

TOWARDS SUSTAINABLE DRILLING: A REVIEW OF FLUID WASTE MANAGEMENT PRACTICES IN THE GARMYAN BLOCK OIL AND GAS FIELDS

KHABAT M. AHMED¹, ALI MOHAMMED SALIH², ROLAND DÓCS^{3*}

¹*Department of Petroleum and Energy Engineering, Sulaimani Polytechnic University, Iraq;*

khabat.ahmad@spu.edu.iq¹

²*Center for Research and Development, University of Halabja; Iraq, ali.salih@uoh.edu.iq*²

^{3*}*Mining and Energy Institute of University of Miskolc, Hungary;*

roland.docs@uni-miskolc.hu³

¹<https://orcid.org/0000-0003-4226-1105>

²<https://orcid.org/0000-0003-0968-3250>

^{3*}<https://orcid.org/0000-0002-1456-2990>

Abstract: This study evaluates drilling fluid waste generation and management in onshore operations, focusing on the Garmyan Block, Kurdistan Region of Iraq. Field observations and laboratory analyses of soil, untreated cuttings, and treated cuttings were conducted using data from Gazprom Neft Middle East B.V. Results showed that heavy metals in treated cuttings were below European landfill disposal limits, while soil contained elevated barium and lead. Quicklime-cement solidification reduced contaminant mobility by over 90 %, and remediated sites achieved over 70 % vegetation coverage. The method reduced soil and water contamination and greenhouse gas emissions compared with thermal treatment. A three-tier framework is proposed to support environmentally and economically appropriate waste management.

Keywords: waste minimization, environmental compliance, sustainable deep drilling practices, Garmyan Block, quicklime-cement solidification, heavy metals, ecosystem recovery

1. INTRODUCTION

1.1 Background

Waste management of drilling fluids is an essential component of oil and gas extraction, enabling proper handling of discharge materials and reducing environmental threats and harm to human health. During drilling operations, drill cuttings are brought to the surface by drilling mud. Solid control equipment separates these cuttings from the mud, after which they are placed into reserve pits, while mud tanks store the mud for future reuse. The procedure includes testing both drilling fluids and rock waste materials after drilling operations are finished. Materials can proceed to disposal, be reused, or transformed into new products after passing non-hazardous examination. Two waste management

categories exist: onshore and offshore disposal, since the U.S. Environmental Protection Agency (EPA) and European Union (EU) enforce rigorous environmental regulations for safe and sustainable practices (Veil 2020; OSPAR Commission 2025).

During the 1970s, environmental organizations and regulatory bodies began investigating industrial waste disposal after formal attention to drilling waste management issues began to rise (Kingston 2002). The discovery of unsafe hazardous substances in drilling fluids led the oil and gas industry to embrace more strict regulatory measures (Rena 2008). Modern technological progress and regulatory systems have decreased the deployment of dangerous chemicals, yet some dangerous materials continue to exist with proper oversight. Hazardous caustic soda, toxic diesel oil, and ignitable alcohols represent materials still being used for drilling operations (Broni-Bediako and Amorin 2010). Company compliance with regulations alongside inventory management systems enables safe disposal procedures for harmful chemicals to reduce their negative impact on the environment.

1.2 Research Gap

Despite growing awareness of drilling waste management issues, significant knowledge gaps persist, particularly in the Kurdistan Region of Iraq. The existing literature on drilling waste management is predominantly focused on offshore operations in the North Sea, Gulf of Mexico, and other mature petroleum provinces (Murray et al. 2018; Kingston 2002). Limited research exists on onshore drilling waste management practices in emerging oil and gas regions, particularly in the Middle East and North Africa (MENA) region (Sharif et al. 2017). Furthermore, few studies have quantitatively evaluated the effectiveness of specific treatment technologies, such as quicklime-cement solidification, under the geological and climatic conditions specific to the Kurdistan Region (Salih et al. 2021). The Kurdistan Region presents unique challenges for drilling waste management, including complex geology with reactive shale formations, limited waste treatment infrastructure, evolving regulatory frameworks, and environmental sensitivity of agricultural lands and water resources (Khudhur et al. 2022; Ministry of Natural Resources 2010). These factors necessitate region-specific research to develop appropriate waste management strategies that balance environmental protection with operational efficiency.

1.3 Research Objectives

This study aims to address these knowledge gaps by evaluating drilling fluid waste management practices in the Garmyan Block oil and gas fields. The specific objectives are:

- To characterize the types, quantities, and physicochemical properties of drilling wastes generated in the Garmyan Block.

- To assess the effectiveness of current waste management practices, including storage, treatment, and disposal methods.
- To evaluate the environmental performance of quicklime-cement solidification as a treatment technology for drill cuttings.
- To compare local practices with international best practices and regulatory standards.
- To develop a classification framework for guiding operators in selecting appropriate waste management strategies.

1.4 Significance and Scope

This research contributes to the growing body of knowledge on sustainable drilling practices by providing empirical data from an understudied region. The findings have practical implications for oil and gas operators, regulatory authorities, and environmental managers in the Kurdistan Region and beyond. The study focuses on onshore drilling operations within the Garmyan Block, with specific attention to water-based mud (WBM) systems and associated drill cuttings. While the research acknowledges the use of oil-based muds (OBMs) and synthetic-based muds (SBMs) in certain applications, the primary focus is on WBM wastes due to their predominance in the study area.

2. LITERATURE REVIEW

2.1 Drilling Fluid Types and Compositions

Drilling fluids serve multiple critical functions in well operations, including cooling and lubricating the drill bit, carrying cuttings to the surface, maintaining wellbore stability, and controlling formation pressures (Caenn et al. 2017). The three primary categories of drilling fluids are water-based muds (WBMs), oil-based muds (OBMs), and synthetic-based muds (SBMs).

Water-based muds are the most commonly used drilling fluids due to their lower environmental impact and cost-effectiveness (Neff 2005). These fluids typically consist of water, clay minerals (primarily bentonite), and various chemical additives to control properties such as viscosity, density, and filtration characteristics. WBM systems can be further classified based on their composition, including spud muds, polymer muds, and inhibitive muds (Amannullah 2007). Spud muds are used for initial drilling and typically consist of simple bentonite-water mixtures. Polymer muds incorporate long-chain polymers to improve rheological properties and shale inhibition. Inhibitive muds, such as lime or gypsum-treated systems, are designed to prevent clay swelling and maintain wellbore stability.

Oil-based muds offer superior performance characteristics, including enhanced shale inhibition, better lubricity, and improved wellbore stability (Caenn et al. 2017). These fluids use diesel or mineral oil as the continuous phase, with water and solids dispersed throughout. While OBMs provide operational advantages, they pose significant environmental challenges due to their hydrocarbon content and potential for soil and water contamination (Al-Haleem et al. 2019). The high oil content of OBMs requires specialized treatment and disposal procedures to prevent environmental damage.

Synthetic-based muds represent an intermediate option, using synthetic organic compounds as the continuous phase instead of petroleum-derived oils (Neff et al. 2000). SBMs offer performance characteristics similar to OBMs while presenting reduced environmental risks due to their biodegradability and lower toxicity. Common synthetic base fluids include esters, olefins, and paraffins, which are designed to degrade more rapidly in the environment.

2.2 Environmental Impacts of Drilling Wastes

Drilling wastes can cause various environmental impacts depending on their composition and disposal methods. The primary concerns include soil contamination, groundwater pollution, surface water impacts, and ecosystem disruption (Gbadebo et al. 2010). Heavy metals present in drilling fluids, such as barium, chromium, and lead, can accumulate in soils and affect plant growth (Adebayo et al. 2019). Hydrocarbons from oil-based muds can persist in the environment for extended periods, affecting soil microbial communities and potentially contaminating groundwater resources (Al-Haleem et al. 2019).

The salinity of produced water and formation brines associated with drilling operations can cause soil salinization and affect vegetation (Veil et al. 2004). Chemical additives used in drilling fluids, including biocides, corrosion inhibitors, and surfactants, may exhibit toxicity to aquatic organisms and disrupt ecological balance (Broni-Bediako and Amorin 2010). The cumulative effects of these contaminants can result in long-term degradation of environmental quality.

Research has documented various pathways through which drilling wastes can enter the environment, including leaching from storage pits, runoff from disposal areas, and atmospheric deposition of volatile compounds (Ball et al. 2012). The mobility of contaminants depends on factors such as soil permeability, groundwater flow patterns, and the chemical properties of the waste constituents (Murray et al. 2018).

2.3 Regulatory Framework

The regulatory landscape for drilling waste management varies significantly across jurisdictions. International conventions, such as the London Convention and Protocol, provide guidelines for waste disposal in marine environments (OSPAR Commission

2025). National regulations typically establish standards for waste characterization, treatment, and disposal, with specific requirements for different waste categories. For example, Agwa et al. (2012) documented the evolution of Egyptian environmental regulations governing offshore drilling discharges, illustrating how national frameworks in emerging petroleum regions continue to develop in response to environmental concerns.

In the Kurdistan Region of Iraq, environmental regulations governing oil and gas operations have evolved in recent years. The Kurdistan Region Environmental Protection and Improvement Board establishes environmental standards and monitoring requirements (Ministry of Natural Resources 2010). However, implementation and enforcement challenges remain, highlighting the need for enhanced regulatory capacity and industry compliance.

The legal framework for environmental protection in the Kurdistan Region includes provisions for environmental impact assessment, waste management, and pollution control (Khudhur et al. 2022). Oil and gas operators are required to obtain environmental permits and comply with discharge standards. However, the effectiveness of these regulations depends on adequate monitoring, enforcement, and penalties for non-compliance.

2.4 Best Available Techniques

Best Available Techniques (BAT) for drilling waste management encompass a range of technologies and practices designed to minimize environmental impact while maintaining operational efficiency (AECOM 2016). These include:

- **Waste Minimization:** Source reduction strategies, such as using environmentally friendly drilling fluids and optimizing drilling processes, can significantly reduce waste generation (Johnson et al. 2021). The selection of drilling fluid systems with lower toxicity and higher recyclability can reduce both waste volumes and environmental risks.
- **Recycling and Reuse:** Closed-loop systems allow for the recovery and reuse of drilling fluids, reducing both waste volumes and raw material consumption (ASME 2007). Advanced solids control equipment can extend the life of drilling fluids and reduce the volume of contaminated cuttings.
- **Treatment Technologies:** Various treatment methods, including thermal desorption, bioremediation, and solidification/stabilization, can reduce the toxicity and volume of drilling wastes (Ball et al. 2012). Thermal treatment can achieve high removal efficiencies for hydrocarbons, while bioremediation offers a lower-cost option for appropriate waste types (Zhou et al. 2025).

- Disposal Options: Proper disposal methods, such as secure landfill, deep-well injection, and land farming, must consider waste characteristics and site-specific environmental conditions (Gaurina-Međimurec 2020). The selection of disposal methods should follow the waste management hierarchy, prioritizing options with lower environmental impact.

2.5 Synthesis and Knowledge Gaps

The literature review reveals several important gaps in current knowledge:

- Regional Focus: Most studies focus on offshore operations in mature petroleum provinces, with limited research on onshore operations in emerging regions like the Kurdistan Region of Iraq.
- Treatment Technology Evaluation: Few studies provide quantitative performance data for specific treatment technologies under varying geological and climatic conditions.
- Regulatory Effectiveness: Limited research exists on the effectiveness of environmental regulations in emerging oil and gas regions.
- Long-term Monitoring: Most studies report short-term results, with limited data on long-term environmental outcomes of waste management practices.

This study addresses these gaps by providing empirical data from onshore operations in the Kurdistan Region, evaluating treatment technology performance, and assessing regulatory compliance.

3. MATERIALS AND METHODS

3.1 Study Area

The Garmyan Block, located in the Kurdistan Region of Iraq, encompasses several oil fields across approximately 1,500 km² (Figure 1). The block comprises formations ranging from Cretaceous to Tertiary age, including the Shiranish, Kometan, and Qamchuqa formations. The geological complexity of the area, particularly the presence of reactive shale formations, necessitates the use of inhibitive drilling fluids and careful management of drilling wastes.



Figure 1

Location map of the Garmyan Block showing study sites (Sarqala S-1, S-2, and S-5).

The stratigraphy of the Garmyan Block presents varying drilling conditions and fluid requirements. The Shiranish Formation consists of marly limestones and shales, requiring inhibitive mud systems to prevent clay swelling. The Kometan Formation comprises well-indurated limestones with potential for lost circulation. The Qamchuqa Formation, a major reservoir interval, requires specialized fluids to minimize formation damage.

3.2 Research Design

This study employed a mixed-methods research design combining quantitative and qualitative approaches. The research design was selected to enable comprehensive characterization of waste streams, assessment of management practices, and evaluation of environmental performance. The study was conducted over a twelve-month period (January 2024 to December 2024) to capture seasonal variations and operational changes.

The research design incorporated three phases:

- Descriptive Phase: Field surveys and document review to characterize current practices.
- Analytical Phase: Sampling and laboratory analysis to quantify waste properties.

- Evaluative Phase: Assessment of environmental performance and comparison with best practices.

3.3 Data Collection

Data collection employed multiple approaches to ensure comprehensive coverage.

3.3.1 Field Surveys

Comprehensive surveys were conducted at active drilling sites to document waste generation rates, storage practices, and disposal methods. Field observations were recorded using standardized forms and photographic documentation. A total of 12 site visits were conducted across three operational sites (Sarqala S-1, S-2, and S-5). The surveys documented:

- Waste pit dimensions and construction
- Liner types and integrity
- Waste volumes and characteristics
- Treatment and disposal methods
- Site remediation status

3.3.2 Sampling and Analysis

Drilling fluid and waste samples were collected from various operational stages. A total of 45 samples were collected, comprising:

- 15 drilling fluid samples (5 WBM, 5 OBM, 5 SBM)
- 15 drill cuttings samples (5 untreated, 5 treated, 5 soil)
- 15 water samples (5 produced water, 5 leachate, 5 groundwater)

Sampling followed standard protocols to ensure representativeness and prevent contamination. Samples were stored in appropriate containers and transported to accredited laboratories within 48 hours of collection.

3.3.3 Interviews and Questionnaires

Structured interviews were conducted with 45 drilling engineers, environmental officers, and waste management personnel across multiple operational sites. The interview protocol covered:

- Current waste management practices
- Challenges and constraints
- Regulatory compliance issues
- Improvement opportunities

- Interviews were conducted with informed consent and anonymized to protect participant confidentiality.

3.3.4 Document Review

Operational records, environmental reports, and regulatory documents were reviewed to establish baseline conditions and compliance status. Data on waste generation, treatment, and disposal were extracted from operator records and regulatory filings for the period 2020–2024.

3.4 Analytical Methods

Laboratory analysis followed standard environmental testing methods.

3.4.1 pH and Salinity

Determination of pH was made using a calibrated electrode method (APHA 2017, Method 4500-H+ B). Salinity was measured using a conductivity meter and expressed as total dissolved solids (TDS) in mg/L.

3.4.2 Heavy Metals

Heavy metals (barium, lead, cadmium, chromium, mercury) were analyzed using atomic absorption spectroscopy (AAS) following acid digestion (U.S. EPA 1996, Method 3050B). Detection limits were 0.1 mg/kg for barium and chromium, 0.05 mg/kg for lead, 0.02 mg/kg for cadmium, and 0.01 mg/kg for mercury.

3.4.3 Total Petroleum Hydrocarbons

Total petroleum hydrocarbons (TPH) were measured using gas chromatography with flame ionization detection (GC-FID) following solvent extraction (U.S. EPA 2003, Method 8015D). Detection limit was 10 mg/kg.

3.4.4 Toxicity Testing

Toxicity testing employed standard bioassay procedures using *Daphnia magna* (48-hour acute toxicity; OECD 2004) and *Vibrio fischeri* (Microtox®; Azur Environmental 1998). Results were expressed as EC50 values.

3.4.5 Quality Assurance and Quality Control

- QA/QC procedures included:
- Analysis of duplicate samples (10 % of total)

- Analysis of spiked samples (5 % of total)
- Analysis of certified reference materials
- Method blanks with each batch

Laboratory accreditation to ISO/IEC 17025 ensured compliance with international standards. Recovery rates for spiked samples ranged from 85 % to 115 %, and relative standard deviations for duplicate samples were below 10 %.

3.5 Assessment Framework

An integrated assessment framework was developed to evaluate waste management practices based on environmental performance, regulatory compliance, and operational efficiency (Figure 2). The framework incorporated:

Quantitative Indicators:

- Waste generation rates (m^3/well)
- Treatment efficiency (% contaminant removal)
- Disposal compliance (% meeting standards)
- Environmental quality indicators (soil, water, air)

Qualitative Assessments:

- Management system effectiveness
- Regulatory compliance status
- Stakeholder engagement
- Continuous improvement practices



Figure 2

Integrated assessment framework for drilling waste management

The framework considered the full life cycle of drilling wastes, from generation through final disposal. Performance was scored on a 1–5 scale (1 = poor, 5 = excellent) for each indicator, with overall performance calculated as a weighted average.

3.6 Statistical Analysis

Statistical analysis was performed using SPSS version 28.0. Descriptive statistics (mean, standard deviation, range) were calculated for all parameters. Comparisons between groups were made using one-way ANOVA with post-hoc Tukey tests. Significance was set at $*p < 0.05$. Correlation analysis was performed to identify relationships between waste properties and treatment performance.

3.7 Limitations

As for any study, our also acknowledges several limitations that contribute to the results:

- Limited sample size (3 sites) may affect generalizability.
- Confidentiality agreements restricted access to some operational data.
- Short monitoring period (12 months) limits assessment of long-term outcomes.
- Laboratory analysis was conducted at a single accredited laboratory.

4. RESULTS AND DISCUSSION

4.1 Field Observations

4.1.1 Sarqala S-1 Site

The research team inspected Sarqala S-1 (34.751801, 45.151857), which included an underground water well installation to dispose of water collected from oil wells. This well produced approximately 1,000 m³ of drill cuttings. The site had been remediated, and vegetation regrowth was observed on the former waste pit area. The pit construction included a double-liner system comprising high-density polyethylene (HDPE) and geosynthetic clay liner (GCL), providing enhanced containment.

4.1.2 Sarqala S-2 Site

Sarqala S-2 was previously remediated and served as a reference site for evaluating long-term remediation outcomes. The site exhibited successful vegetation establishment, with a diverse plant community indicating ecosystem recovery. Soil quality at the site met regulatory standards for all parameters analyzed.

4.1.3 Sarqala S-5 Site

Sarqala S-5 (34.778277, 45.108448) was the most recently drilled well at the time of the site visit. The drilling rig had been removed approximately two weeks before the visit. The estimated drill cuttings volume was 3,000–5,000 m³. Both mud and water pits were observed and were fresh without any treatments done. Treatment was scheduled to commence soon. The pit was lined with HDPE only (single-liner system).

The main characteristics (dimensions, waste volume, treatment status. etc.) of the studied waste pits are presented in Table 1.

Table 1
Waste Pit Characteristics at Studied Sites

Parameter	Sarqala S-1	Sarqala S-2	Sarqala S-5
Pit Dimensions (m)	50 × 30 × 3	40 × 25 × 2.5	60 × 40 × 3.5
Liner Type	HDPE + GCL	HDPE + GCL	HDPE
Waste Volume (m ³)	~1,000	~800	3,000–5,000
Treatment Status	Completed	Completed	Pending
Vegetation Regrowth	Yes (>70%)	Yes (>80%)	N/A
Soil Compliance	Compliant	Compliant	N/A

4.2 Laboratory Results

4.2.1 Heavy Metal Concentrations in Cuttings

Laboratory analysis of drilling cuttings indicated that heavy metal concentrations were below European Council 2003/33/EC standards for landfill disposal (European Council 2003) (Table 2). Treated cuttings showed significantly lower concentrations than untreated cuttings (* $p < 0.05$), demonstrating the effectiveness of the quicklime-cement solidification treatment.

Table 2
Heavy Metal Concentrations in Untreated and Treated Cuttings vs. Regulatory Standards

Parameter	Untreated Cuttings (mg/kg)	Treated Cuttings (mg/kg)	EC 2003/33/EC Limit (mg/kg)	Compliance Status
Barium	2,450 ± 320	185 ± 42	100,000	Compliant
Lead	42 ± 8	12 ± 3	50	Compliant
Cadmium	1.8 ± 0.4	0.5 ± 0.1	5	Compliant
Chromium	38 ± 7	15 ± 3	100	Compliant
Mercury	0.8 ± 0.2	0.3 ± 0.1	2	Compliant

*Values represent mean ± standard deviation ($n = 15$)

The reduction in heavy metal concentrations following treatment ranged from 85 % for barium to 92 % for lead. These results are consistent with findings from Salih et al. (2021), who reported similar reductions using cement-based solidification for drill cuttings in the Kurdistan Region.

4.2.2 Soil Quality Assessment

Soil samples collected from areas adjacent to waste pits contained barium and lead above allowable differences according to Canadian 2009 standards (CCME 2009) (Table 3). However, soils at remediated sites (S-1 and S-2) showed concentrations below regulatory limits, indicating successful remediation.

Table 3
Soil Quality Results vs. Canadian 2009 Guidelines

Parameter	Soil Concentration (mg/kg)	Canadian 2009 Limit (mg/kg)	Compliance Status
Barium	850 ± 120 (S-5)	750	Non-compliant
Barium	420 ± 65 (S-1)	750	Compliant
Lead	165 ± 28 (S-5)	140	Non-compliant
Lead	85 ± 15 (S-1)	140	Compliant
Cadmium	3.2 ± 0.8 (S-5)	10	Compliant
Chromium	42 ± 9 (S-5)	64	Compliant

*Values represent mean ± standard deviation ($n = 15$)

The elevated barium and lead concentrations at S-5 indicate recent contamination from untreated waste storage. In contrast, the remediated sites (S-1 and S-2) showed concentrations well below regulatory limits, demonstrating the effectiveness of remediation measures. These findings align with Khudhur et al. (2022), who reported similar contamination patterns in Kurdistan Region soils.

4.2.3 Leachate Test Results

Leachate tests indicated that dissolved organic carbon and total suspended solids were marginally above limits but were treated daily (Table 4). Heavy metal concentrations in leachate were below regulatory limits, indicating effective immobilization.

Table 4
Leachate Test Results

Parameter	Result	Regulatory Limit	Compliance Status
Dissolved Organic Carbon (mg/L)	85 ± 12	80	Marginally above
Total Suspended Solids (mg/L)	55 ± 8	50	Marginally above
Barium (mg/L)	0.8 ± 0.2	2.0	Compliant
Lead (mg/L)	0.15 ± 0.04	0.5	Compliant
Chromium (mg/L)	0.08 ± 0.02	0.1	Compliant
pH	8.2 ± 0.3	6.0–9.0	Compliant

*Values represent mean ± standard deviation ($n = 15$)

4.3 Comparative Analysis

4.3.1 Comparison with Iranian Offshore Operations

Table 5 presents a comparison of waste management practices between GPNME onshore operations and Iranian offshore operations (Razmgir and Afsari 2011).

Table 5
Comparison of Waste Management Practices

Parameter	GPNME (Onshore)	Iranian Offshore Fields
Drilling Fluid Type	WBM	WBM, OBM
Waste Management Method	Quicklime-cement solidification, GCL lining	Dewatering, coagulation-flocculation, discharge
Treatment Duration	2+ weeks drying	96 days
Volume Treated	~1,000 m ³ (S-1)	4,224 m ³
Regulatory Compliance	EC 2003/33/EC, Canadian 2009	Iranian environmental regulations
Environmental Outcome	Vegetation regrowth observed	Water disposal with testing

The comparison reveals that GPNME's approach emphasizes containment and treatment, while the Iranian offshore approach focuses on volume reduction and discharge. Both approaches have merit depending on site-specific conditions and regulatory requirements.

4.3.2 Comparison with International Best Practices

The comparison identifies monitoring frequency as a gap, with GPNME conducting annual monitoring compared to continuous monitoring in international best practices (Table 6).

Table 6
GPNME practices with international best practices.

Practice	GPNME Approach	International Best Practice	Gap Analysis
Waste Minimization	WBM only	SBM where technically required	GPNME uses less toxic fluids
Solid Control	Secondary treatment	Advanced cuttings dryers	Comparable
Treatment Method	Quicklime-cement solidification	Thermal treatment, bioremediation	Cost-effective alternative
Liner System	HDPE + GCL	Double GCL or equivalent	Comparable
Laboratory Testing	European laboratories	Accredited laboratories	Comparable
Site Remediation	Topsoil placement, revegetation	Full ecological restoration	Comparable
Monitoring	Annual	Continuous	Gap identified

4.4 Environmental Benefits Assessment

4.4.1 Soil Protection

The quicklime-cement solidification process effectively immobilized heavy metals in treated cuttings, preventing their release into the surrounding soil (Table 7).

Table 7
Environmental Benefits of Quicklime-Cement Solidification

Environmental Parameter	Without Treatment	With Treatment	Improvement (%)
Heavy Metal Mobility (mg/L leachate)	12.5 ± 2.8	1.2 ± 0.3	90.4
Leachate Generation (L/m ³)	45 ± 8	8 ± 2	82.2
Soil pH	5.2–8.5 (variable)	7.8–8.2 (stabilized)	Stabilized
Contaminant Bioavailability (%)	65 ± 12	8 ± 2	87.7

*Values represent mean ± standard deviation ($n = 15$)

4.4.2 Water Resource Protection

The use of HDPE and GCL liners in waste pits provided effective barriers against leachate migration to groundwater (Table 8).

Table 8
Water Resource Protection Benefits

Protection Measure	Effectiveness (%)	Environmental Benefit
HDPE Liner	95	Prevents leachate migration
GCL Liner	90	Provides additional barrier
Double Liner System	99.5	Redundant protection
Clay Cap (2m)	92	Prevents water infiltration

4.4.3 Air Quality Impact

The quicklime-cement solidification method offers significant air quality benefits compared to thermal treatment methods (Table 9).

Table 9

Comparative Air Emissions of Treatment Methods

Treatment Method	CO ₂ Emissions (kg/tonne)	NO _x Emissions (kg/tonne)	SO _x Emissions (kg/tonne)	Particulate Matter (kg/tonne)
Quicklime-Cement Solidification	45 ± 8	<0.1	<0.1	0.5 ± 0.1
Thermal Treatment (Incineration)	320 ± 45	2.8 ± 0.5	1.2 ± 0.3	1.5 ± 0.4
Thermal Treatment (Kiln)	280 ± 38	1.5 ± 0.3	0.8 ± 0.2	1.2 ± 0.3
Landfarming	5 ± 1	<0.1	<0.1	0.2 ± 0.05

*Values represent mean ± standard deviation from literature (Ytrehus et al. 2025)

4.4.4 Ecosystem Recovery

Visual observations at remediated sites (Sarqala S-1 and S-2) documented significant vegetation regrowth, indicating successful ecosystem recovery (Table 10).

Table 10

Ecosystem Recovery Indicators at Remediated Sites

Indicator	S-1 Observation	S-2 Observation	Significance
Vegetation Cover (%)	72 ± 8	85 ± 6	Successful revegetation
Species Richness	12 species	18 species	Ecosystem resilience
Soil Organic Matter (%)	2.8 ± 0.4	3.5 ± 0.5	Remediation effectiveness
Erosion Signs	None observed	None observed	Site stability

*Values represent mean ± standard deviation ($n = 5$ quadrats per site)

4.4.5 Waste Reduction and Resource Recovery

The waste management practices at GPNME resulted in significant waste volume reduction and resource recovery (Table 11).

Table 11

Waste Reduction and Resource Recovery Metrics

Metric	Value	Environmental Benefit
Waste Volume Reduction (%)	35 ± 5	Reduced landfill burden
Fluid Recovery (%)	85 ± 7	Resource conservation
HDPE Liner Recycling (%)	100	Waste diversion
Beneficial Reuse Potential	High	Circular economy contribution

4.4.6 Carbon Footprint Assessment

A quantitative assessment of the carbon footprint associated with GPNME's waste management approach compared to alternative methods is presented in Table 12.

Table 12
Carbon Footprint Comparison

Waste Management Approach	Carbon Footprint (kg CO ₂ /tonne waste)	Key Contributors
Quicklime-Cement Solidification (GPNME)	120 ± 25	Cement production, transportation
Thermal Treatment	450 ± 65	Fuel combustion, equipment operation
Transport to Shore	380 ± 55	Vessel fuel, emissions
Landfarming	45 ± 12	Minimal energy input
Beneficial Reuse	35 ± 10	Transportation only

*Values represent mean ± standard deviation from literature (Ytrehus et al. 2025)

4.4.7 Summary of Environmental Benefits

The quantification of the treatment benefits for each environmental category is listed in Table 13.

Table 13
Summary of Environmental Benefits

Environmental Category	Benefit	Quantification
Soil Protection	Heavy metal immobilization	> 90 % reduction in mobility
Water Protection	Leachate prevention	99.5 % effectiveness (double liner)
Air Quality	Low emissions	Negligible NO _x /SO _x
Ecosystem Recovery	Vegetation regrowth	>70 % cover at S-1
Waste Reduction	Volume reduction	35 %
Resource Recovery	Fluid recycling	85 % recovery
Carbon Footprint	Low-Medium	120 kg CO ₂ /tonne vs. 450 for thermal

4.5 Proposed Classification Framework

Based on the findings, a three-tier classification framework is proposed to guide operators in selecting appropriate waste management strategies (Table 14).

Table 14
Three-Tier Classification Framework for Drilling Waste Management

Tier	Waste Characteristics	Recommended Strategy	Regulatory Compliance
Tier 1	Low toxicity, low volume	Direct disposal with minimal treatment	Local standards
Tier 2	Moderate toxicity, moderate volume	Solidification/stabilization, recycling	National standards
Tier 3	High toxicity, high volume	Thermal treatment, secure landfill	International standards

5. CONCLUSIONS

This study provides a comprehensive assessment of drilling fluid waste management practices in the Garmyan Block fields, identifying both challenges and opportunities for improvement. The findings reveal that while some operators have adopted appropriate waste management practices, significant gaps remain in infrastructure, regulatory compliance, and technical capacity.

Drilling waste in the Garmyan Block exhibit significant variation in composition and properties, requiring tailored management approaches for different waste streams. Water-based muds, oil-based muds, and produced water each present distinct challenges and require appropriate treatment and disposal strategies.

Current waste management practices are inadequate in several respects, including storage containment, treatment efficiency, and disposal compliance. Improvements are needed across all aspects of waste management to reduce environmental risks.

Environmental monitoring data indicate potential impacts from current practices, highlighting the need for improved management. Soil and groundwater contamination were observed at some locations, indicating the need for remediation and enhanced prevention measures.

Multiple barriers constrain effective waste management, including infrastructure limitations, regulatory enforcement challenges, and technical capacity gaps. Addressing these barriers requires coordinated action by operators, regulators, and other stakeholders.

Sustainable waste management strategies, including waste minimization, recycling, treatment, and proper disposal, can significantly reduce environmental impacts. The waste management hierarchy provides a useful framework for prioritizing these strategies.

The quicklime-cement solidification method achieved over 90% reduction in heavy metal mobility, with treated cuttings meeting European Council 2003/33/EC standards for landfill disposal (European Council 2003).

Remediated sites showed successful ecosystem recovery, with vegetation cover exceeding 70% and diverse plant communities established.

The proposed three-tier classification framework provides practical guidance for operators in selecting appropriate waste management strategies based on waste characteristics and regulatory requirements.

5.1 Policy Implications

The findings have several policy implications for the Kurdistan Region:

- **Regulatory Strengthening:** Enhanced enforcement mechanisms and clearer standards are needed to ensure consistent compliance across operators.

- Infrastructure Investment: Development of centralized treatment facilities would improve efficiency and reduce environmental risks.
- Capacity Building: Training programs for regulatory officials and industry personnel would enhance technical capacity.
- Monitoring Requirements: More frequent and comprehensive monitoring should be required to track environmental performance.

5.2 Future Research Directions

Future research should focus on:

- Long-term monitoring of remediated sites to assess ecosystem recovery trajectories.
- Comparative evaluation of treatment technologies under varying geological conditions.
- Economic analysis of waste management options to inform decision-making.
- Development of innovative treatment technologies suitable for local conditions.
- Assessment of cumulative environmental impacts across multiple drilling sites.
- The transition towards sustainable drilling requires commitment from all stakeholders, including operators, regulators, and communities. By adopting the recommendations outlined in this study, the Garmyan Block can serve as a model for sustainable drilling practices in the Kurdistan Region and beyond.

REFERENCES

- Adebayo, A. O., Balogun, A. L., Olaniyi, A. A. (2019). Human health risk assessment of heavy metals in spent synthetic-based drilling mud. *Environmental Geochemistry and Health*, 41 (6), pp. 2675–2692. <https://doi.org/10.1007/s10653-019-00314-6>.
- AECOM (2016). *Drilling waste management technology review*. IOGP Report 557, International Association of Oil & Gas Producers.
- Agwa, A., Sadiq, R., Leheta, H. (2012). Offshore drilling discharge: Egyptian environmental regulations. *SPE International Petroleum Exhibition & Conference*, Abu Dhabi, UAE, 11–14 November 2012.
- Al-Haleem, A. A., Abdulah, H. A., Saeed, A. J. (2019). Characterization of oil-based drill cuttings and evaluation of thermal desorption treatment. *Journal of Petroleum Science and Engineering*, 178, pp. 1045–1053, <https://doi.org/10.1016/j.petrol.2019.04.019>.

- Amannullah, M. (2007). *Environmental friendly mud additives for superior drilling fluid design to meet the current and future technical and environmental challenges*. CSIRO Petroleum.
- American Public Health Association (2017). *Standard methods for the examination of water and wastewater*. 23rd ed., APHA, Washington, DC. Method 4500-H+ B.
- ASME (2007). *Drilling fluids processing handbook*. 1st ed., Gulf Professional Publishing/Elsevier, Burlington.
- Azur Environmental (1998). *Microtox manual: Microtox acute toxicity test with Vibrio fischeri*. Azur Environmental.
- Ball, S. A., Stewart, J. R., Schliephake, K. (2012). A review of the current options for the treatment and safe disposal of drill cuttings. *Waste Management & Research*, 30 (5), pp. 457–473, <https://doi.org/10.1177/0734242X11419892>.
- Broni-Bediako, E., Amorin, R. (2010). Effects of drilling fluid exposure to oil and gas workers presented with major areas of exposure indicators. *Research Journal of Applied Sciences, Engineering and Technology*, 2 (8), pp. 710–714.
- Caenn, R., Darley, H. C. H., Gray, G. R. (2017). *Composition and properties of drilling and completion fluids*. 7th ed., Gulf Professional Publishing/Elsevier, Oxford.
- Canadian Council of Ministers of the Environment (2009). *Canadian soil quality guidelines for the protection of environmental and human health*. CCME. <https://ccme.ca/en/research-reports>
- European Council (2003). Council Decision 2003/33/EC establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC. *Official Journal of the European Communities*, L 11, pp. 27–49, (accessed on 8 October 2026). 11, 27–49. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32003D0033>
- Gaurina-Medimurec, N. (2020). *Deep underground injection of waste from drilling activities*. Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Zagreb.
- Gbadebo, A. M., Taiwo, A. M., Eghele, U. U. (2010). Environmental impacts of drilling mud and cutting wastes from the Igbokoda onshore oil wells, South western Nigeria. *Indian Journal of Science and Technology*, 3 (5), pp. 504–510.
- Johnson, R. T., Wilson, S. A., Thompson, L. M. (2021). Life cycle assessment of drilling fluid systems: A comparative analysis of water-based, oil-based, and synthetic-based

- muds. *Journal of Cleaner Production*, 295, 126432. <https://doi.org/10.1016/j.jclepro.2021.126432>.
- Khudhur, K., Hamid, F. S., Rahman, M. M. (2022). Hydrocarbon contamination in KRI soils: Sources and mitigation. *Journal of Environmental Management*, 305, 114367. <https://doi.org/10.1016/j.jenvman.2021.114367>.
- Kingston, P. F. (2002). Long-term environmental impact of offshore oil and gas activities: The North Sea experience. *Environmental Science & Policy*, 5 (3), pp. 233–245. [https://doi.org/10.1016/S1462-9011\(02\)00038-6](https://doi.org/10.1016/S1462-9011(02)00038-6).
- Ministry of Natural Resources, Kurdistan Regional Government (2010). *Waste management instructions for oil and gas operations*. MNR.
- Murray, J. M., Smith, P. R., Jones, R. D. (2018). Long-term effects of drill cuttings disposal on benthic foraminifera in the North Sea. *Marine Pollution Bulletin*, 131, pp. 567–578, <https://doi.org/10.1016/j.marpolbul.2018.04.062>.
- Neff, J. M. (2005). *Composition, environmental fates, and biological effect of water based drilling muds and cuttings discharged to the marine environment: A synthesis and annotated bibliography*. Petroleum Environmental Research Forum (PERF).
- Neff, J. M., McKelvie, S., Ayers, R. C. (2000). *Environmental impacts of synthetic based drilling fluids*. OCS Study MMS 2000-064, U.S. Department of the Interior, Minerals Management Service.
- Organisation for Economic Co-operation and Development (2004). *Test No. 202: Daphnia sp. acute immobilization test*. OECD Guidelines for the Testing of Chemicals. <https://doi.org/10.1787/9789264069947-en>.
- OSPAR Commission (2025). *Discharges*. <https://www.ospar.org/work-areas/oic/discharges>
- Razmgir, S. M., Afsari, M. (2011). Drilling waste management: A case study of the drilling waste management and environmental control in one of the Iranian offshore fields. *SPE Middle East Unconventional Gas Conference and Exhibition*, Muscat, Oman, 4–7 April 2011. SPE-142487-MS. <https://doi.org/10.2118/142487-MS>.
- Rena, S. (2008). Facts and data on environmental risks – Oil and gas drilling operations. *SPE Asia Pacific Oil and Gas Conference and Exhibition*, Perth, Australia, 20–22 October 2008.
- Salih, A. M., Kamal, I., Pr  at, A., Talabani, N. S. (2021). Utilization of treated drill cuttings as sub-base aggregate for road construction. *Journal of Cleaner Production*, 280, 124367, <https://doi.org/10.1016/j.jclepro.2020.124367>.

- Sharif, M. D., Nagalakshmi, N. V. R., Reddy, K. S. (2017). Drilling waste management and control the effects. *Journal of Advanced Chemical Engineering*, 7 (1), pp. 1–6.
- U.S. Environmental Protection Agency (1996). *Method 3050B: Acid digestion of sediments, sludges, and soils*. Revision 2. <https://www.epa.gov/hw-sw846/sw-846-test-method-3050b-acid-digestion-sediments-sludges-and-soils>
- U.S. Environmental Protection Agency (2003). *Method 8015D: Nonhalogenated organics using GC/FID*. Revision 4. <https://www.epa.gov/esam/epa-method-8015d-sw-846-nonhalogenated-organics-using-gcfid>
- Veil, J. A. (2020). *Offshore waste management – Discharge, inject, or haul to shore*. Argonne National Laboratory, Argonne.
- Veil, J. A., Puder, M. G., Elcock, D., Redweik, R. J. (2004). *A white paper describing produced water from production of crude oil, natural gas, and coal bed methane*. ANL/EA/R-04-1, Argonne National Laboratory, Argonne.
- Ytrehus, J. D., Saasen, A., Brønner, U., Ditlevsen, M. K. (2025). Platform drilling life cycle assessment of drilling waste handling. In: *Proceedings of the ASME 2025 44th International Conference on Ocean, Offshore and Arctic Engineering*, Vol. 6, V006T11A010, ASME. <https://doi.org/10.1115/OMAE2025-155238>.
- Zhou, Y., Deng, C., Chen, X., He, Y., Fang, G., Jin, Z., Liu, Y. J. (2025). Engineering design and application of large-scale oil-based drilling cuttings treatment project. *Waste Management & Research*, 43 (2), pp. 282–292. <https://doi.org/10.1177/0734242X241231393>.