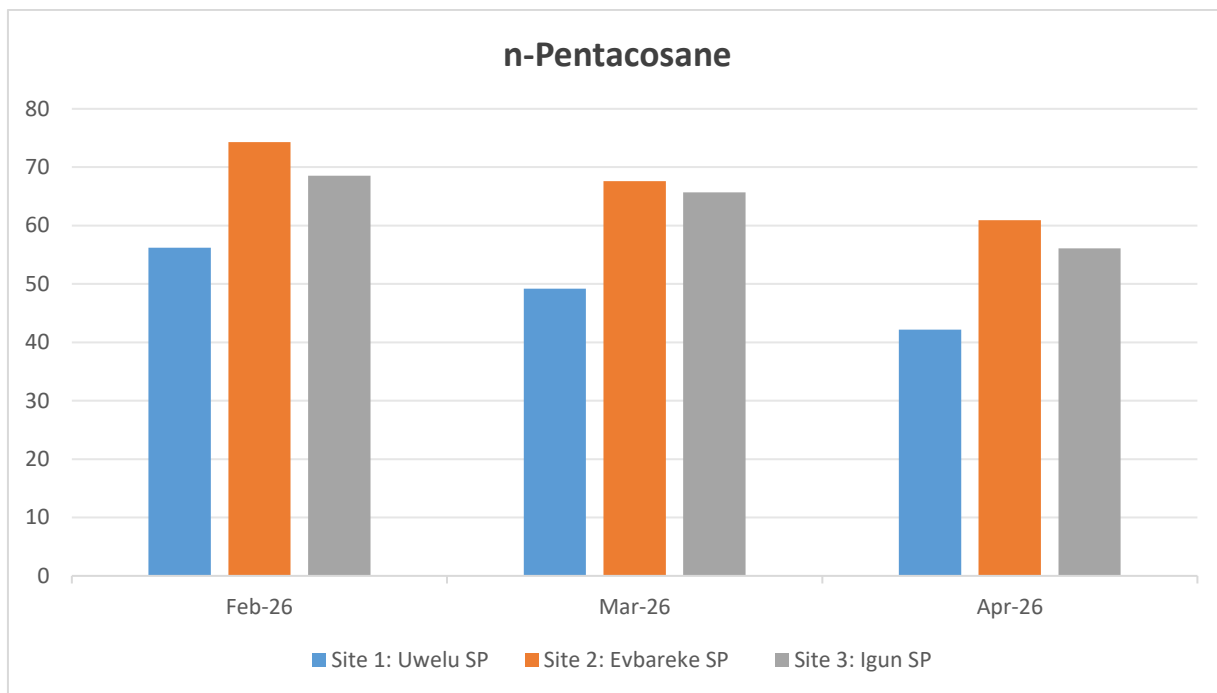


Figure 16: Spatial and temporal variation of n-pentacosane in soil during the sampling months

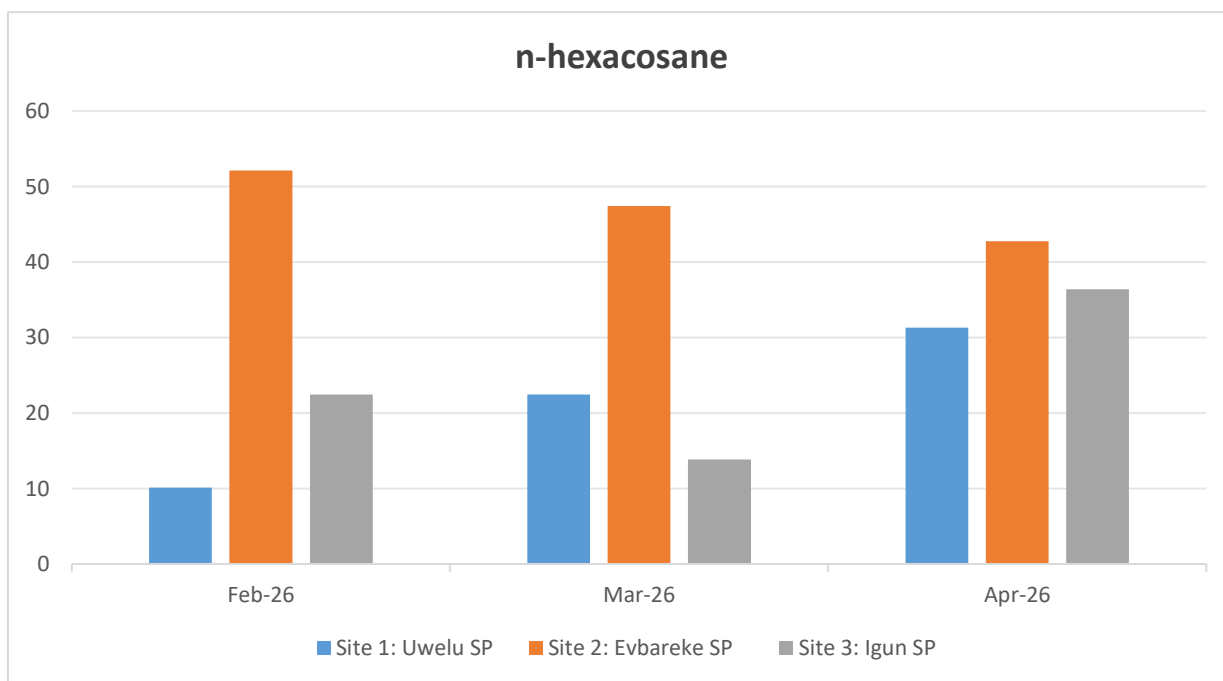


Figure 17: Spatial and temporal variation of n-hexacosane in soil during the sampling months

Total

Figure 4.17 shows the spatial and temporal variations recorded for the total petroleum hydrocarbon concentration in the soil samples collected from the three sampling stations during the study period. The total hydrocarbon fraction decreased consistently across all sampling stations throughout the sampling months. At Site 1 (Uwelu SP), concentrations declined from 4,784.025 mg/kg in February to 4,349.617 mg/kg in March and 3,911.759 mg/kg in April. Similarly, Site 2 (Evbareke SP) recorded the highest total hydrocarbon fraction throughout the study, decreasing from 5,349.530 mg/kg in February to 4,871.090 mg/kg in March before reaching 4,382.053 mg/kg in April. Site 3 (Igun SP) exhibited the greatest reduction, decreasing from 4,762.100 mg/kg in February to 3,990.768 mg/kg in March and 3,243.853 mg/kg in April. Spatially, the highest concentration (5,349.530 mg/kg) was recorded at Site 2 during February, while the lowest value (3,243.853 mg/kg) occurred at Site 3 during April. Overall, the total hydrocarbon fraction showed a clear temporal decline at all sampling stations, indicating a gradual reduction in the concentrations of the quantified hydrocarbon fractions over the sampling period.

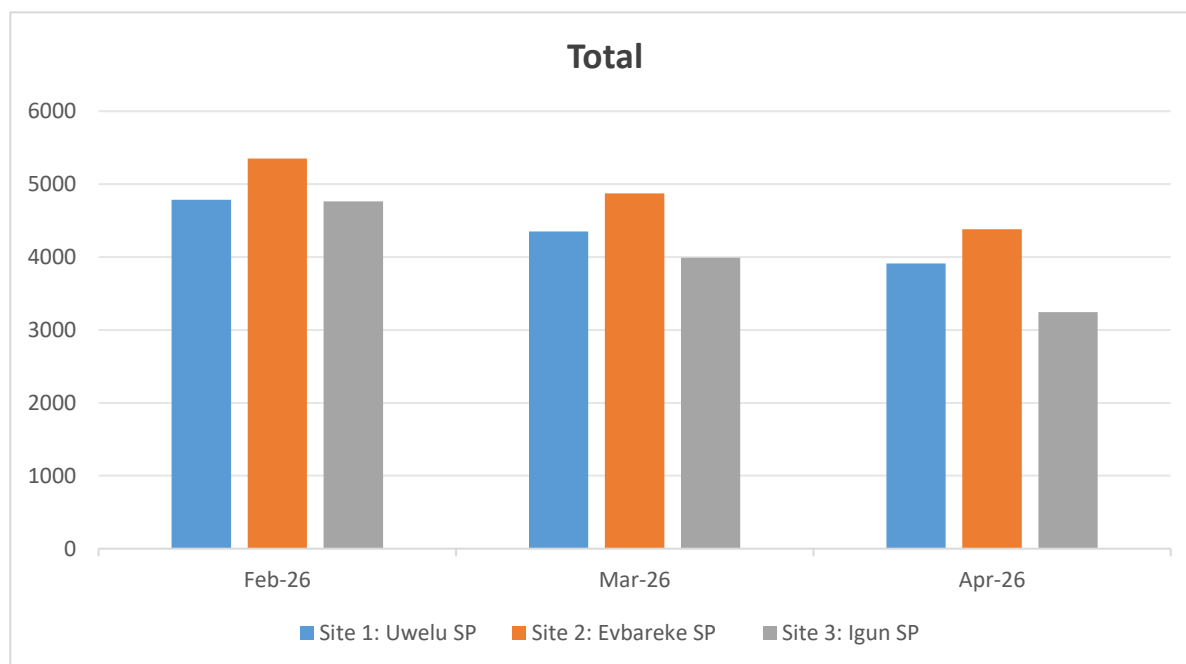


Figure 18: Spatial and temporal variation of the total hydrocarbon fraction concentration in soil during the sampling months

Cluster Analysis for Physicochemical Parameters and Hydrocarbon Fractions in Soils from Auto Mechanic Villages in Benin Metropolis

Table 3 shows the Euclidean similarity and distance indices across the sample stations. Figure 19 presents the dendrogram for cluster analysis based on the concentrations of all the physicochemical parameters and hydrocarbon fractions analyzed in soil samples from the three auto mechanic villages in Benin Metropolis. Figure 20 shows the hierarchical clustering relationship among the measured physicochemical parameters and hydrocarbon fractions in the soil samples.

The sample locations were clustered into three different groups, namely Uwelu, Evbareke, and Igun. The Euclidean dissimilarity and distance indices revealed that the dissimilarity values between the sample locations were 6102.2499 for Uwelu and Evbareke, 6991.0406 for Evbareke and Igun, and 961.9464 for Uwelu and Igun, respectively.

According to the clustering of the dendrogram and the prevailing conditions at the time of sampling, Uwelu (Station 1) and Igun (Station 3) were more similar in terms of their physicochemical properties and hydrocarbon contamination patterns. This similarity suggests that both stations may have been influenced by related contamination sources and environmental conditions. Conversely, the prevailing conditions at Evbareke (Station 2) were considerably different from those recorded at Uwelu and Igun, indicating a distinct contamination profile.

Furthermore, the Euclidean dissimilarity and distance indices showed that Evbareke (Station 2) recorded the highest distance values, indicating the greatest degree of variation among the sampling locations. This dissimilarity, defined by the Euclidean distance and cluster combination using Ward's method, suggests that the physicochemical parameters and hydrocarbon fractions in the soils from the auto mechanic villages exhibited substantial spatial variations. The marked separation of Evbareke may be attributed to more intensive automobile repair activities, a higher frequency of petroleum spills, and differences in soil characteristics at the site.

According to Figure 4.18, several hydrocarbon fractions clustered closely together, indicating similar distribution patterns and suggesting a common source of contamination, primarily from automobile-related activities such as the disposal of spent engine oil, lubricants, and other petroleum products. Similarly, some physicochemical parameters, including electrical conductivity, calcium, magnesium, and bulk density, formed related clusters, indicating that these soil properties may respond similarly to hydrocarbon contamination and influence the retention and behaviour of petroleum hydrocarbons in the soil.

The dendrogram further revealed that Total Hydrocarbon Content (THC) formed a distinct cluster and merged with other variables at a relatively higher distance, indicating that it is one of the major variables contributing to the overall variation in the dataset and plays a significant role in

determining the contamination characteristics of the soils. Overall, the cluster analysis demonstrated that petroleum contamination and soil physicochemical properties are closely interconnected and collectively determine the environmental condition of the studied auto mechanic village soils, also sand and porosity exhibited positive correlation.

Table 3: Cluster Analysis			
	Site 1: Uwelu SP	Site 2: Evbareke SP	Site 3: Igun SP
Site 1: Uwelu SP	0	6102.2499	961.9464
Site 2: Evbareke SP	6102.2499	0	6991.0406
Site 3: Igun SP	961.9464	6991.0406	0

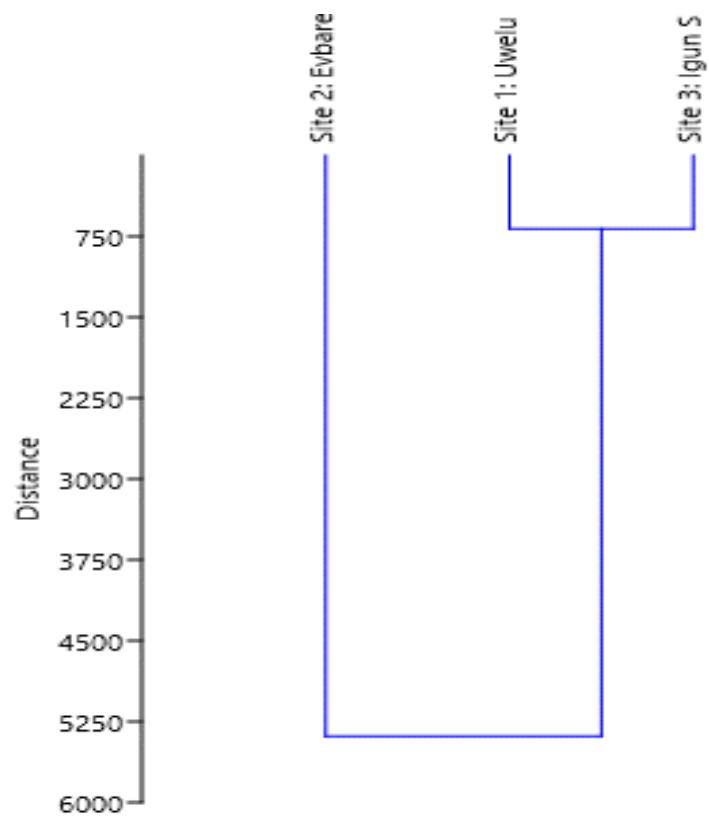


Figure 19: Dendrogram from the cluster analysis of the sample locations

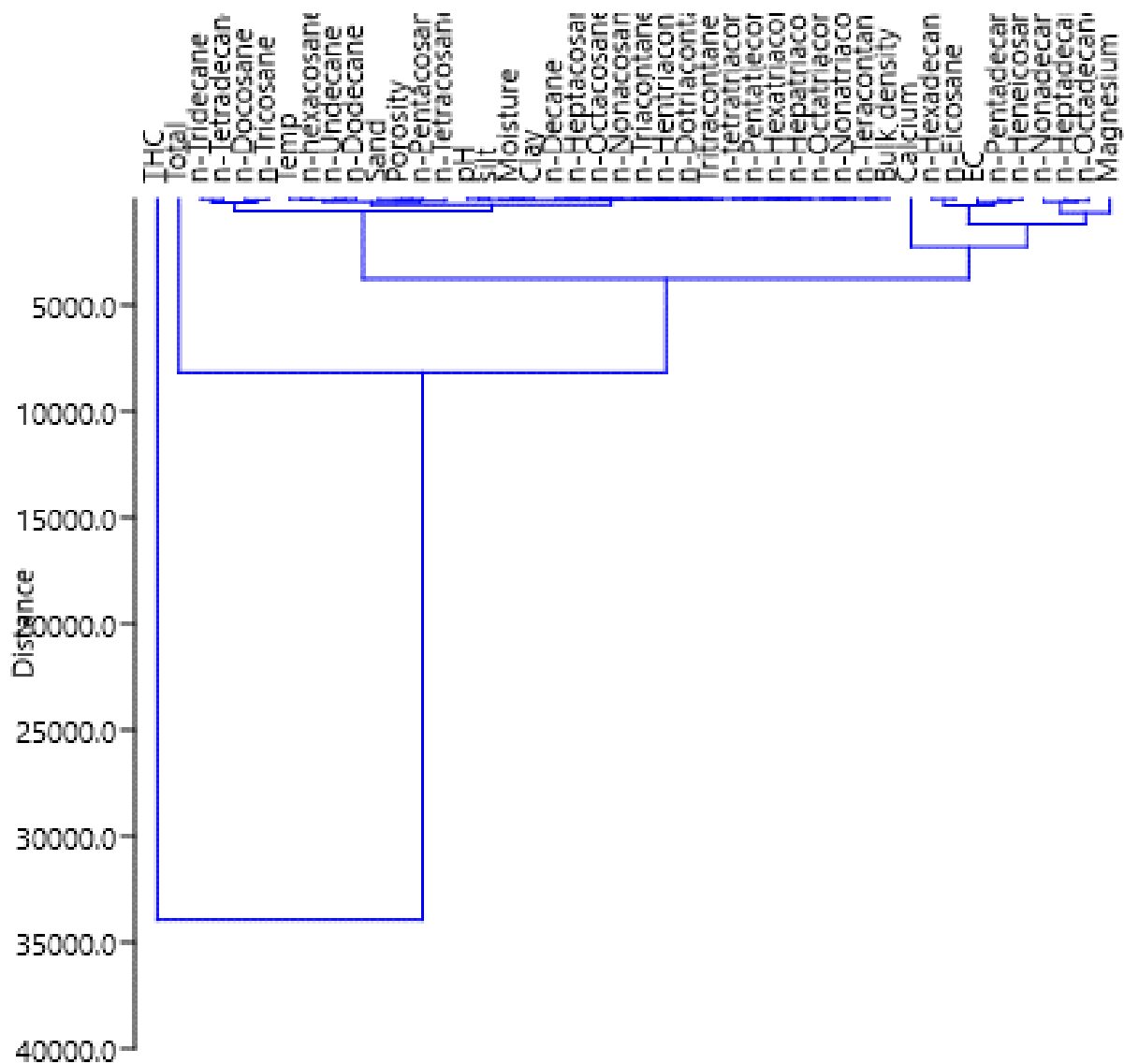


Figure 20: Dendrogram showing the relationships among the measured physicochemical parameters and hydrocarbon fractions

PRINCIPAL COMPONENT ANALYSIS (TPH) OF SOIL SAMPLES FROM AUTO-MECHANIC VILLAGES IN BENIN METROPOLIS

Table 4 presents the Principal Component Analysis of Physicochemical Parameters and Total Petroleum Hydrocarbon Compounds in Soils from Auto Mechanic Villages in Benin Metropolis

In PAST 4.03, Principal Component Analysis (PCA) was used to examine the variations in the measured parameters and to describe the complex interrelationships among the variables through simple patterns expressed as correlations between the parameters. PCA (PAST 4.03) was employed to evaluate the influence of anthropogenic activities on the physicochemical parameters and total petroleum hydrocarbon (TPH) compounds in soils collected from auto mechanic villages in Benin Metropolis. An exploratory factor analysis was conducted to determine the proportion of variation explained by each parameter, and a correlation matrix was generated. The primary data were evaluated for determinant factors, sampling adequacy using the Kaiser-Meyer-Olkin (KMO) test, and sphericity using Bartlett's test before performing factor analysis. Principal components (PCs) with eigenvalues greater than 1.0 were retained for further analysis and subsequently rotated using the varimax rotation method. Adopting Pearson's correlation option and factor loadings after varimax rotation, eigenvectors greater than 0.50 (>0.50) were considered significant, while those less than 0.50 (<0.50) were considered insignificant. The dimensions obtained from the PCA showed relatively high loadings, suggesting that these parameters were reliable contributors to the analysis. There were substantial correlations among the original variables and low residual correlations in the correlation matrix. Table 4.4 shows that four principal components with eigenvalues greater than or equal to 1 (≥ 1) and a cumulative variance of 96.624% were extracted from the soil samples within Benin Metropolis, accounting for most of the variability in the dataset. The contributions of PC₁, PC₂, PC₃, and PC₄ were 41.356%, 32.361%, 16.141%, and 6.766%,

respectively. PC₁ showed high eigenvector loadings for temperature, moisture, bulk density (BD), undecane, dodecane, pentadecane, hexadecane, heptadecane, octadecane, nonadecane, eicosane, heneicosane, and total TPH. PC₂ showed high eigenvector loadings for sand, clay, THC, tridecane, tetradecane, nonadecane, docosane, tricosane, tetracosane, and hexacosane. PC₃ showed high eigenvector loadings for pH, Mg, silt, and porosity, while PC₄ showed high eigenvector loadings for electrical conductivity (EC) and Ca. Table 4 shows the principal component analysis after varimax rotation and the proximity of the lines representing pairs of parameters, which indicates the strength and nature of their relationships in soil samples obtained from the three auto mechanic workshops in Benin Metropolis with respect to the cumulative variability across the principal components. Figure 21 presents the component plot, while Figure 22 shows the scree plot.

Table 4: Principal Component Analysis
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Rotated Component Matrixa					
	Component				Communalities
	1	2	3	4	
Temp	0.937	-0.183	0.214	0.038	0.959
pH	-0.018	-0.297	0.915	-0.253	0.989
EC	-0.473	-0.235	0.248	-0.787	0.961
Moisture	-0.912	-0.028	0.108	0.145	0.865
Ca	-0.003	-0.155	0.419	-0.675	0.655
Mg	0.443	-0.063	0.873	0.159	0.988
Sand	-0.208	-0.892	0.181	-0.217	0.918
Silt	0.132	-0.242	-0.874	0.242	0.898
Clay	0.137	0.951	0.227	0.095	0.984
BD	0.977	-0.022	0.188	-0.081	0.996
Porosity	-0.186	-0.401	0.868	-0.211	0.994
THC	0.086	0.931	-0.209	-0.268	0.99
Undecane	0.925	-0.067	-0.306	0.165	0.982
Dodecane	0.733	-0.45	-0.442	0.212	0.98
Tridecane	0.207	-0.966	0.058	-0.13	0.996
Tetradecane	0.278	-0.948	0.076	-0.114	0.995
Pentadecane	0.87	0.383	0.21	0.225	0.999
Hexadecane	0.882	0.359	0.203	0.225	0.999
Heptadecane	0.974	0.163	-0.1	0.005	0.986
Octadecane	0.989	-0.09	-0.062	-0.025	0.991
Nonadecane	0.699	0.694	-0.058	0.134	0.991
Eicosane	0.951	0.167	0.062	0.245	0.997
Heneicosane	0.919	0.244	0.227	0.209	0.999
Docosane	0.485	0.834	0.13	0.228	0.999
Tricosane	0.385	0.884	0.163	0.204	0.998
Tetracosane	0.444	0.851	-0.086	0.262	0.996
Pentacosane	0.393	0.484	0.77	0.036	0.983
Hexacosane	-0.107	0.946	-0.057	-0.147	0.932
TPH	0.909	0.378	0.063	0.161	0.999
Total	11.993	9.385	4.681	1.962	
% of Variance	41.356	32.361	16.141	6.766	
Cumulative %	41.356	73.717	89.858	96.624	

Component Plot in Rotated Space

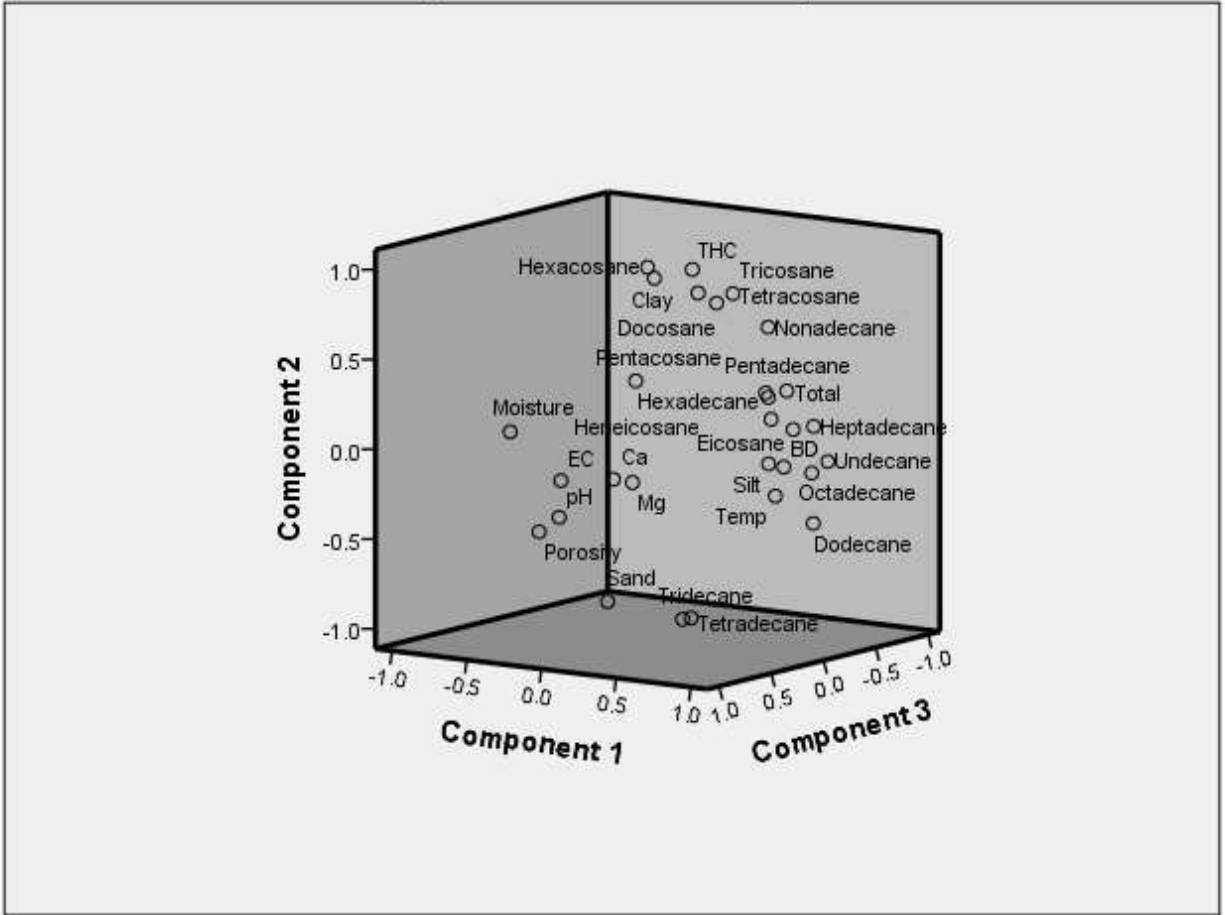


Figure 21: Component plot in rotated space

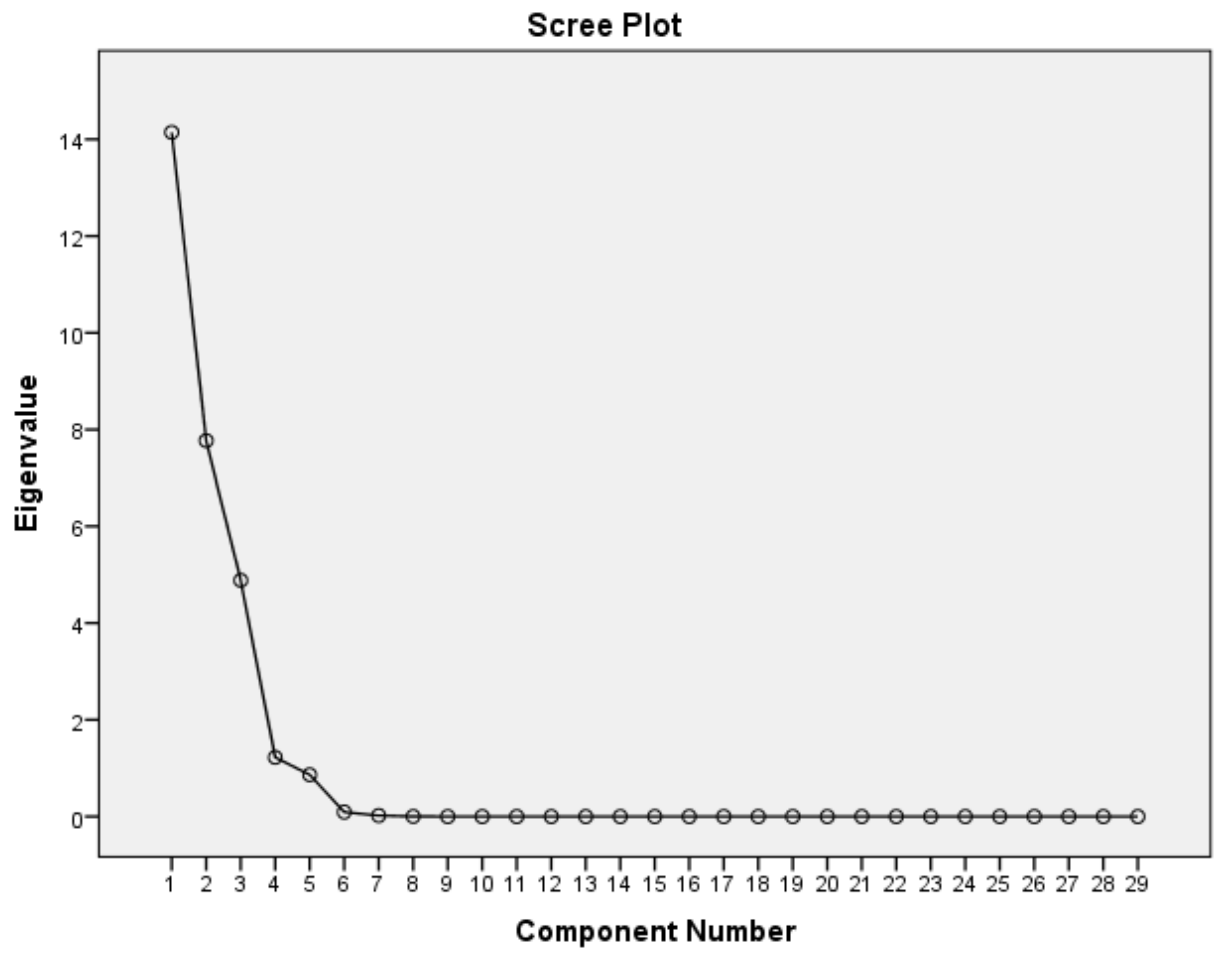


Figure 22: Scree Plot

Correlation Analysis for Physicochemical Parameters and Total Petroleum Hydrocarbon (TPH) Compounds in Soil Samples from Auto-Mechanic Workshops in Benin Metropolis

Figure 23 presents the correlation matrix for the physicochemical parameters and total petroleum hydrocarbon (TPH) compounds in soil samples from three auto-mechanic villages in Benin Metropolis, Edo State. Blue indicates positive correlations, while red indicates negative correlations. The intensity of the ellipses represents the strength of the relationships.

Temperature showed a strong negative relationship with moisture but positive relationships with bulk density and several TPH compounds, particularly the longer-chain hydrocarbons from n-Undecane to n-Hexacosane. Moisture was positively associated with bulk density and several middle- and longer-chain TPH compounds. pH was positively associated with EC and silt but negatively associated with magnesium and porosity. Its relationships with TPH compounds were generally weak to moderate, indicating that pH alone did not consistently control hydrocarbon distribution. EC showed positive relationships with calcium and several TPH compounds. Magnesium was negatively related to pH and sand but positively related to bulk density, silt and several TPH compounds. Silt and clay also showed positive relationships with several hydrocarbons, suggesting that finer soil particles may enhance the retention of petroleum hydrocarbons. Bulk density showed strong positive relationships with temperature and several TPH compounds, particularly n-Pentadecane, n-Hexadecane, n-Heptadecane, n-Octadecane, n-Eicosane and n-Heneicosane. Conversely, porosity was negatively related to bulk density and several TPH compounds, indicating that soil compaction and pore structure may influence hydrocarbon retention. THC was positively associated with several individual TPH compounds, especially the middle- and longer-chain hydrocarbons, as well as some fine soil fractions such as

clay. The TPH compounds showed strong positive correlations with compounds of similar chain lengths. Notably, n-Pentadecane through n-Hexacosane formed a closely associated group, suggesting common petroleum inputs and similar transport, adsorption and retention processes. Overall, the correlation matrix indicates that TPH distribution was influenced by soil physicochemical properties and the relationships among individual hydrocarbon fractions. The strong positive correlations among the middle- and longer-chain hydrocarbons suggest common petroleum-related sources associated with auto-mechanic activities.

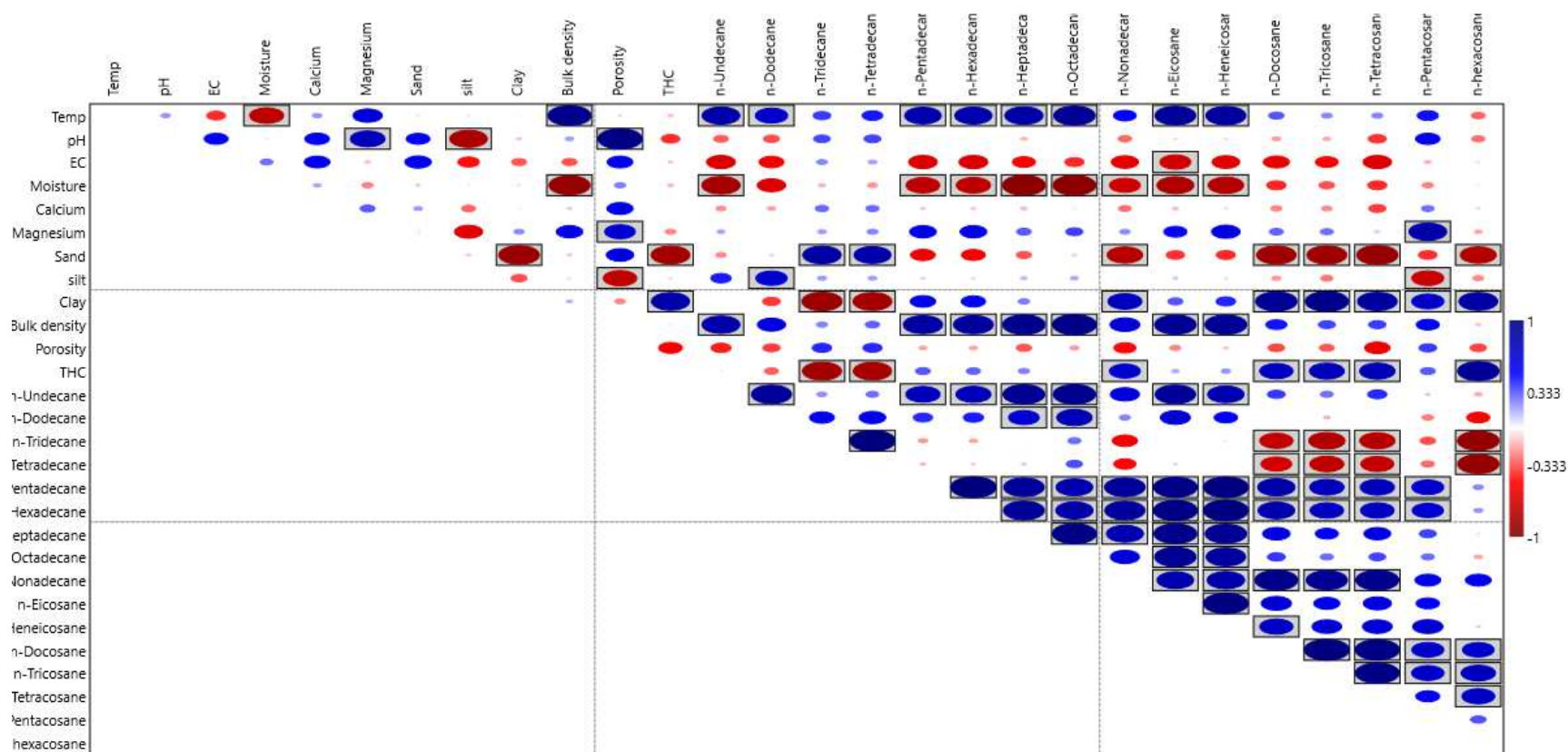


Figure 23: Correlation Matches for Physiochemical and TPH parameters

DISCUSSION OF RESULTS

The soil pH values ranged from neutral to slightly alkaline, with significant variation among the three mechanic villages. Such pH conditions generally favour microbial activity and create a suitable environment for microorganisms capable of degrading petroleum hydrocarbons. Similar findings were reported by Macdonald *et al.* (2021a) and Macdonald *et al.* (2021b), who identified pH as a major factor influencing microbial communities involved in hydrocarbon degradation in petroleum-contaminated soils of Delta State, Nigeria. Likewise, Victoria *et al.* (2025) reported pH values ranging from 4.61 to 5.72 in crude oil-impacted soils in Rivers State, indicating that soil pH remains a critical determinant of contaminant behaviour and microbial activity. Collectively, these studies demonstrate that petroleum-contaminated soils in southern Nigeria commonly maintain pH conditions capable of supporting hydrocarbon biodegradation despite prolonged exposure to petroleum pollutants. Nevertheless, the persistence of high hydrocarbon concentrations in the present study suggests that although soil pH may support microbial degradation, the continuous introduction of petroleum products probably exceeds the natural degradation capacity of the soil ecosystem.

Electrical conductivity showed no statistically significant variation among the mechanic villages despite Igun recording the highest numerical value. Increased electrical conductivity in petroleum-contaminated soils is generally associated with the accumulation of dissolved ions originating from waste lubricants, engine fluids, and other automotive materials. Comparable observations have been reported by Elisha (2012), who attributed elevated conductivity levels in contaminated soils to the presence of soluble salts and ionic constituents introduced through petroleum wastes. Similarly, Kabari *et al.* (2017) assessed over 110 oil-contaminated communities in Ogoniland and

reported widespread alterations in soil quality resulting from long-term petroleum hydrocarbon contamination. The lack of significant differences among the study locations indicates that the ionic composition of the soils has been similarly influenced by automobile repair activities across the three mechanic villages. This suggests that the continuous discharge of petroleum-related wastes has produced relatively uniform effects on soil conductivity across the study area, regardless of the slight numerical increase observed at Igun.

Moisture content, calcium, magnesium and bulk density also exhibited no significant differences among the sampling locations, indicating relatively similar physical and mineral characteristics despite differences in contamination intensity. In contrast, porosity differed significantly among the sites, with Igun recording the highest value. Higher soil porosity increases the movement of water and dissolved contaminants through the soil matrix, thereby enhancing the transport of petroleum hydrocarbons into deeper soil horizons. This observation agrees with Truskewycz *et al.* (2019), who reported that petroleum hydrocarbons undergo dispersion, dissolution, and sorption within terrestrial environments, processes that influence their movement, distribution, and persistence in contaminated soils. Ite and Ibok (2019) similarly emphasized the importance of soil characteristics and plant-microbe interactions in determining the fate and behaviour of petroleum hydrocarbons and the effectiveness of bioremediation. Sui *et al.* (2021) also reported that soil properties influence the migration and distribution of petroleum hydrocarbons within contaminated environments. These findings indicate that soils with greater pore spaces can facilitate the downward movement and wider distribution of petroleum hydrocarbons, potentially increasing the risk of contamination in deeper soil layers and groundwater.

The Total Hydrocarbon Content (THC) analysis revealed considerable hydrocarbon contamination in soils from all three mechanic villages. Although Evbareke recorded the highest mean THC concentration, followed by Uwelu and Igun, statistical analysis showed that the differences were not significant. This finding indicates that hydrocarbon contamination is relatively widespread across the mechanic villages and may result from prolonged exposure to similar pollution sources. Comparable findings were reported by Adebisi *et al.* (2011), who detected high total hydrogen content levels in soils around automobile workshops and recorded higher concentrations of several elements in oil-contaminated soils compared with other Nigerian soils. Obini *et al.* (2013) also reported elevated hydrocarbon concentrations around automobile workshops, linking the contamination to the improper handling and disposal of used petroleum products. Similarly, Nyarko *et al.* (2019) found that petroleum fuels and lubricants altered soil properties around automobile workshops, with significant correlations between temperature and electrical conductivity ($r = -0.689$, $p < 0.01$), pH and conductivity ($r = 0.549$, $p < 0.01$), and moisture and nitrate ($r = 0.787$, $p < 0.01$). These findings support the present study by demonstrating that automobile workshop activities contribute substantially to petroleum hydrocarbon contamination and associated changes in soil properties. The uniformly high THC concentrations observed in the present study therefore demonstrate that automobile maintenance activities continue to constitute a major source of hydrocarbon pollution in urban soils.

The distribution of individual petroleum hydrocarbon fractions provides additional evidence regarding the origin and persistence of petroleum contamination. The complete absence of n-Decane from all sampling locations suggests that lighter hydrocarbon fractions had undergone extensive volatilisation following their release into the environment. This observation agrees with Kanghee *et al.* (2020), who investigated the removal of total petroleum hydrocarbons from

contaminated soils and reported that hydrocarbon removal increased with irradiation time and temperature, with coarse soil achieving a removal efficiency of 91.1% within 15 minutes, while fine soil recorded 71.2% after 30 minutes. The authors also established that soil particle size and permeability influenced hydrocarbon evaporation. Similarly, Bassazin *et al.* (2024) reviewed the degradation and removal of petroleum hydrocarbons and identified volatilisation and biodegradation among the processes responsible for reducing hydrocarbon concentrations in contaminated soils. These findings support the absence of n-Decane in the present study, as its relatively low molecular weight makes it more susceptible to volatilisation and weathering than heavier hydrocarbon fractions. Conversely, several medium-chain and higher molecular weight hydrocarbons remained abundant in the present study, indicating the persistence of weathered petroleum products within the mechanic villages.

Significant spatial variations were observed for several petroleum hydrocarbon fractions, including n-Undecane, n-Dodecane, n-Tridecane, n-Tetradecane, n-Nonadecane, n-Docosane, n-Tricosane, n-Tetracosane, n-Pentacosane and n-Hexacosane. Evbareke consistently recorded higher concentrations of many of the heavier hydrocarbon fractions, particularly n-Nonadecane, n-Docosane, n-Tricosane, n-Tetracosane and n-Hexacosane. These compounds are relatively resistant to weathering and biodegradation and are commonly associated with used lubricating oils and aged petroleum residues. Their predominance suggests prolonged hydrocarbon accumulation arising from continuous automobile servicing activities. Similar hydrocarbon profiles have been documented in petroleum-contaminated soils where long-term waste engine oil disposal resulted in the persistence of higher molecular weight hydrocarbons.

In contrast, hydrocarbon fractions from n-Heptacosane (C27) to n-Tetracontane (C40) were not detected in any of the soil samples. Their absence may indicate either complete degradation over time or concentrations below the analytical detection limits. The predominance of hydrocarbons between C11 and C26 therefore suggests that contamination within the mechanic villages is largely associated with weathered engine oils, lubricants and related petroleum products rather than crude petroleum itself.

The multivariate statistical analyses provided further insight into the relationships among the measured soil variables. Cluster analysis demonstrated that Uwelu and Igun exhibited greater similarity in their physicochemical characteristics and hydrocarbon composition than either site shared with Evbareke. This clustering pattern suggests that Uwelu and Igun have been influenced by comparable contamination sources and environmental conditions, whereas Evbareke possesses a relatively distinct contamination profile. The greater Euclidean distance recorded for Evbareke indicates higher variability in its soil properties and hydrocarbon composition, which may be related to more intensive automobile repair activities, greater volumes of petroleum products handled, differences in waste disposal practices, or variations in soil texture. Similar patterns were reported by Biose *et al.* (2025) who demonstrated substantial spatial variation in petroleum contamination across five oil-producing communities, with total PAH concentrations ranging from 926.537 in the control site at Sapele to 10,049.543 in Emevor, while total TPH concentrations ranged from 1,218.361 µg/kg at Sapele to 6,788.221 µg/kg at Emevor. These findings support the present clustering pattern, as differences in contamination intensity and environmental conditions can produce distinct chemical profiles among sampling locations.

The hierarchical clustering of the measured variables further demonstrated close associations among several hydrocarbon fractions, indicating that these compounds originated from common anthropogenic sources. Similarly, electrical conductivity, calcium, magnesium and bulk density clustered together, suggesting that these soil properties respond collectively to petroleum contamination and may influence hydrocarbon retention within the soil matrix. The distinct clustering of Total Hydrocarbon Content further confirms its importance as one of the principal variables characterising petroleum contamination across the study area.

CONCLUSION

Soils from the selected auto-mechanic villages in Benin Metropolis were contaminated with petroleum hydrocarbons associated with prolonged automobile repair and maintenance activities. Although Total Hydrocarbon Content (THC) did not differ significantly among the study sites, the elevated concentrations of petroleum hydrocarbon compounds and the results of multivariate statistical analyses confirmed the widespread occurrence of hydrocarbon contamination and identified anthropogenic activities as the major sources. The predominance of sandy soils, together with significant relationships among the measured physicochemical properties and hydrocarbon compounds, indicates favourable conditions for the movement and persistence of petroleum pollutants in the affected soils. The widespread occurrence of petroleum hydrocarbons across the study locations highlights potential ecological and human health risks associated with continued contamination of auto-mechanic environments. Improper handling and disposal of used engine oil, fuels, lubricants and other petroleum-containing wastes may contribute to the persistence and spread of these pollutants. More stringent enforcement of environmental regulations governing petroleum waste management in auto-mechanic villages is therefore necessary. Improved waste

management practices, regular environmental monitoring and appropriate remediation measures should be prioritised to protect soil quality and reduce potential ecological and human health risks. Bioremediation and phytoremediation should also be considered as sustainable approaches for restoring contaminated soils. Consistent monitoring of soil quality and petroleum hydrocarbon concentrations would provide valuable information for early detection of contamination and timely intervention.

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