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REVIEW

Assessment of petroleum contamination in soil, water, and atmosphere: a comprehensive review

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Abstract

In recent decades, the discovery, extraction, and export of petroleum have significantly strengthened the economy. However, the processes of petroleum exploration, development and production have localized negative impacts on the atmosphere, soil, sediments, surface, groundwater, marine environment, and terrestrial ecosystems. The presence of petroleum hydrocarbons and waste streams has led to environmental pollution that poses risks to human health, affects socioeconomic conditions, and impacts communities in oil-producing countries. It is therefore crucial to promote a deeper understanding of petroleum contamination in soil, water, and atmosphere—an understanding that is actively evolving. The literature will mark a new milestone in the study of petroleum contamination and highlight significant advances in this environmental field. This comprehensive review examines the wide-ranging impacts of petroleum contamination on soil, water, and the atmosphere and aims to identify potential mitigation strategies that can reduce the impact on the environment and human health. Focusing on the latest technologies and practices for petroleum spill monitoring, remediation, and prevention, the report addresses all facets of this issue and helps researchers identify opportunities and gaps. It provides an assessment of the different treatment approaches for the period from 2010 to 2022 and discusses the advantages and disadvantages of each technique. Finally, it addresses the challenges that need to be overcome in the detection and treatment of oil spills.

Keywords Petroleum contamination · Environmental impact · Mitigation strategies · Monitoring technologies · Treatment approaches

Abbreviations

AAS	Atomic absorption spectrophotometer
AE	Autoencoders
AH	Aliphatic hydrocarbons
ANN	Artificial neural networks
ANOVA	Analysis of variance
AOP	Advanced oxidation processes
AVH	Aromatic volatile hydrocarbons
BR	Bioremediation
BTEX	Benzene, toluene, ethylbenzene, and xylene
CLEA	Contaminated land exposure assessment
CNN	Convolutional neural networks
COD	Chemical oxygen demand
COPD	Chronic obstructive pulmonary disease
DBN	Deep belief networks

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DDPH	Dissolved dispersed petroleum hydrocarbons
DL	Deep learning
DNAPL	Dense non-aqueous phase liquid
DRS	Diffuse reflectance spectroscopy
DT	Decision tree
EQC	Equilibrium criterion
ERCB	Energy resources conservation board
ESI-MS	Electrospray ionization mass spectrometry
GAN	Generative adversarial networks
GC-FID	Gas chromatography-flame ionization detector
GC-MS	Gas chromatography-mass spectrometry
GC-MSD	Agilent gas chromatograph-mass selective detector
GHG	Greenhouse gas protocol
GIS	Geographic information systems
HFO	Heavy fuel oil
HM	Heavy metal
HPLC	High-performance liquid chromatography
HRS	Hyperspectral remote sensing
IDINT	Inverse distance interpolation
IDW	Inverse distance weighted
IV	Intervention value
KSTM	Korean standard test method
LSD	Least significant difference
MAH	Monocyclic aromatic hydrocarbons
MIR	Mid-infrared
ML	Machine learning
NDVI	Normalized difference vegetation index
NOx	Nitrogen oxides
NSZD	Natural source zone depletion
PAH	Polycyclic aromatic hydrocarbon
Pb	Lead
PC	Petroleum contamination
PH	Petroleum hydrocarbons
PRI	Polluted risk intensity
PXRF	Portable X-ray fluorescence
QCL	Quantum cascade lasers
RBCA	Risk-based corrective action
RBC	Risk-based corrective action
RF	Random forest
RNN	Recurrent neural networks
RSP	Respirable suspended particulate
SAR	Synthetic aperture radar
SAS	Seep assessment study
SLAR	Side-looking airborne radar
SO2	Sulfur dioxide
SPSS	Statistical Package for the Social Sciences
SVM	Support vector machine
TDS	Total dissolved solids
TEQ	Toxic equivalent quantity
TIR	Thermal infrared
TLC	Thin-layer chromatography
TOC	Total organic carbon
TPH	Total petroleum hydrocarbons
UCM	Unresolved complex mixture
UVF	Ultraviolet fluorimeter
VisNIR	Visible near-infrared
VOC	Volatile organic compounds
WSF	Water-soluble fractions of oil

Introduction

The presence of petroleum hydrocarbon pollutants in soil, water, and the atmosphere has a significant impact on the environment and poses a serious threat to humans and other life forms in the affected areas (Sammarco et al. 2016). These pollutants, which make up a large proportion of organic chemicals and by-products, are classified as priority environmental pollutants due to their persistence and viscosity—examples include persistent organic pollutants (POPs) and polycyclic aromatic hydrocarbons (PAHs). As they cannot be degraded, they remain in the environment for long periods of time (Gennadiev et al. 2015). Studies on pollutant sources show that the primary pollutant groups often co-occur in pollution, although their composition can vary depending on location, source activity, season, weather, and time of year (Dickey 2000).

Despite the progress that has been made in modernizing the petroleum industry, it continues to be a major contributor to soil pollution as it introduces an abundance of oily compounds into this fragile environment (Wang et al. 2011; Ambaye et al. 2022). This pervasive pollution affects the structure of the soil, the intricate web of microorganisms, including bacteria and fungi, and the vital network of plant roots (Borowik and Wyszkowska 2018). The inherent value of petroleum as a precious global resource underscores the widespread extraction and large-scale drilling in regions rich in this vital commodity. The dual identity of oil as a vital resource and as a major cause of environmental damage requires a nuanced approach. To protect the health and resilience of our invaluable soils, a delicate balance must be struck between the imperative need for extraction and the implementation of sustainable practices.

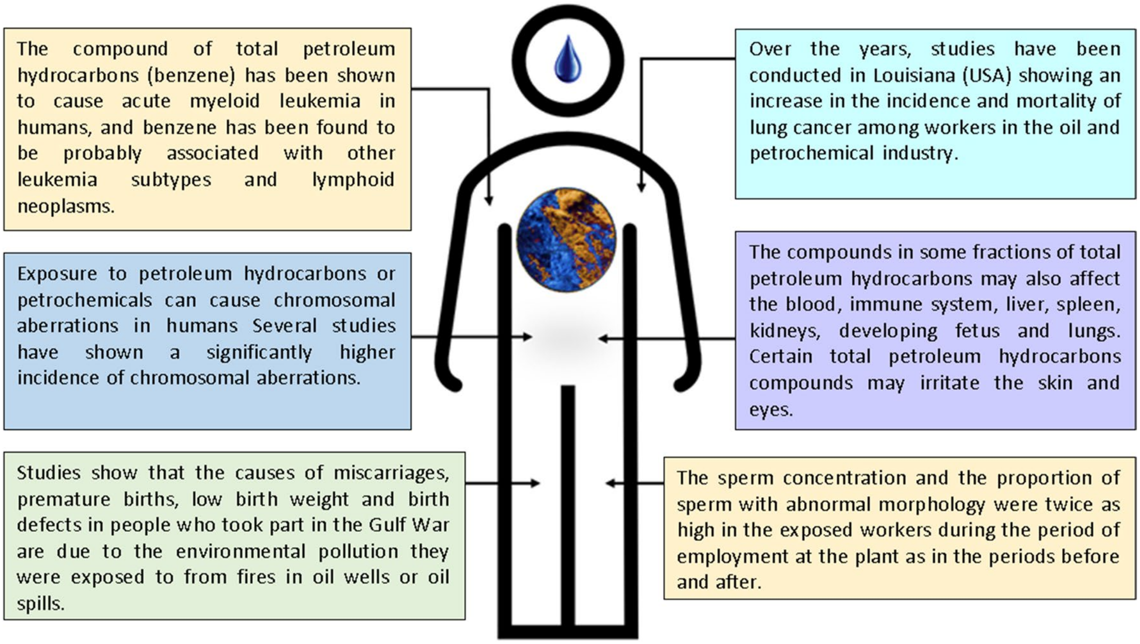
Oil field drilling, especially during the multi-layered processes of oil extraction, transportation, and processing, is one of the main causes of water pollution (Fang et al. 2022). The impact is profound, as the release of carcinogenic, teratogenic, and mutagenic petroleum contaminants during oil production has a significant and far-reaching impact on the quality of water resources (Islam et al. 2014). The intricate interplay between these industrial activities and aquatic ecosystems underscores the urgency of addressing and mitigating multiple water quality issues throughout the oil life cycle and highlights the urgent need for comprehensive strategies and heightened awareness to protect our vital water sources.

Air pollution is one of the greatest environmental challenges of our time. Many pollutants pose risks such as cancer and tumors and have harmful effects on human health and the environment. To tackle this problem, expensive chemicals and microfilters are used that require constant maintenance to effectively remove air pollutants (Sheoran et al. 2022). In addition, petroleum contamination of soil and water bodies can contribute to the production of greenhouse gases, particularly methane, which increases the negative impact on air quality and exacerbates climate change. Therefore, there is an urgent need to tackle petroleum contamination in all environmental sectors to reduce the negative impact on air quality.

This review paper makes an important contribution by providing a thorough analysis and summary of petroleum contamination in soil, water, and atmosphere. It includes an assessment of the risks to human health from petroleum contamination, the identification of available information on detection methods, and the evaluation and presentation of different treatment approaches. The advantages and disadvantages of the individual methods are then presented in a differentiated discussion. Finally, this review addresses the challenges that need to be overcome in the detection and remediation of mineral petroleum contamination.

Petroleum contamination has a significant impact on human well-being and comes from sources such as oil production, refining, and the natural gas industry. It is one of the most conspicuous pollutants affecting both the living environment and the ecosystem with its living and nonliving components. Numerous studies point to the increased health risks for people living near oil fields and wells or involved in the cleanup of oil spills (Yakubu 2017). The consequences of these pollutants manifest themselves in various diseases, including skin and eye irritation, mucous membrane damage, kidney and liver problems and complications during pregnancy (Otitolaiye and Al-Harethiya 2022). In addition, some studies indicate an increase in petroleum-related complaints such as skin rashes, sore throats, organ inflammation, infertility, and miscarriages (Ramirez et al. 2017). Some studies have shown that petroleum-induced DNA damage is directly linked to genetically unstable cellular metabolic enzymes that lead to malignancies such as leukemia. Figure 1 shows selected studies that have investigated the effects of petroleum pollutants on human health.

The novelty and originality of this critical review lies in the comprehensive analysis of the effects of petroleum contamination on all three major environmental components—soil, water, and atmosphere. In addition, this review paper critically assesses the latest technologies and techniques for monitoring and remediating petroleum spills, providing valuable insights into potential solutions to this environmental problem.



The compound of total petroleum hydrocarbons (benzene) has been shown to cause acute myeloid leukemia in humans, and benzene has been found to be probably associated with other leukemia subtypes and lymphoid neoplasms.

Over the years, studies have been conducted in Louisiana (USA) showing an increase in the incidence and mortality of lung cancer among workers in the oil and petrochemical industry.

Exposure to petroleum hydrocarbons or petrochemicals can cause chromosomal aberrations in humans Several studies have shown a significantly higher incidence of chromosomal aberrations.

The compounds in some fractions of total petroleum hydrocarbons may also affect the blood, immune system, liver, spleen, kidneys, developing fetus and lungs. Certain total petroleum hydrocarbons compounds may irritate the skin and eyes.

Studies show that the causes of miscarriages, premature births, low birth weight and birth defects in people who took part in the Gulf War are due to the environmental pollution they were exposed to from fires in oil wells or oil spills.

The sperm concentration and the proportion of sperm with abnormal morphology were twice as high in the exposed workers during the period of employment at the plant as in the periods before and after.

Fig. 1 The adverse effects of petroleum contamination on human health

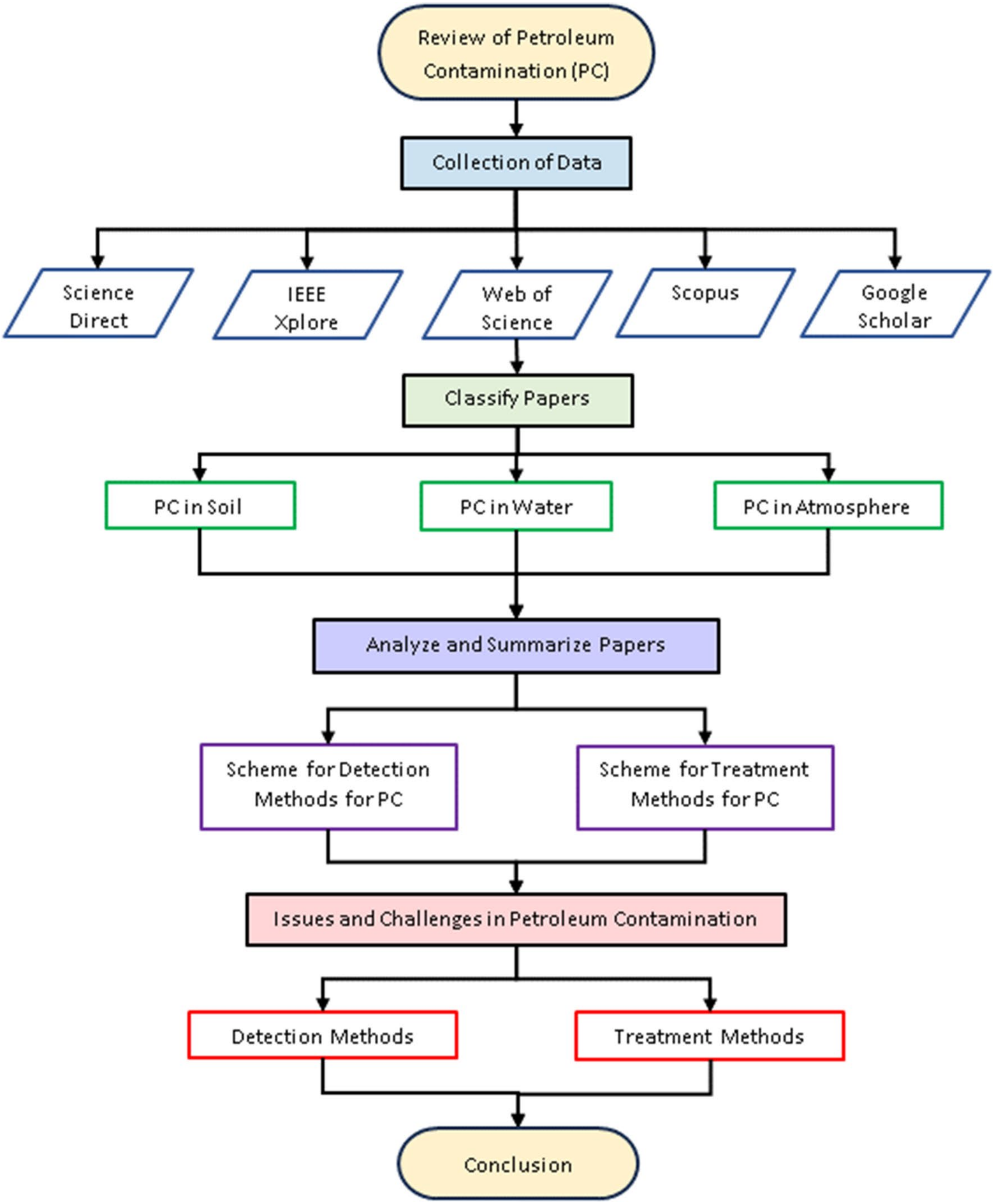


Fig. 2 Methodology for the investigation of petroleum contamination

Methodology

The methodology for this review, illustrated in Fig. 2, involves several phases that are critical to the accurate conduct of the study. The first phase involves obtaining data from reputable academic databases such as Science Direct, IEEE Xplore, ResearchGate, Web of Science, and Google Scholar to compile all relevant studies on petroleum contamination. In the second phase, the identified articles are classified by specific categories of petroleum contamination (soil, water, and atmosphere) and then analyzed in detail and organized into tables with individual references.

Based on the findings from the accident studies, a synthesis of the different methods for detecting petroleum spills and the strategies and techniques for pollution management will then be formulated. The next step is to identify the challenges and key gaps in the investigation and characterization of petroleum spills. The systematic review applies a structured process to identify, select, and critically evaluate relevant studies and summarize the results in a transparent and reproducible manner. This systematic approach increases the rigor and reliability of the review while minimizing bias.

The study includes the development of a comprehensive search strategy, explicit application of inclusion and exclusion criteria, assessment of study quality, and data analysis using multiple sources and methods. Network analysis is used to visually represent and analyze relationships between entities or nodes in a network. This facilitates the visualization of links between studies, authors, or keywords in the field of petroleum contamination and highlights important actors, clusters, and trends.

Taxonomy studies on petroleum contamination

This section deals with basic studies that examine the effects of petroleum contamination on soil, water, and the atmosphere (Fig. 3). Another important aspect of these critical studies is to examine the potential long-term effects of petroleum contamination on these environmental areas. Conducting long-term studies is crucial to shed light on the persistence and accumulation of petroleum-related compounds in the environment and thus assess the effectiveness of different remediation strategies over time.

Petroleum contamination in soil

The global problem of soil pollution by petrochemical hydrocarbons is becoming increasingly important and affects several countries with a significant number of identified sites where petroleum hydrocarbons are the main pollutant (Gao et al. 2019). According to the Environmental Protection Agency, 45% of the natural environment in Europe is contaminated by petroleum hydrocarbons and their derivatives (Borowik and Wyszkowska 2018). Therefore, the remediation of soils contaminated with these hydrocarbons has become a priority societal concern that is crucial for the protection of both the environment and human health. Table 1 provides an overview of the relevant research on the identification of petroleum contamination in soil.

Chemical elements of petroleum contamination in soil

Recent technological advances associated with human activities have led to the accumulation of various soil pollutants, especially heavy metals (such as copper (Cu), lead (Pb), cadmium (Cd), chromium (Cr) and others) in the environment (Yaseen 2021). Although some chemical elements occur naturally in soil as components of minerals, they can become toxic at certain concentrations. Human activities, including accidental releases and spills of chemicals used in commercial or industrial applications, contribute to soil pollution. In addition, certain pollutants are transported through the atmosphere and settle as dust or through precipitation (Shayler et al. 2009).

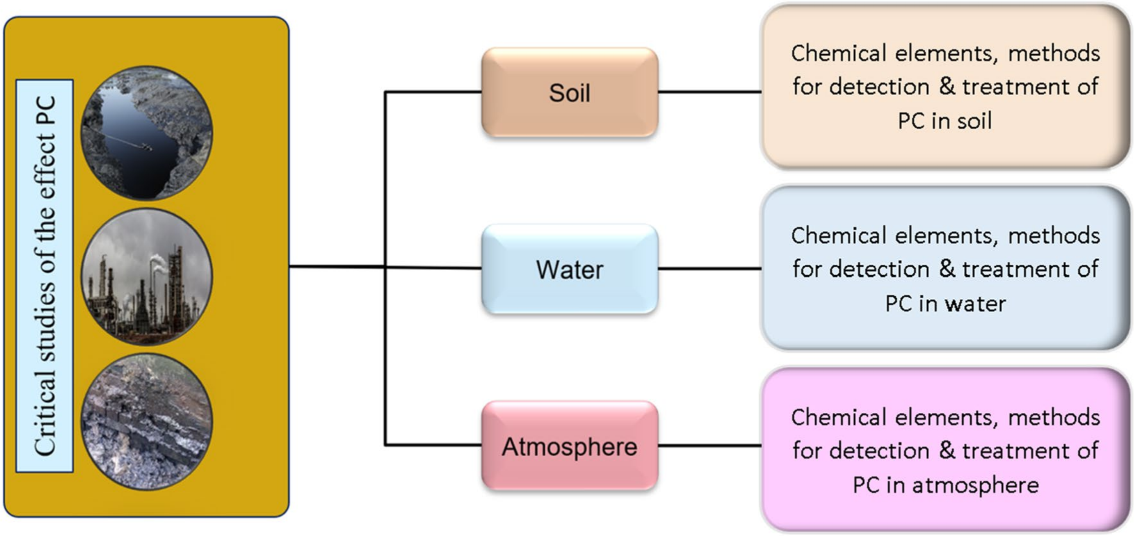


Fig. 3 Taxonomic representation of petroleum contamination

Table 1 Comprehensive overview of studies on petroleum contamination in soil

References	Case study	Chemical element	Methods of analysis	Type of treatment	Technology uses	Research remark
Ambaye et al. 2022)	Review paper	PHs, PAHs, and n-alkanes	Next generation of sequencing (NGS)	Bioremediation method	Bio-electrochemical systems	Eco-friendly of PH degrading mechanisms
Kim and Choi 2019)	Eastern coast of Korea	Pb and Zn	X-ray fluorescence and GIS	Pollution identification	GIS (kriging-IDW)	Pb (consider higher risk), Zn (consider lower risk)
Park and Park 2010)	Korea	Chemical component (non-volatile and insoluble)	Soil sample analysis using the direct method	Target risk-based corrective action (RBCA)	Equilibrium criterion (EQC) model	Dangerous EC8-1, EC10-21 contribute 96% of the hazard index (HI)
Ao 2012)	Niger Delta	Petroleum hydrocarbons	GC-FID	Bioremediation method (BR)	Quantitative analysis (methods 8000C)	Gas chromatography and BR are the best approach
Wang et al. 2013)	Jilin Province, China	Total petroleum hydrocarbon (TPH), NaHCO3, and TOC	Gravimetric Technique	Phytoremediation method	SAS—Least squares means	Phytoremediation using C. angustifolia is a useful treatment method
Okparanma et al. 2014)	Nigeria	PAH	PAH concentrations determined by SUSEeGC		SUSGEGC is the reference chemical technique	Soil diffuse reflectance decreases with PAH content
Shen et al. 2018)	Xi'an, China	Nitrogen, TPH, phosphorus, and potassium	Creating contaminated soil for simulation	Phytoremediation method	QIIME Pipeline version 1.7.0	Addition of different nitrogen sources improves remediation outcomes
Ekperusi and Aigbodion 2015)	Niger Delta region of Nigeria	$CO_{2,}$ SO_4^{-2}, NO3-, Na, and Mg	GC-FID	Bioremediation method	AAS used to quantify TPH	Earthworm H. africanus has the potentials to bioaccumulate and biodegradation of TPH
Shahi et al. 2016)	Istanbul, Turkey	N-alkanes and PAHs	Shimadzu TOC-5000A Total Organic Carbon Analyzer	Biostimulation method	Shapiro–Wilk's and Levine's tests	The qPCR data, 16S rRNA, and functional genes are useful for soil observation and treatment
Chakraborty et al. 2012)	Louisiana-USA	TPH	DRS in the VisNIR spectrum to detect TPH	Contamination determination	ArcGIS (Geostatistical analyses and kriging)	VisNIR and geostatistics can detect TPH spatial trends without expensive laboratory tests
Karamalidis et al. 2010)	Greece	TPH and n-alkanes	ESI-MS method	Bioremediation methods	Ultrasonic for extraction hydrocarbons	Biostimulation is the optimum technique
Baoune et al. 2018)	Ouargla city, Algeria	Za, Bm and Hydrocarbons	GC-FID	Biodegradation strains (streptomycesge-nera)	The R (3.2.2) software	Endophytic actinobacteria show the capacity to digest crude petroleum
Mohsenzadeh et al. 2012)	Arak refinery (Iran)	MgSO4, hydrochloric acid (HCl) and Na2SO4	A visual inspection of the soil might possibly identify soil pollution	Bioremediation method (fungal strains)	Analyzing the experimental using ANOVA and LSD	Fungal enzymes play an important role in the decomposition of petroleum
Chen et al. 2015)	China	PAHs and HM	Samples from contaminated soil	Bioremediation method	Biostimulation methods and monitored natural attenuation	Composting is a cost-effective soil remediation technique

Table 1 (continued)

References	Case study	Chemical element	Methods of analysis	Type of treatment	Technology uses	Research remark
Liu et al. 2015)	Dagang Oilfield, China	Alkanes and aromatic hydrocarbon (AH)	The LSD-t approach for sampling	Microorganisms to enzymatic breakdown of PHs	Kruskal–Wallis and Levin's test	Huge potential of bioremediation techniques for removing petroleum from soil
Pinedo et al. 2013)	Netherlands	AVHs, BTEX and PAHs	TTE consultant provides ready data of polluted soil	Quantifying the quantity of oil products in soil	Assessing polluted soil using mathematics and correlations	Intervention value (IV) of TPH not appropriate for lighter oil soil risk evaluation
Lu et al. 2010)	Tianjing, China	TPH and PAHs	Modified Casida (1977) method	Phytoremediation (eleusine indica)	T test and SPSS 13.0	Goosegrass should be planted away from farming locations due to its harmful impacts
Baig et al. 2022)	Haripur, Pakistan	Naphthalene and Pyrene	Wet oxidation technique	Bioremediation methods	Bacteria (P. Putida-Pseudomonas)	Pseudomonas play an important role in increasing soil PAHs dissipation
Apul et al. 2022)	Midwestern United States	TPH and TOC	Laboratory tests	Chemical method	H2O2 to boost biodegradability	Oxidants slowed TPH biodegradation by reducing viable microorganisms
Stepanova et al. 2022)	Russian	Aromatic hydrocarbons	Study for treatment only	Bioremediation method	Microbial in bioremediation	Enormous potential of BR method for removing petroleum from soil
Bingari et al. 2022)	UK	Crude oil	NIR spectroscopy	Monitoring crude oil pollutants	Techniques of remote sensing	Inverse correlation between spectra and oil concentration
Deng et al. 2020)	China	Petroleum hydrocarbons	Method to repair petroleum-contaminated soil	Chemical treatment	Advanced oxidation processes (AOP)	AOPs may be further developed as a promising method for TPH
Cocârţă et al. 2017)	Romanian	PAHs, TPH, VOCs and MAHs	High-performance liquid chromatography (HPLC)	Identifying the risk of contamination	RBCA, CSOIL, CLEA and RECOLAND v1.0	RECOLAND tool is important to assess risks on humans
Yuniati 2018)	Review	Hydrocarbon		Physicochemical and biological treatment	Each method has special techniques	Microbiological decontamination is efficient and economic
El-Hadidy et al. 2022)	Egypt	Hydrocarbon, phosphate, and iron	GIS (spatial analyst)		Hyperspectral (EO-1, Hyperion) and multispectral (Landsat7)	Hyperion images map mineral alteration accurately and save time, money, and effort
Saad Almutairi 2021)	Kuwait	TPH, acetone and hexane	Gravimetric and GC-MS	Chemical treatment	The solvent extraction technique	Hexane was the most successful at eliminating TPH

Table 1 (continued)

References	Case study	Chemical element	Methods of analysis	Type of treatment	Technology uses	Research remark
Luo and Schrader 2022)	Germany	PAXHs, toluene, CH2Cl2 and C3H6O	ESI, APCI, and APPI methods	Chemical treatment	Multidimensional ionization for ultrahigh resolution mass spectrometry	Over 95% of contaminated crude oil could be recovered using toluene, CH2Cl2 and C3H6O
Wojtowicz et al. 2022)	Poland	PAHs	Evaluation of the efficiency of biodegradation	Biodegradation method	Respirometry, chromatographic and toxicological evaluations	Within six months of administering the biopreparation, pollutant components (TPH, BTEX and PAH) were reduced
Liu et al. 2022)	China	TPHs	TEQ for estimate TPHs		Predicated degradable potential of PHs on geochemical indicators of n-alkanes and PAHs	High environmental risk demonstrated in petroleum-related areas
Okwonna and Otaraku 2022)	Nigeria	THC and TOC	Total nitrogen concentration used as an indicator	Chemical method	Bone char (organic) and inorganic NPK fertilizers	Effectiveness of fertilizers for the degradation of pollutants in the soil
Lee et al. 2022)	Dongducheon, Korea	Na, K, Mg, Ca, NO3-N and P	Quality comparison between TPH degradations	Biological (phytoremediation)	Regression and correlation analysis	Compost, vermicompost, and chlorella effectively enhance soil properties
Li et al. 2022a)	China	Na2S2O8, Na2S2O3, and CCl4	gravimetric technique	Treatment with ultrasonically/ thermally activated persulfate	GC-MS	The treatment leads to degraded TPH by 78.2% and 72.6% within 72 h

The environment is polluted by many hydrocarbon components from petroleum, as these are relatively diverse. The release of petroleum hydrocarbon pollutants, whether accidental or deliberate and uncontrolled, poses a direct or indirect threat to all living organisms in the affected area (Sajna et al. 2015; Souza et al. 2014). Petroleum hydrocarbons have the potential to alter various soil properties, including mineral and heavy metal concentrations, composition, texture, compaction, structural condition, penetration resistance, and saturated hydraulic conductivity (Hreniuc et al. 2015). Although pollution can have different causes, the effects, consequences, and impacts are the same. The extraction of natural petroleum resources, both deep inland and offshore, is one of the main methods by which petroleum hydrocarbon pollutants enter the soil environment. In this context, the soil serves as a repository and recipient of the pollutants (Varjani 2017).

Methods for the detection of petroleum contamination in soil

Oil spills are one of the biggest environmental problems associated with petroleum and petroleum derivatives in the world today. The causes of oil spills on land range from pipeline ruptures and tanker accidents to inadequate sealing, airplane accidents, and even conflicts and wars. Therefore, the development of methods to detect petroleum in soil is of paramount importance for assessing damage and developing effective remediation strategies for sites affected by such spills (Ukhurebor et al. 2021).

Current methods for detecting petroleum residues in affected areas include spectroscopic and chromatographic methods such as gas chromatography, mass spectrometry, and hyphenated separation/detection techniques. Despite their effectiveness, these methods cannot be read in real time (Gallagher et al. 2005) and often require longer detection times, which is critical for addressing the challenges associated with pollution. Several research studies have identified alternative methods such as mid-infrared laser spectroscopy (MIR) (Pacheco-Londoño et al. 2013) and remote sensing techniques based on the analysis of satellite imagery as more efficient and faster analytical techniques that overcome the limitations of conventional methods (Okparanma and Mouazen 2013). Conversely, the integration of artificial intelligence (AI) has proven to be a promising avenue for real-time control of pollution reduction techniques, as evidenced by recent studies (Galán-Freyle et al. 2020).

Treatment of petroleum contamination in soil

Contamination of soil with petroleum hydrocarbons poses a significant risk to human health, underscoring the importance of effective treatment methods and remediation processes for comprehensive cleanup, containment, removal, remediation, and restoration of contaminated areas. The choice of a remediation strategy for each contaminated environment is site-specific and depends on variables such as the nature and composition of the contaminants, the physical, chemical, and biological conditions of the affected environment, and the microbial community present or required for enhancement. In addition, considerations of process, regulatory requirements, cost, and schedule must also be taken into account when selecting an appropriate remediation method (Vidonish et al. 2016).

Soils are typically contaminated with high and low molecular weight petroleum hydrocarbons, volatile organic compounds (VOC), semi-volatile organic compounds (SVOC), polycyclic aromatic hydrocarbons (PAH), persistent organic pollutants (POP), polychlorinated biphenyls (PCB), organochlorine pesticides (OCP), hydrophobic organic compounds (HOC), and non-aqueous phase liquids (NAPLs). Pollution experts use various remediation options to deal with contaminated environments (Thavamani et al. 2015). Various approaches and strategies have been explored for the remediation of petroleum-contaminated soils, most of which utilize biological, chemical, and physicochemical methods (Zhang et al. 2015; Zhou et al. 2019).

Bioremediation is considered a cost-effective and environmentally friendly method and is attracting great interest from researchers. Figure 4 illustrates the main pathways by which petroleum contaminants enter the soil, primarily through petroleum spills. The annual global leakage of 600,000 tons of natural petroleum underscores the staggering scale of petroleum contamination, which affects an estimated 3.5 million sites in Europe alone.

Controlled or spontaneous bioremediation uses biological, particularly microbiological, mechanisms to convert pollutants into less or nontoxic substances to reduce pollution. Key factors for characterizing a polluted site include the ability of pollutants to be degraded by biological processes, the extent of their dispersion, leaching, chemical reactivity, soil type and properties, oxygen availability, and the presence of compounds that hinder degradation (Ossai et al. 2020). Successful bioremediation of organic pollutants requires a thorough understanding of the physiology and ecology of the biological species or consortia involved, as well as the characteristics of the polluted sites, both soil and water Martín Moreno et al. (2004).

Petroleum contamination in water

Water pollution is caused by the introduction of chemical, physical, or biological elements that impair the ability of a body of water to function optimally. The level of pollution required to affect a water body depends on its type, location, and intended use. Water that is unfit for human consumption

Fig. 4 The main sources of petroleum contamination in soil

may serve other purposes. We focus here on spills of petroleum products and not on natural events that may jeopardize water supplies in certain situations (Schweitzer and Noblet 2018). Oil spills that have the greatest impact on plants and animals, particularly seabirds, are primarily influenced by the physical properties of the oil. The sticky nature of the material means that natural fats, waxes, and other substances are less mobile on surfaces such as human skin and feathers (National Research Council (U.S.) 2003). Some aromatic petroleum hydrocarbons can also cause direct damage through absorption or penetration through body surfaces such as gills (Heubeck et al. 2003), while many hazardous and nontoxic hydrocarbons evaporate and are naturally degraded by microbes in a short time (National Research Council (U.S.) 2003). The relevant studies for the determination of petroleum contaminants in water are listed in Table 2.

Petroleum pollution of water bodies can have various causes, e.g., accidents, leaks from underground storage tanks and runoff from industrial activities. Once petroleum enters water bodies, it can have a negative impact on aquatic life and pose a risk to human health. Petroleum pollutants include several substances such as benzene, toluene, ethylbenzene, and xylene, collectively known as BTEX compounds (Fig. 5). These compounds are known to be toxic and have potentially harmful effects on the environment and human health, including the risk of cancer and neurological disorders. To minimize the risk of water pollution, preventative measures such as proper handling and storage of petroleum products and the implementation of effective spill response plans are critical. In cases where contamination has occurred, remediation measures, including soil and groundwater treatment, can help to limit the damage and clean up the affected area.

Chemical elements of petroleum contamination in water

Heavy metals (HMs) are among the most dangerous pollutants as they are non-degradable, persistent, and toxic in

Table 2 Comprehensive overview of studies on petroleum contamination in water

References	Case study	Chemical element	Methods of analysis	Type of treatment	Technology uses	Research remark
Fang et al. 2022)	China	Benzene, toluene, ethylbenzene, and xylene	GIS	Diagnostic study	Groundwater modeling system (GMS, Version 10.4)	GMS has become a popular groundwater modeling tool
Muhammad and Usman 2022)	Northern Pakistan	Cr, Mn, Fe and Ni other HM	Laboratory test	Only assessment of possible risk and source assignment is required	The SPSS (univariate and multivariate)	Calculations of possible dangers was based on heavy metal concentrations in water
Lu et al. 2009)	China	NH3-N, K2HPO4	GC/MS	Chemical method	Infrared spectrophotometry	Hydrolysis acidification/bio-contact oxidation system (HA/BCO) is important method for treatment
Tysiąc et al. 2022)	Siberia	Oil	Remote sensing (Landsat data)	Biological method	The satellite bands, namely visible, short, medium infrared and microwave radar bands	Using satellite imagery for oil spill research is very beneficial
Demenev et al. 2022)	Russian	TPH and HM	Electrophoresis system	Biodegradation	Kapel-104-T capillary electrophoresis system	Bioaugmentation and biostimulation consider promising technology
Chan 2011)	China	Methylene chloride, sodium sulfate	GC-FID	Bioremediation method	Oil/water interface meter (Heron Instruments Canada)	A decrease in TPH was inversely linked to an increase in bacterial population
Yuan et al. 2022)	China	TPH	Field investigation and high-resolution remote sensing images	Bioremediation method	R programs, ANOVA	It is important to use NDVI and NNDWI1 to interpretate the remote sensing image
Yuan et al. 2022)	China	TPH, Nitrogen and phosphorus	Laboratory testing	A study of using vegetation cover indicators to measure oil pollution	NDVI, NNDWI1 and remote sensing	High-resolution remote sensing imagery were utilized to assess oil extraction's impact on vegetation deterioration
Atta et al. 2020)	Egypt	NH_4OH, KI and n-alkane	Field ionization mass spectrometry (FIMS)	Phytoremediation	Magnetite nanoparticles (MNPs)	As oil exposure increased, so did plant sulfur bioaccumulation
Rajasekhar et al. 2018)	India	PAHs (C12H10, C13H10, C14H10, C15H10 and C16H10)	Laboratory tested	Bioremediation	Point value and probabilistic methods for exposure	Ozonation combined with bioremediation is an important approach for treatment
Zrafi-Nouira et al. 2009)	Tunisia	hydrocarbons (n-alkanes)	Gas chromatograph	Diagnostic study	GC-FID and GC-MS	
Zhang et al. 2012)	China	TAH, AHs, Al_2O_3	Gas chromatography, mass spectrometry technology	Biodegradation method	The program CANOCO 4.5	Moisture in soil and sewage boosted organic contaminants' downward movement

Table 2 (continued)

References	Case study	Chemical element	Methods of analysis	Type of treatment	Technology uses	Research remark
Oliveira Lemos et al. 2014)	Brazil	DDPHs	UV-Fluorescence	Environmental hygiene guidelines only	The Mann–Whitney (M–W) rank-sum test	The dry season had greater median DDPH concentrations than the rainy season
Anjos et al. 2011)	Brazil	PAHs	WSF and gas chromatography	Biological treatment	The Shapiro-Wilks test and ANOVA (STATISTICA 8.0 software)	Gene (Cyp1a) is the most sensitive and consistent indication of petroleum contamination
Camilli et al. 2009)	USA Coast	Aromatic and halogenated hydrocarbons	GC-MS and acoustic navigation	Study for detecting contamination	A SHARPS transmitter	Spatial resolutions larger than one decimeter are required to identify contamination
Nemirovskaya 2007)	Japan	AHC and PAH	Chloroform (organic compound)		Infrared spectroscopy and TBT chromatograph	Bottom sediments caused secondary pollution of the body of water
Lindén and Pålsson 2013)	Nigeria	AHs	GC-MSD	Thermal method	CEM MARS microwave extraction	The pollution in the study area is mostly from vandalism
Sari and Trihadiningrum 2018)	Indonesia	TPH	Soxhlet and gravimetric methods	Biological method	Fourier transform infrared (FT-IR) spectrometer	There was no standard for TPH in surface water; therefore, contamination was unknown
Ayotamuno et al. 2006)	Nigeria	GAC and PAC	Simulated polluted water was made	Chemical method	Activated carbon (AC) in the treatment	Powdered carbon is more effective than granular carbon in the treatment
Santo et al. 2012)	Portugal	TPH, Al2(SO4)3, Fe2(SO4)3 and polyaluminium chloride	Partition-infrared spectrophotometer	Physicochemical method	Coagulation–flocculation/flotation	The effectiveness of organic carbon removal reduced as the pH increased
Zhang et al. 2014)	Xi'an, China	AHs, n-alkanes	T-test	Only a contamination diagnostic study	SPSS, ANOVA, LSD, multiple comparisons, linear regression and CANOCO	Low-molecular-weight, water-insoluble hydrocarbons predominated
Freire et al. 2022)	Brazil	Oil	Remote sensing		ENVI 5.5 programme to classify the image	To get more accuracy, it is important to digitally process satellite images
Acharya et al. 2022)	India	TPH	Machine learning models	The COVID-19 shutdown led to the lowest quantities of petroleum hydrocarbons	Using UVF0 spectroscopy	ML appears to be a promising forecasting technique, and more models are recommended

Table 2 (continued)

References	Case study	Chemical element	Methods of analysis	Type of treatment	Technology uses	Research remark
Alsalka et al. 2011)	Syria	BTEX and PAH	HPLC	Electrochemical treatment	Clarity Chrom software (Knauer GmbH)	Electrochemical approaches are ideal for removing aromatic compounds from water
Madu et al. 2021)	Nigeria	Phosphates, nitrates, and chloride	Gravimetric analysis	Physicochemical method	Candle filters to remediation	Candle filters are useful for water remediation in high-pollution areas
Murphy et al. 2022)	Australia	Naphthalene, benzene, and toluene	GS-MS and GS-FID	Biological method	Slurping/vacuum extraction, bioventing	Naphthalene concentration drives chemotactic and hydrocarbon-degrading bacteria
Onyegeme-Okerenta et al. 2022)	Rivers State, Nigeria	TPHs and PAHs	GC-FID	Environmental awareness and permanent pipeline protection	ANOVA	Seafood in contaminated water may increase the risk of acquiring cancer
Jamoussi et al. 2022)	Saudi Arabia	Amino acid, hydrocarbon	GM-MS	Highlighting the danger of eating fish in this contaminated area	High-pressure liquid chromatography	Coral fish indicators to detect oil pollution
Zanardi-Lamardo and Schettini 2022)	Brazilian	DDPH	UV–Vis fluorescence spectroscopy	Diagnostic study	Spectra Max M3 molecular devices	Spectroscopy is a sensitive, rapid, and affordable way
Mityagina and Lavrova 2022)	Caspian Sea	Oil spill, hydrocarbon	Remote sensing	Diagnostic study	Satellite SAR and multispectral sensors	Remote sensing is unquestionably the finest approach out there
Leifer et al. 2022)	California	Coal Oil Point (COP)	Remote sensing	Diagnostic study	High-resolution thermal infrared (TIR)	Estimated floating (thick) heavy oil via distant sensing
Omokpariola et al. 2022)	Nigeria	TPHs and AHs	GC-FID	Biodegradation	Agilent GC-FID	Hazard index > 1 for aromatics showed probable health risks for children and adults

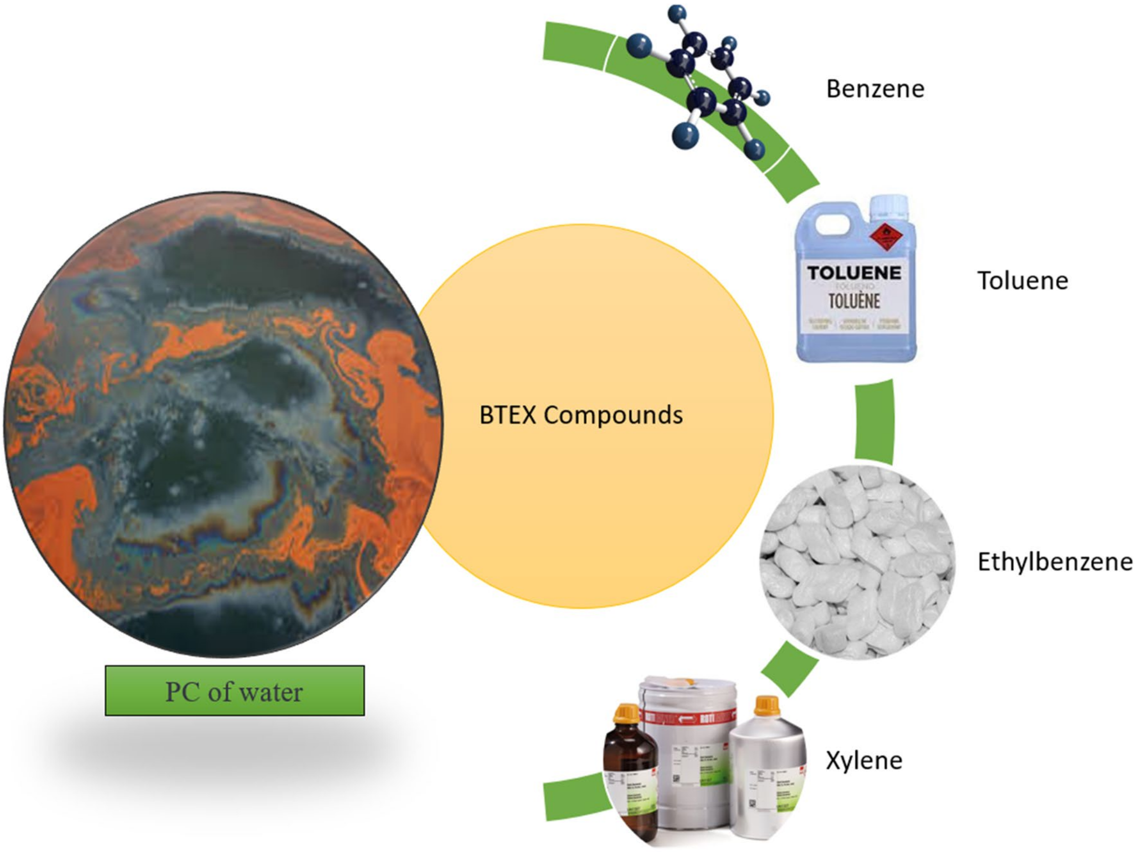


Fig. 5 The main sources of petroleum contamination in water

water (Proshad et al. 2021). These metals can harm living organisms, including humans (Deng et al. 2020), through direct ingestion of contaminated water and indirect ingestion of contaminated food (Edogbo et al. 2020). While certain HMs such as iron (Fe) and copper (Cu) are essential to human life within a certain range, they can become harmful if safe limits are exceeded. Others, such as cadmium (Cd), chromium (Cr) and cobalt (Co), pose a toxicity risk even at trace levels. Cd, for example, can lead to hepatotoxicity and nephrotoxicity, while Co causes thyroid dysfunction and polycythemia when ingested.

Manganese (Mn) and copper (Cu) in drinking water have been linked to Alzheimer's disease, and iron (Fe) in drinking water can cause problems with the blood, cardiovascular system, liver, kidneys, and central nervous system. Children exposed to lead (Pb) have been found to have an increased susceptibility to memory loss, behavioral changes, and anemia (Muhammad and Usman 2022). Microbes play a crucial role as primary catalysts for biochemical processes that influence various important ecosystem services (Kearns et al. 2016). They are responsible for monitoring nutrient recycling and pollutant degradation (Ribeiro et al. 2013; Lu et al. 2009). Maintaining microbial diversity is essential for sustaining these services, and a decline in diversity could have a negative impact (Delgado-Baquerizo et al. 2016).

Methods for the detection of petroleum contamination in water

Petroleum spills, especially catastrophic ones such as those in the Gulf of Mexico (Kappell et al. 2014), can have devastating effects on coastal and estuarine habitats (Ribeiro et al. 2013). The lack of advanced measurement devices and techniques poses a challenge when it comes to assessing subsurface oil pollution or the movement of heavy fuel oil (HFO) in real time. Survey systems, such as snares, are often used to identify large areas of sediment pollution, but cannot accurately determine the exact location or size of the area, nor the extent of pollution, occasionally leading to false-negative results (Reddy 2008).

While many methods for investigating polycyclic aromatic hydrocarbons (PAHs) in water bodies are costly and time-consuming, the UV fluorescence method provides a cheap, simple, and efficient tool for rapidly assessing the integrity of the system and identifying 'hot spots' for further investigation (Doval et al. 2006; Bícego et al. 2009). Satellite imagery has been used extensively by researchers to investigate oil spills in water reservoirs (Sun et al. 2018), using various satellites such as Landsat 5, Landsat 7, and Sentinel-2A. GIS techniques are used to categorize milestones and assess pollution by processing satellite imagery (Tysiąc et al. 2022).

Treatment methods of petroleum contamination in water

Remediation of water bodies involves cleaning contaminated surfaces and groundwater, depending on the degree of contamination. The effectiveness of any treatment technique at a given site depends on planning, modification of system operation, and understanding of contaminant characteristics and system performance. The integration of remediation approaches, either simultaneously or sequentially, can result in a synergistic or combined effect (Demenev et al. 2022). Bioremediation of petroleum hydrocarbons in contaminated water using a bacterial food chain is a viable technique that converts fuel oils to microbial biomass without causing secondary pollution (Chan 2011; Superczynski and Christopher 2011). Various physical remediation techniques such as air sparging and bioventing have been developed to clean contaminated areas and limit the spread of petroleum hydrocarbons such as LNAPL (Light Non-Aqueous Phase Liquids) (Ossai et al. 2020).

Petroleum contamination in the atmosphere

Urban dwellers worldwide are confronted with the threat of air pollution, which is a critical environmental problem (Cohen et al. 2005). There is no doubt that air pollution is a major challenge affecting urban areas worldwide. Various research centers and regulatory agencies have established monitoring networks to assess the deterioration of air quality in these urban areas. The results of these monitoring networks show considerable temporal and geographical variation (Gerdol et al. 2014). Numerous monitoring programs have been conducted to measure air quality. Extensive data on the concentration of pollutants such as particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, and others have been collected in different regions of the world. However, the sheer volume of data continues to make it difficult for scientists, government officials, policy makers, and the public to understand the state of air quality. The solution to this challenge lies in measuring the Atmospheric Quality Index (AQI), which provides a clear and accurate understanding (Murena 2004).

The risks to the environment and human health posed by air pollutants such as aliphatic hydrocarbons (PAH), polycyclic aromatic hydrocarbons (PAHs), and heavy metals (HMs) have long been known and well documented. In recent decades, concerted efforts by the relevant authorities to regulate air pollution have yielded positive results, leading to a significant reduction in air pollutants (Azimi et al. 2005). Table 3 contains a list of research studies on petroleum pollution of the atmosphere.

Chemical elements of petroleum contamination in atmosphere

In investigating the extent of air pollution, numerous studies have identified the main pollutants, focusing on nitrogen dioxide (NO2), sulfur dioxide (SO2), and carbon monoxide (CO) (Mohammed et al. 2019; Barakat and Bek 2002). In these studies, various techniques were used to identify the sources of the chemical elements causing the pollution. In this study, the applicability of an inverse model under different environmental conditions is investigated and its effectiveness in attributing the sources of atmospheric lead (Pb) is evaluated. The analysis includes organic molecules such as n-alkanes, isoprenoids, PAHs, sulfur-containing heterocycles, terpenes, and aromatic steroid compounds such as steranes/diasteranes (Murena 2004). The method allows a comparison between model-based results and predicted lead emissions and provides information on the likely sources and processes contributing to Pb contamination of the atmosphere. The integration of model-based results and Pb aerosol data helps to understand the extent of Pb contamination in the atmosphere after the elimination of leaded petroleum (Samanta et al. 2022).

Methods for the detection of petroleum contamination in atmosphere

Monitoring atmospheric contamination at different locations in a research region is usually difficult, resource-intensive, and costly. The results of such monitoring provide information on the extent of pollution at specific locations. Therefore, spatial interpolation methods are essential for the creation of a surface grid or contour map. By applying interpolation methods, it is possible to predict concentrations throughout the study area based on concentrations at known locations. Geographic information system (GIS) software for organizing, analyzing, storing, and visualizing spatial data is proving invaluable in conjunction with the expertise of a GIS analyst working on various spatial problems. Many researchers have begun to use GIS technology to analyze the temporal and spatial distribution of pollutants (Maantay 2007).

Treatment of petroleum contamination in atmosphere

Current environmental conditions and regulations issued by environmental authorities have significantly influenced the

Table 3 Comprehensive overview of studies on petroleum contamination in atmosphere

References	Case study	Chemical element	Methods of analysis	Type of treatment	Technology uses	Research remark
Zhang et al. 2012)	China	n-alkanes and TAH	Gas chromatography,	Determine petroleum contamination in the atmosphere	Redundancy analysis	Highest UCM and TAH observed in summer and fall, while winter showed the least
Barakat and Bek 2002)	Egypt	n-alkanes	GC-MS	Physical method	Mass selective detector (MSD)	Temperature plays a major role in the breakdown of aromatic hydrocarbons
Chandra et al. 2013)	China	Sulfur, oxygen, and nitrogen		Bioremediation method	The shape and molecular weight of a hydrocarbon molecule dictate its susceptibility to biodegradation	Bioremediation is a highly efficient and cost-effective method
Simoneit et al. 1980)	USA	Carbon monoxide and ozone	Mass spectrometric, high-volume filtration from quartz fiber	Chemical method	Filtration from quartz fiber, Finnigan-Incos Model 2300 data system	Vascular plant waxes cause contamination
Ite and A., J. Ibok, U. 2013)	Nigeria	VOCs and PAHs	Analyze acid rain for pollution indications	Evidence-informed decision-making (EIDM)		NOx and SO2 emissions are caused by anthropogenic pollution, gas flaring and fossil fuel burning
Johnson and Coderre 2011)	Canada	Methane	Gathering data from oil and bitumen batteries		SQL database for analysis	Venting activity attributed to new production activity of predominantly heavier oils
Liu et al. 2021)	China	Methylsiloxanes	GC/MS	Chemical method		Refinery employees may be exposed to more methylsiloxane analogues than the general population
Fernández-Martínez et al. 2001)	Spain	VOCs and aliphatic compounds	GC-MS		Mass spectrometry	Aromatic chemicals dominated the samples
Chattopadhyay et al. 2010)	India	SO2 and NO2	Remote sensing		GIS (IDNT)	Rain led to an increase to SO2 and NO2 concentrations
Raheja et al. 2022)	United States	NOx, PM, SO2 and VOCs	Laser particle counters from PurpleAir PM2.5 sensors	Community knowledge of air pollution and the need to avoid oil industrial areas	PurpleAir sensors	Chosen for cost, precision, and real-time data transfer
Mohd Shafie et al. 2022)	Malaysia	PM10	Global Moran's I		GIS (IDW)	Competent authorities should reduce the impact of carbon emissions
Pratt et al. 2022)	Mexico	PM2.5	AERMOD model	Determine the risk of emission only	Lakes Environmental Software, AERMOD View	Statistics imply that anyone working near combustion facilities may be exposed to PM2.5

Table 3 (continued)

References	Case study	Chemical element	Methods of analysis	Type of treatment	Technology uses	Research remark
Balogun and Odjugo 2021)	Nigeria	CO, VOC, H2S, NO2, SO2 and PM	T-tests	Utilized friendly energy	Regression analysis	Organize industrial and residential areas according to the distance and orientation of pollutant sources
Gonzalez et al. 2022)	California	CO, NO2, O3 and VOCs	Preconcentration techniques, gas chromatography and ion-mass spectrometry		EPA method, O_3 scrubber, and ultraviolet absorption spectroscopy	Geographical and temporal variation to identify the quantity of pollution
Samanta et al. 2022)	Indian	Pb	Simulation-based inversion model		Inversion model	The model estimated that COVID-19's lockout reduced Pb consumption by 65%
Shah et al. 2022)	India	Heavy metals and organic chemicals	GC-MS		X-ray system and a scanning electron microscope, ultrasmall particles (EDX)	Time and location affect chemical concentrations in the atmosphere
Bodor et al. 2022)	Romania	PM2.5, PM10 and HM	Non-dispersive infrared spectroscopy, chemiluminescence and ultraviolet fluorescence	Determine the link between air contaminants and meteorological conditions	Principal component analysis (PCA) and cluster analysis	High concentration of pollution is recorded in winter season
Li et al. 2022b)	California	PM and NOX	CA-TIMES model	Energy-economic model CA-TIMES and emission inventory model CA-REMARQUE		The GHGAi deep GHG reduction scenario decreased emissions
Rodriguez-Gonzalez and Torres-Garrido 2022)	Ecuador	PM2.5	Remote Sensing		GIS (geospatial analysis)	Environmental Justice Atlas may be used to quickly measure distributive
Martynova and Budarova 2022)	Russia	CH3OH, NO_2, SO_2 and CO	Contamination monitoring	Measured contamination only	Maximum allowed concentrations from Hygienic Standards (GN 2.1.6.1338-03, 2003)	The highest emission value recorded was methanol

development of innovative technologies for the treatment of contaminated air. There are four primary air treatment techniques: chemical, physical, biological, and biochemical (combinations of methods or multi-stage air treatment systems that integrate chemical and biological approaches) (Fulazzaky et al. 2014). Effective treatment options are crucial. Currently, physical and chemical treatments are costly and leave hazardous residues in the environment. Due to their excellent efficacy, low cost, and synergistic effects on the environment, biological methods are a potential solution for the treatment of petroleum hydrocarbon contaminants. An analysis of the factors influencing the degradation of petroleum has been carried out (Chandra et al. 2013**).** Various technologies are available for cleaning contaminated air, including wet scrubbers, activated carbon combustion adsorption, biofilters (BF), and biotrickling filters (Kennes and Veiga September 2004).

Wet scrubbers show satisfactory efficiency with polluted air. However, they generate significant amounts of wastewater that require additional treatment, prompting researchers to explore alternative methods for cleaning contaminated air (Jensen and Webb 1995). Incinerators offer another way to treat polluted air by releasing an atmosphere containing organic pollutants. The high temperatures in incinerators convert the organic pollutants into carbon dioxide and water. Although incinerators effectively remove odors and organic pollutants, they are energy intensive and emit significant amounts of carbon dioxide and other by-products (National Research Council Incineration Processes and Environmental Releases 2000).

An alternative method of treating a polluted atmosphere is to absorb pollutants with activated carbon. Activated carbon is the international standard for the purification of liquid and vapor streams and removes organic trace pollutants. Removal rates of 95 to 99% can be achieved with this method. In cases where the recovered organic substances are valuable, carbon adsorption is used. For example, carbon adsorption is often used to recover perchloroethylene, a chemical used in dry cleaning (Kennes and Veiga September 2004).

Biological treatment processes for polluted air are environmentally friendly and do not produce nitrogen oxides (NOx), SO2, or secondary pollutants. The environmental benefits of biofiltration, combined with its ability to treat a polluted atmosphere with a low concentration of pollutants and a large volume of polluted air, make it a cost-effective technology for the removal of volatile organic compounds (VOCs). Worldwide, biofiltration processes have proven to be effective in removing volatile organic compounds from polluted air and offer an environmentally friendly solution without generating harmful by-products (Darvin and Serageldin 2015).

In biofiltration, a method widely used in biological processes, microorganisms adhere to carrier materials through which contaminated air flows. These microorganisms metabolize and decompose the pollutants present in the air and convert them into water and carbon dioxide. Under ideal conditions, biofiltration technology can completely remove pollutants and is particularly effective in treating large quantities of polluted air with a volatile organic compound (VOC) concentration of less than 3 g/m^3 (Fulazzaky et al. 2014).

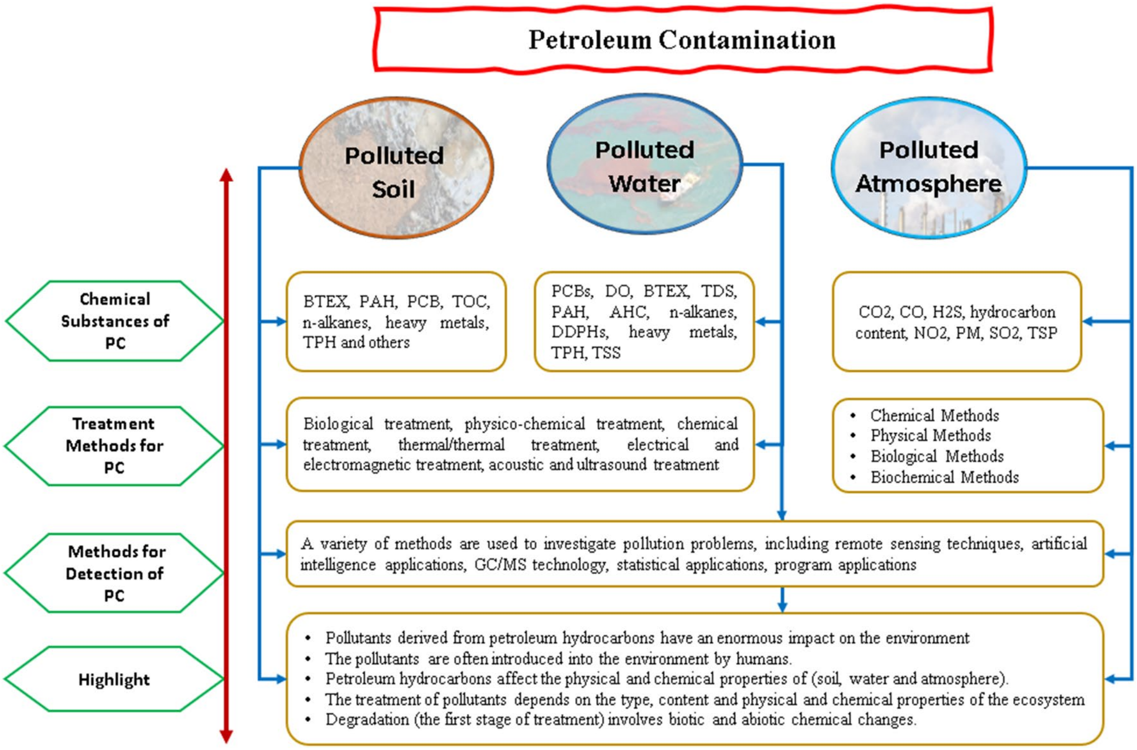
Summary of petroleum contamination

This section provides an overview of the practices and measures used to address petroleum pollution in the three critical areas of soil, water, and air. Petroleum pollution is caused by a variety of sources, with a significant number of individual pollutants (hydrocarbons) present. The unauthorized or unintentional release of hydrocarbon pollutants into the environment caused by human activities poses a direct and indirect threat to the health of all living beings in the affected area. Examples of such activities include drilling for oil or gas, transportation and storage of petroleum products, sabotage of pipelines, leaks from tanks, spills during loading and unloading, ballasting, and unloading or bunkering.

These threats manifest themselves through changes in population dynamics, disruption of trophic interactions, and the natural community structure of the ecosystem (Sajna et al. 2015; Souza et al. 2014; Bejarano and Michel 2010). In response to these challenges, numerous nations and authoritative bodies have conducted extensive research on oil pollution issues. They have developed a variety of methods and applications for assessing pollution and have devised different approaches, techniques, and procedures for dealing with it, as shown in Fig. 6.

Methods for the detection of petroleum contamination

In recent decades, remote sensing data have been widely used for the detection and monitoring of oil spills. These data are usually collected using passive and active systems. Active sensors use their energy source to illuminate objects and record the backscattered energy, while passive sensors capture naturally reflected and emitted solar radiation. Remote sensing methods for oil spill detection and monitoring, oil-type characterization, and layer thickness estimation include multispectral and multispectral infrared sensors, hyperspectral sensors, thermal sensors, microwave sensors, and laser Fluor sensors. As each approach has its advantages and disadvantages, it can be a challenge to obtain



A variety of methods are used to investigate pollution problems, including remote sensing techniques, artificial intelligence applications, GC/MS technology, statistical applications, program applications

- Pollutants derived from petroleum hydrocarbons have an enormous impact on the environment
- The pollutants are often introduced into the environment by humans.
- Petroleum hydrocarbons affect the physical and chemical properties of (soil, water and atmosphere).
- The treatment of pollutants depends on the type, content and physical and chemical properties of the ecosystem
- Degradation (the first stage of treatment) involves biotic and abiotic chemical changes.

Fig. 6 Summary of petroleum contamination categories

the necessary information for a fast and effective oil spill response from a single data source. The general structure of remote sensing techniques is shown in Fig. 7 (Schultz 2013).

Optical images, which are less commonly used in oil spill investigations than microwave images due to their dependence on weather and daylight, are affected by clouds and lack of sunlight Brekke and Solberg (2005). However, optical sensors offer special spectral characteristics that complement microwave images and can provide important information to distinguish between oil spills and water surface features, such as algal blooms (Reddy 2008; Bodor et al. 2022; Li et al. 2013, 2017; Zhao et al. 2014).

Active microwave sensors, particularly synthetic aperture radar (SAR) and side-looking airborne radar (SLAR) systems, are commonly used to detect and analyze oil spills Gil and Alacid (2018), Singha et al. (2016). These sensors have a long range and can collect data day and night under different climatic conditions. Both SAR (satellite-based) and SLAR (airborne) systems transmit and receive backscattered radio waves and record the reflections to create two-dimensional representations of the environment (Li et al. 2017; Chen et al. 2017).

Machine learning (ML), a subfield of artificial intelligence, has been used in recent decades to detect oil spills based on optical and SAR images and distinguish them from their mimics. ML models, together with deep learning (DL) models, have shown remarkable performance in efficient monitoring systems to mitigate the impact of oil spills. The classification includes different types of classical and advanced ML models as well as DL models for oil spill detection, identification, and localization using remote sensing data (Topouzelis and Psyllos 2012; Shen et al. 2020). Figure 7 shows different classical and advanced ML models for these purposes.

Traditional ML models such as artificial neural networks (ANN), support vector machine (SVM), decision tree (DT), and fuzzy logic have been widely used for oil spill detection based on SAR images (Li et al. 2013; Gibril et al. 2018). In contrast, versatile DL models, including convolutional neural networks (CNNs), autoencoders (AEs), recurrent neural networks (RNNs), deep belief networks (DBNs), and generative adversarial networks (GANs), have shown excellent performance in detecting oil spills from SAR and optical images by automatically extracting discriminative features. These DL models are used for tasks such as object identification, patch-based classification, oil spill semantics, and instance segmentation of oil spills (James 2020; Zhang et al. 2016).

In addition, various applications and statistical methods are used to analyze and assess oil spills. These include the Seep Assessment Study (SAS), the least squares method, the software R (3.2.2), SPSS, ANOVA and Least Significant Difference (LSD). In addition, there are scattered applications, each with its own style and approach, such as RECOLAND v1.0, Monte Carlo simulations and ENVI Modeler.

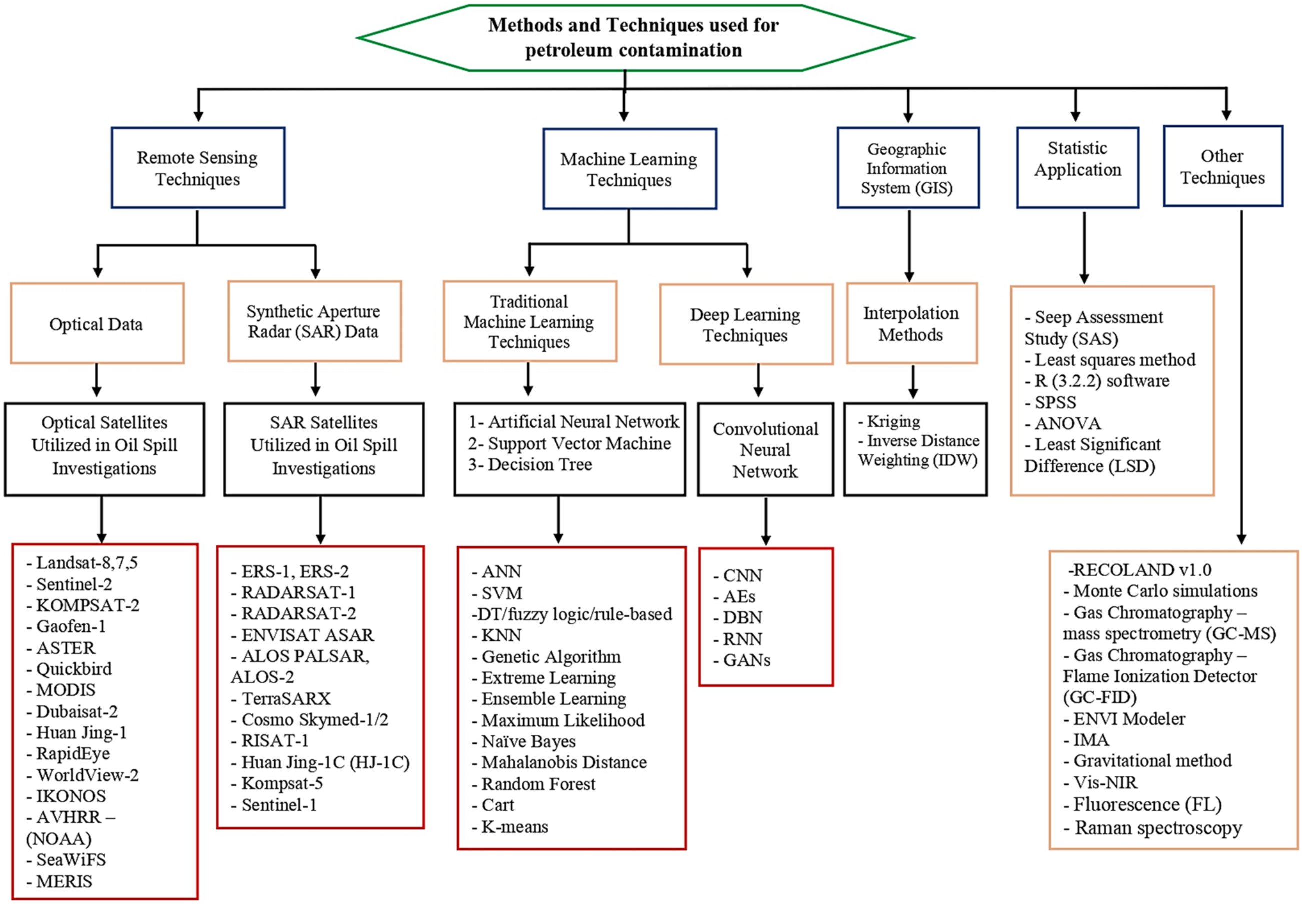


Fig. 7 Common methods for the detection of petroleum contamination

Numerous spectroscopic and non-spectroscopic methods have been developed for the analysis of total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAH) in contaminated samples, using techniques such as immunoassay (IMA), general gravimetry, laboratory-based gas chromatography (GC) with flame ionization detection (FID) or mass spectrometry (MS), infrared (IR) spectroscopy, Raman spectroscopy and fluorescence spectroscopy, which are commonly used.

Treatment methods for petroleum contamination

In line with the sustainable development goals that emphasize human health, a standing guideline of the World Health Organization, remediation methods are central to achieving comprehensive cleanup, containment, removal, restoration, and remediation of the contaminated environment (Fig. 8). The chosen remediation strategy for a particular contaminated site must be tailored to its unique characteristics, considering factors such as the nature and composition of the contaminants, the physical, chemical, and biological conditions of the affected environment, and the microbial community present or required for growth.

Rapid global growth has prompted countries to enact regulations and legislation to address the threat of air pollution. This in turn has significantly influenced the development of new technologies to treat contaminated atmospheres. There are four main types of air treatment processes: chemical, physical, biological, and biochemical. Some treatment systems use a combination of chemical and biological processes, known as mixed process or multi-stage atmospheric treatment systems (Fig. 8).

The process, regulatory requirements, cost, and time constraints must also be considered when selecting an

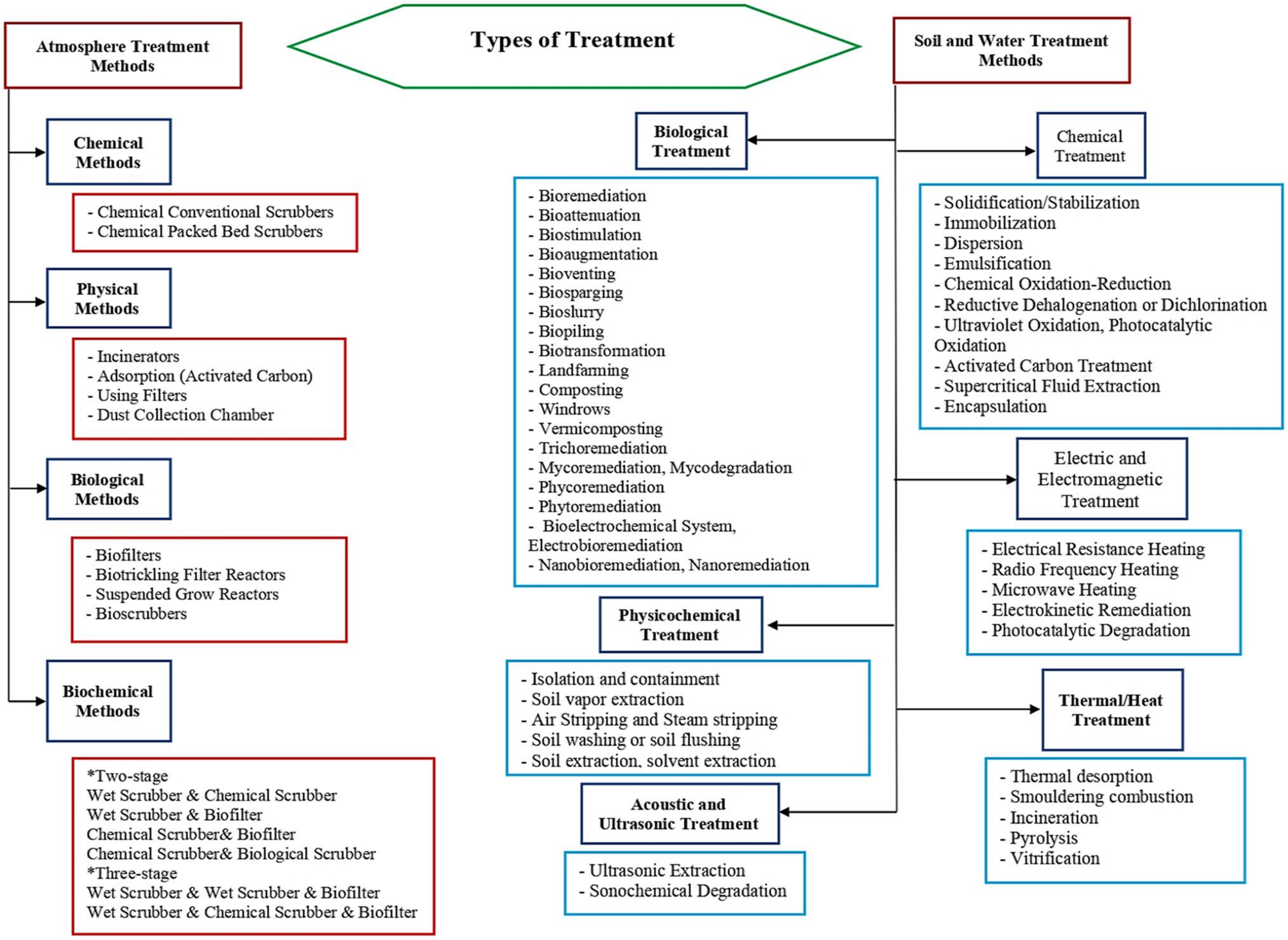


Fig. 8 Classification of treatment methods for petroleum contamination

appropriate remedial method. In response to the increasing need to address pollution, environmental scientists are now emphasizing risk-based management approaches to remediate contaminated environments (Fig. 5). This shift is driven by the need to address health risks and control adverse effects on the affected area.

The scheme shown in Fig. 8 outlines various remediation and remedial measures to combat soil, water, and atmospheric pollution from petroleum hydrocarbon compounds and other organic chemicals. While there are several remediation methods for both soil and water, none of them is optimal for all types of contaminants and the different site-specific variables in the affected areas (Thavamani et al. 2015). The selection of a remediation method depends on a comprehensive understanding of the conditions of the affected environment, the nature, composition and properties of the contaminants, the fate, transport and distribution of the contaminants, the degradation process, the interactions and relationships with microorganisms, and the intrinsic and extrinsic factors affecting remediation. The possible effects of the selected remediation measure must also be considered.

The effective removal, containment, or elimination of contaminants and hazardous substances from damaged areas may require the application or integration of several remediation methods in a process sequence (Maletić et al. 2011). However, an informed decision requires the selection of one or more remediation methods considering the many conflicting aspects. Therefore, it is advisable to choose remediation methods that are adaptable, scientifically defensible, sustainable, non-invasive, environmentally friendly, and cost-effective, as the removal of petroleum hydrocarbon spills is a colossal, challenging, and costly endeavor.

Issues and challenges in petroleum contamination

This section deals with the various aspects of the study of petroleum contamination in soil, water, and the atmosphere and its impacts. It addresses the challenges faced by detection and treatment techniques and emphasizes the need for a deeper understanding. Despite the effectiveness of current environmental technologies, obstacles remain. This review paper highlights pollution issues to gain insights and avoid common mistakes. A major challenge is the indispensability of petroleum in the economy combined with the high cost of detection and treatment methods. While existing methods are promising, complete control of oil pollution remains elusive.

Issues and challenges in the detection of petroleum contamination

There are various methods for detecting petroleum contamination. It is helpful to divide these methods into two main categories: traditional and modern/advanced approaches. In the following sections, we will look at the advantages and disadvantages of each strategy. It is important to note that this categorization is for organizational purposes only—it is not meant to discredit or dismiss the effectiveness of traditional methods.

Traditional methods

In discussing these methods, we will differentiate them based on key characteristics such as portability, economic considerations, uptime, labor protection, safety, and accuracy. Over the years, numerous spectroscopic and non-spectroscopic methods have evolved for the analysis of total petroleum hydrocarbons (TPHs) and polycyclic aromatic hydrocarbons (PAHs) in contaminated samples. Widely used techniques include immunoassay (IMA), general gravimetry, laboratory-based gas chromatography (GC) with flame ionization detection (FID) or mass spectrometry (MS), infrared (IR) spectroscopy, Raman spectroscopy and fluorescence (FL) spectroscopy. Figure 3 illustrates the development of methods such as portable GC-MS and new generation near-infrared analysis with visible and near-infrared spectroscopy (Vis–NIR) and shows their potential for the measurement of TPH and PAH in contaminated samples.

Originally, laboratory-based GC-MS systems, fluorescence spectroscopy, and Raman spectroscopy were used for PAH analysis in environmental samples. However, GC-MS systems were preferred due to their relative selectivity and sensitivity. Fluorescence spectroscopy has proven to be particularly efficient in various investigations and is characterized by good operating time and sufficient safety data. IMA is characterized by its affordability, portability, accuracy, and sufficient uptime and safety data (Fig. 7), although it is based on solvent extraction.

Although GC-based techniques have high precision, their suitability is not determined by their analytical capabilities alone. Considerations such as health and safety, cost efficiency, and uptime play a crucial role in the overall assessment. While portable GC-MS devices increase the mobility of the method, they do not necessarily have a significant impact on cost-effectiveness, uptime or health and safety, given the high cost and reliance on time-consuming extraction procedures.

Improvements to conventional techniques could include operating methods that favor non-chlorinated solvents without compromising analyte recovery. In addition, an instrument design that eliminates the need for sample extraction prior to analysis would improve the timeliness of analysis. Gravimetry, which is considered inexpensive and accurate, is a laboratory-based method with a poor health and safety record and moderate uptime due to the extraction phase.

IR and Vis–NIR spectroscopy are suitable for the detection of impurities, with IR spectroscopy benefiting from the greater precision and mobility of portable devices. Vis–NIR spectroscopy is characterized by its mobility and uptime as well as a good economic balance and a good health and safety balance. However, its relatively low accuracy compared to other methods (Fig. 4) indicates a need for improvement, as Vis–NIR predictions are based on overtones and combinations of fundamental vibrations in the mid-IR range. Improving the accuracy of Vis–NIR spectroscopy is crucial for its continued effectiveness.

Modern methods

This approach, which relies primarily on remote sensing data, faces several problems, such as the energy source of the satellites acquired, the distinguishing features in the satellite images or the atmosphere, the degree of coverage and the amount of data required to identify or verify the pollution. Oil spills pose a constant threat to marine biodiversity, species, and ecosystems, highlighting the need for remote monitoring, identification, and management. Over the last decade, significant progress has been made in oil spill detection thanks to the increasing availability of remote sensing data, growing computing power, cloud computing infrastructure and the introduction of state-of-the-art ML algorithms.

Satellite and airborne remote sensing methods play a crucial role in oil spill detection. They include multispectral, hyperspectral, thermal, microwave, and laser ground sensors in the visible and infrared spectrum. Satellite-based microwave radar data using synthetic aperture radar (SAR), which is independent of sunlight and can penetrate clouds, is very popular for oil spill detection. Satellite-based multispectral data, which are increasingly available and have special spectral characteristics, help to distinguish oil spills from other substances. While additional sensors such as ultraviolet and laser-fluorine sensors are uncommon in oil spill detection systems, combining data from different sources can supplement information, bridge temporal gaps, and improve the timeliness and effectiveness of oil spill monitoring and response.

The accuracy of oil spill detection systems is compromised when optical and SAR images contain duplicates that resemble oil spills and other natural or man-made sites. Evaluating the effectiveness of derived features from optical and SAR images requires considerable effort. Many oil spill research studies rely on manual extraction and assimilation of different feature categories, depending on the analyst's expertise.

The effectiveness of classification algorithms depends on several critical factors, in particular the collection and selection of representative training samples (ground-truth samples) that are acceptable, of high quality and available in sufficient numbers. As outlined in a study (Maxwell et al. 2018), the minimum number of samples required for ML classification methods still needs to be clarified. The development of accurate and reliable classification systems requires extensive, representative training samples of oil spills and their analogs. Collecting correctly labeled samples of oil spills is a difficult task that requires special attention due to the presence of 'lookalikes,' i.e., natural events that produce similar signals to oil spills. In certain situations, even a human expert may have difficulty recognizing dark spots on an image as oil slicks or something else, leading to potentially false positives and negatives.

Over the past decade, both classical and advanced ML models have been used to detect and classify oil spills. Many studies have investigated the use of classical ML models such as artificial neural networks (ANNs), support vector machines (SVM), decision trees (DT), and fuzzy logic. The development of automatic oil spill detection systems from synthetic aperture radar (SAR) images using conventional ML models involves pre-processing of remote sensing data, dark spot identification and segmentation, discriminative feature extraction and image pixel/object classification. The selection of the optimal model involves the comparison of different conventional ML classifiers based on the same data source, the preprocessing approaches, the number of training samples, the number and quality of the selected features, and the parameter values of the classification algorithms.

Recent studies have shown the success of versatile deep learning (DL) models in detecting oil spills from SAR and optical images. DL models, including convolutional neural networks (CNNs), autoencoders (AE), recurrent neural networks (RNNs), deep belief networks (DBNs), and generative adversarial networks (GANs), have shown the ability to automatically extract discriminative features and distinguish between oil spills, lookalikes, and other targets. The generalization capability of DL models addresses the case-specific nature of traditional ML approaches. Tasks such as object identification, patch-based classification, and semantic and instance segmentation of oil spills have been performed using DL algorithms with different architectures. Among the DL models, CNNs and AEs are commonly used for oil spill identification and segmentation. Despite the increasing prevalence and promising results of various DL models and architectures in oil spill/oil slick identification and detection, there are still problems, such as dark spots caused by natural phenomena in low wind speed regions and shadows caused by waves in satellite images.

Issues and challenges in the treatment of petroleum contamination

The choice of a remediation option is influenced by various scientific and non-scientific factors that affect the efficiency and acceptance of remediation at a technical level. Lack of clarity about the various biotic and abiotic components that affect remediation processes can limit effectiveness. Therefore, a comprehensive knowledge of biological characteristics, environmental characteristics, contaminant characteristics, physicochemical characteristics, type, composition, concentration, heterogeneity, source, age, material handling characteristics, variable site conditions, geohydrological conditions, space requirements, process location (in situ, ex situ, on-site, in containers, off-site), monitoring difficulties, required remediation phases, extended treatment time and risk management is essential.

Biological processes have been shown to be effective both in situ and ex situ in remediating or degrading petroleum hydrocarbons and organic contaminants without long-term environmental damage. However, these processes can take months to years to optimally remove contaminants, and high concentrations of contaminants can inhibit microbial activity, reducing effectiveness. Chemical–physical treatment is crucial for the remediation of polluted soils and waters and offers in situ or ex situ solutions. Although effective, this method is costly and has a negative impact on the environment.

There are various methods (Fig. 8), each with different properties, mechanisms of action and side effects. Given the daunting, arduous, and expensive task of eliminating petroleum hydrocarbon pollution, it is crucial to choose adaptable, scientifically defensible, sustainable, non-invasive, environmentally friendly, and cost-effective treatment methods.

The world population is expected to grow in the near future, which will lead to an increase in air pollution. The annual increase in the use of chemical substances in industry exacerbates this problem. The slow development of new air pollution control technologies could pose serious problems. The challenges of air pollution control technologies include not only the negative impacts of individual technologies, but also considerations of suitability, cost, and other factors.

Wet scrubbers, a process in which polluted air is introduced into a liquid such as water to remove suspended particles and gases, have one major drawback: they produce large quantities of polluted water. This disposal problem has prompted scientists to look for alternative solutions. Incineration, another important approach to removing odors and organic contaminants, involves feeding polluted air containing organic compounds into incinerators that operate at high temperatures. Major obstacles to this technology include excessive energy consumption and the release of significant amounts of carbon dioxide and other by-products.

Activated carbon, which is released into the atmosphere to remove suspended pollutants, achieves impressive purification rates of over 95%. However, due to its high cost, this technology is only used when valuable organic compounds are to be recovered from the atmosphere. Biological therapy, an effective and environmentally friendly process, produces no by-products. Biofiltration technology can remove pollutants under optimal conditions and is well suited for the treatment of large quantities of polluted air containing volatile organic compounds (VOC). It stands out as one of the most promising technologies capable of removing a significant percentage of suspended solids from polluted air over a large area at a lower cost than other processes.

Conclusion

This paper provides an insight into the petroleum contamination in soil, water, and atmosphere. Various aspects are covered, including the chemical elements involved in the contamination, methods of analysis, and forms of treatment. The development of different variables, both analytical and detection methods for total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAH) in contaminated areas, is essential. There is a growing need for simple, cost-effective environmental diagnostic tools that can provide reliable data quickly. Research shows that no analytical approach is without challenges, although some are less problematic. Remote sensing techniques are proving promising and crucial for detecting contamination and ensuring continuous monitoring. Recent studies emphasize the importance of combining remote sensing and artificial intelligence techniques. While various remediation methods exist, no single approach is generally optimal for all contaminants and the numerous site-specific variables in the affected areas. The selection of a remediation method depends on a thorough understanding of the conditions in the affected areas, the nature and characteristics of the contaminants, the fate and transport of the contaminants, the degradation processes, the interactions with microorganisms, the intrinsic and extrinsic factors influencing remediation, and the potential impact of the chosen remedial action. Bioremediation is the preferred technique because it is cost-effective, acceptable, and environmentally friendly. However, conflicting criteria in nature play an important role in the decision-making process, so careful selection of one or more remediation methods is crucial.

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Author contributions KTF did conceptualization; data curation; formal analysis; methodology; investigation; visualization; writing the original draft; review and editing; resources. SFMR done supervision;

conceptualization; project management; writing, reviewing, and editing. KNAM performed supervision; conceptualization; review and editing. SIA and ZMY contributed to conceptualization and review and editing.

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Declarations

Conflict of interest The authors confirm that there is no conflict of interest for this study.

Ethical approval We assured that the present study was conducted ethically, and all authors have given their approval for the final version.

Consent to participate No consent is required for this study.

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