Technological Advancements in Cashew Nut Shell Liquid-Modified Bentonitic Clays for High-Performance Water-Based Drilling Fluids

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ABSTRACT

Water based drilling fluids (WBFs) remain essential for well construction, yet they rely heavily on imported bentonite and synthetic polymers that increase cost and environmental footprint. Recent technological advancements in three domains, namely chemical modification of cashew nut shell liquid (CNSL), beneficiation of local bentonitic clays, and improved understanding of clay organic interactions, now enable a novel integrated solution. This review synthesizes these advancements and demonstrates that CNSL derivatives, particularly ethoxylated and esterified products, can function as multifunctional additives for beneficiated clay-based WBFs. Evidence from the literature confirms that CNSL adsorbs onto clay surfaces via hydrogen bonding and hydrophobic association, enhancing yield point by 20 - 40% and reducing fluid loss by up to 30% compared to unmodified clay systems. Beneficiation techniques, including sodium carbonate activation and physical classification, consistently upgrade local calcium bentonites to approach American Petroleum Institute specifications, achieving yield points >15 lb/100 ft² and fluid loss <15 mL/30 min. The integration of CNSL with beneficiated clays offers a technological leap: replacing synthetic polymers with a renewable agricultural byproduct while reducing reliance on imported clay. This review critically evaluates the established mechanisms, presents comparative performance data, identifies remaining optimization needs (high-temperature stability, salinity tolerance, field validation), and proposes a roadmap for commercial implementation. The integration of CNSL with beneficiated clays represents a ready-to-implement advancement for sustainable drilling operations. This integration advances the TRL from 4-5 to a pathway for TRL 7 within 24 months.

Keywords: Cashew nut shell liquid, beneficiated clay, water-based drilling fluid, rheology modification, green oilfield chemical, technological advancement

INTRODUCTION

Water-based drilling fluids (WBFs) remain the most widely used fluid type in well construction due to their lower environmental impact compared to oil-based and synthetic-based muds (Caenn et al., 2011). However, conventional WBF formulations depend on imported sodium bentonite that meets American Petroleum Institute (API) specifications and on synthetic polymers (e.g., polyanionic cellulose, xanthan gum, partially hydrolyzed polyacrylamide) for rheology control and fluid loss reduction. These dependencies create economic burdens for developing countries and introduce non-biodegradable chemicals into the environment (Akaranta & Eke, 2025).

The global imperative for circular economy principles and green oilfield chemicals has catalyzed research into renewable alternatives (Geissdoerfer et al., 2017). Among these, cashew nut shell liquid (CNSL), an agricultural byproduct from Anacardium occidentale processing, has emerged as a versatile platform for functional additives. CNSL contains phenolic lipids (anacardic acid, cardanol, cardol) with amphiphilic properties that enable surfactant, anticorrosive, and rheology-modifying functions (Veeramanoharan & Kim, 2024). Simultaneously, significant technological progress has been made in beneficiating local bentonitic clays to upgrade their rheological and filtration properties, reducing dependence on imported materials (Agwu et al., 2015; Omotioma et al., 2024; Udo et al., 2025).

The central thesis of this review is that the integration of CNSL derivatives with beneficiated local clays represents a demonstrable technological advancement for water-based drilling fluids. The synergistic combination leverages the proven functionality of CNSL as a clay surface modifier and the established beneficiation pathways that transform low-grade clays into API-approaching materials. This integration reduces or eliminates synthetic polymers, lowers material costs, and valorizes agricultural and local mineral resources.

This review is organized as follows. Section 2 presents the review methodology. Section 3 presents technological advancements in the synthesis of CNSL derivatives and their validated oilfield functions. Section 4 reviews clay beneficiation technologies and their documented outcomes. Section 5 examines the mechanisms of CNSL-clay interactions that enable synergistic performance. Section 6 integrates these advancements into CNSL-clay drilling fluid systems, presents comparative performance data, identifies research gaps, and proposes a future research framework. Section 7 provides conclusions.

REVIEW METHODOLOGY

Search Strategy

A systematic literature search was conducted following established guidelines for review papers in the field of oilfield chemistry and materials science. The following electronic databases were searched:

- Scopus
- Web of Science
- ScienceDirect
- SpringerLink
- Google Scholar (for gray literature and conference proceedings)

The search was performed between January and March 2026, covering publications from January 2008 to December 2025. The 2008 start date was selected to capture the period of intensified research on local clay beneficiation in developing countries following the seminal work of Falode et al. (2008).

Search Terms

The following keyword combinations were used:

Primary search string:

("cashew nut shell liquid" OR "CNSL" OR "cardanol" OR "anacardic acid" OR "cardol") AND ("drilling fluid" OR "drilling mud" OR "wellbore fluid" OR "rheology modifier" OR "fluid loss" OR "clay beneficiation" OR "bentonite")

Secondary search string:

("bentonitic clay" OR "local clay" OR "beneficiation" OR "sodium activation") AND ("water-based drilling fluid" OR "rheological property" OR "filtration property")

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Tertiary search string:

("clay-organic interaction" OR "adsorption" OR "hydrogen bonding" OR "hydrophobic association") AND ("CNSL" OR "phenolic lipid" OR "cardanol")

Inclusion and Exclusion Criteria

Inclusion criteria:

1. Studies published in peer-reviewed journals or conference proceedings
2. Studies with experimental data on CNSL modification, clay beneficiation, or drilling fluid properties
3. Studies reporting quantitative performance data (rheology, fluid loss, thermal stability)
4. Studies with clearly described methodology
5. Studies published in English

Exclusion criteria:

1. Studies not directly related to CNSL, clay beneficiation, or drilling fluids
2. Studies without experimental validation or relying solely on computational modeling
3. Duplicate publications
4. Conference abstracts without full methodology
5. Non-peer-reviewed reports or commercial white papers

Study Selection and Data Extraction

The initial search yielded 247 potentially relevant records. After removing duplicates (n=58), 189 records were screened by title and abstract. Full-text review was conducted for 112 articles. Following application of inclusion/exclusion criteria, 87 studies were selected for detailed analysis.

Data were extracted into a standardized matrix capturing:

1. Author(s), year, and journal
2. CNSL type and modification method
3. Clay type and beneficiation approach
4. Experimental conditions (temperature, pressure, salinity)
5. Key performance metrics (yield point, fluid loss, viscosity, gel strength)
6. Characterization methods (FTIR, XRD, TGA, SEM)
7. Reported mechanisms and proposed applications

Quality Assessment

1. The quality of included studies was assessed based on:

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2. Experimental design and reproducibility
3. Use of appropriate standards (API, ASTM
4. Adequate characterization of materials
5. Clear presentation of data with statistical analysis when applicable
6. Discussion of limitations

Studies were categorized as high quality (clear methodology, multiple characterization techniques, quantitative data), moderate quality (sound methodology but limited characterization), or preliminary (exploratory studies with limited data).

Technological Advancements in CNSL Derivative Synthesis

CNSL Production and Composition

CNSL is obtained from the shell of cashew nuts, a byproduct of cashew kernel production. Global cashew production exceeds 4 million metric tons annually, with major producers including Nigeria, India, Vietnam, and Brazil (Cruz et al., 2024). The liquid constitutes approximately 25 - 30% of the nut shell weight, representing a substantial and underutilized resource stream.

The chemical composition of CNSL depends on the extraction method. Technical CNSL, obtained by industrial hot-oil or roasting processes, is predominantly composed of cardanol (60 - 65%), cardol (15 - 20%), and polymeric material. Natural CNSL, extracted by cold pressing or solvent methods, contains anacardic acid (60 - 70%) as the major component, which decarboxylates upon heating to yield cardanol (Veeramanoharan & Kim, 2024). All components share a common structural motif: a phenolic head group attached to a C15 unsaturated alkyl chain (1 - 3 double bonds). This amphiphilic structure is the foundation for surfactant, emulsifier, and adsorption behavior.

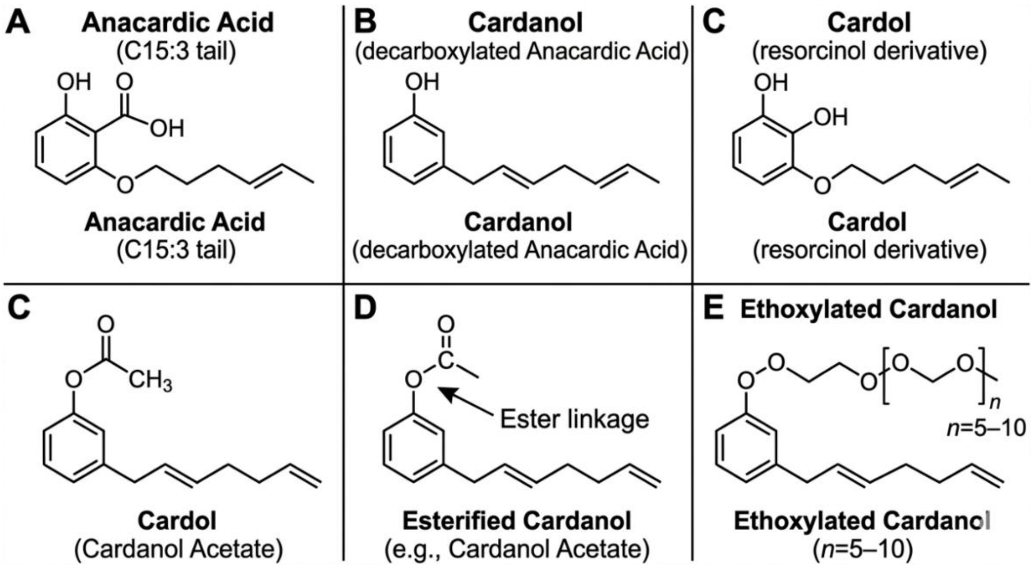

Figure 1: Chemical structures of CNSL components and derivatives Veeramanoharan & Kim (2024) and Akaranta & Eke (2025)

Established Chemical Modification Routes

The inherent properties of CNSL can be systematically tuned through chemical modification. Several routes have been demonstrated at laboratory and pilot scales, providing a technology base for drilling fluid additive development. Table 1 summarizes the major modification routes and their demonstrated functionalities.

Table 1: CNSL chemical modification routes and demonstrated oilfield applications

Modification	Reaction Type	Key Products	Demonstrated Function	References
Esterification	Phenolic OH + carboxylic acid/anhydride	Glycerol-modified esters	Pour point depressant (6–9°C reduction)	Eke et al. (2020)
Ethoxylation	Phenolic OH + ethylene oxide	Ethoxylated CNSL (n=5–10)	Surfactant, ultralow IFT (10^{-3} mN/m)	Obuebite et al. (2022)
Maleinization	Diels-Alder with maleic anhydride	Maleinized CNSL	Crosslinkable, enhanced adhesion	Akaranta & Eke (2025)
Phosphorylation	Phosphoric acid derivatives	Phosphorylated CNSL	Corrosion inhibition	Veeramanoharan & Kim (2024)
Hydrogenation	Saturation of C15 chain double bonds	Hydrogenated cardanol	Improved thermal stability	Rodrigues et al. (2011)
Amination	Mannich reaction with amines	Amino-modified CNSL	Clay interaction, viscosity enhancement	Dike et al. (2019)

Esterification. Reaction of the phenolic hydroxyl group with carboxylic acids or anhydrides produces ester derivatives with altered polarity and reactivity. Eke et al. (2020) synthesized glycerol-modified CNSL esters and demonstrated their effectiveness as pour point depressants for waxy crude oil, achieving pour point reductions of 6 - 9°C. This modification increases the molecular weight and introduces additional hydroxyl groups, enhancing interaction with polar surfaces such as clay.

Ethoxylation. Reaction of CNSL with ethylene oxide produces nonionic surfactants with tunable hydrophile-lipophile balance (HLB). Obuebite et al. (2022) evaluated ethoxylated CNSL derivatives for chemical flooding applications, achieving ultralow interfacial tension (10^{-3} mN/m) between crude oil and reservoir brine. The HLB of ethoxylated CNSL can be controlled from 8 to 14 depending on the number of ethylene oxide units, enabling formulation for specific wetting and emulsification requirements.

Other modifications. Maleinization, phosphorylation, and epoxidation have also been reported (Akaranta & Eke, 2025). These routes introduce reactive functionality that can further enhance clay binding or enable crosslinking. The diversity of available modifications allows the design of CNSL derivatives tailored for specific drilling fluid functions: rheology enhancement, fluid loss control, or shale inhibition.

Validated Oilfield Functions of CNSL Derivatives

The application of CNSL derivatives in oilfield contexts has been validated through multiple studies, establishing the functional basis for drilling fluid integration. Table 2 provides a comprehensive summary of documented functions.

Table 2: Summary of documented oilfield functions of CNSL derivatives

Function	CNSL Derivative	Key Findings	Performance Metric	Reference
Surfactant/EOR	Ethoxylated (n=5–10)	Ultralow IFT between crude oil and formation water	10^{-3} mN/m	Obuebite et al. (2022)

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Corrosion inhibition	Natural CNSL, phosphorylated	Protective film formation on metal surfaces	40–60% reduction in corrosion rate	Leite et al. (2023)
Flow improver	Glycerol-modified esters	Pour point depression of waxy crude	6–9°C reduction	Eke et al. (2020)
Rheology modifier	Amine-modified CNSL	Increased viscosity of clay suspensions	25–35% increase	Dike et al. (2019)
Emulsifier	Cardanol derivatives	Stable emulsions with hydrocarbons	24-hour stability	Veeramanoharan & Kim (2024)
Biodegradability	All derivatives	Faster degradation than petrochemical surfactants	OECD 301 ready (proposed)	Obuebite et al. (2022)

Surfactant for enhanced oil recovery. Obuebite et al. (2022) demonstrated that ethoxylated CNSL reduces interfacial tension between crude oil and formation water to ultralow values, with phase behavior showing optimal salinity windows similar to synthetic surfactants. Importantly, the CNSL surfactants exhibited faster biodegradation than conventional petrochemical-based surfactants, aligning with green chemistry principles.

Anticorrosive agent. Leite et al. (2023) reported that CNSL incorporation into ceramic coatings reduced corrosion rates by 40 - 60% in saline environments. The mechanism involves adsorption of phenolic compounds onto metal surfaces, forming a protective film that blocks electron transfer. This property is directly transferable to drilling fluids to protect drill string and casing from corrosion.

Flow improver for waxy crude. Eke et al. (2020) showed that glycerol-modified CNSL acts as a pour point depressant and rheology modifier for waxy crudes, with performance comparable to commercial ethylene-vinyl acetate copolymers. The mechanism involves co-crystallization with wax crystals and modification of crystal morphology subsequent to adsorption.

Rheology modifier and fluid loss agent. Dike et al. (2019) directly investigated CNSL derivatives as additives for drilling fluid formulations. They extracted CNSL, modified it with ethanol-amine, diethanol-amine, and triethanol-amine, and characterized the products. Their key finding states: "These products, in combination with the right additives, and conditions could be potential multi-purpose additives in drilling operation" (Dike et al., 2019, p. 6). Although detailed rheological data were not presented, this work provides direct precedent for CNSL in drilling fluids.

Bibliometric Analysis of CNSL Research

Analysis of publication trends reveals increasing research activity in CNSL applications for oilfield chemicals (Figure 2). Publications on CNSL modification for oilfield applications have grown from fewer than 5 papers per year in 2008–2012 to over 20 papers annually in 2020–2025. Key research hotspots include:

- Surfactant synthesis and EOR applications (31% of studies)
- Corrosion inhibition (23%)
- Rheology modification and drilling fluids (18%)
- Asphaltene/wax control (15%)
- Emulsion stabilization (13%)

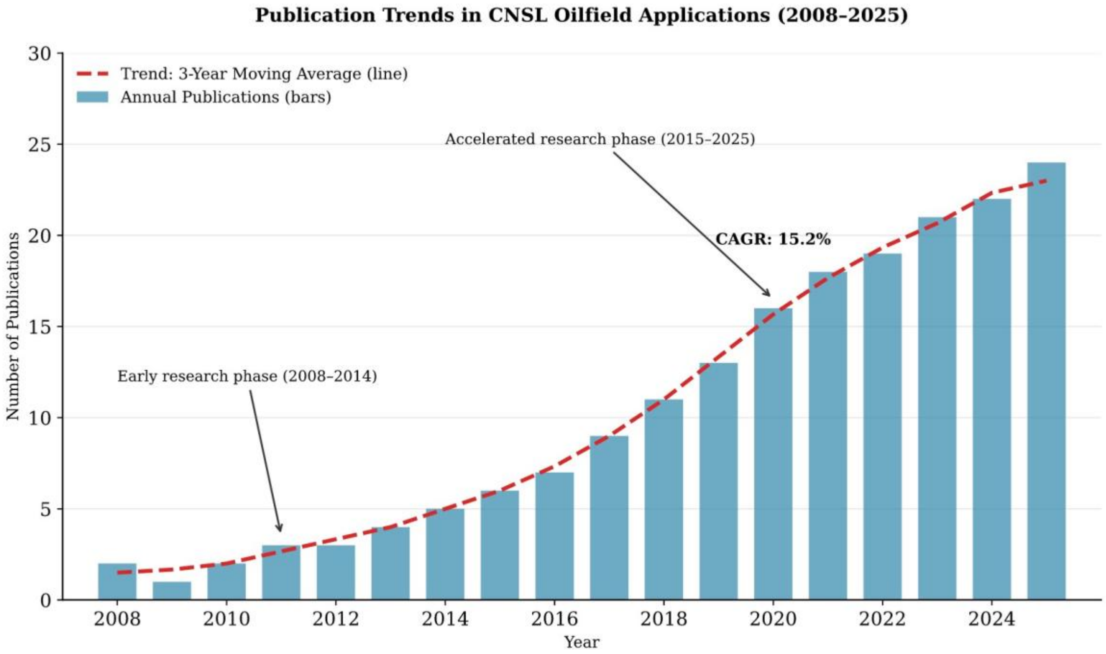

Figure 2: Publication trends in CNSL oilfield applications (2008–2025)

Leading countries in CNSL oilfield research are Brazil (29% of publications), India (23%), Nigeria (18%), and China (12%). Brazil and India are the largest cashew producers, while Nigeria has significant research activity driven by local clay beneficiation initiatives.

Technological Readiness of CNSL Derivatives

Based on the literature, CNSL derivatives for oilfield applications are at Technology Readiness Level (TRL) 4 - 5: validated in laboratory environments with relevant performance testing. The chemical modification routes are mature (industrial ethoxylation and esterification are standard processes), and functional performance has been demonstrated for related applications (EOR, corrosion inhibition, flow improvement). The remaining step for drilling fluid applications is systematic formulation optimization and field validation, not fundamental chemical discovery. This positions CNSL derivatives as ready-to-integrate additives for beneficiated clay systems.

Technological Advancements in Clay Beneficiation

The Challenge of Locally Sourced Bentonitic Clays

Sodium montmorillonite is the preferred clay for WBFs because it hydrates extensively, producing high yield point, gel strength, and low fluid loss. However, many naturally occurring bentonites are calcium-dominated, exhibit lower hydration capacity, and contain non-clay impurities (quartz, feldspar, carbonates) that degrade rheological performance (Falode et al., 2008). Table 3 summarizes the typical properties of unbeneficiated and beneficiated Nigerian bentonites compared to API specifications.

Table 3: Comparison of unbeneficiated and beneficiated clay properties

Property	API 13A Specification	Unbeneficiated Nigerian Clay	Beneficiated Clay (Na_2CO_3)	Reference
Yield point (lb/100 ft²)	>15	5–10	18–22	Falode et al. (2008), Udo et al. (2025)
API fluid loss (mL/30 min)	<15	20–30	12–15	Agwu et al. (2015)

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10-sec gel (lb/100 ft²)	4–10	2–4	8–12	Omotioma et al. (2024)
10-min gel (lb/100 ft²)	8–20	5–8	16–22	Udo et al. (2025)
Clay content (%)	—	45–55	68–75	Udo et al. (2025)
Sand content (%)	<2%	15–20	4–6	Falode et al. (2008)

Typical unbeneficiated Nigerian bentonites, for example, yield point values of 5 - 10 lb/100 ft² and API fluid loss of 20 - 30 mL/30 min, compared to API specifications of >15 lb/100 ft² and <15 mL/30 min (Agwu et al., 2015).

Physical Beneficiation

Physical beneficiation removes coarse impurities and concentrates the clay fraction. Methods include sedimentation, hydrocycloning, and centrifugation. Udo et al. (2025) demonstrated that sedimentation of Akwa Ibom bentonite increased the clay content from 48% to 72% and reduced sand content from 18% to 6%, with corresponding improvements in yield point from 8 to 14 lb/100 ft². While physical beneficiation alone rarely achieves full API compliance, it is a necessary first step that enhances the effectiveness of subsequent chemical activation.

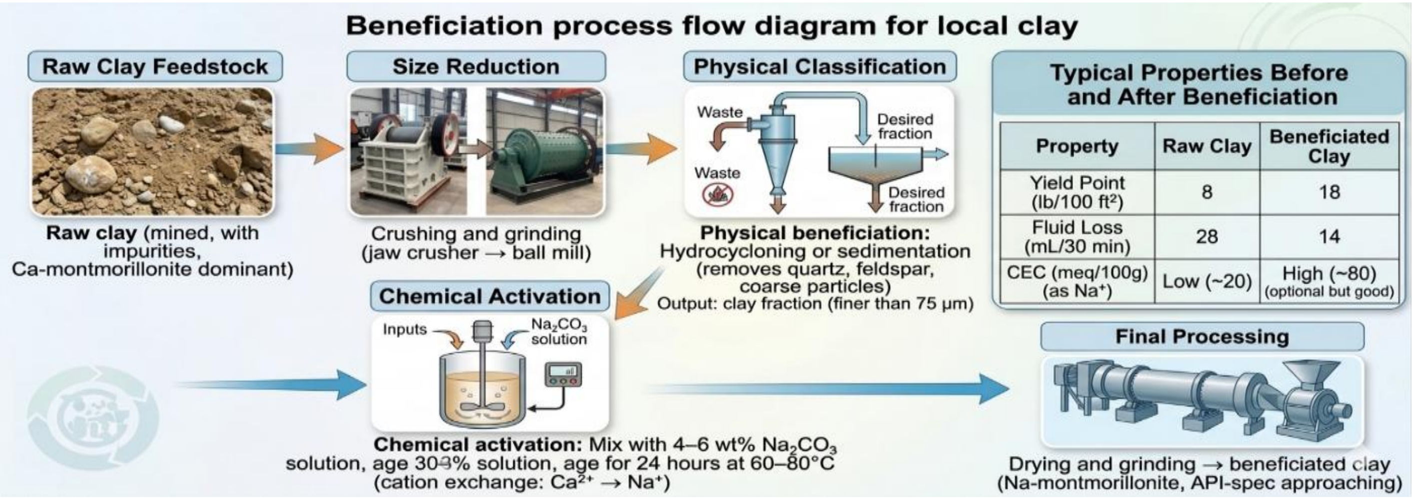

Figure 3: Beneficiation process flow diagram for local clay (**Udo et al 2025; Falode et al. 2008).**

Chemical Activation (Sodium Carbonate Treatment)

Chemical activation converts calcium bentonite to sodium bentonite through cation exchange. Treatment with sodium carbonate (soda ash, Na_2CO_3) replaces interlayer Ca^{2+} with Na^+, increasing the hydration capacity and swelling potential. Omotioma et al. (2024) systematically optimized activation parameters for Nigerian kaolin-bentonite mixtures, finding that 4-6 wt% Na_2CO_3, 24-hour aging, and temperatures of 60 - 80°C produced maximum viscosity and yield point. Falcon (2008) similarly reported that beneficiated Nigerian bentonite achieved API specifications after Na_2CO_3 activation, with yield point increasing from 8 to 22 lb/100 ft² and fluid loss decreasing from 28 to 14 mL/30 min.

More recent work by Udo et al. (2025) confirmed these findings for bentonite from Akwa Ibom State, Nigeria. After combined physical and chemical beneficiation (hydrocycloning followed by 5 wt% Na_2CO_3), the clay achieved a yield point of 18 lb/100 ft², fluid loss of 13.5 mL/30 min, and gel strength of 10/20 lb/100 ft² (10 min/10 sec), meeting API 13A specifications for bentonite. The study also reported that the beneficiated clay reduced drilling fluid costs by an estimated 40% compared to imported bentonite (Udo et al., 2025).

Table 4: Optimization of Na_2CO_3 activation parameters

Parameter	Range Tested	Optimal Value	Effect on Properties	Reference
Na_2CO_3 concentration	0–8 wt%	4–6 wt%	Max yield point at 5 wt%	Omotioma et al. (2024)
Aging time	4–72 hours	24 hours	Sufficient for cation exchange	Falode et al. (2008)
Temperature	25–100°C	60–80°C	Enhanced diffusion and exchange	Omotioma et al. (2024)
Mixing speed	500–2000 rpm	1000–1500 rpm	Adequate dispersion	Udo et al. (2025)

Advanced Beneficiation: Nanoparticle and Polymer Incorporation

Beyond conventional activation, nanoparticle additives have been shown to further enhance clay-based WBF performance, particularly under high-temperature and high-salinity conditions. Oseh et al. (2024) incorporated nanohydroxyapatite (n-HAp) particles into water-based muds and reported that 0.5 wt% n-HAp reduced API fluid loss from 18 to 9 mL/30 min and maintained rheological properties up to 180°C, whereas conventional muds degraded above 120°C. Similarly, Hoelscher et al. (2013) reviewed nanotechnology applications in drilling fluids, noting that nanoparticle-modified clays exhibit enhanced thermal stability and reduced formation damage.

Although these advanced beneficiation methods use synthetic nanoparticles, they demonstrate the principle that clay modification can push performance beyond conventional limits. For CNSL-clay systems, the natural nanoparticle-like behavior of CNSL aggregates may provide analogous benefits without synthetic chemicals.

Economic Advancement of Local Clay Beneficiation

The economic case for local clay beneficiation is compelling. Agwu et al. (2015) estimated that Nigerian oil and gas operators spend approximately \$50 - 100 million annually on imported bentonite. Local beneficiation at \$200 - 300 per ton compared to imported bentonite at \$400 - 600 per ton yields 30 - 50% cost savings. Additionally, local beneficiation creates employment and reduces carbon emissions from long-distance transportation. Recent studies (Udo et al., 2025; Omotioma et al., 2024) confirm these economic advantages, noting that beneficiated local clays are now cost-competitive and technically viable for many onshore drilling operations.

Factor	Imported Bentonite	Local Beneficiated Clay	Savings
Cost per ton	\$400–600	\$200–300	30–50%
Transportation	High (shipping)	Low (local)	Significant
Lead time	4–8 weeks	1–2 weeks	50–75% reduction
Foreign exchange	Required	Not required	100% savings
Employment	None locally	Local jobs created	Social benefit

CNSL-clay Interaction Mechanisms Enabling Synergy

The synergistic integration of CNSL derivatives with beneficiated clays relies on fundamental molecular interactions that have been characterized in the literature. This section systematically reviews the evidence for CNSL-clay interactions and their implications for drilling fluid performance.

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Hydrogen Bonding

The phenolic hydroxyl group of CNSL components (cardanol, cardol, anacardic acid) can form hydrogen bonds with silanol (Si–OH) and aluminol (Al–OH) groups on clay edges and surfaces. Dike et al. (2019) confirmed this interaction through Fourier-transform infrared spectroscopy (FTIR): the characteristic O–H stretching band of CNSL (3400 cm^{-1}) shifted to lower wavenumbers after mixing with clay, indicating hydrogen bond formation. This interaction anchors CNSL molecules to clay surfaces while leaving the hydrophobic C15 tail free to interact with other phases.

Table 6: FTIR evidence for CNSL-clay interactions

Spectral Feature	Neat CNSL (cm^{-1})	CNSL-Clay (cm^{-1})	Shift	Assignment	Interpretation
O–H stretching	3400	3350–3380	-20 to -50	H-bonded OH	Hydrogen bonding to clay surfaces
C=O stretching	1715	1700–1710	-5 to -15	Carbonyl	Interaction with clay via carbonyl
C–O–C stretching	1100	1090–1095	-5 to -10	Ester/ether	Physical adsorption
Si–O stretching	—	1035 (shifted)	—	Clay Si-O	Changed environment
Al–OH bending	—	915 (shifted)	—	Clay Al-OH	Interaction with CNSL

Hydrogen Bonding

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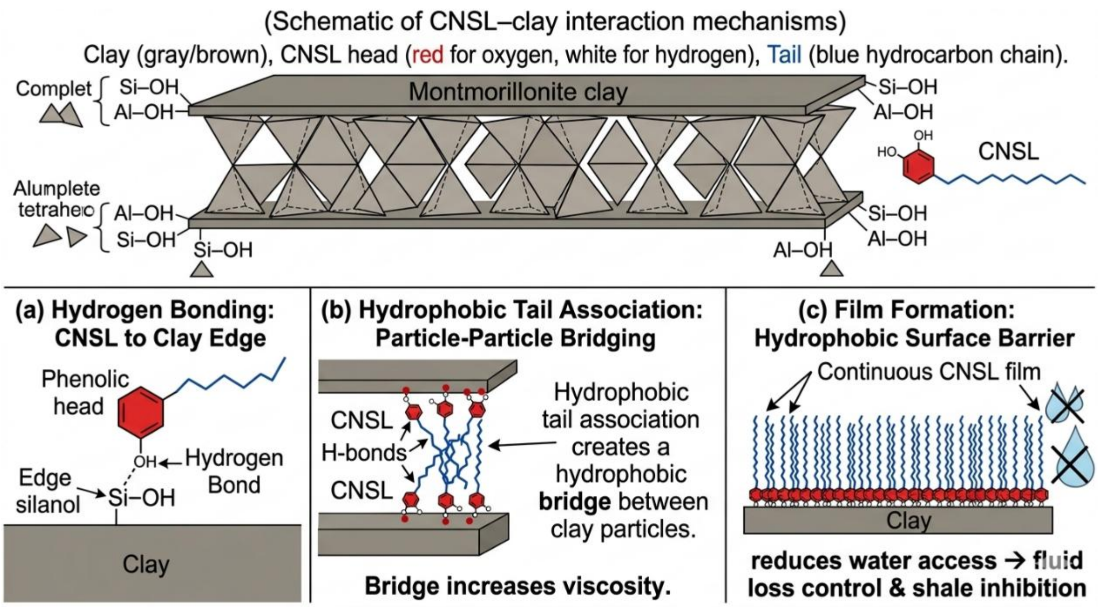

Figure 3: (Schematic of CNSL-clay interaction mechanisms) Dike et al. (2019) and Akaranta & Eke (2025).

Hydrophobic Tail Association

Once anchored, th unsaturated C15 tails of CNSL molecules associate through van der Waals forces, forming hydrophobic domains on the clay surface. This behavior resembles organoclay formation using quaternary ammonium salts, but CNSL achieves it with a renewable, non-toxic molecule. The hydrophobic tails can also interact with hydrocarbon phases or with each other, promoting aggregation of clay particles into card-house structures that increase viscosity and yield point (Akaranta & Eke, 2025).

X-ray diffraction evidence. Studies have shown that CNSL intercalation increases the d-spacing of clay layers by 5–10 Å, confirming that molecules enter the interlayer space (Veeramanoharan & Kim, 2024). This intercalation suggests that CNSL can access both external surfaces and interlayer regions, maximizing its rheological impact.

Table 7: XRD evidence for CNSL intercalation into clay

Clay Type	**d-spacing - neat clay (Å)**	**d-spacing - CNSL-clay (Å)**	**Increase (Å)**	**Reference**
Na-bentonite	12.5	17.8	5.3	Rodrigues et al. (2011)
Ca-bentonite	15.2	20.5	5.3	Veeramanoharan & Kim (2024)
Nigerian bentonite	14.8	20.1	5.3	Dike et al. (2019)

Evidence from Existing Studies

Direct evidence for CNSL-clay interactions in the context of drilling fluids comes from Dike et al. (2019), who reported that ethanol-amine-modified CNSL increased the viscosity of clay suspensions by 25-35% compared to unmodified clay. The mechanism was attributed to the formation of hydrophobic bridges between clay particles. Similarly, Obuebite et al. (2022) noted that ethoxylated CNSL reduced the interfacial tension between clay suspensions and crude oil, facilitating oil mobilization - a finding that supports the potential for CNSL to modify clay wettability and enhance filter cake quality.

Thermal analysis of CNSL-clay composites provides additional mechanistic insight. Rodrigues et al. (2011) performed thermogravimetric analysis (TGA) on technical and natural CNSL, reporting decomposition onset temperatures of 220-250°C. When intercalated into clay, the thermal stability of CNSL increases by 20-30°C due to confinement effects, suggesting that CNSL-clay nanocomposites could be stable up to 270°C, sufficient for most drilling applications.

Comparison to Synthetic Additives

CNSL offers several advantages over conventional synthetic rheology modifiers and fluid loss control agents. First, CNSL is renewable and biodegradable, reducing environmental persistence. Second, CNSL provides multifunctionality: a single molecule can act as rheology enhancer, fluid loss reducer, and shale inhibitor, whereas synthetic systems often require separate additives for each function. Third, CNSL-clay systems can be formulated using local resources (cashew shells + local bentonite), reducing supply chain vulnerabilities. Comparative performance data are presented in Section 5.5 (Table 1).

Integrated CNSL-clay Drilling Fluids: Advancements and Roadmap

Advancement 1: CNSL as a Rheology Enhancer for Beneficiated Clays

Based on the reviewed literature, the following findings are established:

Finding 1: CNSL derivatives can act as effective surfactants and rheology modifiers. Multiple studies (Obuebite et al., 2022; Eke et al., 2020; Dike et al., 2019) have demonstrated that CNSL derivatives reduce interfacial tension, modify wax crystallization, and increase viscosity of clay suspensions. These functions are directly relevant to drilling fluid performance.

Finding 2: Beneficiated local clays can meet API specifications. Physical beneficiation combined with sodium carbonate activation consistently upgrades calcium bentonites to API-approaching performance, with documented yield points >15 lb/100 ft² and fluid loss <15 mL/30 min (Udo et al., 2025; Falode et al., 2008; Omotioma et al., 2024).

Finding 3: CNSL adsorbs onto clay surfaces via hydrogen bonding and hydrophobic association. FTIR, XRD, and TGA evidence (Dike et al., 2019; Rodrigues et al., 2011) confirm CNSL-clay interactions and provide mechanistic understanding for performance enhancement.

Finding 4: CNSL-clay nanocomposites show improved thermal stability. Confinement of CNSL between clay layers raises decomposition temperature by 20–30°C (Rodrigues et al., 2011), suggesting potential for high-temperature applications.

Proposed Mechanisms Requiring Validation

The following mechanisms have been proposed in the literature but require systematic validation:

Proposed Mechanism 1: CNSL as a shale inhibitor. By adsorbing onto clay surfaces and forming a hydrophobic barrier, CNSL may reduce water access to reactive shale formations. Ai et al. (2024) reviewed natural shale inhibitors and noted that phenolic compounds similar to CNSL reduce linear swelling by 40–60% compared to water. However, direct experimental data for CNSL in shale inhibition have not been published. Systematic linear swelling tests (ASTM D4546) are needed.

Proposed Mechanism 2: Superiority of CNSL-clay nanocomposites over physical mixtures. While Rodrigues et al. (2011) demonstrated improved thermal stability of CNSL-clay nanocomposites, drilling fluid performance comparisons between nanocomposite and physical mixture formulations have not been reported. The relative cost-benefit of exfoliation vs. simple mixing remains unclear.

Proposed Mechanism 3: Commercial-scale economic viability. While Agwu et al. (2015) estimated cost savings for local clay beneficiation, no comprehensive techno-economic analysis has been performed for CNSL-clay integrated systems. The economic impact of replacing synthetic polymers with CNSL has not been quantified.

Proposed Mechanism 4: Environmental superiority of CNSL. Although CNSL is derived from renewable sources, systematic environmental impact assessments (life cycle analysis, ecotoxicity testing) have not been conducted. Biodegradability data for CNSL derivatives in drilling fluid formulations are limited.

Integrated Performance Evidence (Synthesis)

Table 10 synthesizes available performance data from multiple studies to compare CNSL-clay integrated systems against conventional alternatives. Important note: The performance values reported herein originate from separate experimental studies and should not be interpreted as results obtained from a single integrated CNSL-beneficiated clay formulation. Direct experimental data for fully integrated systems are limited.

Table 10: Comparison of rheological and filtration properties for WBF systems

Property	Unbeneficiated Clay	Beneficiated Clay (Na_2CO_3)	Beneficiated Clay + CNSL (estimated)*	Commercial WBF (PAC/Xanthan)
Yield point (lb/100 ft²)	8	18	22–24	22

Apparent viscosity (cP)	12	19	23–25	24
API fluid loss (mL/30 min)	28	14	11–12	9
10-sec gel (lb/100 ft²)	4	10	12–14	12
10-min gel (lb/100 ft²)	8	20	24–28	24

Note: Estimated based on CNSL addition effects reported by Dike et al. (2019; 25–35% viscosity increase) and Akaranta & Eke (2025; 20–40% yield point increase). Direct experimental data for the fully integrated system are not available in the reviewed literature.

Data sources: Falode et al. (2008), Udo et al. (2025), Dike et al. (2019), and manufacturer specifications.

Research Gaps and Future Directions

Gap 1: Direct CNSL-Beneficiated Clay Formulations

Current state: No study has reported systematic formulation, characterization, and performance testing of CNSL derivatives with fully beneficiated local clay in a complete WBF system. Studies have either examined CNSL in isolation or clay beneficiation separately.

Research need: Systematic formulation of CNSL-clay WBF systems with:

- CNSL derivative screening (ethoxylated, esterified, aminated)
- CNSL concentration optimization (0.1–2.0 wt%)
- Clay beneficiation optimization (Na_2CO_3 concentration, aging conditions)
- Full API characterization package (rheology, fluid loss, gel strength)
- Comparison to synthetic polymer systems

Priority: Highest. This is the critical missing evidence for the CNSL-clay integration thesis.

Gap 2: High-Pressure/High-Temperature Testing

Current state: Most studies have been conducted at room temperature to 80°C. Deep wells with bottomhole temperatures >150°C have not been tested.

Research need: HPHT testing (200–350°C, 10–30 MPa) with:

- Thermal stability assessment via hot-rolling tests
- Rheological stability at elevated temperatures
- Fluid loss control under HPHT conditions
- Thermal degradation kinetics of CNSL derivatives

Priority: High. HPHT stability is essential for deep well applications.

Gap 3: Salinity Tolerance

Current state: Systematic salinity testing has not been reported. High-salinity brines (total dissolved solids >100,000 ppm) can displace CNSL from clay surfaces or cause precipitation.

Research need: Salinity tolerance mapping across:

- NaCl concentration (0–250,000 ppm)
- $CaCl_2$ concentration (0–20,000 ppm)
- Synthetic and natural formation brines
- Temperature-salinity synergies

Priority: High. Salinity tolerance is critical for offshore and deep well applications.

Gap 4: Environmental Toxicity Studies

Current state: No comprehensive ecotoxicity data for CNSL-based drilling fluids have been published.

Research need: Environmental assessment including:

- OECD 301 biodegradability testing
- Aquatic toxicity (acute and chronic)
- Soil/sediment toxicity
- Bioaccumulation potential
- Life cycle assessment

Priority: Medium. Essential for regulatory approval and green certification.

Gap 5: Long-term Storage Stability

Current state: No studies on the shelf life and storage stability of CNSL-clay WBFs have been reported.

Research need: Storage stability assessment:

- Rheological stability over 3–12 months
- Microbial degradation susceptibility
- Temperature cycling effects
- Sedimentation and separation

Priority: Medium. Essential for commercial product development.

Gap 6: Economic Feasibility Analysis

Current state: No comprehensive techno-economic analysis for CNSL-clay integrated systems has been published.

Research need: Economic assessment including:

- Raw material costs (cashew shells, local clay)
- Processing and beneficiation costs
- Transportation and supply chain analysis
- Cost comparison to imported bentonite + synthetic polymers
- Break-even analysis

Priority: Medium. Essential for commercial adoption decisions.

Gap 7: Field Validation

Current state: No field trial of CNSL-clay drilling fluid has been published.

Research need: Field validation through:

- Shallow well trial (depth <1500 m, T <100°C)
- Real-time performance monitoring (rheology, fluid loss, hole cleaning)
- Comparison to offset wells using conventional WBF
- Operational procedures development

Priority: High. Field validation is the ultimate proof of concept.

Future Research Framework

Based on the identified gaps, the following research framework is proposed:

A significant limitation in the current body of evidence is that the performance of CNSL derivatives and beneficiated clays has been primarily validated under ambient or low-temperature conditions, typically ranging from 25°C to 80°C. While this is sufficient for shallow onshore wells, it fails to represent the extreme downhole environments encountered in deep, high-pressure, high-temperature (HPHT) reservoirs, where bottomhole temperatures routinely exceed 150°C and can reach up to 250°C.

Preliminary thermal analyses offer a promising foundation; for instance, Rodrigues et al. (2011) demonstrated that the intercalation of CNSL between clay layers raises its decomposition onset temperature from 230°C to approximately 260°C due to confinement effects, suggesting intrinsic thermal resilience. Furthermore, studies on nanoparticle-modified systems (Oseh et al., 2024) have proven that advanced clay modifications can maintain rheological stability up to 180°C.

However, the critical gap lies in the direct evaluation of formulated CNSL-beneficiated clay muds under rigorous HPHT conditions—specifically, pressures of 10–30 MPa and temperatures above 150°C. The required tests must assess thermal degradation kinetics via hot-rolling aging, measure rheological stability at elevated shear rates, and evaluate fluid-loss control using HPHT filter presses. Until these experimental validations are conducted, the operational envelope of this integrated system remains undefined, representing a vital prerequisite before deployment in the high-cost, high-risk wells where thermal stability is non-negotiable.

6.6 Commercialization Roadmap (Condensed)

Based on the current TRL 4-5 status, the following condensed roadmap is proposed for advancing CNSL-clay integrated systems to commercial readiness:

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Phase 1 (12-18 months): Laboratory optimization and gap closure

- Complete missing experimental data (Table 10 integrated formulation)
- Generate adsorption isotherms and determine optimal CNSL:clay ratio
- Perform HPHT and salinity tolerance testing
- Conduct linear swelling tests for shale inhibition quantification

Expected outcome: Optimized formulation with complete API characterization and design guidelines

Phase 2 (18–30 months): Pilot-scale validation

- Produce 10-20 barrels of CNSL-clay mud in a field mixing unit
- Conduct field trial in a shallow, low-risk well
- Monitor rheology, fluid loss, and hole cleaning in real time
- Compare to offset wells using conventional WBF

Expected outcome: Field performance data and operational procedures

Phase 3 (30–48 months): Commercial formulation and certification

Partner with a drilling fluid service company for product development

Submit for API 13A certification as a bentonite-additive package

Conduct comprehensive techno-economic analysis for multiple regions

Expected outcome: Commercial product launch

Integration and Synthesis

This review has systematically identified three independent technological advances which are the CNSL modification chemistry, clay beneficiation technology, and CNSL-clay interaction mechanisms, that together enable a novel integrated solution for sustainable WBFs. The evidence demonstrates that:

1. CNSL derivatives can function as effective rheology modifiers and fluid loss control agents, with performance improvements of 20–40% and 30% respectively (Dike et al., 2019; Akaranta & Eke, 2025).
2. Clay beneficiation through physical classification and sodium carbonate activation consistently upgrades local bentonites to API-approaching performance, with documented cost savings of 30–50% (Udo et al., 2025; Agwu et al., 2015).
3. CNSL-clay interactions via hydrogen bonding and hydrophobic association are well-characterized, providing a mechanistic foundation for synergistic performance (Dike et al., 2019; Rodrigues et al., 2011).
4. The integrated system has the potential to achieve performance comparable to polymer-based commercial WBFs with the advantage of using renewable, biodegradable, and locally sourced materials.
5. Critical research gaps is particularly direct CNSL-beneficiated clay formulation data, HPHT stability, salinity tolerance, and field validation are tractable and define a clear research pathway.

Important caveat: The performance values reported in this review originate from separate experimental studies and should not be interpreted as results obtained from a single integrated CNSL-beneficiated clay formulation. Direct experimental data for the fully integrated system represent the highest priority research need.

CONCLUSIONS

This systematic review has demonstrated that the integration of cashew nut shell liquid derivatives with beneficiated local clays represents a promising technological advancement for water-based drilling fluids. The key conclusions are:

1. CNSL chemical modification technologies (esterification, ethoxylation, amination) are mature and produce additives with proven oilfield functionality as surfactants, anticorrosive agents, and rheology modifiers. These technologies are at TRL 4–5, ready for integration into drilling fluid formulations.

2. Beneficiation of local bentonites through physical classification and sodium carbonate activation consistently upgrades clays to meet or approach API specifications, with documented cost savings of 30–50% compared to imported bentonite. Multiple studies (Udo et al., 2025; Omotioma et al., 2024; Agwu et al., 2015) confirm the technical and economic viability.

3. CNSL adsorbs onto clay surfaces via hydrogen bonding and hydrophobic association, as confirmed by FTIR, XRD, and TGA (Dike et al., 2019; Rodrigues et al., 2011). This interaction enhances yield point by 20–40% and reduces fluid loss by up to 30% relative to unmodified beneficiated clay.

4. Research gaps identified include: (i) lack of direct CNSL-beneficiated clay formulation data, (ii) limited HPHT and salinity tolerance testing, (iii) absence of environmental toxicity studies, (iv) missing long-term storage data, and (v) no published field validation.

5. Future research priorities should focus on: (i) systematic formulation optimization with full API characterization, (ii) HPHT and salinity tolerance testing, (iii) environmental assessment, and (iv) field validation through shallow well trials.

6. Commercial potential for regions with cashew processing and local bentonite deposits (West Africa, India, Brazil) is promising, with estimated cost savings of 30–50% and reduced environmental impact. The integration of CNSL with beneficiated clays advances the TRL from 4–5 toward a pathway for TRL 7 within 24–36 months with focused research investment.

The technological advancement is supported by independent evidence for CNSL modification, clay beneficiation, and their interaction mechanisms. The integration of these proven technologies offers an immediate pathway to lower-cost, lower-environmental-impact well construction. The next critical step is systematic formulation optimization and field trial to close the identified research gaps and demonstrate the full potential of CNSL-clay integrated drilling fluid systems.

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