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ORIGINAL PAPER

Enhancing petroleum-contaminated soil remediation using pulverized rice straw

S. U. Oghoje[1,5] · **I. C. Omoruyi**[2] · **C. Ejeomo**[3] · **I. H. Ifijen**[4] · **J. E. Ukpebor**[5] · **A. K. Asiagwu**[1] · **E. E. Ukpebor**[5] · **E. U. Ikhuoria**[5]

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Abstract

This study investigated the effect of pulverized rice straws (PRS, *Oryza sativa*) on the water retention capacity (WRC) of diesel-contaminated soils and the leaching of diesel-range organics (DROs). Diesel contamination at levels of 5, 10, and 15% reduced the WRC by ~ 6, 11, and 26%, respectively. However, adding PRS to 15% diesel-contaminated soils improved the WRC by ~ 18, 31, 53, and 75% for PRS concentrations of 1, 2.5, 5, and 10%, respectively. Furthermore, PRS concentrations of 2.5, 5, and 10% decreased the DROs leaching from 20% diesel-contaminated soil by 34, 75, and 100%, respectively. The findings of this study indicate that composting with PRS enhances WRC and significantly reduces contamination leaching in oil-contaminated soils. This suggests that PRS and similar green composts could optimize landfarming of organically contaminated soils, offering an innovative approach to repurposing waste plant biomass.

Keywords Pulverized rice straw · Improved landfarming · Petroleum hydrocarbons · Contaminated soil

Introduction

Pollution, one of the most pervasive consequences of industrialization and rapid urbanization, continues to imperil global ecosystems (Ifijen et al. 2020; Ikhuoria et al. 2021; Mokobia et al. 2024; Ifijen et al. 2022; Ize-Iyamu et al. 2018; Oyiborhoro et al. 2024). The soil, as the foundation of our terrestrial environment, bears the brunt of many pollutants, particularly petroleum hydrocarbons (Oghoje et al. 2023; Anegbe et al. 2024). The contamination and degradation of soil not only impacts agriculture and ecosystems but also presents risks to human health and the broader environment (Oghoje et al. 2021). Given this backdrop, the development and adoption of effective remediation techniques become indispensable.

Landfarming has emerged as a promising remediation technique within the domain of enhanced natural attenuation (RENA) technologies, specifically aimed at treating and rejuvenating petroleum hydrocarbon-contaminated soils (Oghoje et al. 2021). At its core, this technique involves tilling and spreading excavated soils, expediting the degradation of petroleum derivatives (Mmom et al. 2010; Anegbe et al. 2024). While research attests to landfarming's effectiveness in recuperating vast tracts of oil-contaminated terrains, its cost-effectiveness in detoxifying varied soil contaminants further solidifies its appeal (Oghoje et al. 2021; Mmom et al. 2010; Anegbe et al. 2024). Nevertheless, challenges persist volatile oil fractions readily evaporate, and the process may induce increased rainwater infiltration, leaching, run-off, and reduced soil water retention due to the act of tilling.

Effective bioremediation in oil-contaminated areas demands a harmonious blend of abiotic and biotic conditions, coupled with rich nutritional content (Mmom et al. 2010; Anegbe et al. 2024; Radwan and AL-Mailem et al.. 2000; Ambaye et al. 2023; Zhang et al. 2019). As Mmom

✉ S. U. Oghoje
oghojesteve@yahoo.com; uoghoje@delsu.edu.ng

[1] Department of Chemistry, Faculty of Science, Delta State University, Abraka, Delta State, Nigeria

[2] Department of Environmental Management and Toxicology, University of Delta, Agbor , Delta State, Nigeria

[3] Department of Chemistry, Faculty of Science, Michael and Cecilia Ibru University, Agbarha-Otor, Delta State, Nigeria

[4] Department of Research Outreach, Rubber Research Institute of Nigeria, Iyanomo, Benin City, Nigeria

[5] Department of Chemistry, Faculty of Physical Science, University of Benin, Benin City, Edo State, Nigeria

and Deekor (Mmom et al. 2010; Anegbe et al. 2024) posit, the efficacy of landfarming is modulated by several factors, with well-drained terrains often registering superior outcomes. Influencing variables range from the soil's physical and chemical attributes to site hydrology and ambient temperatures. Notably, Dibble and Bartha (1979) pinpointed an optimal pH range of 6.50–8.0 for hydrocarbon degradation. Atlas (1981) echoed this sentiment, proposing a neutral to 8.5 pH range as ideal for bioremediation of hydrocarbon-laden soils.

Expanding the remediation spectrum, bioremediation encapsulates the utilization of natural or inoculated microorganisms such as fungi and bacteria. These microbes act as catalysts, transforming pollutants, such as those stemming from oil, into benign, eco-friendly by-products such as H_2O and CO_2 (Ifijen et al. 2018; Niazi et al. 2023). In order for landfarming to achieve its maximum potential as a RENA strategy, it is essential to create environments that are favorable for microbial growth and activity. This same requirement also applies to the utilization of soil remediation plants for phytoremediation (Ifijen et al. 2018; Niazi et al. 2023). Prior studies underscore the enhancement of soil water content upon the integration of composts like paper sludge (Onwudide et al. 2016; Rehman et al. 2020; Adekunle 2011). Furthermore, organic entities are credited with boosting soil's propensity to absorb and absorb metals and organic contaminants (Onwudide et al. 2016; Rehman et al. 2020).

Lending credence to this theory, Glaser et al. (2002) discerned an 18% spike in water retention capacity within biochar-treated soils vis-à-vis their untreated counterparts. In a similar vein, Steiner et al. (2007) documented augmented nitrogen retention in charcoal-amended soils. Moreover, biochar's introduction into tropical acidic soils triggered enhanced WRC and escalated concentrations of plant-available Ca and Mg (Major et al. 2010; Major et al. (2010); ; ; ; ; Chen et al. 2024). Biochar is usually made from concrete or solid biomass (including food and agricultural wastes from plants and animals) and spent parts of soil remediation plants (Major et al. (2010); Chen et al. 2024) via a thermochemical conversion technic known as pyrolysis. The process involves some technicality and much consumption of energy thereby making biochar relatively expensive for soil conditioning during soil remediation. Yet pulverized tender green wastes such as barley and rice straws, grass, rice husks and melon seed skins (peels), orange, plantain and cassava peels, wheat and sorghum shrubs, wood-back, and leaf mulch could serve similar purpose as biochar for soil conditioning. The pulverization of these biomass is quite simple and less expensive. Hence, the use of the pulverized products could be less expensive, thereby making their usage as soil conditioners cost effective during bioremediation of polluted soils.

Pulverized rice straw (PRS), replete with organic carbon, might mirror biochar's effects on WRC and the leaching of organic pollutants. While comprehensive insights into PRS's capabilities remain scant, this research, therefore, investigated PRS's impact on WRC in diesel-contaminated soils and its potential in curbing diesel-range organics (DROs) leaching. Through this endeavor, we aim to enrich the existing compendium on bioremediation of petroleum-afflicted soils, especially in oil-sensitive Nigerian locales like the Niger Delta.

Experimental

Study area and materials

Soil sampling and analytical chemical acquisition

The research took place at the University of Benin's Chemistry Department, located in Benin City. Using a sterilized metal spade, we gathered composite soil specimens from the University's Igue oil palm farm, focusing on a depth range of 0–30 cm. After collection, the soil was left to air-dry in a designated greenhouse, then ground and sifted using a 2-mm mesh. The processed soil was stored in a sealed plastic container for experimental purposes. We procured an *n*-alkane surrogate standard, spanning C10–C30 alkanes, from Thames Restek Limited, UK. Trichlorobenzene (TCB) served as the internal benchmark for GC–MS analyses of the DROs, while dichloromethane (DCM) facilitated the extraction of DROs. Other necessary chemicals, including silica gel and sodium sulfate, were sourced from Sigma-Aldrich, Germany, ensuring all were of analytical grade.

Rice straws sampling and processing

Rice straw samples were gathered from a farmer in Kano, Kano State. These samples were spread out on a wooden platform within a greenhouse for air-drying. Once dried, an electric blender was used to pulverize the straws. The pulverized material was subsequently sieved using a 2-mm mesh to yield the PRS utilized in this study (as shown in Fig. 1a, b).

Physico-chemical characterization

Analyses of physico-chemical properties and soil texture were undertaken. The pH was gauged using a Thermo Fisher Orion 4 pH meter (model 420A, Thermo Fisher, UK) with a soil–water ratio of 1:2.5 and a PRS–water ratio of 1:5. Electro-conductivity (EC) was measured using a Hanna conductivity instrument (Model HI 99300, Hanna, UK). The particle size distribution was derived from the Bouyoucos hydrometer method as delineated by Okalebo et al.

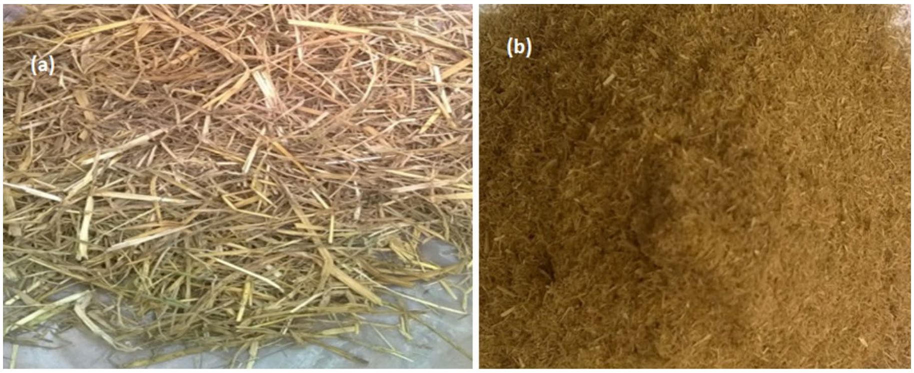

Fig. 1 Raw air-dried (**a**) and pulverized (< 2 mm sieved) (**b**) rice straws

(2002) and referenced by Day (1953). Total nitrogen (TN) was evaluated through the Kjeldahl approach (Bremmer and Blark 1965). Total organic carbon (TOC) was assessed using the wet combustion technique propounded by Walkley and Black (1934), while the Murphy and Riley technique (Murphy and Riley 1962) was employed to ascertain total phosphorus (TP). Concentrations of magnesium (Mg) and calcium (Ca) were gauged via an atomic absorption spectrophotometer, whereas sodium (Na) and potassium (K) levels were ascertained using a flame photometer (model 410 Sherwood, UK). For analyzing DROs, GC–MS was utilized.

Water retention capacity (WRC) determination

The method for determining the WRC was based on the Aitken approach as described by Tandy et al. (2011). A 100-g sample was soaked in water for roughly 3 h and then left to drain completely over an approximate period of 16 h. Subsequently, the sample was oven-dried at 105 °C until it reached a stable weight. The WRC was computed by comparing the weight difference between the oven-dried and the drained sample, expressed as a percentage.

Effects of diesel on the water retention capacity of soils

Each soil sample, weighing 100 g, was mixed with diesel fuel at concentrations of 5, 10, and 15%, while a control sample remained diesel-free. When determining the WRC for these oil-contaminated samples, adjustments were made to account for the evaporation of volatile components in the oil during oven-drying. A prior experiment indicated that direct application of the Aitken method could lead to an overestimation of the soil's WRC. As a result, both air-drying and oven-drying techniques were employed to ascertain the WRC of the diesel-infused soils. Initially, all samples, including those spiked with diesel, were air-dried. The control sample (0% diesel contamination) was subsequently oven-dried at 105 °C for a duration of 6 h. The WRC for each diesel-contaminated sample was then adjusted by deducting the moisture adjustment factor. This factor was determined by the average percentage weight disparity between the air-dried and oven-dried samples without diesel contamination.

Effects of PRS on WRC of diesel-contaminated soils

Additional subsets of the soil samples, each weighing 100 g, were treated with diesel at concentrations of 0, 5, 10, and 15%. Subsequently, these samples, reflecting varying levels of diesel contamination, were mixed with PRS, constituting 0, 1, 2.5, 5, and 10% of the soil's weight. Following thorough mixing to ensure homogeneity, the WRC of these mixtures was assessed as outlined in Sect. "Water retention capacity (WRC) determination".

Effects of PRS on the leaching of diesel compounds from contaminated soils

Soil samples, air-dried and sieved to 2 mm, each weighing 100 g, were treated with 20% diesel to simulate environments with high diesel pollution. To ensure moisture content remained at 65% of the WRC, an addition of 25 mL of distilled water was made. These samples were then combined with PRS in proportions of 0, 2.5, 5, and 10% relative to the soil's weight. After ensuring uniform mixing, the composite was filled into standardized soil columns measuring 15 cm in length and 3 cm in diameter. Adhering to the guidelines of OECD/OCDE 312, artificial rain simulators were utilized to pour 150 mL of distilled water over each column, replicating natural rainfall conditions (OECD, OCDE. 2004). The DROs from the resultant leachate were then extracted using DCM. After extraction, the samples underwent a purification process involving a 3-g layer of sodium sulphate atop a silica gel column.

For analysis, the purified samples were subjected to a GC–MS. The organic components were isolated and examined using a Trace 1300GC/ITQ900 Ion Trap Mass Spectrometer (located in Waltham, US). This equipment was fitted with a Restek RTS1 PONA DB 5 column, which had dimensions of 30 m × 0.25 mm and an internal diameter of

0.25 m. The settings used included a split injection mode, helium as the carrier gas, an injection temperature of 250 °C, a transfer line temperature of 300 °C, an ion source temperature of 200 °C, and a terminal temperature set to 320 °C.

Statistical analysis

The assessments were conducted in triplicate. The t-test was employed to detect significant disparities between the control and the treated samples, using a 95% confidence level ($P < 0.05$). For the creation of all graphs and charts, SigmaPlot® and Excel 2010 were utilized.

Results and discussion

Physico-chemical properties of soil and Barley straws

The physical and chemical properties of a soil play a pivotal role in determining its response to contamination and subsequent remediation strategies. In the quest for "Enhancing Petroleum-Contaminated Soil Remediation Using Pulverized Rice Straw," understanding these properties is crucial.

Table 1 illustrates the physico-chemical attributes of both the soil and the pulverized rice straw (PRS) used in this research. One of the critical characteristics is the pH level. The soil exhibited a pH of 5.53, signaling a mild acidic nature. Such acidity levels can influence the behavior and mobility of contaminants, as well as the microbial activity crucial for bioremediation. The observed pH values align with those reported in prior studies conducted in the Niger Delta region (Ekebafe and Oviasogie 2015). This consistency suggests that the findings of this research may have broader implications and could be applicable to other similar soils in the region.

Table 1 Physico-chemical properties of soil and rice straws used in this study

Parameters	Soil	PRS
pH	5.53	7.52
EC (µs/cm)	151.67	2578.00
FBC (%)	–	53.50
OMC (%)	6.30	89.63
WHC (%)	36.80	86.70
K (mg/kg)	96.20	2264.60
Na (mg/kg)	28.66	64.42
Ca (mg/kg)	1377.63	2220.96
Mg (mg/kg)	702.20	287.16
TP (mg/kg)	439.10	1740.40
C (%)	4.61	45.12
N (%)	0.40	0.49
C: N	0.09	0.01

OMC organic matter content, *WHC* water-holding capacity, *TP* total phosphorus, *FBC* fiber content

The PRS showed a pH of 7.52, which is very slightly alkaline and significantly different from the soil's natural pH. By integrating a weak alkaline agent like PRS into the mildly acidic soil, there could be potential benefits in terms of modifying the soil environment, making it more conducive for remediation processes. Moreover, the PRS exhibited a fiber content of 53.50%. Fibrous materials in plants, such as lignin, hemicellulose, and cellulose, are known for their ability to retain water molecules (Subagyo and Chafidz 2020; Watkins et al. 2015; Liang et al. 2023; Wu et al. 2022). By incorporating PRS into petroleum-contaminated soil, there could be enhanced water retention. Such increased moisture levels can favor microbial activities, which, in turn, can expedite the breakdown of hydrocarbon contaminants. Furthermore, other properties such as electro-conductivity (EC), soil organic matter (SOM), and the general soil texture, which were found to be in line with several soils of the Nigerian Niger Delta region (Ekebafe and Oviasogie 2015; Benka-Coker and Ekundayo 1995), further highlight the representative nature of the sample. These similarities suggest that the potential benefits of using PRS as an enhancer for petroleum-contaminated soil remediation could be extended to a wider scope in the Niger Delta region.

In a nutshell, the distinct physico-chemical attributes of both the soil and PRS underscore their potential symbiotic relationship in the remediation process. The PRS, with its water retention capability and weak alkaline pH, could substantially enhance the efficiency of remediation efforts in petroleum-contaminated soils, particularly those with characteristics similar to the ones highlighted in this study.

Identification of the DROs in the local diesel sample used for the study

The GC–MS fingerprint, as depicted in Fig. 2, provides a comprehensive view of the diesel-range organics (DROs) present in the local diesel sample used for the study. Further insights into their specific retention times (RTs) are tabulated in Table 2.

These findings reveal a diverse range of DROs within the sample, spanning from decane (C10) up to hexacosane (C26), among other compounds. Such a broad spectrum of DROs emphasizes the complexity of the diesel sample, underscoring the need for comprehensive remediation strategies when dealing with soil contaminated by such diesel (USEPA 1994, 2007, 2008; Holzer et al. 1992).

Crucially, the identification of these compounds was meticulously achieved by juxtaposing their RTs, M+ masses, and specific fragmentation patterns against those derived

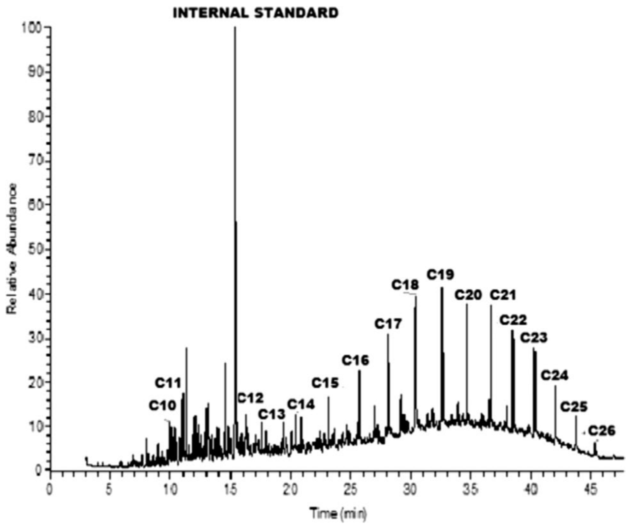

Fig. 2 GC–MS chromatogram showing profile for 0.25-g/L diesel

Table 2 Retention time(s) and major chemical components of the locally sourced diesel

S/N	RT (min)	DROs identified	Carbons numbers	Molecular masses (g/mol)	M^+ masses
1	11.35	Decane	C_{10}	142.29	141.00
2	14.54	Undecane	C_{11}	156.31	156.19
3	17.60	Dodecane	C_{12}	170.34	170.14
4	20.47	Tridecane	C_{13}	184.37	184.24
5	23.18	Tetradecane	C_{14}	198.39	198.16
6	25.73	Pentadecane	C_{15}	212.42	212.14
7	28.14	Hexadecane	C_{16}	226.45	226.11
8	30.43	Heptadecane	C_{17}	240.47	240.00
9	32.60	Octadecane	C_{18}	254.50	267.08
10	34.67	Nonadecane	C_{19}	268.53	282.20
11	36.65	Icosane	C_{20}	282.55	296.49
12	38.54	Heneicosane	C_{21}	296.58	310.54
13	40.36	Docosane	C_{22}	310.61	324.56
14	42.09	Tricosane	C_{23}	324.63	336.47
15	43.76	Tetracosane	C_{24}	338.66	353.24
16	45.37	Pentacosane	C_{25}	352.69	365.37
17	46.92	Hexacosane	C_{26}	366.71	380.47

from a surrogate standard of typical alkanes (Oghoje et al. 2020). This comparative approach ensures the precision of compound identification, enhancing the credibility of the findings. In the context of "Enhancing Petroleum-Contaminated Soil Remediation," understanding the specific constituents of diesel is pivotal. Recognizing the range and nature of DROs present offers insights into the challenges posed by contamination and aids in tailoring the remediation strategies, particularly when using agents like PRS.

The effects of diesel fuels on soil water retention capacity

Figure 3 illustrates the influence of diesel fuels on the water retention capacity (WRC) of soil. For the pristine, uncontaminated soil, the WRC stood at about 36%. However, as diesel contamination levels rose, there was a noticeable decrease in WRC: 34% for 5% diesel contamination, 31% for 10%, and a substantial drop to 26% for 15% contamination.

Delving deeper, Table 2, at a 95% confidence level, highlights the significant impact of these changes. The associated significant values (*p*-values) dwindled from 8.00E-04 (at 5% diesel contamination) to an extremely low 1.90E-14 (at 15% contamination). In statistical terms, a diminishing *p*-value suggests heightened significance; the impact becomes more pronounced as the *t*-test value drops. This trend echoes findings from Kayode et al. (2009), who observed an 18% reduction in the water-holding capacity (WHC) of soils spiked with 5% waste engine oil. Such a decline in WRC due to diesel pollution holds significant ramifications for soil remediation. Soil water plays a pivotal role in shaping soil chemistry and fostering microbial activity. A decreased WRC due to diesel contamination could severely hamper landfarming efforts, given the critical importance of moisture for microbial-mediated breakdown of contaminants.

However, the silver lining might be found in the pulverized rice straw (PRS). Its relatively high-fiber content potentially contributes to its pronounced WRC. When introduced to diesel-contaminated soils, the rich nutrient profile of rice straws—inclusive of elements such as potassium, calcium, magnesium, and phosphorus—might bolster the soil's nutritional matrix, thereby enhancing the landfarming process. The nutritive augmentation composts provide to bioremediation has been well-documented (Radwan and AL-Mailem et al. 2000; Rehman et al. 2020; Semple et al. 2001; Shrestha et al. 2019; Yang et al. 2021), and PRS might just be a game-changer in this realm (Table 3).

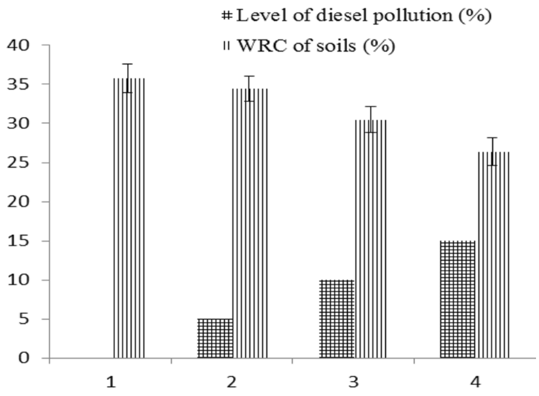

Fig. 3 Set of bar charts showing the effects of diesel contamination on the WRC of soil in relation to the levels of contamination

Table 3 Statistical analysis of the WRC of diesel-contaminated soil

Level of pollution	Ave. WRC	% effects on WRC	*t*-test values
0	35.79	–	–
5	34.43	3.80	8.00E−04
10	30.49	14.81	5.40E−11
15	26.40	26.24	1.90E−14

Effects of rice straws on the WRC

This research has shed light on the efficacy of composting diesel-contaminated soils with PRS, highlighting its potential to mitigate the adverse effects of diesel on both water retention capacity (WRC) and the soil's capability to absorb diesel-range organics (DROs). As visualized in Fig. 4, even a modest addition of 2.5% PRS through composting was potent enough to enhance the WRC of soils polluted with 5% and 10% diesel by 41% and 38%, respectively. However, for soils with a higher contamination level of 15% diesel, an increment in composting to around 5% was needed to achieve a comparable 41% boost in WRC.

A deeper dive into the WRC of diesel-contaminated soils, presented in Table 4, showed the steadily enhancing effect of PRS composting across different contamination levels. These improvements were statistically noteworthy at a 95% confidence level. Indeed, the significance values for the three diesel contamination tiers—5, 10, and 15%—were compelling, especially when comparing composted and non-composted soils. But while the gains were evident, it is crucial to note that even with composting, the WRC of the soils did not revert to the original 36% exhibited by uncontaminated soils. A closer examination, illustrated in Fig. 4, showcases that a 1% composting could bring the WRC to 34% and 31% for soils with 10% and 15% diesel pollution, respectively. But to push the WRC of similarly contaminated samples to 38% and 35%, a 2.5% composting was necessary. To achieve a WRC of 41% for the 15% diesel-contaminated samples, a composting of about 5% was essential. This suggests a nuanced relationship between the extent of diesel contamination, the required PRS input, and the resulting WRC. The overarching goal is to elevate the WRC of the polluted soil close to or at the level of its uncontaminated counterpart, and the optimal PRS amount hinges on the degree of diesel contamination.

Table 4 The level of significance of PRS composting on WRC of different levels diesel-spiked soils

Level of treatment with PRS (%)	Levels of contamination with diesel (%)		
	5	10	15
t-test values			
0			
1	4.071E−02	1.57E−03	4.40E−05
2.5	1.33E−04	3.60E−04	1.11E−05
5	1.97E−05	6.65E−04	3.16E−07
10	1.53E−06	9.76E−05	4.22E−08

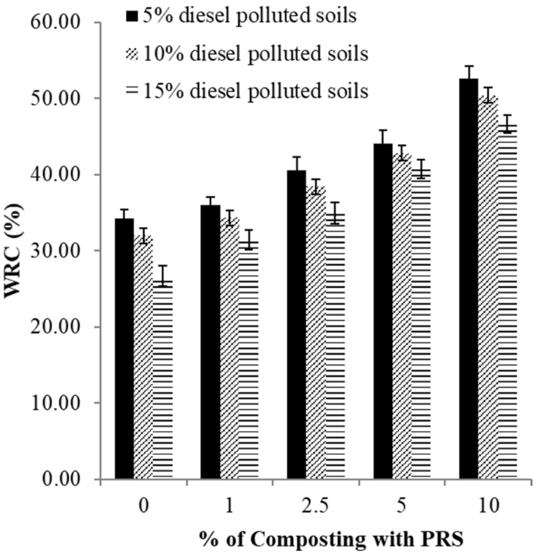

Fig. 4 The effects of PRS composting on the WRC of diesel-contaminated soils

Interestingly, a previous study has hinted at the potential of straws in augmenting the bioremediation process (Molina-Barahona et al. 2004). Though initially perceived as mere bulking agents, the presence of straws likely improved the moisture equilibrium within the polluted environment. Such an equilibrium could foster favorable soil chemistry and microbial growth, paving the way for more effective remediation.

The effect of PRS on leaching of the DROs from soil

The way organic pollutants migrate within soil structures is significantly influenced by soil organic matter (SOM) and the specific type of soil. Two critical factors, SOM and clay (a type of soil particle), play pivotal roles in this movement. They tend to adsorb or absorb specific pollutants present in the soil, preventing these contaminants from seeping further down into the soil layers (Shrestha et al. 2019; Jones et al. 2011; Gul et al. 2019; Siedt et al. 2021).

In a past exploration that delved into how compost composition and soil type interplayed to affect the leaching of crude oil, an interesting observation was made. Specifically, as the proportion of clay or compost in the soil increased, there was a concomitant reduction in the amount of oil that leached out. Drawing from the insights of Jones et al. (Jones et al. 2011), an intriguing inverse correlation emerges: As the quantity of bio-char introduced to the soil rises, there was a reduction in the amount of the herbicide simazine that gets leached post its application.

In the context of this research, there is a striking revelation: Composting with PRS could markedly diminish the leaching of DROs from soils contaminated with diesel. The concentration of these compounds in various leachates is reflected by the area covered by the respective DROs' GC–MS peaks (or peak area ratio (PAR). An examination of the GC–MS chromatograms—sourced from the leachates of soils having 20% diesel contamination and different PRS composting levels—provides clarity. As illustrated in Fig. 5a–d, a discernible trend emerges. As PRS composting levels escalate, there is a proportional reduction in the sizes of the chromatograms. Strikingly, upon reaching a 10%

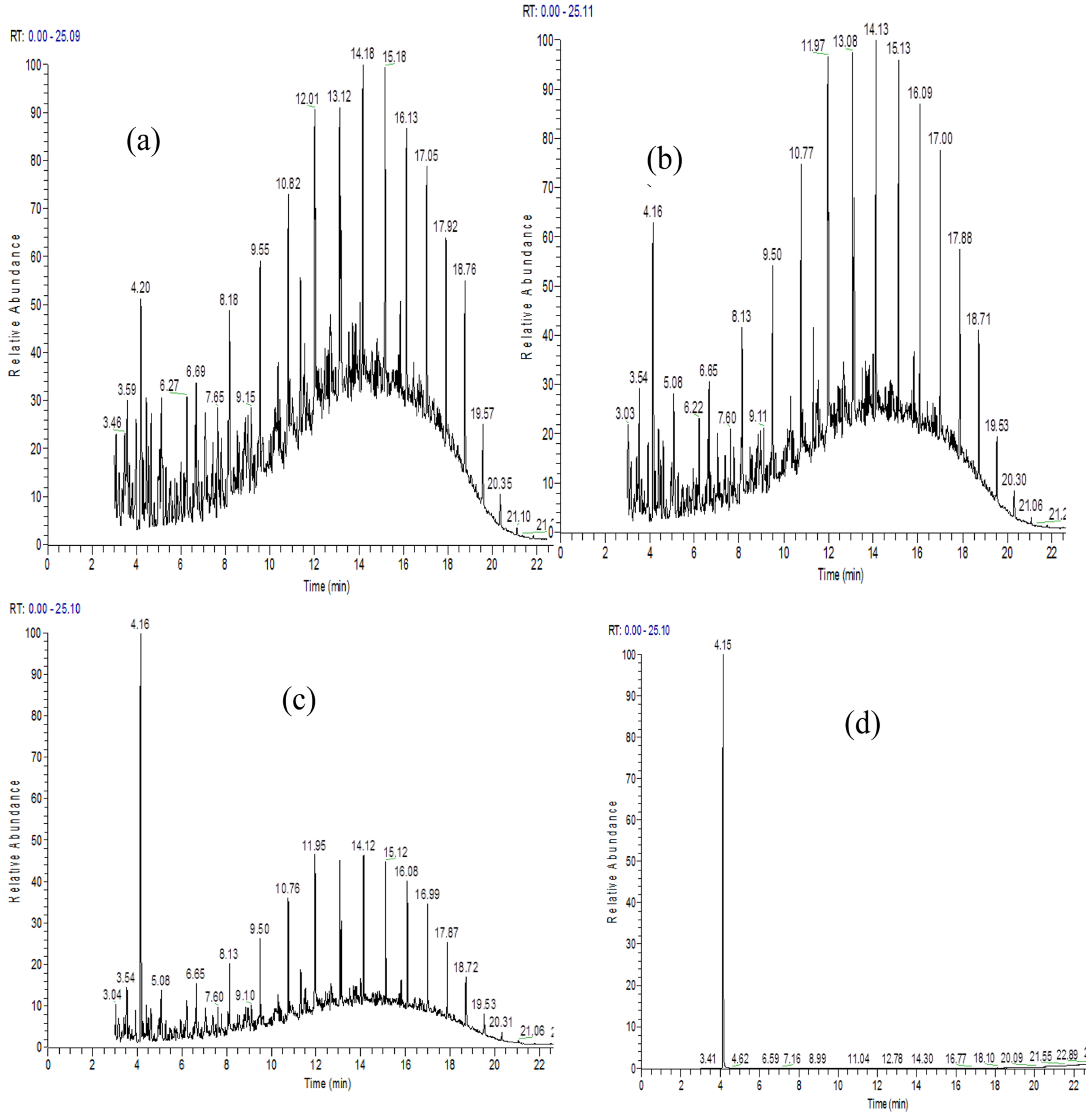

Fig. 5 Chromatograms of the leachates from **a** 0% PRS composted, **b** 2.5% PRS, **c** 5% PRS composted, and **d** 10% composted 20% diesel-contaminated soils

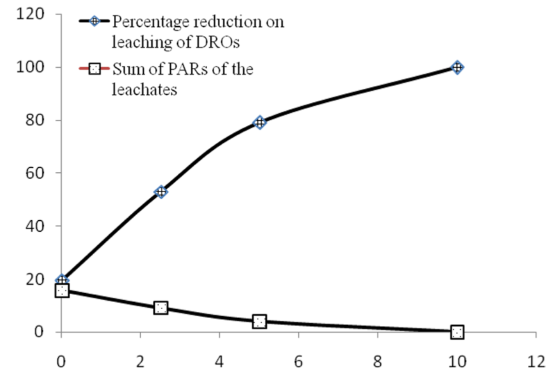

Fig. 6 Graphical presentation of the effects of PRS composting on the percentage reduction on leaching of DROs and the sum of PARs of 20% diesel-contaminated soils

composting threshold with this green compost, the chromatograms diminish to zero, showcasing the potent remedial efficacy of PRS composting.

The efficacy of composting with PRS in the remediation of diesel-contaminated soils becomes strikingly evident when considering the total peak area ratio (TPAR). For the leachate derived from a non-composted diesel-contaminated soil, the TPAR was registered at 15.99. In stark contrast, soils that underwent composting at rates of 2.5%, 5%, and 10% recorded TPAR values of 12.07, 3.97, and an impressive 0%, respectively. Simply put, as the levels of PRS composting increased, there was a corresponding and substantial reduction in both peak sizes and TPAR. This relationship is visually represented in Fig. 6, which juxtaposes the reduction percentage of DROs in the leachates with their respective TPARs. It is pivotal to recognize that the PARs are indicative of the specific DRO concentrations within the varied analytes. A noteworthy observation is the complete absence of detectable DROs in the leachates upon reaching the 10% PRS composting mark.

A statistical comparison with the leachates from non-composted counterparts reveals the significance in DRO reduction, with values of 2.15E-03, 2.15E-07, and 5.39E-07 corresponding to the 2.5%, 5%, and 10% PRS composting levels (and all of this at a 95% confidence interval).

In the broader environmental context, both organic and inorganic soil pollutants, especially toxic metals and their potential to contaminate subsurface and surface water sources, have been a focal point of scientific scrutiny in recent times. Many of these studies have consistently identified an inverse correlation between composting rates and the amount of contaminants found in soil leachates (Shrestha et al. 2019; Gul et al. 2019; Siedt et al. 2021; Beesley et al. 2010; Banks et al. 2006). However, it is essential to mention Worrall et al.'s (2001) revelation, which emphasized the hydrophilic nature of a substance as a determinant for its absorption by organic matter or compost in soils. Diesel, characterized by its hydrophilic properties, exhibited a pronounced adherence to the PRS-blended soils in our study, further underscoring the efficacy of PRS composting in remediating diesel-contaminated (and by extension petroleum contaminated) terrains.

Conclusion

Landfarming, a bioremediation strategy for petroleum-contaminated terrains, presents challenges such as soil moisture evaporation and oil leaching due to tilling. The study illuminates the benefits of composting diesel-contaminated soils with biomass products like PRS. Composting enhances soil water retention and mitigates contaminant leaching. Incorporating green composts like PRS into landfarming can improve hydrocarbon bioremediation effectiveness. However, while the laboratory research mimicked field conditions, actual field dynamics may differ. Further field-level studies are crucial for optimizing landfarming and understanding PRS's potential in hydrocarbon-contaminated soils.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethics approval and consent to participate Not applicable.

Consent for publication Each author in this manuscript has given permission for this work to be published.

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