

Article

Research on Environmentally Friendly Drilling Fluid System and Exploration of Waste Utilization in Desert Saline–Alkali Lands

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Abstract

The Tarim Basin, as the core strategic replacement area for oil and gas resources in western China, holds immense deep oil and gas development potential. However, this region features extensive deserts, fragile saline–alkali ecosystems, and extreme geological conditions—160 °C high temperatures, high-salt/high-alkali formation fluids, and well-developed microfractures—that impose stringent dual requirements on drilling fluids for both engineering performance and environmental compatibility. Traditional drilling fluids suffer severe performance deterioration under high-temperature/high-salt coupling, and their poorly biodegradable, toxic additives exacerbate ecological pollution upon disposal, failing to meet green development demands. To address these issues, this study prepared four eco-friendly, temperature- and salt-resistant drilling fluid additives via chemical modification of natural degradable materials, and constructed a 160 °C-resistant eco-friendly water-based drilling fluid system using orthogonal experiments. Furthermore, an innovative “waste-to-resource” strategy was proposed to repurpose spent drilling fluid for saline–alkali land restoration, investigating its improvement effects and environmental safety. The results show that the system withstands 160 °C and 15% NaCl, with excellent engineering performance (HTHP filtration loss ≤ 9.0 mL at 160 °C, friction coefficient ≤ 0.18) and compliance with national environmental standards ($EC_{50} = 36,000$ mg/L, $BOD_5/COD = 6.8\%$). Applied at an optimal 10–15% dosage, the spent fluid significantly improves saline–alkali soil properties, promotes *Haloxylon ammodendron* growth, and achieves >90% pollutant degradation within 3 months without secondary pollution. This integrated technology synergizes drilling engineering and ecological protection, providing technical support for green oil and gas development and saline–alkali land restoration in the Tarim Basin.

Keywords: desert saline–alkali soil; environmentally friendly drilling fluid; temperature and salt resistance; soil improvement



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1. Introduction

Oil and gas resources are core strategic resources for ensuring national energy security. With the decline in production capacity of conventional oil and gas fields in eastern China, the Tarim Basin, endowed with abundant deep oil and gas reserves, has become a key strategic replacement area for increasing national oil and gas production and reserves [1–4]. However, this region faces dual challenges of extremely complex geological conditions and fragile ecological environments: it is covered by extensive deserts and saline–alkali lands with six typical soil types (including Na_2SO_4 -type, NaCl -type, and soda-type saline–alkali soils), which are characterized by high salinity, strong alkalinity, poor structure, and low fertility [5,6]. Hossain et al. [6] first proposed the feasibility of using natural plant materials as eco-friendly drilling fluid additives, pointing out that their biodegradability can effectively reduce the ecological impact on saline–alkali lands, but their poor high-temperature stability limits practical application. Meanwhile, the deep formations exhibit harsh engineering geological features, such as 160 °C high temperature, high-concentration brine, strongly alkaline formation fluids, and well-developed micro-nano fractures in fractured dolomite and gypsum-salt beds [7]. These extreme conditions impose stringent dual requirements on drilling fluids: they must not only possess excellent engineering performance (high temperature resistance, salt–alkali tolerance, plugging capacity, and lubricity) to ensure drilling safety, but also meet strict environmental protection standards to avoid exacerbating the ecological degradation of saline–alkali lands [8–12].

Currently, deep drilling in the Tarim Basin mainly relies on polysulfonate and oil-based drilling fluid systems. While these systems can meet basic temperature and salt resistance requirements, they have significant limitations under extreme coupling conditions and environmental constraints [13]. Polysulfonate drilling fluids are prone to additive degradation and performance deterioration at 160 °C high temperature and high salt–alkali conditions, leading to downhole accidents such as wellbore collapse and stuck pipe. Oil-based drilling fluids have outstanding inhibition and lubricity, but their high cost and potential environmental risks limit their large-scale application. More importantly, both systems use poorly biodegradable and highly toxic treatment agents, and their waste disposal not only incurs high costs but also aggravates soil salinization and ecological pollution in saline–alkali areas, which is inconsistent with the concept of green development [14–17]. Therefore, developing specialized drilling fluids with excellent temperature and salt resistance as well as environmental characteristics, while realizing resource utilization of waste liquid, has become a core issue that needs to be urgently solved in the development of oil and gas in this region, with both important engineering and ecological value [18,19].

In recent years, domestic and foreign scholars have conducted extensive research on high-temperature and high-salt drilling fluids, and improved the stability of drilling fluids in single extreme environments through nanomodification and biopolymer optimization [20–22]. However, the existing research still has obvious systematic gaps: most studies focus on single salt ions, medium-low temperatures (≤ 120 °C), or weakly alkaline environments, and lack systematic research on the extreme coupling conditions of 160 °C high temperature, 15% high salinity, and strong alkalinity in the Tarim Basin, resulting in poor adaptability of the developed systems [23]. Prakash et al. [7] developed a natural product-based filtrate reducer that showed good performance below 120 °C, but suffered severe thermal degradation at 160 °C with filtration loss exceeding 20 mL. Ekunke et al. [24] pointed out in their review that over 80% of existing eco-friendly drilling fluids can only adapt to temperatures below 140 °C, and their anti-salt capacity is generally less than 10% NaCl . Al-Hameedi et al. [25,26] used agricultural wastes such as peanut shells and mandarin peels to prepare biodegradable additives, but their anti-calcium pollution ability was limited, and performance deteriorated significantly in formation fluids containing

high concentrations of Ca^{2+} . Abdalqadir et al. [27] further confirmed that most bio-based additives cannot simultaneously balance high-temperature stability, salt–alkali resistance and biodegradability. Furthermore, the majority of research prioritizes engineering performance while neglecting environmental protection and waste resource utilization. The temperature and salt-resistant additives used are generally toxic and difficult to degrade, and the existing saline–alkali soil remediation technologies are costly and have not been integrated with drilling waste disposal, leading to double consumption of resources and costs [28–31]. The potential of waste drilling fluids for soil improvement and environmental resource utilization has not been fully explored (Table 1 and Figure 1).

Table 1. Limitations of existing drilling fluid technologies and core research gaps.

Technology Type	Temperature Resistance	Salt/Alkali Resistance	Environmental Performance	Waste Resource Utilization	Core Deficiencies
Traditional polysulfonate drilling fluid	140–150 °C	$\leq 12\%$ NaCl, poor alkali resistance	Poor biodegradability, high toxicity	Only solidification and landfill, high cost	Performance deterioration under 160 °C high-temperature and high-alkali coupling; serious secondary pollution
Traditional oil-based drilling fluid	180–200 °C	Excellent	Non-biodegradable, high toxicity	Cannot be used for soil improvement, high disposal cost	High cost; irreversible damage to soil ecology; cannot realize resource utilization
Existing eco-friendly water-based drilling fluid	≤ 120 °C	$\leq 10\%$ NaCl, poor calcium resistance	Good biodegradability, low toxicity	No systematic research on waste utilization	Cannot adapt to 160 °C + 15% NaCl extreme conditions; lack of integrated technology for drilling and ecological protection
Research objectives of this study	≥ 160 °C	$\geq 15\%$ NaCl, good calcium/alkali resistance	Non-toxic grade biodegradable	Waste fluid used for saline–alkali soil improvement	Solve the contradiction between engineering performance and environmental protection; realize “treating waste with waste”

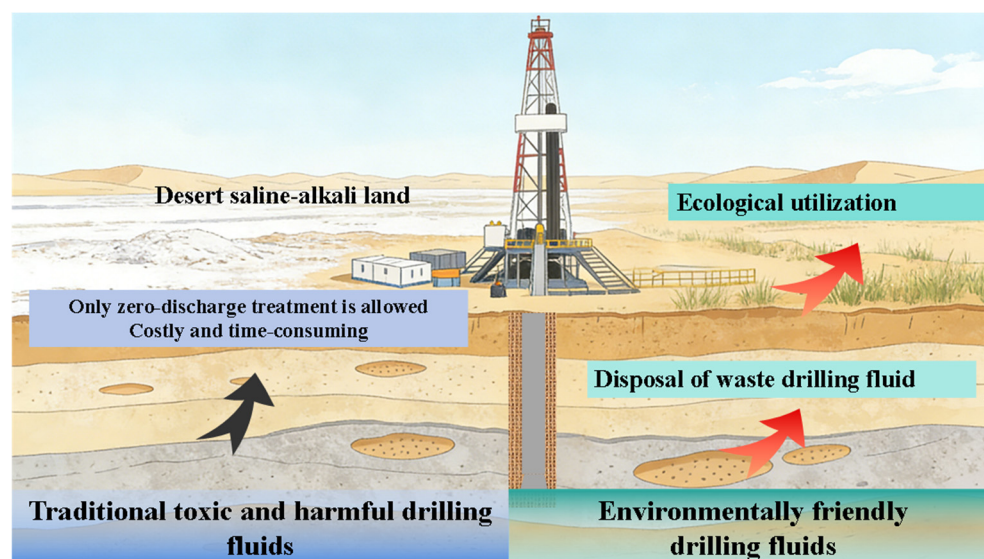


Figure 1. Comparison of traditional drilling fluid and eco-friendly drilling fluid treatment methods.

In response to the above research gaps and field engineering challenges, this study takes the deep formations of desert saline–alkali lands in the Tarim Basin as the research object, breaks through the traditional R&D concept of “valuing engineering performance over environmental protection”, and constructs an integrated technical path of “eco-friendly drilling fluid development-waste fluid resource utilization”. Using natural biomass as raw materials, four core eco-friendly treatment agents (viscosifier, filtrate reducer, lubricant, and plugging agent) with 160 °C temperature resistance and non-toxic properties were prepared through chemical modification to resolve the contradiction between engineering performance and environmental protection. Combined with regional geological characteristics, an orthogonal experiment was used to optimize the formula and construct a dedicated eco-friendly water-based drilling fluid system, whose comprehensive performance is systematically evaluated. Meanwhile, based on the concept of “treating waste with waste”, the waste drilling fluid was innovatively used as a soil amendment to explore its improvement effect on saline–alkali soil, its impact on the growth of *Haloxylon ammodendron* (a typical desert salt-tolerant plant), and its environmental safety; the optimal application ratio was determined. This research aims to provide technical support for the green development of regional oil and gas resources, offer new ideas for the resource utilization of drilling waste and ecological restoration of saline–alkali lands, and promote the coordinated development of oil and gas development and ecological protection.

2. Materials and Methods

2.1. Experimental Materials and Instruments

The main experimental materials include corn starch, acrylamide (AM), 2-acrylamido-2-methylpropanes sulfonic acid (AMPS), N,N'-methylenebisacrylamide (MBA), sodium carboxymethyl cellulose (CMC), acrylic acid (AA), nano-silica, rapeseed oil, polyethylene glycol (PEG-400), bentonite, barite, NaCl, CaCl₂, KCl, Na₂CO₃, and other chemical reagents of analytical purity. All were purchased from Shanghai Maclin Biochemical Technology Co., Ltd. The experimental soil was collected from the surface desert saline–alkali land in the Tarim Basin.

The main instruments include a six-speed rotational viscometer, API filtration tester, HTHP filtration tester, friction coefficient tester, thermostatic water bath, high-temperature aging roller furnace, simulated plugging evaluation device, pH meter, conductivity meter, and organic element analyzer. (The rotational viscometer (ZNN-D6) and API filtration

tester (SD6A) were manufactured by Qingdao Haitongda Special Instruments Co., Ltd. (Qingdao, China). The HTHP filtration tester (GGS42-2) and simulated plugging evaluation device were produced by Jiangsu Huaian Oil Instrument Co., Ltd. (Huaian, China). The pH meter (PHS-3C) and conductivity meter (DDS-11A) were purchased from Shanghai Leici Instrument Factory (Shanghai, China). Data analysis and plotting were performed using OriginPro 2023 software (OriginLab Corporation, Northampton, MA, USA).

2.2. Preparation Methods of Environmentally Friendly Drilling Fluid Additives

Four key environmentally friendly additives were prepared by chemical modification using natural biomass materials:

Viscosifier (HTDF-VIS): Starch-g-AM/AMPS copolymer was synthesized by graft copolymerization using corn starch as raw material. Filtrate reducer (HTCMC-NAFL): Composite modified filtrate reducer was prepared with CMC, AA and nano-SiO₂. Lubricant (HT-LUBE): Bio-based lubricant was synthesized from rapeseed oil and PEG through alcoholysis. Plugging agent (HT-SEAL): Core-shell structural nano-composite plugging agent was prepared by emulsion polymerization.

2.3. Viscosifier Optimization

The base slurry used in all additive performance evaluations was prepared as follows: 400 mL deionized water + 16.0 g sodium bentonite + 0.6 g Na₂CO₃, stirred at 8000 rpm for 20 min, and aged at room temperature for 24 h before use.

Natural corn starch with good biodegradability and low toxicity was selected as the raw material, and high temperature and salt resistant groups were introduced through graft copolymerization modification: Acrylamide (AM) was used as the hydrophilic monomer, 2-Acrylamide-2-methylpropanesulfonic acid (AMPS) as the salt-resistant monomer, N,N'-Methylenebisacrylamide (MBA) as the crosslinking agent, and the starch-g-AM/AMPS copolymer viscosifier HTDF-VIS was prepared under the initiation of Ammonium Persulfate (APS) in a water bath at 60 °C for 4 h. The crosslinking density was optimized by adjusting the dosage of MBA (0.05%, 0.1%, 0.15%, 0.2%). The results showed that 0.1% MBA achieved the best balance between thermal stability and water solubility. Excessively high crosslinking density led to poor water solubility, while excessively low density reduced thermal stability. For the optimized viscosifier, the high temperature resistance stability evaluation was carried out in the laboratory at 120 °C and 160 °C.

2.4. Filtrate Reducer Optimization

The filtrate reducer needs to form a dense filter cake in a high temperature and high pollution environment to control the filtration loss of drilling fluid. Sodium carboxymethyl cellulose was selected as the matrix, and a composite filtrate reducer HTCMC-NAFL was prepared by composite modification grafting Acrylic Acid (AA) and nano-silica. The specific preparation process is as follows: dissolve CMC in deionized water, add AA and nano-SiO₂ (mass ratio CMC:AA:nano-SiO₂ = 5:3:2), react at 70 °C for 3 h under the action of initiator APS to obtain a white flocculent product, which is washed, dried and crushed to form the composite filtrate reducer HTCMC-NAFL.

The conventional 160 °C aging evaluation of the optimized filtrate reducer was carried out in the laboratory. At the same time, 1.0% HTCMC-NAFL was added to the high-salt and high-calcium base slurry containing 10% NaCl and 5% CaCl₂, and the contaminated base slurry with 5% montmorillonite respectively to evaluate the filtrate reduction effect after aging at 160 °C for 16 h.

2.5. Lubricant Optimization

The lubricant needs to reduce the friction coefficient between the drilling fluid and the drilling tool, as well as the borehole wall, and have environmental protection performance. Degradable bio-based material rapeseed oil was selected as the base oil, and the polyethylene glycol (PEG) chain segment was grafted onto the fatty acid molecule through alcoholysis reaction to significantly improve its hydrophilicity and dispersibility in water-based drilling fluid. In the preparation process, rapeseed oil and polyethylene glycol (PEG-400) were mixed at a mass ratio of 1:0.8, 1.0% KOH as an alkaline catalyst was added, reacted at 120 °C for 6 h, and stabilized to prepare the rapeseed oil polyoxyethylene ether ester lubricant HT-LUBE.

In the laboratory, a drilling fluid friction coefficient tester was used to add 2.0% HT-LUBE to the base slurry, age at 160 °C for 16 h, and determine the friction coefficient before and after hot rolling. At the same time, 10% NaCl and 5% CaCl₂ were added to the base slurry to form a high-salt and high-calcium base slurry to evaluate the pollution resistance, and the friction coefficient after hot rolling was tested.

2.6. Plugging Agent Optimization

The plugging agent is a key additive in the drilling fluid system to prevent formation loss, and its performance directly affects drilling safety and efficiency. Aiming at the formation characteristics of high temperature and high pressure and well-developed micro-nano fractures in the Tarim Basin, a core-shell structured plugging agent was optimized and developed. In the laboratory, inorganic nano-silica was used as the core, and polystyrene-butyl acrylate-acrylic acid as the shell (monomer mass ratio 10:2:1), and the core-shell structured plugging agent HT-SEAL was prepared by emulsion polymerization. The optimized optimal reaction conditions are as follows: monomer concentration 20%, initiator potassium persulfate dosage 0.5% of monomer mass, emulsifier sodium dodecyl sulfate dosage 1.5% of monomer mass, reaction temperature 70 °C, reaction time 8 h, and finally the plugging agent HT-SEAL is obtained.

Laboratory experiments were carried out to evaluate the plugging effect of HT-SEAL at room temperature (25 °C) and normal pressure. A simulated loss evaluation device was used to mix 3.0% HT-SEAL into the base slurry according to the designed concentration, the pressure was increased step by step, the change in loss volume under different pressure gradients was monitored in real time, and the corresponding relationship of time-pressure-loss volume was recorded to evaluate the plugging capacity and stability under dynamic conditions.

2.7. Establishment Method of Drilling Fluid System

Based on the 4 developed key environmentally friendly drilling fluid additives (HTDF-VIS viscosifier, HTC MC-NAFL filtrate reducer, HT-LUBE lubricant, HT-SEAL plugging agent), combined with the geological characteristics of deep high-temperature formations in the desert saline-alkali land of the Tarim Basin (temperature 160 °C, salt content 10–15%, density requirement 1.6 g/cm³), the formula of the environmentally friendly drilling fluid system was optimized through orthogonal tests. The factors selected in the orthogonal test are HTDF-VIS dosage (0.3%, 0.5%, 0.7%), HTC MC-NAFL dosage (1.0%, 1.2%, 1.4%), HT-LUBE dosage (1.5%, 2.0%, 2.5%), HT-SEAL dosage (2.5%, 3.0%, 3.5%), and the evaluation indicators are Apparent Viscosity (AV), API filtration loss, HTHP filtration loss, friction coefficient and environmental performance. The environmental performance is graded as: Grade I (excellent), Grade II (good), Grade III (general).

2.8. Drilling Fluid Performance Evaluation Methods

The performance of the drilling fluid was tested in accordance with relevant national standards and industrial specifications, where rheological properties including apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) were measured using a six-speed rotational viscometer; filtration performance was evaluated by testing API filtration loss and HTHP filtration loss at 160 °C and 3.5 MPa; lubricity was determined via a friction coefficient tester; plugging performance was assessed through a simulated leakage device to verify the multi-scale plugging effect; high temperature resistance was examined by aging the samples at 120 °C, 140 °C, 160 °C, and 180 °C for 16 h and recording the corresponding performance changes; salt resistance was tested under NaCl concentrations of 5%, 10%, 15%, and 20%; and environmental performance was characterized by measuring biological toxicity (EC50) and biodegradability (BOD₅/COD_{Cr}).

2.9. Orthogonal Experimental Design and Data Analysis Method

An orthogonal experiment was designed to optimize the formulation of the environmentally friendly drilling fluid system, in which four factors including viscosifier dosage (A), filtrate reducer dosage (B), lubricant dosage (C), and plugging agent dosage (D) were set at three dosage levels respectively; the evaluation indicators covered apparent viscosity, API filtration loss, HTHP filtration loss, friction coefficient, and environmental performance; range analysis was adopted to determine the influence degree of each factor and obtain the optimal formula combination, and the importance of each indicator was comprehensively considered to ensure that the system could meet the requirements of high temperature resistance, salt resistance, and environmental protection.

2.10. Experimental of Soil Improvement

Taking the surface saline–alkali soil in the Tarim Desert as the test soil and the constructed waste environmentally friendly drilling fluid as the modifier, a soil improvement experiment was carried out. The experiment set 4 groups with different addition amounts of waste drilling fluid (0%, 5%, 10%, 15%), denoted as S (control group), K1 (5%), K2 (10%), K3 (15%) respectively, with 3 repetitions in each group and 10 kg of test soil sample in each repetition. The experimental steps are as follows: (1) Air-dry and crush the test soil, and pass it through a 2 mm sieve; (2) add different amounts of waste drilling fluid to the soil, stir evenly, adjust the water content to 20%, and let it stand for 7d; (3) determine the physicochemical properties of the improved soil and the plant growth status.

Haloxylon ammodendron, a typical salt-tolerant plant in desert areas, was selected as the test plant with uniform seed size and good germination rate. The planting density was 10 seeds per pot with a growth cycle of 60d. During the growth period, the soil water content was maintained at 18–22%, and the plant growth status (plant height, root length, fresh weight) was recorded regularly; at the same time, the physicochemical properties (pH value, salt content, organic matter content, water retention capacity) of the soil before and after improvement were determined.

2.11. Evaluation Method for Environmental Performance of Drilling Fluid

The environmental performance of the system was evaluated in accordance with national environmental protection standards, including biological toxicity (EC50) and biodegradability (BOD₅/COD_{Cr}). The biological toxicity was detected by the luminescent bacteria acute toxicity test, and the biodegradability was detected by the dilution and inoculation method.

All experiments in this study were performed with three parallel replications, and the average values were adopted to ensure accuracy and reliability. Data processing, statistical

analysis, and curve fitting were conducted using Origin 2023. For orthogonal experiments, range analysis was used to determine the optimal formula and the influence degree of each factor.

3. Results and Discussion

3.1. Research on Key Environmentally Friendly Drilling Fluid Additives for Saline–Alkali Land

3.1.1. Viscosifier

As presented in Table 2, after adding 0.5% HTDF-VIS viscosifier to the base slurry, the apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) of the drilling fluid exhibited a gradual decreasing trend with increasing aging temperature. Specifically, the AV, PV, and YP were 23 mPa·s, 14 mPa·s, and 9 Pa at 25 °C; decreased to 21 mPa·s, 13 mPa·s, and 8 Pa at 120 °C; and further declined to 18 mPa·s, 11 mPa·s, and 7 Pa at 160 °C, respectively. The magnitude of the decrease was minimal between 25 °C and 120 °C, indicating excellent thermal stability of the viscosifier at medium temperatures. While performance attenuation became more pronounced between 120 °C and 160 °C, the viscosifier still retained sufficient viscosifying capacity and gel structure strength. Quantitatively, the performance retention rates of AV, PV, and YP at 160 °C reached 78.3%, 78.6%, and 77.8%, respectively, demonstrating strong high-temperature stability. This limited performance degradation confirms that the grafted sulfonic acid groups and crosslinked structure effectively inhibit thermal degradation and maintain the extended conformation of molecular chains [8,32]. Even after 16 h of aging at 160 °C, HTDF-VIS still provides adequate rheological support to meet the requirements of deep high-temperature drilling in desert saline–alkali regions.

Table 2. Drilling fluid performance after aging at different temperatures.

Sample Formula	Aging Temperature (°C)	Aging Time (h)	Apparent Viscosity (AV) (mPa·s)	Plastic Viscosity (PV) (mPa·s)	Yield Point (YP) (Pa)
Base slurry	25	16	23	14	9
+ 0.5%	120	16	21	13	8
HTDF-VIS	160	16	18	11	7

The superior thermal and salt resistance of HTDF-VIS originates from its tailored molecular structure. Hydroxyl groups on the starch backbone undergo graft copolymerization with acrylamide (AM) and 2-acrylamido-2-methylpropanesulfonic acid (AMPS), introducing amide groups (–CONH₂) and sulfonic acid groups (–SO₃H). The amide groups enhance adsorption onto clay particles via hydrogen bonding, thereby improving the viscosifying efficiency of the drilling fluid [33,34]. The sulfonic acid groups possess strong hydrophilicity and salt tolerance, which maintain the extended molecular chain conformation in high-salt environments and prevent viscosity loss caused by electric double layer compression. Additionally, the crosslinked network structure reinforces the thermal stability of the molecular chains and resists thermal degradation at 160 °C.

The biological toxicity EC₅₀ of the viscosifier is 38,500 mg/L, which is much higher than the non-toxic evaluation threshold of 30,000 mg/L, belonging to a low-toxic and environmentally friendly additive. Its BOD₅/CODCr ratio is 7.2%, which meets the biodegradable requirement (≥5%) specified in the oil and gas industry standard SY/T 6787-2010 for drilling fluid additives [35]. It should be clarified that this index represents biodegradable rather than readily biodegradable (the threshold for readily biodegradable is usually >20%). The slightly low short-term BOD₅/CODCr is mainly due to the introduction of temperature-resistant and salt-resistant sulfonic acid groups in the modified starch

molecule, which reduces the accessibility of microorganisms to a certain extent in the short term (Table 3).

Table 3. Environmental performance evaluation of viscosifier HTDF-VIS.

Test Item	Test Method	Test Result	Conclusion
Biological toxicity	Luminescent bacteria method	EC50 = 38,500 mg/L	Meets non-toxic grade requirements
Biodegradability	BOD5/CODCr method	BOD5/CODCr = 7.2%	Meets biodegradable requirements

3.1.2. Filtrate Reducer

As illustrated in Figure 2, the addition of 1.0% HTCMC-NAFL filtrate reducer to the base slurry yielded a filtration loss of only 6.8 mL after hot rolling at 160 °C for 16 h, demonstrating excellent filtration control performance. Under the combined contamination condition of 10% NaCl and 5% CaCl₂, the filtration loss increased to 9.2 mL but remained below the industry-accepted threshold of 10 mL, indicating favorable salt and calcium tolerance. In the solid-phase contamination environment induced by 5% bentonite, the filtration loss was 8.5 mL, which also satisfied the engineering requirements and reflected good resistance to bentonite contamination. Collectively, HTCMC-NAFL can effectively control filtration loss under various downhole working conditions, and its comprehensive performance meets the fundamental requirements for field engineering applications.

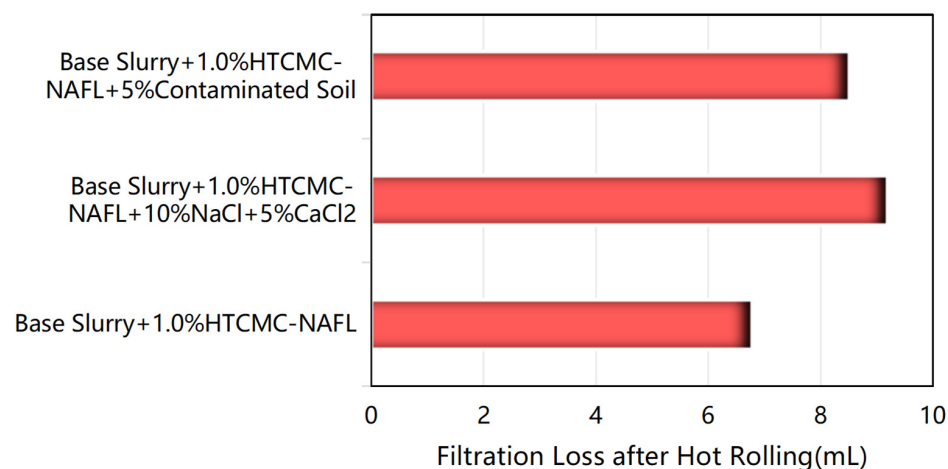


Figure 2. Evaluation of filter loss reduction effect of filter loss reduction agent in different environments.

The superior filtration control performance of HTCMC-NAFL can be attributed to the synergistic effects of its three functional components. First, carboxyl groups (-COOH) derived from acrylic acid (AA) form chelation bonds with clay particles, strengthening the interparticle bonding of the filter cake. Second, nano-SiO₂ particles (20–50 nm in diameter) fill the micro-pores within the filter cake and reduce its permeability [36]. Third, the rigid backbone of carboxymethyl cellulose (CMC) retains its structural integrity at elevated temperatures, preventing the filter cake structure from being damaged by thermal degradation.

3.1.3. Lubricant

The experimental results are shown in Table 4. After adding 2.0% HT-LUBE to the base slurry and high-salt high-calcium base slurry systems respectively, the friction coefficients measured at room temperature and after high temperature aging at 160 °C are all at a low

level, and the value changes little after aging at 160 °C for 16 h. The friction coefficient after aging at 160 °C in the high-salt and high-calcium environment of 10% NaCl and 5% CaCl₂ is only 0.14, which meets the lubrication performance requirements, indicating that HT-LUBE has an excellent lubrication performance, strong high temperature resistance, and salt and calcium resistance capacity, and can maintain stable lubrication performance under complex drilling conditions of high temperature, high salt and high calcium.

Table 4. Influence of different base slurries and lubricant dosages on lubricity.

Base Slurry Type	HT-LUBE Dosage	Treatment Condition	Friction Coefficient
Base slurry	2.0%	Room temperature	0.12 ± 0.008
Base slurry	2.0%	Aged at 160 °C for 16 h	0.13 ± 0.011
Base slurry + 10% NaCl + 5% CaCl ₂	2.0%	Aged at 160 °C for 16 h	0.14 ± 0.013

3.1.4. Plugging Agent

It can be seen from the time-pressure-loss volume curve in Figure 3 that the plugging agent HT-SEAL shows a rapid plugging response in the initial stage of the experiment (0–1 min): with the pressure increasing from 0 MPa to about 2 MPa, the loss volume reaches a peak (about 20 mL) at 1 min. This stage is mainly the process of plugging agent particles migrating to the loss channel and initial bridging, accompanied by a small amount of initial loss. In the 1–2 min interval, the loss volume drops rapidly to about 8 mL, and the pressure continues to rise to about 3 MPa, indicating that the plugging structure has initially formed and begins to bear pressure effectively. With the extension of the experiment time to 5 min, the pressure continues to rise to about 7 MPa, while the loss volume gradually drops to about 1 mL, indicating that HT-SEAL can still maintain a stable plugging structure under high pressure conditions, and the plugging strength is continuously strengthened through particle accumulation and compaction. On the whole, HT-SEAL has the dual advantages of rapid plugging and high pressure stability, and can respond in a timely manner and provide reliable pressure bearing capacity in drilling operations.

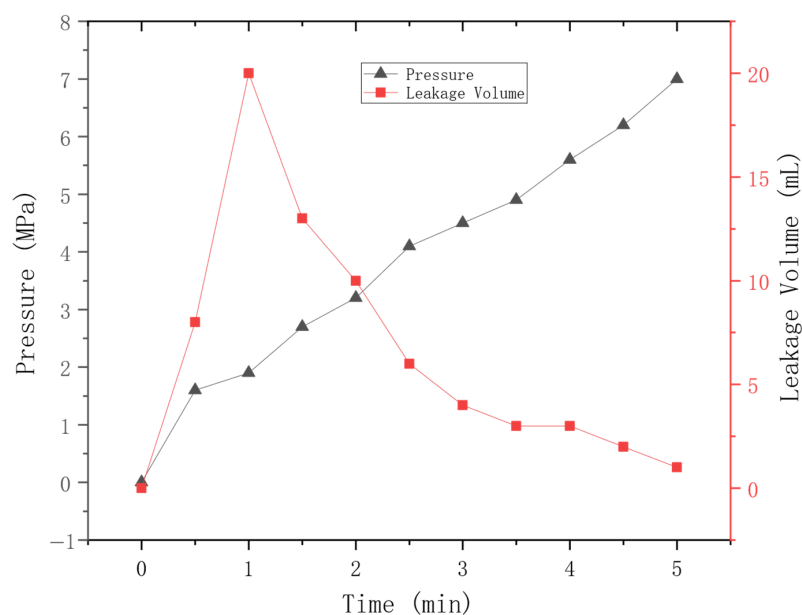


Figure 3. Plugging effect of HT-SEAL.

3.2. Construction and Evaluation of Environmentally Friendly Drilling Fluid System for Saline–Alkali Land

3.2.1. Construction of Environmentally Friendly Drilling Fluid System

Through the orthogonal test and range analysis in Table 5, the optimal formula of the high-temperature environmentally friendly drilling fluid system for desert saline–alkali land was determined as: fresh water + 4.0% bentonite + 0.7% HTDF-VIS viscosifier + 1.2% HTCMC-NAFL filtrate reducer + 2.0% HT-LUBE lubricant + 3.0% HT-SEAL plugging agent + 8.0% NaCl + 2.0% KCl + 1.5% Na₂CO₃ + an appropriate amount of density regulator (barite). The system density was adjusted to 1.6 g/cm³ by adding barite to meet the pressure balance requirements of deep drilling.

Table 5. Orthogonal test results and range analysis of environmentally friendly drilling fluid system formula optimization.

Test No.	A Viscosifier	B Filtrate Reducer	C Lubricant	D Plugging Agent	Apparent Viscosity (mPa·s)	API Filtration Loss (mL)	HTHP Filtration Loss (160 °C, mL)	Friction Coefficient	Environmental Performance
1	0.3	1.0	1.5	2.5	32	7.6	18.2	0.32	II
2	0.3	1.2	2.0	3.0	38	5.2	14.5	0.21	I
3	0.3	1.4	2.5	3.5	43	6.1	15.8	0.27	II
4	0.5	1.0	2.0	3.5	40	6.8	16.3	0.24	II
5	0.5	1.2	2.5	2.5	45	5.7	15.1	0.23	I
6	0.5	1.4	1.5	3.0	47	5.4	14.8	0.29	II
7	0.7	1.0	2.5	3.0	50	6.3	16.7	0.25	I
8	0.7	1.2	1.5	3.5	52	4.8	13.6	0.18	I
9	0.7	1.4	2.0	2.5	48	5.3	14.2	0.22	I

3.2.2. Rheological Property

The results in Table 6 show that the apparent viscosity of the system at room temperature is 40 mPa·s, the plastic viscosity is 29 mPa·s, the yield point is 11 Pa, and the YP/PV ratio is 0.38, which is within the optimal range of 0.36–0.45, indicating that the system has good cuttings carrying capacity and shear thinning performance. After aging at 160 °C for 16 h, the apparent viscosity is 36 mPa·s, the plastic viscosity is 26 mPa·s, the yield point is 10 Pa, and the YP/PV ratio is 0.38, which is basically the same as that before aging, indicating that the system has good temperature stability.

Table 6. Rheological property evaluation of drilling fluid system.

Evaluation Condition	Apparent Viscosity (AV) (mPa·s)	Plastic Viscosity (PV) (mPa·s)	Yield Point (YP) (Pa)	YP/PV Ratio
25 °C (room temperature)	40	29	11	0.38
160 °C (after aging for 16 h)	36	26	10	0.38

3.2.3. Filtration Performance

To comprehensively evaluate the filtration performance of the drilling fluid system, an API filtration tester and HTHP filtration tester were used to carry out systematic tests in the experiment. The API filtration loss and filter cake thickness of the system were measured at room temperature and normal pressure, and its HTHP filtration characteristics were evaluated at 160 °C and 3.5 MPa; then, the drilling fluid system was hot-rolled and aged in a 160 °C environment for 16 h, the changes in filtration loss before and after aging were compared, and the filtration curve was drawn by recording the filtration volume at different

time points within 0–30 min to analyze the filtration control capacity and performance stability of the system.

The experimental results in Figure 4 show that the API filtration loss of the system at room temperature increases gradually with time and tends to be stable. The final filtration loss before hot rolling (before aging) is 4.0 mL, corresponding to a filter cake thickness of 1.2 mm. The filter cake is thin and dense, effectively controlling the filtration loss; at 160 °C and 3.5 MPa, the HTHP filtration loss of the system before hot rolling is 8.3 mL, with a filter cake thickness of 1.5 mm, meeting the technical requirement of HTHP filtration loss ≤ 10 mL in drilling engineering; after aging at 160 °C for 16 h, the API filtration loss of the system rises to 4.5 mL, and the HTHP filtration loss rises to 9.0 mL. The filtration loss only has a small fluctuation, and the overall filtration performance stability is good, indicating that the system can still maintain a reliable filtration control effect after high temperature aging.

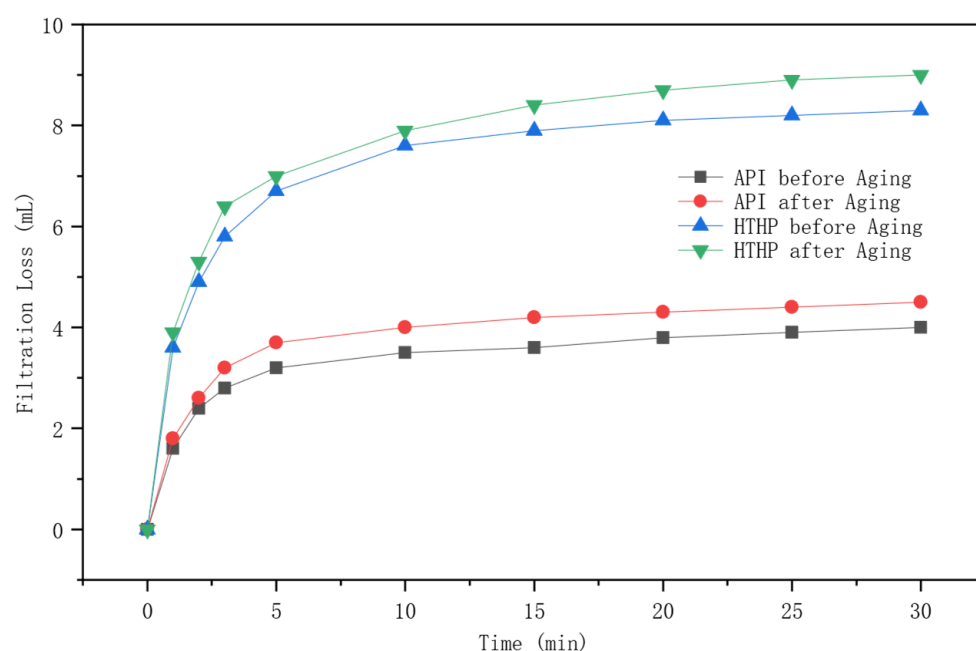


Figure 4. Filtration loss curve before and after hot rolling.

3.2.4. High Temperature Resistance Performance

As presented in Table 7, all performance parameters of the drilling fluid system exhibited minimal fluctuations at aging temperatures up to 160 °C. Compared with the room temperature (25 °C) baseline, the apparent viscosity, plastic viscosity, yield point, and YP/PV ratio remained nearly unchanged, while the filtration loss increased only gradually from 4.0 mL to 4.8 mL. The overall rheological and filtration control properties remained stable within this temperature range.

However, when the aging temperature increased to 180 °C (exceeding the 160 °C threshold), the system experienced severe performance degradation: the apparent viscosity dropped sharply from 40 mPa·s to 25 mPa·s, the plastic viscosity decreased from 29 mPa·s to 18 mPa·s, the yield point declined synchronously, and the filtration loss increased dramatically to 11.0 mL. This indicates that 180 °C causes irreversible damage to the colloidal structural stability of the system.

Table 7. High temperature resistance evaluation of drilling fluid.

Evaluation Condition	Apparent Viscosity (mPa·s)	Plastic Viscosity (mPa·s)	Yield Point (Pa)	YP/PV	Filtration Loss (mL)
25 °C	40	29	11	0.38	4.0
Aged at 120 °C for 16 h	38	28	10	0.36	4.2
Aged at 140 °C for 16 h	37	27	10	0.37	4.5
Aged at 160 °C for 16 h	36	26	10	0.38	4.8
Aged at 180 °C for 16 h	25	18	7	0.39	11.0

The significant performance deterioration at 180 °C can be attributed to two primary mechanisms: (1) Irreversible thermal cleavage of glycosidic bonds in modified starch and cellulose chains, leading to molecular weight reduction and loss of functional properties [37]; (2) destruction of the core-shell structure of the HT-SEAL plugging agent, where the polymer shell detaches from the silica core, resulting in complete loss of plugging capacity. These results establish that the upper temperature limit of the developed drilling fluid system is 160 °C.

3.2.5. Salt Resistance Performance

As shown in Table 8, all performance parameters of the drilling fluid system remained relatively stable at NaCl concentrations up to 15%. Compared with the blank control (0% NaCl), the apparent viscosity, plastic viscosity, and filtration loss were 39 mPa·s, 28 mPa·s, and 4.2 mL at 5% NaCl; 38 mPa·s, 27 mPa·s, and 4.4 mL at 10% NaCl; and 37 mPa·s, 26 mPa·s, and 4.6 mL at 15% NaCl, respectively. All indicators exhibited minimal fluctuations and no abnormal performance, confirming that the system maintained excellent rheological and filtration control properties under these salinity conditions.

Table 8. Salt resistance evaluation of drilling fluid.

Evaluation Condition	Apparent Viscosity (mPa·s)	Plastic Viscosity (mPa·s)	Yield Point (Pa)	YP/PV	Filtration Loss (mL)
25 °C (room temperature, 0% NaCl)	40	29	11	0.38	4.0
25 °C, 5% NaCl	39	28	11	0.39	4.2
25 °C, 10% NaCl	38	27	10	0.37	4.4
25 °C, 15% NaCl	37	26	10	0.38	4.6
25 °C, 20% NaCl	28	20	8	0.40	8.0

However, when the NaCl concentration increased to 20% (exceeding the 15% threshold), the apparent viscosity and plastic viscosity decreased sharply to 28 mPa·s and 20 mPa·s, respectively, while the filtration loss increased dramatically to 8.0 mL, accompanied by slight flocculation of the system and significant performance degradation. These results demonstrate that the salt resistance limit of the developed drilling fluid system is 15% NaCl, which fully meets the application requirements for high-salt environments in desert saline-alkali lands.

3.2.6. Environmental Performance

The results in Table 9 show that the EC50 of the system is 36,000 mg/L, which is greater than 30,000 mg/L, indicating that the system has low biological toxicity and no harm to the ecological environment; the BOD5/CODCr of the system is 6.8%, which is

greater than 5%, indicating that the system has good biodegradability and can be degraded by microorganisms in the environment to reduce environmental pollution.

Table 9. Environmental performance evaluation of drilling fluid.

Test Item	Test Method	Test Result	Conclusion
Biological toxicity	Luminescent bacteria method	EC50 = 36,000 mg/L	Meets non-toxic grade requirements
Biodegradability	BOD5/CODCr method	BOD5/CODCr = 6.8%	Meets biodegradable requirements

3.3. Exploration on Waste Utilization of Environmentally Friendly Drilling Fluid for Saline–Alkali Land

3.3.1. Effect on Soil Physicochemical Properties

As illustrated in Figure 5, the waste eco-friendly drilling fluid exerted a significant dose-dependent ameliorative effect on the physicochemical properties of desert saline–alkali soil. Compared with the untreated control group (S), the soil pH values of the K1, K2, and K3 groups decreased by 0.3, 0.7, and 0.9 units, respectively, and the soil salt contents were reduced by 12.5%, 23.8%, and 31.2%, respectively. Specifically, the soil pH dropped from an initial 8.9 to 8.0 in the K3 group, and the salt content decreased from 1.2% to 0.83%, further confirming the remediation efficacy of the waste drilling fluid treatment.

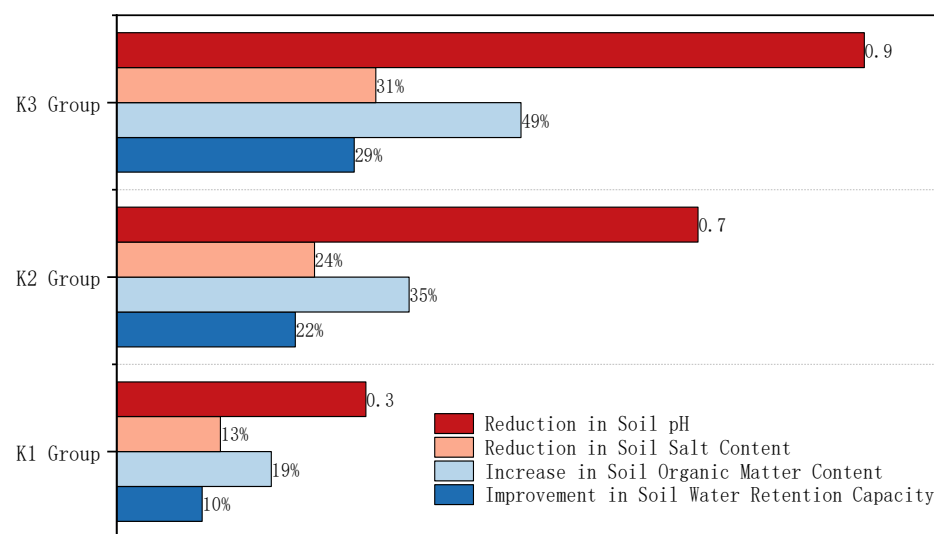


Figure 5. Impact of waste drilling fluid on soil physicochemical properties.

This dual improvement in soil alkalinity and salinity can be attributed to the organic components in the waste drilling fluid: the organic matter neutralizes soil alkalinity, while the humus formed via microbial degradation of organic matter effectively adsorbs soluble salt ions, thereby reducing the soil salt content. Furthermore, the soil organic matter contents of the K1, K2, and K3 groups increased by 18.6%, 35.2%, and 48.7%, respectively, and the corresponding soil water retention capacities were enhanced by 10.3%, 21.5%, and 28.6%. The K3 group achieved the maximum improvement in both indicators. This is because the waste drilling fluid contains abundant modified natural polymers that can be decomposed into soil organic matter by indigenous microorganisms, and the combined action of organic matter and solid particles (bentonite, barite) ameliorates the soil aggregate structure, thus enhancing water retention capacity.

3.3.2. Effect on Plant Growth

As shown in Figure 6, the waste eco-friendly drilling fluid significantly promoted the growth of *Haloxylon ammodendron* in a clear dose-dependent manner. Relative to the untreated control group (S), the plant height, root length, and fresh weight of *H. ammodendron* increased by 12.1%, 10.8%, and 15.6% in the K1 group (5% application rate), 25.3%, 22.4%, and 30.8% in the K2 group (10% application rate), and 32.5%, 29.7%, and 38.9% in the K3 group (15% application rate), respectively. Notably, the K3 group exhibited the most pronounced growth-promoting effects across all measured parameters. However, further increasing the dosage beyond 15% may lead to a slight elevation in soil salinity, which exerts a mild inhibitory effect on plant growth. Collectively, these findings confirm that the optimal application rate of waste drilling fluid for desert saline–alkali soil improvement is 10–15%.

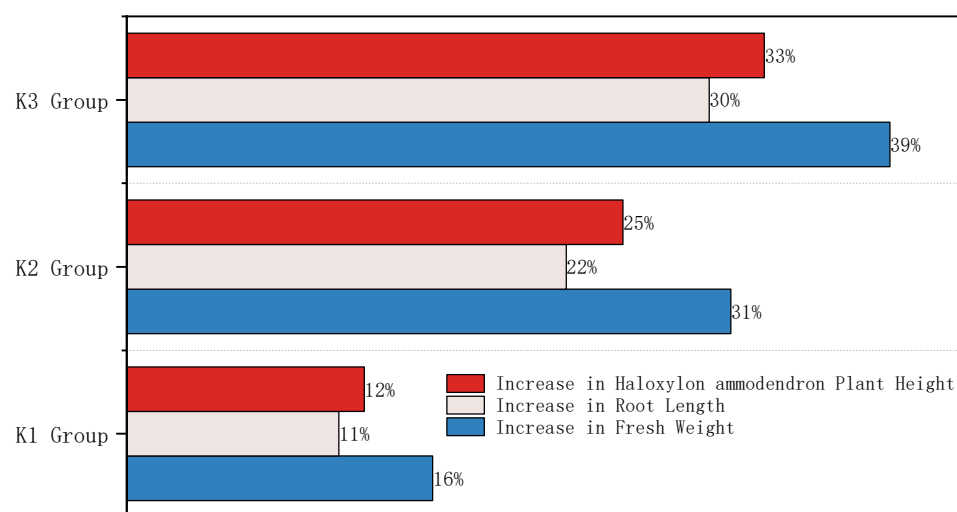


Figure 6. Effect of waste drilling fluid on plant growth.

3.3.3. Environmental Safety Assessment

After the soil improvement experiment, the leachate of the improved soil was collected to detect its biological toxicity and heavy metal content. The results in Table 10 show that the EC50 of the leachate is 32,000 mg/L, which is greater than 30,000 mg/L, and the heavy metal contents (Pb, Cd, Hg) are lower than the National Soil Environmental Quality Standard, indicating that the use of waste drilling fluid for soil improvement will not cause secondary pollution to the environment with good environmental safety. Regarding the organic pollutant degradation performance, the initial COD concentration of the waste drilling fluid used in the experiment was 12,800 mg/L. After three months of natural degradation in soil, the COD concentration decreased to 1152 mg/L, with a degradation rate exceeding 90%. As a result, the diluted leachate fully meets the National First-Class Discharge Standard (COD $\leq$ 100 mg/L) [38], along with the COD and petroleum substance degradation rates of the improved soil after three months of treatment both exceeding 90%.

Table 10. Environmental safety performance evaluation of waste drilling fluid.

Detection Index	Detection Result	National/Reference Standard	Environmental Safety Evaluation
Leachate EC ₅₀	32,000 mg/L	>30,000 mg/L (safety threshold)	Safe
Heavy Metal Content (Pb, Cd, Hg)	Below standard	National Soil Environmental Quality Standard	No secondary pollution
COD Degradation Rate (3 months)	>90%	National First-Class Discharge Standard	Qualified
Petroleum Degradation Rate (3 months)	>90%	National First-Class Discharge Standard	Qualified

3.3.4. Feasibility Analysis of Waste Utilization

Collectively, these findings demonstrate that the waste eco-friendly drilling fluid effectively ameliorates the physicochemical properties of desert saline–alkali soils, promotes the growth of salt-tolerant plants, and exhibits excellent environmental safety [39,40]. Notably, repurposing waste drilling fluid for soil improvement not only addresses the long-standing challenge of drilling waste disposal and mitigates environmental pollution, but also rehabilitates degraded desert saline–alkali lands and achieves resource valorization of industrial waste, delivering significant economic, environmental, and social co-benefits. The proposed microbial-soil integrated treatment technology features a simple process flow, low operational cost, and easy field implementation, holding great potential for large-scale promotion and application in desert saline–alkali regions worldwide.

3.3.5. Preliminary Economic Feasibility Analysis

From an economic perspective, this waste utilization technology presents prominent cost advantages compared with conventional disposal methods. The treatment cost of traditional solidification and landfill for waste drilling fluid is about 175 US dollars per cubic meter, while the overall cost of the resource recycling method proposed in this study is only 50 US dollars per cubic meter. Based on the actual waste production of a single well, it is calculated that approximately 41,000 US dollars of waste treatment cost can be saved for individual well operation. In addition to the direct economic benefits, the rational reuse of waste drilling fluid can effectively improve the physical and chemical properties of saline–alkali soil, reduce the investment cost of commercial soil amendments, and bring long-term ecological benefits and sustainable land utilization value. This fully confirms that the proposed waste treatment mode has excellent economic rationality and popularization prospect.

3.3.6. Limitations of the Study

All experiments in this study were carried out under strictly controlled laboratory conditions, with three independent parallel replicates set for each experimental group. The experimental data showed excellent reproducibility and extremely low dispersion, which guaranteed the reliability of the results to a certain extent. However, formal statistical significance analysis was not conducted on the relevant experimental data in this study, which is a limitation of the present research. In the future, more systematic statistical analysis methods will be adopted to process the experimental data, so as to further verify the stability and credibility of the research results and improve the scientificity and rigor of the relevant conclusions.

4. Conclusions

- (1) Four natural-modified eco-friendly additives (starch-based viscosifier HTDF-VIS, composite filtrate reducer HTC MC-NAFL, rapeseed oil lubricant HT-LUBE, core-shell plugging agent HT-SEAL) exhibit 160 °C high-temperature resistance and salt/calcium tolerance, forming the core material basis for desert saline-alkali land eco-friendly drilling fluid systems.
- (2) The optimized system withstands 160 °C and 15% NaCl, delivers stable excellent rheological, filtration, plugging and lubricating properties, and meets non-toxic biodegradable standards. It addresses the environmental drawbacks and poor complex geology adaptability of traditional polysulfonate/oil-based drilling fluids in the region.
- (3) Waste eco-friendly drilling fluid is reused for desert saline-alkali soil improvement at an optimal 10–15% dosage. It significantly reduces soil pH and salinity, increases organic matter and water retention, and promotes *Haloxylon ammodendron* growth. The improved soil has no secondary pollution, with qualified leachate toxicity and >90% degradation rates of COD and petroleum hydrocarbons.
- (4) The integrated “eco-friendly drilling fluid construction-waste fluid resource utilization” scheme adopts a simple, low-cost microbial-soil combined treatment technology, realizing green drilling fluid application and waste recycling. It provides technical support for efficient green oil/gas development and saline-alkali land ecological restoration in the Tarim Basin.

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