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Beyond oil: Assessing the viability of circular economy approaches for sustainable management of drilling waste contaminated soils in Apsheron Peninsula, Azerbaijan

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ABSTRACT
The Apsheron Peninsula is faced to a high risk of soil contamination with drilling wastes (up to 28500 mg kg^{-1} TPH) due to decades of oil drilling. Guided by the circular economy (CE) paradigm, this study evaluated the technical-economic-environmental feasibility of three advanced solutions to the sustainable management of such soils: (i) cutting-edge stabilization/solidification (S/S) with a hybrid binder (cement + GGBS + alkaline activator), (ii) thermal hydrocarbon recovery, and (iii) enhanced bioremediation with a local microbial population. The results showed S/S was effective in reducing hydrocarbon leakage (TCLP) by 98.2% and producing construction materials with a compressive strength of 28.5 MPa at high salinity conditions (EC ~12 dS m^{-1}). Thermal recovery at 320 °C recovered 76.4% of the stored hydrocarbons to a fuel with calorific value of 41.2 MJ kg^{-1}. Bioremediation also achieved 89.7% TPH reduction at 180 days under native salinity. Life cycle assessment (LCA) revealed 48-83% global warming potential saving and life cycle cost analysis (LCC) revealed 39% net present value (NPV) gain in CE solutions compared to the traditional landfill. This study confirms the effectiveness of CE to transform the waste issue into an opportunity for resource recovery according to the current conditions in Apsheron, but the preferable technology choice is dependent upon the initial pollution level and household energy price.

Keywords: Circular economy, Drilling waste-contaminated soils, Apsheron Peninsula, Resource recovery, Life cycle assessment.
Article type: Research Article.

INTRODUCTION
The Absheron Peninsula, as the throbbing heart of the Republic of Azerbaijan's oil and gas sector, has a legacy of large-scale hydrocarbon exploration and production activity. Drilling operations over years have generated immense volumes of contaminated drilling waste, some part of which has been improperly disposed and brought extensive and theatrical pollution to the soils of this ecologically sensitive and highly populated region (Aliyev *et*

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al. 2023; Abdel-Hammed *et al.* 2024). These toxicants consist mainly of toxic hydrocarbon chemicals, heavy metals, and drilling muds that not only severely damage the health of ground environments and groundwater, but also severely threaten the human health and food security of the residents in the region by transmitting them along the food chain (Guliyev & Akhundov 2022; Alrashedi *et al.* 2024). Remediation and restoration of these contaminated soils are an undeniable necessity for the environmental sustainability and public health on the Absheron Peninsula. Traditional techniques of excavation wastes and contaminated soils treatment such as landfilling or incineration are largely linear in nature and face important environmental and economic issues. Landfilling is the risk of long-term leakage of contaminants and aquifer contamination with valuable land lost forever, while incineration is high energy with greenhouse gas and air pollutant emissions (Kogbara *et al.* 2020). Not only do these methods miss solving the problem at its source, but by relying solely on end disposal, they cause an astronomical financial burden on industry and society and are in blatant conflict with the principles of sustainable development. Thus, there is a necessity for an urgent change in the treatment of such complex wastes. For this purpose, Circular Economy (CE) as a new and envisioned alternative paradigm focuses on closing the loops of material and energy, optimizing resource recovery, and reducing raw material consumption and waste (Kirchherr *et al.* 2023). In the context of soil contaminated with drilling waste, circular economy strategies can focus on recovering and extracting value from such "waste" streams beyond cleanup. These include technologies such as advanced stabilization/solidification to produce safe building materials, thermal extraction or soil leaching to extract hydrocarbons or precious metals, or the use of biological processes such as phytoremediation or bioremediation to reduce toxicity and gradually reshape soil ecological processes (Al-Tabbaa *et al.* 2022; Ochilov *et al.* 2024). All of these hold the potential for transforming a costly environmental issue into an opportunity for recovering resources and creating added value. Although the vast possibilities of the circular economy are well recognized, comprehensive implementation and rigorous techno-economic-environmental (TEE) analysis of these measures especially in managing drilling waste-polluted soils under the unique geological, climatic, and pollution conditions of the Apsheron Peninsula are considerably lacking. Previous studies have focused mainly on some treatment or disposal features and have not provided a general life cycle assessment (LCA) and life cycle costing (LCC) of such alternative solutions compared to the conventional linear method, especially at the field scale, with consideration of regional conditions (Mikayilov *et al.* 2021; Panfilov *et al.* 2021; Teshaev *et al.* 2024). This knowledge gap prevents stakeholders in the region to make an informed decision and invest in cleaner solutions. Therefore, in the case of the Apsheron Peninsula in particular, this study answers the basic question of how much circular economy approaches can be employed as pragmatic, efficient, cost-reducing, and sustainable methods of controlling and rehabilitating soil contamination through drilling wastes in the peninsula. A meticulous and well-documented examination of the technical feasibility, economic expense, and environmental benefits of such approaches compared to traditional ones is not only essential to developing more efficient management plans for the Apsheron, but can be used as a model in other oil-producing regions of the world facing similar challenges. Conducting this study is a critical step towards reducing reliance on environmentally unsound linear waste management practices, protecting valuable land resources, reducing the region's petroleum industry's environmental footprint, and establishing a more sustainable post-oil future. Several works has been accomplished on excavated waste-polluted soils, where attention has been focused on traditional treatment options such as engineered landfills, soil washing, and bioremediation (Kogbara *et al.* 2020; Furaijl *et al.* 2025). Although these treatments are efficient in reducing contaminant levels, they are costly, energy intensive, generate secondary waste, and never look at recovery of value or resources (Al-Tabbaa *et al.* 2022). These linear strategies cause long-term sustainability problems through the importation of pollution from one system to another or the creation of new forms of waste, and are against the principles of the CE, which aims to prevent waste, respect material flows, and restore natural systems (Kirchherr *et al.* 2023; Shavkatov *et al.* 2024). In the last few years, the circular economy has emerged as an alternative paradigm to industrial waste management, such as drilling wastes. Early findings suggest that CE strategies, such as changing stabilized drilling wastes to construction materials (i.e., bricks, blocks, or fillers), hydrocarbon recovery and extraction remaining for reutilization as energy, or recovery of precious heavy metals from polluted soils, have great potential to reduce initial primary resource consumption, reduce final disposed waste volume, and generate new revenue streams (Iwar *et al.* 2021; Al-Tabbaa *et al.* 2022). For example, research has shown that the application of advanced stabilization/solidification with stable materials such as alkali-activators or nanomaterials can provide products with positive engineering properties and controlled release of pollutants (Olanrewaju *et al.* 2023). However, the application and evaluation of these circular processes are very limited, especially in the Apsheron Peninsula drilling wastes-polluted soils. The local research in the region has mainly focused on assessing the intensity and scale of pollution (Aliyev *et al.* 2023), assessing ecological risk (Guliyev & Akhundov 2022), or preliminary testing of traditional biological or chemical remediation technologies. More profound research that addresses the holistic techno-economic-environmental (TEE) analysis of CE-based activity (Latifah *et al.* 2024), taking into account the Apsheron local conditions (e.g., specific composition of on-site drilling wastes, arid climate, saline and alkaline soils, and accessible infrastructure), is remarkably missing (Mammadova 2023). Its absence obstructs the understanding of real potentiality and implementation challenges for building circular economy in this region. Furthermore, life cycle assessment (LCA) and life cycle costing (LCC) analysis comparing conventional linear methods and CE-based options for the treatment of drilling-contaminated soils in the Apsheron is a topic which has not been extensively addressed. The limited global studies suggest that CE technologies are more expensive in the short-term, but may be more economic and sustainable in the long term through reduced final disposal expense, by-product sales, and environmental externality prevention (García *et al.* 2024). However, the lack of LCA/LCC data for the Apsheron area, including impacts related to transportation, energy consumption of different technologies under local conditions, and marketability of reclaimed products, is a big obstacle for policymakers and the sector to make sound decisions (Mikayilov *et al.* 2021; Abed & Abdulmajeed 2021; Abed 2024). Lastly, the existing literature suggests that the success of CE strategies requires not just adequate technologies, but also facilitating policy frameworks, new business models, and stakeholder engagement (Kirchherr *et al.* 2023). For the Absheron, as in the case of the institutional, legal, and socio-economic issues confronting the integration of the circular economy into the oil waste management industry, it is still very limited (Abdullayeva 2022). Therefore, a wider systematic review and field research seem to be necessary in order to close these vital knowledge gaps, assess the real potential and viability of CE solutions under the local Absheron conditions, and provide an integrated TEE assessment framework. This study tries to make some contribution to these gaps.

MATERIALS AND METHODS

Study area and sampling characteristics

Apsheron Peninsula was selected as the study area. Soil samples with drilling waste contamination were collected from 15 active, shut-in oil and gas drilling sites following US EPA 5035A standard. The samples were collected at 0-50 cm surface and 50-100 cm subsurface using a corer with cylindrical shape. For the representativeness of samples, composite sampling method was used in each site. Control samples were also collected from adjacent background regions. All of the samples were preserved in the dark non-porous glass containers at 4 °C prior to analysis (US EPA 2020; Aliyev *et al.* 2023).

Physicochemical and contaminant analysis

Physicochemical characteristics of soil including texture, pH, electrical conductivity (EC), total organic matter (SOM), cation exchange capacity (CEC) were determined using ASTM D422, D4972, D2974 standard methods. The total petroleum hydrocarbon (TPH) concentrations were determined by gas chromatography-mass spectrometry (GC-MS; EPA 8015D), and heavy metals (lead, cadmium, nickel, vanadium, copper) by X-ray fluorescence spectroscopy (XRF; EPA 6200) and confirmed by atomic absorption spectrometry (AAS; EPA 7000B). Individual organic compound identifications (PAHs, benzene, toluene, ethylbenzene, xylenes) were also done in accordance with EPA 8270D (Kogbara *et al.* 2020; US EPA 2020).

Design and implementation of circular economy approach

Three of the most advanced literature-based circular economy strategies with supporting seabed conditions were selected and validated at laboratory and pilot scales:

Advanced stabilization/solidification (S/S). Stabilization of contaminated samples were examined using stable binder materials such as alkali-activated modified Portland cement, fly ash (FA), blast furnace slag (GGBS), and alkaline activators (sodium silicate and sodium hydroxide) at the best mixing proportion. The mixtures were moulded and on curing (standard temperature and humidity conditions, 28 days), compressive strength (ASTM C39), permeability (ASTM D5084) and emission of pollutants (TCLP; EPA 1311) were analyzed to establish the possibility for use as construction materials (blocks, road subgrade; Al-Tabbaa *et al.* 2022; Olanrewaju *et al.* 2023).

Thermal hydrocarbon recovery and extraction. A temperature-controlled thermal extraction pilot plant (200-350 °C) was used to separate and condense medium and light hydrocarbons from contaminated soils. Recovered hydrocarbon quality and yield (as petrochemical feedstock or substitute fuel) was quantified by GC-MS. The residual soil was also scanned for the TPH concentration removal and toxicity (Iwar *et al.* 2021).

Enhanced bioremediation. Native microbial consortium isolated and acclimatized from salinity soils was enhanced with biostimulants (biosurfactants, nutrients, molasses). Efficiency of removal of TPH and metals (by biosorption/dissolution) in the rhizosphere under real-time simulated high salinity and pH was monitored for 180 days (ISO 11266-1:2020). The suitability of using the enhanced biomass produced as biochar was also found (García *et al.* 2024).

Techno-economic-environmental assessment (TEE)

Life Cycle Assessment (LCA). Cradle-to-Grave life cycle assessment (LCA) was performed for all CE strategies and compared with engineered landfill (conventional linear strategy) according to ISO 14040:2006/Amd 1:2020. SimaPro v9.3 software with Ecoinvent v3.8 database and ReCiPe 2016 (Endpoint H) method was used for the calculation of the carbon footprint, acidification potential, eutrophication and resource depletion. The energy, transport, and material inputs and air, water, and soil pollution outputs were modified according to local requirements (distances, energy source; García *et al.* 2024).

Life Cycle Cost (LCC). Every capital investment (CAPEX), operational (OPEX), maintenance, and end-of-life costs (including external environmental costs as per LCA results) were calculated for a 20-year period and brought to net present value (NPV) at 5% discount rate (Mikayilov *et al.* 2021). Every income through the sale of by-products (building materials, recycled hydrocarbons, biochar) was also considered.

Sensitivity and Uncertainty Analysis. Dominant parameters' sensitivity analysis (energy price, discount rate, recycled product price, technological efficiency) and uncertainty analysis (Monte Carlo method) were conducted in order to assess the sustainability of economic and environmental results (Abdullayeva 2022).

Statistical analysis

All the analysis were performed in triplicate and data were presented as mean ± standard deviation. One-Way ANOVA test was applied to analyze the means and significant group differences were analyzed using Tukey HSD test at 95% confidence level ($p < 0.05$) through SPSS v28 software. Pearson correlation analysis was employed to test the correlation between soil parameters and pollutant concentration.

RESULTS

The initial characterization of drilling waste-contaminated soils across the Absheron Peninsula revealed consistently elevated salinity and alkalinity, with pH ranging from 8.2 to 9.1 and electrical conductivity (EC) measurements between 4.8 and 12.3 dS m^{-1}. Soil textures were predominantly sandy loam (62% of sites) and loamy sand (38%), with low organic matter content (0.8–2.1% SOM) and moderate CEC [11.5–18.7 cmol(+) kg^{-1}]. These baseline physicochemical parameters established critical constraints for subsequent remediation strategies, particularly influencing binder efficiency in stabilization and microbial activity in bioremediation processes.

Table 1. Baseline physicochemical properties of contaminated soils.

Parameter	Range	Mean ± SD	Reference method
pH	8.2 - 9.1	8.6 ± 0.3	ASTM D4972
EC (dS m^{-1})	4.8 - 12.3	7.9 ± 2.1	ASTM D1125
SOM (%)	0.8 - 2.1	1.4 ± 0.4	ASTM D2974
CEC [cmol(+) kg^{-1}]	11.5 - 18.7	14.2 ± 2.3	ASTM D7503
Sand (%)	68 - 84	76.2 ± 5.1	ASTM D422
Silt (%)	12 - 24	17.3 ± 3.8	ASTM D422
Clay (%)	4 - 12	6.5 ± 2.4	ASTM D422

Contaminant analysis confirmed severe hydrocarbon and heavy metal pollution, with total petroleum hydrocarbons (TPH) reaching 28,500 ± 3,200 mg kg^{-1}, exceeding Azerbaijan's regulatory threshold (1,000 mg kg^{-1}) by 28-fold. Vanadium (V) and nickel (Ni) were the predominant metals at 412 ± 38 mg kg^{-1} and 287 ± 29 mg kg^{-1}, respectively, correlating strongly (r = 0.87, $p < 0.01$) with TPH concentrations due to their association with crude oil matrices. Polycyclic aromatic hydrocarbons (PAHs), particularly naphthalene and benzo[a]pyrene, posed significant carcinogenic risks, with concentrations 15–40 times higher than permissible limits. Advanced stabilization/solidification (S/S) using 15% Portland cement + 10% GGBS + 5% sodium silicate activator achieved optimal performance, reducing TPH leachability by 98.2% (TCLP) while producing monolithic blocks with compressive strength of 28.5 ± 2.3 MPa—exceeding ASTM C90 specifications (17 MPa) for load-bearing masonry. The hybrid binder system effectively encapsulated vanadium and nickel, reducing their mobility by 94% and 96%, respectively, as confirmed by sequential extraction analysis. This formulation demonstrated superior performance to cement-only or lime-based treatments under high-salinity conditions.

Table 2. Contaminant concentrations in drilling waste-affected soils.

Contaminant	Range (mg kg^{-1})	Mean ± SD (mg kg^{-1})	Regulatory limit (mg kg^{-1})
TPH	18,400 - 35,700	28,500 ± 3,200	1,000
Vanadium (V)	340 - 485	412 ± 38	150
Nickel (Ni)	225 - 345	287 ± 29	80
Lead (Pb)	98 - 165	132 ± 21	100
Σ16 PAHs	86 - 215	142 ± 38	10
Benzo[a]pyrene	8.2 - 14.7	11.2 ± 1.9	0.3

Table 3. Performance of optimized S/S treatment (Binder: 15% PC + 10% GGBS + 5% Na_2SiO_3).

Parameter	Untreated soil	Treated product	Reduction (%)	Standard
TPH Leachability (mg L^{-1})	145 ± 18	2.6 ± 0.4	98.2	EPA 1311
V Leachability (mg L^{-1})	9.8 ± 1.2	0.6 ± 0.1	94.0	EPA 1311
Ni Leachability (mg L^{-1})	7.2 ± 0.9	0.3 ± 0.05	96.0	EPA 1311
Compressive Strength (MPa)	-	28.5 ± 2.3	-	ASTM C39
Permeability (cm s^{-1})	-	$3.2\times10^{-8} \pm 0.4\times10^{-8}$	-	ASTM D5084

Thermal treatment at 320 °C for 45 minutes recovered 76.4 ± 3.8% of residual hydrocarbons as reusable oil, with a calorific value of 41.2 ± 1.3 MJ kg^{-1}, comparable to light crude. GC-MS analysis confirmed the recovered fraction consisted primarily of C10–C25 alkanes (68%) and monoaromatics (22%). Post-treatment TPH in soil decreased to 2,150 ± 310 mg kg^{-1}, meeting industrial reuse standards (≤ 2,500 mg kg^{-1}) for non-sensitive applications. Energy consumption averaged 1.25 kWh per kg of treated soil, with net energy recovery feasibility confirmed when processing soils with >18,000 mg kg^{-1} TPH. Bioaugmentation with native *Pseudomonas aeruginosa* ABS-7 and *Bacillus subtilis* ABS-3, combined with nutrient-amended (C:N:P = 100:10:1) molasse supplementation, degraded 89.7 ± 4.2% of TPH within 180 days under in-situ salinity (8–12 dS m^{-1}). Metal bioleaching reduced nickel and vanadium bioavailability by 62% and 58%, respectively, as confirmed by DTPA extraction. The resulting microbial biomass, pyrolyzed at 450 °C, yielded biochar with 32.5 m² g^{-1} surface area and 85% PAH adsorption capacity, demonstrating valorization potential.

Table 4. Hydrocarbon recovery efficiency via thermal treatment (320 °C, 45 min).

Metric	Value	Unit	Method
Hydrocarbon Recovery	76.4 ± 3.8	%	Gravimetric
Calorific Value	41.2 ± 1.3	MJ kg^{-1}	ASTM D240
Residual TPH in Soil	2,150 ± 310	mg kg^{-1}	EPA 8015D
Energy Consumption	1.25 ± 0.15	kWh kg^{-1} soil	Process Monitoring
Dominant Hydrocarbons	C10-C25 alkanes	% of total	GC-MS (EPA 8270D)

Table 5. Bioremediation performance with native microbial consortia (180 days).

Parameter	Initial value	Final value	Reduction/Increase	Method
TPH	28,500 ± 3,200	2,950 ± 420	89.7%	EPA 8015D
Bioavailable Ni	142 ± 18	54 ± 8	62.0%	DTPA Extraction
Bioavailable V	218 ± 24	92 ± 11	58.0%	DTPA Extraction
Microbial Count	10^3 CFU g^{-1}	10^8 CFU g^{-1}	5 orders magnitude	ISO 6222
Biochar Surface Area	-	32.5 ± 3.1	-	BET Analysis

Comparative life cycle assessment revealed that S/S and thermal recovery reduced global warming potential (GWP) by 52% and 48%, respectively, relative to conventional landfilling (baseline = 1,850 kg CO_2-eq/tonne soil). Bioremediation exhibited the lowest GWP (320 kg CO_2-eq/tonne) but required 40% more land area. Water consumption was minimized in thermal treatment (0.8 m³/tonne vs. 3.5 m³/tonne for bioremediation), a critical advantage in arid Absheron.

Table 6. Comparative LCA results per tonne treated soil (ReCiPe 2016 Endpoint H).

Impact Category	Landfilling (Baseline)	S/S treatment	Thermal recovery	Bioremediation
Global Warming (kg CO_2-eq)	1,850	890 (-52%)	960 (-48%)	320 (-83%)
Water Consumption (m^3)	0.5	1.2	0.8	3.5
Eutrophication (kg N-eq)	4.8	3.1 (-35%)	2.7 (-44%)	5.2 (+8%)
Resource Depletion (USD)	65.2	42.5 (-35%)	78.3 (+20%)	29.8 (-54%)

Life cycle cost analysis demonstrated bioremediation's economic superiority, with a net present value (NPV) of -$128/tonne over 20 years, compared to -$210/tonne for landfilling. Thermal recovery achieved breakeven at $18/tonne when recovered oil prices exceeded $75/barrel, while S/S generated $12/tonne revenue through construction material sales. Externalities (carbon credits, avoided groundwater remediation) improved CE economics by 22-38%.

Table 7. 20-Year life cycle cost analysis (USD per tonne soil; Discount rate 5%)

Cost/Revenue Stream	Landfilling	S/S treatment	Thermal recovery	Bioremediation
Capital Costs (CAPEX)	85	120	195	70
Operational Costs (OPEX)	145	55	105	90
End-of-Life Costs	40	0	0	5
Material Sales Revenue	0	-67	-132	-15
Net Present Value (NPV)	-210	-108	-18	-128
Breakeven Oil Price	-	-	75 USD/bbl	-

Sensitivity analysis identified oil price (thermal recovery) and binder costs (S/S) as dominant economic variables. A 20% increase in energy prices raised thermal treatment costs by 18%, while a 30% decrease in cement prices improved S/S NPV by 24%. Bioremediation exhibited the lowest uncertainty (± 11% NPV variance), whereas thermal recovery showed highest sensitivity (± 32%) to market fluctuations. Monte Carlo simulation confirmed CE robustness under 85% of projected scenarios. Statistical analysis confirmed significant differences ($p < 0.001$, ANOVA) among treatment efficacies. Tukey's HSD test established distinct performance clusters: thermal and S/S formed a high-efficiency group for contaminant immobilization, while bioremediation dominated in operational sustainability. Strong correlations ($r^2 = 0.91$) between initial TPH concentrations and treatment energy requirements underscored the importance of site-specific technology selection.

Table 8. Sensitivity analysis of key economic parameters (NPV impact).

Technology	Parameter	+20% Change	-20% Change	Elasticity
Thermal Recovery	Oil Price	+38%	-42%	2.0
	Energy Cost	-18%	+22%	-1.0
S/S Treatment	Cement Price	-24%	+26%	-1.3
	Material Sales	+16%	-18%	0.9
Bioremediation	Nutrient Cost	-9%	+11%	-0.5
	Labor Cost	-6%	+7%	-0.3

DISCUSSION

The results of this study demonstrate the enormous potential of circular economy (CE) approaches for sustainable dealing with Apsheron Peninsula drilling wastes-contaminated soils. The technical efficiency of super stabilization/solidification (S/S) in obtaining safe construction materials (compressive strength 28.5 MPa, 98% TPH leak reduction) even at conditions of high salinity (EC ~12 dS m^{-1}) is a key observation here, consistent with previous observations in temperate environments (Olanrewaju *et al.* 2023). and indicative of the innovation of using alkaline activators (Na_2SiO_3) in overcoming the limiting properties of Apsheron alkaline soils. On the other hand, 76.4% hydrocarbon recovery through thermal extraction with energy input 1.25 kWh kg^{-1} is a development above previous studies (Iwar *et al.* 2021) since it, besides reducing the residual contamination to the acceptable industrial level (2150 mg kg^{-1}), created a new source of income through the production of alternative fuel (41.2 MJ kg^{-1}). From an environmental perspective, 83% global warming potential (GWP) abatement by bioremediation supplemented with indigenous consortium (ABS-7 and ABS-3) compared to traditional landfilling (Table 6) aligns with global reports (García *et al.* 2024) but with the added innovation of modification to the native salinity of the Apsheron. However, the 8% eutrophication potential rise with this method due to molasses use demonstrates the requirement for nutrient ratio optimization (C:N:P). Life cycle costing (LCC) analysis also showed that while there is higher initial investment in CE methods (e.g. $195/tonne for thermal recovery), by-product sales (construction materials, recovered hydrocarbons) and internalization of externalities (carbon offsets, avoided groundwater cleanup) can yield a break-even point ($18/tonne) and even net profitability (positive NPV; Table 7), a finding which greatly removes the economic barriers presented in previous research (Abdullayeva 2022). The strong correlation ($r^2 = 0.91$) between the original TPH content and the energy required in heat treatments substantiates the need for selecting the technology appropriate based on the level of contamination. Accordingly, soils heavily contaminated (> 18,000 mg kg^{-1} TPH) are more appropriate for thermal recovery and moderately contaminated soils (5,000–18,000 mg kg^{-1}) for S/S or biodegradation. The possibility of biological performance stability at 12 dS m^{-1} salinity (89.7% TPH reduction) is encouraging, although its potential effectiveness within high vanadium levels (> 400 mg kg^{-1}) must be further investigated.

CONCLUSION

Three circular economy methods (improved stabilization/solidification, thermal hydrocarbon recovery, and improved bioremediation) were comprehensively examined in this research in order to treat the soils contaminated with drilling wastes under the given conditions of the Apsheron Peninsula. According to the results:

1. The hybrid binder technology (cement + GGBS + alkaline activator) has the capability to produce safe construction materials with compressive strengths greater than ASTM specification (28.5 MPa) and 98% reduced hydrocarbon leakage, even in the alkaline and saline soils of the Apsheron Peninsula;
2. Thermal recovery at 320 °C can convert 76.4% of the residual hydrocarbons into high calorific value fuel (41.2 MJ kg^{-1}) and normalize the treated soil to an acceptable level for industrial use;
3. Bioremediation with a native microbial consortium was successful in the degradation of TPH by 89.7% and nickel bioavailability by 62% and can possibly produce biochar with PAH adsorption capacity.

From the perspective of environmental sustainability, all the CE solutions had significant decrease in the carbon footprint (up to 83%) and life cycle cost (up to 39%) over traditional landfill. However, the optimum technology to be implemented depends on initial pollution intensity, regional energy price and local infrastructure. These results close the knowledge gap addressed in previous studies (Mammadova 2023) on CE application in offshore oilfields and provide the basis for policymaking on sustainable waste management in similar oil-bearing regions. Future studies must focus on the large-scale field implementation, national standards formulation for recycled commodities, and social life cycle analysis (SLCA).

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