



Multi-Scale Regulation of High-Temperature and High-Salinity Water-Based Drilling Fluids

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Abstract

Deep and ultra-deep well drilling subjects water-based drilling fluids (WBDFs) to multiple simultaneous disturbances: elevated temperature, high salinity, high-density solids and acid gas contamination. Conventional studies usually classify materials separately as “polymers, nanomaterials and bio-based materials”, yet this makes it difficult to explain why the same material behaves so differently in different base muds and evaluation protocols, and equally difficult to handle the trade-offs among rheology retention, fluid-loss control, plugging and wellbore stability. In this work, the 61 full texts provided by the user served as the candidate pool; after title-and-abstract screening and full-text review, 46 were included, of which 33 served as core evidence. The studies on high-temperature, high-salinity WBDFs are reorganised across five scales: molecular structure, particle interface, mesoscopic network, filter-cake/wellbore barrier, and engineering performance. The analysis shows that high-temperature, high-salinity failure is not a single “polymer degradation” event, but a continuous process comprising clay dehydroxylation and loss of hydrophilicity, electrical double-layer compression, polymer chain coiling or desorption, particle aggregation, and pore

interconnection within the filter cake. Temperature- and salt-tolerant polymers synergistically maintain hydration, adsorption and steric hindrance through sulfonate groups, zwitterions, rigid rings, polyether side chains and hydrophobic association structures; nano- and organic–inorganic composites rely on dispersion stability and particle-size grading to build low-permeability filter cakes; natural polymers must undergo hydrophobisation, grafting, crosslinking or compositing to cross the boundary of harsh conditions; and thermo-responsive, self-healing and film-forming materials are driving the transition of these systems from passive tolerance to on-demand response. The main bottleneck in the current evidence is not a shortage of new materials, but the inconsistency of base-mud composition, aging regimes, salt type, measurement temperature and HTHP conditions, which makes reported performance figures non-comparable across studies and leaves long-term cycling, combined contamination and field validation insufficiently addressed. Future work should focus on standardised multi-factor evaluation, in-situ multi-scale characterisation, data-driven formulation optimisation, full-life-cycle green assessment, and material–system–formation co-design.

Keywords: water-based drilling fluid; high temperature and high salinity; polymer; rheological regulation

1 Introduction

Drilling fluids perform multiple functions: transporting and suspending cuttings, balancing formation pressure, cooling and lubricating the drill string, stabilising the wellbore and transmitting downhole information. Instability in their performance simultaneously amplifies risks such as lost circulation, pipe sticking, wellbore collapse, reservoir damage and loss of control over the equivalent circulating density. As oil and gas exploration advances towards deep, ultra-deep and unconventional reservoirs, bottomhole temperature, salinity, solids content and contaminant concentration continue to rise. Drilling fluids therefore no longer face a single environmental variable, but operate under the combined action of high temperature, high pressure, high salinity, high density and acid gas contamination. Oil-based drilling fluids generally offer strong thermal stability, lubricity and shale inhibition, but cost, waste disposal and environmental compliance pressures limit their widespread use. Consequently, enabling water-based drilling fluids to achieve oil-based-like stability under harsh conditions has long been a key objective of drilling-fluid materials research [1,3,7,38].

A high-temperature, high-salinity water-based drilling fluid is essentially a complex dispersion containing clay particles, soluble polymers, inorganic salts, weighting materials and various functional additives. Its macroscopic rheological and filtration behaviour is determined jointly across multiple scales: whether molecular chains remain chemically intact and in an extended conformation; whether additives can adsorb onto the surfaces of clay or weighting materials; whether interparticle interactions can form a reversible network that is not excessively structured; whether the pores inside the filter cake form continuous seepage channels; and whether a barrier combining low permeability with mechanical integrity can be established between the filter cake and the wellbore wall. Discussing only the heat resistance of a single functional group, or reporting only the filtrate volume of one formulation after aging, is insufficient to explain why a system works. Having reviewed the structure–property relationships of high-pressure, high-temperature drilling fluids, Gautam et al. pointed out that sulfonate groups, rigid and heterocyclic structures are often associated with thermal stability, that amide, hydroxyl, quaternary ammonium and acrylic structures influence rheology and filtration, and that carboxylate, sulfonate and polyoxyethylene chains contribute to dispersion stability in saline environments [1]. This conclusion suggests that additive design should shift from “single-function addition” to the synergistic configuration of functional units.

Existing reviews mainly follow material origin or chemical category as their organising thread. For example, reviews of synthetic polymers systematically summarise the temperature-resistant fluid-loss control of acrylamide-based copolymers [3,5]; reviews of modified starch and xanthan gum emphasise the sustainability and rheological functions of bio-based polymers [22,23]; and recent studies regard thermo-responsive polymers and supramolecular materials as important candidates for intelligent drilling fluids [29,30]. These works laid the foundation for material classification, but three shortcomings remain. First, materials of different categories often act through similar interfacial and filter-cake mechanisms, so category-based narratives tend to be repetitive and lack a unified explanation. Second, rheology, filtration, plugging and wellbore stability are usually evaluated separately, neglecting their coupling and conflicts in real systems. Third, testing protocols differ markedly between studies; without discussing temperature, salt type, aging time, pressure differential and base-mud composition, simply ranking “lowest filtrate volume” may lead to misleading conclusions.

On this basis, the research question of this paper can be condensed as follows: under high-temperature, high-salinity and related complex contamination conditions, how can multi-scale design at the molecular, interfacial, mesoscopic-network and filter-cake/wellbore levels enable

a water-based drilling fluid to simultaneously maintain controllable rheology, low fluid loss and wellbore stability? Rather than centring on a list of additives, the article develops its logic along “failure chain – regulation scale – material route – evidence boundary – engineering translation”. The candidate pool used here consists of 61 PDFs in the folder specified by the user, spanning 2019–2027, among which a few 2026–2027 entries are journal pre-publications or papers already assigned to an issue. A full-text readability check confirmed that all 61 could be extracted. Screening by aqueous system, harsh conditions, material–performance relevance and full-text traceability yielded 46 included papers, with 33 entering core evidence extraction. Because this corpus was not systematically expanded through databases such as Web of Science or Scopus, the paper is positioned as a completed mechanism-oriented topical review rather than a systematic review claiming exhaustive retrieval.

2 Failure Chain of Water-Based Drilling Fluids under High-Temperature, High-Salinity Conditions

High temperature, high salinity, high-density solids and acid gas contamination are not independent of one another; they are progressively amplified through molecular degradation, interfacial destabilisation, network rearrangement and filter-cake failure, ultimately manifesting as rheological drift, increased fluid loss and wellbore instability. Figure 1 summarises this continuous failure chain and its positive feedback relationships.

2.1 Degradation of Clay Layers, Surface Hydroxyl Groups and Hydration Films

Montmorillonite in bentonite relies on its layered structure, surface negative charge and hydration to form dispersed particles and a weak gel network. At ambient temperature, face–face, edge–face and edge–edge interactions between particles jointly control yield stress, gel strength and filter cake structure. Upon heating, the thermal motion of water molecules intensifies, the hydration layer on the clay surface thins, and the crystal layers and surface functional groups may also undergo irreversible changes. Combining molecular dynamics, XPS, XRD, Zeta potential, contact angle, SEM and rheological and filtration experiments, Liu et al. showed that high temperature destroys the layered structure of clay, reduces surface aluminium and hydroxyl contents, and lowers surface electronegativity and hydrophilicity; when the temperature rises from 25 °C to 200 °C, the surface hydroxyl content falls by about 45%, the median particle size of the clay increases by about 2.7 times, and the filtrate volume increases by about 1.6 times [2]. The importance of this study lies in connecting “increased fluid loss

after high temperature” to a continuous evidence chain linking surface chemistry, particle aggregation and a loosened filter cake, rather than attributing it merely to a decrease in macroscopic viscosity.

Clay failure also exhibits a pronounced time dependence. Zhong et al. compared the long-term aging behaviour of bentonite, the commercial synthetic polymer Driscal-D and a β -cyclodextrin polymer microsphere system at 200 °C, and found that the filtrate volume of the plain bentonite system rose rapidly within the first few hours, the Driscal-D system progressively lost stability with prolonged aging, whereas the cyclodextrin microsphere system stabilised after early-stage changes [18]. Therefore, evaluating a material by “single-point performance after 16 h of aging” may obscure kinetic processes such as aggregation followed by rearrangement, or degradation followed by the formation of new structures. For ultra-deep wells subject to prolonged static periods, tripping or interrupted circulation, aging time is just as decisive a variable as temperature.

2.2 Polymer Chain Degradation, Coiling and Interfacial Desorption

Polymeric additives in water-based drilling fluids provide viscosity enhancement, fluid-loss control, encapsulation, inhibition and lubrication, and their failure involves at least three mechanisms. The first is chemical degradation such as backbone scission, side-group hydrolysis or oxidation, which reduces molecular weight and effective chain length. The second is the deterioration of solvent quality caused by high salinity, which coils the chain segments and reduces the hydrodynamic volume. The third is the weakening of adsorption due to ionic competition and changes in clay surface chemistry, which desorbs the protective layer from the particle surface. Natural starch, cellulose and some acrylamide-based polymers are especially susceptible to hydrolysis, thermal degradation or microbial attack, while multivalent ions may further aggravate flocculation through bridging [3,4,22].

“Heat resistance” and “salt resistance” cannot be treated as the same property. Rigid aromatic or heterocyclic rings can improve the thermal stability of the backbone, but do not necessarily guarantee dissolution and extension in high salinity; strongly ionic groups can increase hydration, yet in high salinity they may lose their repulsive effect through charge screening; and high molecular weight favours bridging and viscosification, but may cause excessive structuring in high-density systems. The high-temperature fluid-loss polymers reviewed by Balaga and Kulkarni show that combinations of amphoteric copolymers and clay can maintain relatively stable performance at about 300–400 °F and about 10 wt% CaCl₂, but the literature generally lacks systematic statistical relationships between polymer molecular

weight, degree of substitution and filtration performance, and high-temperature evaluation protocols are inconsistent [3]. This means that material design must address chemical stability, solution conformation and particle adsorption simultaneously.

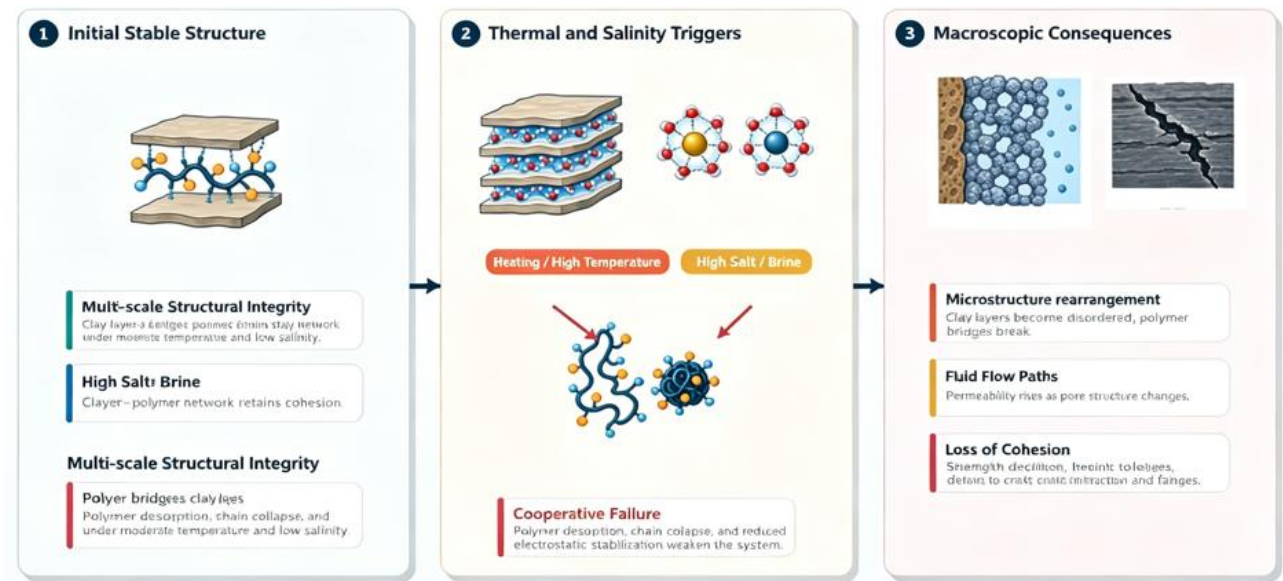


Figure 1 Cross-scale instability mechanisms of clay-polymer systems under high-temperature, high-salinity conditions, from interlayer hydration and chain-conformation changes to filter-cake defects and wellbore risks (summarised from [1-4,8,15,18])

2.3 Electrical Double-Layer Compression, Ionic Bridging and Combined Contamination

The effect of salt on water-based drilling fluids is not merely “increased ionic strength”. NaCl compresses the electrical double layer of clay particles and reduces the electrostatic repulsion between them, making the particles more prone to aggregation; multivalent ions such as Ca^{2+} and Mg^{2+} can strengthen local connections between particles and polymers through ionic bridging, and compete with anionic functional groups for hydration. High salinity also alters the coil size, hydrophobic association strength and critical aggregation behaviour of polymers. The same material may achieve dispersion in low salinity by increasing the absolute value of the Zeta potential, yet in high salinity may rely on steric hindrance or the anti-polyelectrolyte effect to maintain its conformation. Simply increasing charge density therefore does not necessarily deliver better salt tolerance.

Real downhole environments also involve combined contamination from CO_2 , H_2S , gypsum, drill cuttings and weighting materials. Dissolved CO_2 causes acidification and shifts the carbonate/bicarbonate equilibrium, which can induce clay aggregation and abnormal

viscosification. The comb-shaped polymer DN-1 designed by Deng et al. provides steric repulsion through polyether side chains at 200 °C under carbonate/bicarbonate contamination, re-dispersing the agglomerated clay; 1 wt% DN-1 reduced the apparent viscosity, yield value and API filtrate volume from 27 mPa·s, 15 Pa and 41 mL to 15 mPa·s, 8 Pa and 20 mL, increased the absolute Zeta potential from 13.8 mV to 45 mV, decreased the particle size from 16.2 µm to 8.21 µm, and kept the main performance changes within 20% after five temperature–contamination cycles [8]. This result indicates that anti-contamination materials should target the interfacial structural changes caused by contamination, rather than relying solely on raising the base viscosity as compensation.

2.4 Coupling and Conflicts among Macroscopic Properties

Rheology, fluid loss and plugging are not three independently optimisable indicators. Increasing polymer concentration or network strength generally favours the suspension of weighting materials and cuttings transport, but may raise the plastic viscosity, pump pressure and equivalent circulating density; enhancing particle dispersion can avoid flocculation-induced viscosification, yet may make the particle size too fine to form effective bridges; and strong adsorption with a thick protective layer can reduce filter-cake permeability, but may also increase cake thickness or cause irreversible reservoir adsorption. The comparison of metal oxide nanoparticles illustrates this particularly well: in xanthan gum-based water-based systems, ZnO helps maintain the yield value and low-temperature, low-pressure fluid loss, but its HTHP sealing integrity is inferior to that of MgO; MgO showed lower HTHP fluid loss in the same study, and the differing morphology, reactivity and in-situ hydration of the particles led to different performance combinations [15]. Therefore, the “best additive” is meaningful only once the objective function and operating constraints have been specified.

Wellbore stability in turn links fluid properties to formation properties. Low fluid loss can only reduce liquid invasion and does not automatically mean that the mechanical strength of the rock has been restored; a dense filter cake can lower permeability, but if it lacks toughness it may crack under pressure fluctuations and wellbore deformation; and overly strong plugging may increase reservoir damage or be difficult to remove. Studies of deep coal-rock and fractured shale show that effective wellbore control generally requires the synergy of multiple mechanisms, including particle bridging, polymer film-forming, surface hydrophobisation and cementation enhancement [28,33,34]. This is also why the present paper adopts a multi-scale framework rather than ranking materials by a single filtration indicator.

Table 1 Main failure stages of high-temperature, high-salinity water-based drilling fluids and their diagnostic paths

Failure scale	Dominant change	Observable manifestation	Priority diagnostic indicators	Main regulation direction
Molecular scale	Chain scission, hydrolysis, coiling or imbalanced hydrophobic association	Decreased molecular weight; drift of solution viscosity or cloud point	GPC, FTIR, thermal analysis, temperature-sweep rheology	Stabilise the backbone; rigid units; controlled hydration
Interfacial scale	Thinner hydration film, double-layer compression, adsorption competition	Decreased Zeta potential, increased particle size, precipitation or bridging	Zeta potential, particle size, adsorption amount, contact angle	Steric hindrance, zwitterions, multi-point adsorption
Mesoscopic network	Aggregation, excessive network strength or insufficient shear recovery	Abnormal yield value, sedimentation or increased pump-start pressure	Full shear curve, thixotropic loop, oscillatory rheology	Reversible association, network strength and dosage window
Filter cake / wellbore	Pore interconnection, brittle cracking, re-invasion or irreversible adsorption	Increased fluid loss, thicker filter cake, decreased pressure-bearing capacity	HTHP fluid loss, permeability, micro-CT, core strength	Particle-size grading, rigid–flexible compositing, film-forming and repair

3 Multi-Scale Regulation Framework: from Molecular Structure to Wellbore Barrier

The core of the multi-scale framework is not to link evaluation indicators in a simple sequence, but to require that every material function have a verifiable result at the adjacent scale and ultimately enter a closed loop of core, fracture or field evidence, as shown in Figure 2.

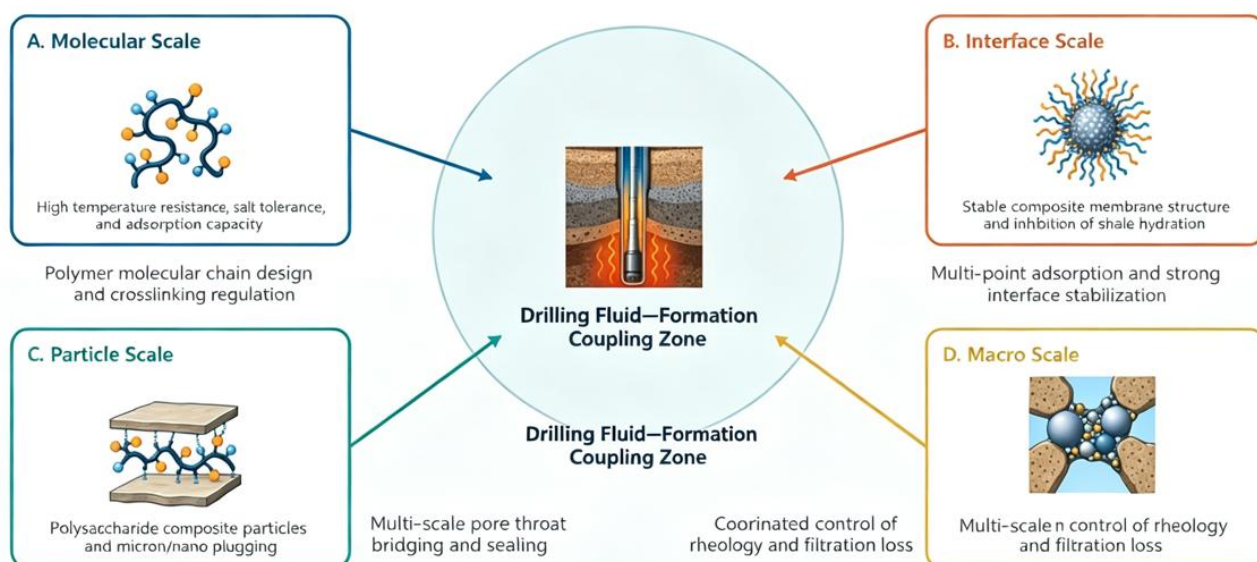


Figure 2 Principles of multi-scale synergistic regulation at the molecular, interfacial, particle and barrier levels, centred on the wellbore–formation coupling zone (summarised from [2,7,8,10,18,20,32-35])

3.1 Molecular Scale: Chemical Integrity and Solution Conformation

The molecular scale first determines whether an additive can “arrive alive” at the target interface. Sulfonate groups have strong hydration and salt-tolerance capabilities, and monomers such as AMPS are widely incorporated into high-temperature polymers because of their steric hindrance and the stability of the sulfonate group; N-vinylpyrrolidone, styrene sulfonate and units containing benzene rings or rigid heterocycles help improve chain rigidity and thermal stability; polyether side chains provide hydration and steric hindrance; and a rational combination of quaternary ammonium, carboxylate and sulfonate groups can form zwitterions or polyampholytes, causing the polymer to extend its chain or maintain a larger hydrodynamic volume in the presence of salt [1,4,9]. Functional groups, however, are not simply additive: too many rigid units impair solubility, too many hydrophobic units cause premature association at low temperature, and overly dense ionic groups may increase synthesis cost and alter the mode of adsorption onto clay.

Molecular design should also distinguish between “permanent stability” and “conditional triggering”. Conventional temperature-resistant polymers aim to keep their structure as unchanged as possible throughout the circulation process, whereas thermo-responsive or supramolecular materials allow chain segments to undergo reversible dehydration, association or phase transition at a specific temperature, so that they strengthen the network and plugging at the bottomhole and recover flowability upon returning to a low-temperature zone [27,29,30].

The two strategies are not mutually exclusive: the former is suited to maintaining the stability of the base system, while the latter is suited to on-demand functions in local pore throats, fractures or temperature windows.

3.2 Interfacial Scale: Adsorption, Dispersion and Competition

Additives must be converted into macroscopic performance through interfacial interactions such as clay–water, polymer–clay, particle–particle and oil–water. Amide, hydroxyl, carboxyl and cationic sites on polymers can adsorb onto clay surfaces through hydrogen bonding, electrostatic and coordination interactions; the adsorbed layer increases the hydration and steric hindrance of the particle surface on the one hand, but may also form cross-particle bridges when adsorption is insufficient on the other. Zeta potential, particle-size distribution and adsorption amount can provide clues to interfacial stability, but cannot independently prove that the filter cake is low-permeability, because the cake is also affected by particle morphology, grading and compaction. Studies of DN-1, the SW starch–walnut shell composite and the P-DADL zwitterionic–hydrophobically associating polymer all link changes in Zeta potential or particle size to improved rheology and filtration [8,10,25], indicating that interfacial evidence should be interpreted jointly with macroscopic results.

Under high temperature and high salinity, once electrostatic interactions are screened, the importance of steric hindrance, hydrophobic association and host–guest interactions increases. Cyclodextrin has a hydrophilic exterior and a hydrophobic cavity, and can participate in host–guest inclusion and supramolecular assembly; zwitterionic polymers may exhibit the anti-polyelectrolyte effect in salt; and hydrophobically associating chain segments maintain the network through reversible physical crosslinking. Their common feature is extending the stabilisation mechanism from single long-range electrostatic repulsion to short-range hydration, steric hindrance and reversible association, thereby improving robustness against salt screening [13,18,20,30].

3.3 Mesoscopic Scale: Reversible Network, Shear Thinning and Suspension

A drilling fluid must remain pumpable during high-shear circulation, and possess sufficient yield stress and gel strength to suspend cuttings and weighting materials at low shear or when static. The ideal structure is not a permanently rigid gel, but a reversible network that can be deconstructed under shear and recover rapidly after the shear stops. Hydrophobic association, hydrogen bonding, host–guest interactions and particle–polymer bridging can all build such a network, but its strength must be controlled. P-DADL forms a spatial network in water and

adsorbs strongly onto clay; after aging at 180 °C for 16 h, the 2 wt% system still retained an apparent viscosity of 62 mPa·s and a viscosity retention of 70.86%, gave an API filtrate volume of 6.4 mL in 35 wt% NaCl, and maintained more than 98% suspension stability in saturated brine within 48 h [10]. Together, these indicators show that it does not merely “increase viscosity”, but simultaneously affects the network, particle stability and filter-cake formation.

Research on xanthan gum serves as a reminder that higher static viscosity is not equivalent to better dynamic cuttings transport. Comparing xanthan gum, the natural gum Ogbonno and their blends at ambient temperature, Ohaegbulam et al. found that the blended formulations had higher plastic viscosity, apparent viscosity, yield value and gel strength, and stronger static suspension; however, Herschel–Bulkley fitting and annular flow experiments showed that the xanthan gum formulation alone was more balanced in dynamic hole cleaning, achieving an average cuttings transport efficiency of 87.67%, an improvement of 26.9% relative to the base mud [39]. Although this study did not simulate HPHT conditions, its “static structural strength versus dynamic flow efficiency” distinction is equally methodologically significant for high-temperature, high-salinity systems.

3.4 Filter-Cake and Wellbore Scale: Low Permeability, Toughness and Functional Integration

The ultimate goal of fluid-loss control is to form a thin, dense, low-permeability filter cake with some toughness, while minimising the invasion of liquid phase and fine particles into the formation. Polymers can reduce filtrate migration through adsorption and viscosification, nanoparticles can fill micropores, flexible microspheres can deform into pore throats, and rigid–flexible composites accommodate both bridging and compaction. Cyclodextrin polymer microspheres undergo hydrothermal carbonisation at high temperature to generate nano/micro carbon spheres and clay–carbon sphere composite structures, illustrating the possibility of in-situ “secondary material formation” under downhole conditions [18,20]. Such mechanisms cannot be explained solely by the initial particle size of the additive; the chemical transformation after aging and the grading of newly formed particles must also be considered.

The wellbore barrier can also serve cementation, film-forming, hydrophobisation, self-healing and thermal insulation functions. Deep coal-rock drilling fluids plug medium- and large-pore fractures with adaptive organic–inorganic microspheres, and use additives bearing adsorptive and hydrophobic groups to cement and form films in micro-pore fractures, thereby combining “preventing liquid invasion” with “improving the overall strength of the rock mass and reducing surface hydrophilicity” [33]. Hollow silica nanospheres, by contrast, turn the filter

cake into a thermal insulation layer: their intrinsic thermal conductivity is about 0.024 W/(m·K), and a 2 wt% addition reduced the thermal conductivity of the mud cake to 0.577 W/(m·K), 16.5% lower than the unmodified cake, while the equilibrium temperature on the cold side dropped by 26.8 °C under simulated conditions [35]. This suggests that future filter-cake design should be upgraded from a single permeability barrier to a multifunctional mechanical, thermal and chemical interface.

3.5 Evaluation Indicators Should Form a Closed Loop from Fluid to Formation

Multi-scale design needs to correspond to multi-scale evaluation. At the rheological level, plastic viscosity mainly reflects liquid-phase viscosity and mechanical friction between solids, the yield value characterises the structural strength required to establish continuous flow, and low-shear readings and gel strength relate to static suspension and pump-start pressure. Reporting only AV, PV and YP remains insufficient, because the same three parameters may correspond to different shear-thinning curves and thixotropic recovery. For complex polymer and particle networks, the full shear-rate range should be fitted with at least the Bingham, power-law or Herschel–Bulkley model, reporting the goodness of fit, temperature conditions and shear history; if the material exhibits thermo-responsive or self-healing behaviour, heating–cooling cycles, oscillatory rheology and structural recovery tests should also be performed. The fact that the ranking of static viscosity and dynamic cuttings-transport efficiency were not fully consistent in the xanthan gum and Ogbonno study [39] precisely shows that single-point viscosity cannot replace annular transport evaluation.

At the filtration level, API fluid loss is suitable for basic screening, while HTHP fluid loss is closer to the pressure differential and temperature of deep wells, but the two cannot be used interchangeably. In addition to cumulative filtrate volume, the instantaneous filtration rate, filter-cake thickness, water content, compressibility and permeability should be reported. Low fluid loss may originate from high liquid-phase viscosity or from particle grading and a low-permeability filter cake; the former may increase pumping resistance, while the latter is more likely to balance rheology. The poly(ionic liquid)–cyclodextrin system [13], SiO₂-reinforced microspheres [16] and the SW starch–walnut shell composite [25] all link filtration improvement to filter-cake structure, but cross-study comparison still requires unified pressure differential and temperature-measurement positions. For plugging materials, the pore-throat or fracture size, forward and reverse pressure-bearing capacity, breakthrough pressure, plugging rate, flowback/plug removal and multiple pressure cycles should also be reported.

Interfacial and structural characterisation should answer mechanistic questions rather than decorate a paper. Zeta potential and particle size are used to judge colloidal stability and aggregation changes; adsorption amount and total organic carbon can assess the partitioning of additives onto the solid phase; XRD, XPS and FTIR can identify changes in clay layers, elemental valence states and functional groups; and SEM/EDS and micro-CT are used to observe filter-cake pores, particle distribution and wellbore fractures. Different characterisation techniques need to point in a consistent direction: if a material is claimed to reduce fluid loss by enhancing dispersion, one should simultaneously observe a narrower particle-size distribution or reduced aggregation, evidence of Zeta potential/steric hindrance, and reduced filter-cake porosity; if bridging plugging is claimed, it should not be explained solely by improved dispersibility. The combination of molecular simulation, surface chemistry and macroscopic performance by Liu et al. for high-temperature clay failure [2] is representative of such an evidence loop.

At the formation level, the ultimate question is whether the wellbore and reservoir benefit. Linear swelling, rolling recovery and immersion dispersion are used for preliminary screening of shale inhibition, but cannot fully represent fracture propagation and wellbore load-bearing capacity; they should be further combined with core permeability, shear/compressive strength, acoustic emission, CT fracture evolution and the mineral composition of real rock samples. The CaCO₃-enhanced coalbed fluid used CT and seepage simulation to verify the suppression of fractures around the wellbore [34], and self-healing microcapsules reported both permeability and shale shear strength [32]; both are closer to the goal of wellbore stability than a single filtrate volume. The ideal closed loop for engineering evaluation should be: material structure confirmable, interfacial action measurable, rheological and filter-cake performance reproducible, core or fracture effects verifiable, and finally feedback obtained from field operating parameters and complex situations.

4 Structural Design of Temperature- and Salt-Tolerant Synthetic Polymers

The design of synthetic polymers can be understood as the combination of several functional modules: sulfonate groups maintain hydration, rigid structures suppress coiling, zwitterions regulate conformation in salt, comb-shaped side chains provide steric hindrance, and hydrophobic units build a reversible network. As emphasised in Figure 3, these modules

are simultaneously constrained by engineering factors such as water solubility, molecular weight, degree of substitution, degree of crosslinking and residual monomers.

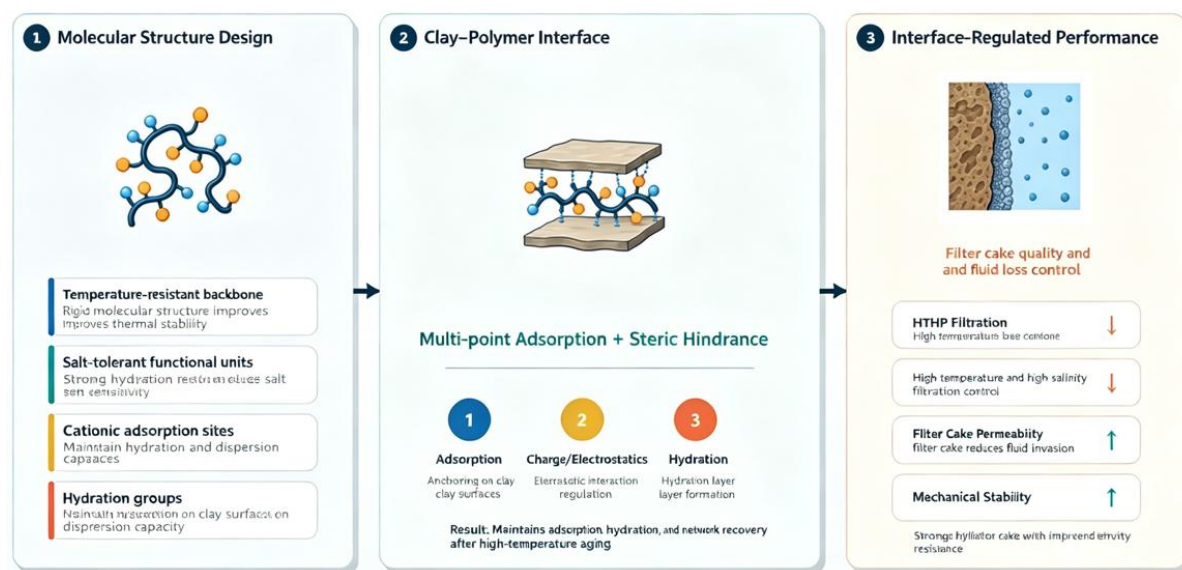


Figure 3 Functional modules of polymers and their structure–interface–performance mechanisms (summarised from [3,4,8-13,29,30])

Table 2 Roles and design costs of functional units in temperature- and salt-tolerant polymers

Functional unit	Main function	Expected benefit	Risk of excess or mismatch	Representative refs.
AMPS and sulfonates	Strong hydration, steric protection, salt tolerance	Maintains chain extension and fluid-loss control	Higher monomer cost and ionic load	[3,4,12]
Aromatic or heterocyclic rings	Increase chain rigidity and barriers to thermal motion	Improves structural retention at high temperature	Reduced water solubility; slower dissolution at low temperature	[4,11,12]
Zwitterion	Anti-polyelectrolyte effect, multi-point adsorption	Maintains conformation in high salinity and adapts to various minerals	Charge-ratio mismatch can cause internal association or excessive adsorption	[7,9,10]
Comb-shaped polyether side chain	Provides a hydration layer and steric hindrance	Resists aggregation induced by salt and CO ₂ contamination	Overly dense side chains weaken backbone adsorption	[8,27]

Functional unit	Main function	Expected benefit	Risk of excess or mismatch	Representative refs.
Hydrophobic or host-guest units	Builds a reversible physical network	Improves shear recovery, suspension and responsiveness	Premature association at low temperature or long-term shear instability	[10,13,18,20,30]

4.1 Sulfonation, Rigidity and Anti-Hydrolysis Units

The core advantage of synthetic polymers is that their structure is programmable. Using monomers such as AM, AMPS, DMAM, NVP/NVCL, styrene sulfonate and quaternary ammonium salts allows molecular weight, chain rigidity, hydration, adsorption and salt tolerance to be tuned separately. The sulfonate group of AMPS provides strong hydration and relatively high chemical stability, and the steric hindrance created by the branched methyl group can protect the amide bond; DMAM and lactam monomers reduce the hydrolysis risk of conventional primary amides; and aromatic rings or bulky rigid structures raise the barrier to chain-segment thermal motion. Wang et al. introduced a home-made p-vinylbenzyl sulfonate-type monomer and copolymerised it with DMAM, AMPS and NVCL to obtain a fluid-loss additive tolerant of 220 °C and 5 wt% salt, with an API filtrate volume of about 6.0 mL and an HTHP filtrate volume of about 20.0 mL after aging [12]. This study shows that combining strongly hydrating sulfonate groups with rigid aromatic rings can improve structural retention at extreme temperatures, although performance still depends on the base mud, dosage and evaluation pressure differential.

Resin-type polymers offer an alternative heat-resistant backbone. Conventional sulfomethylated phenol-formaldehyde resins have relatively high thermal stability, but raw-material cost and the hydrophilicity/adsorption balance can still be optimised. Liu et al. partially replaced phenol with urea to prepare a sulfomethylated phenol-urea-formaldehyde copolymer; the amino groups introduced by urea increase hydrophilicity and bentonite adsorption while maintaining the balance between condensation and sulfomethylation. After aging at 210 °C, its HTHP filtrate volume was 15.6 mL, lower than the 24.8 mL of conventional sulfomethylated phenolic resin, with raw-material cost reduced by 14.7%, and the synthesis was scaled up in a 20 L reactor [11]. Compared with studies reporting only laboratory performance, this work provides both cost and scale-up evidence, but 20 L is still a pre-pilot scale, and industrial continuous production, batch consistency and wastewater treatment remain to be verified.

4.2 Zwitterions and the Anti-Polyelectrolyte Effect

Zwitterionic polymers contain both positive and negative charge groups on the same chain. Under low-salinity conditions, intra- or inter-chain electrostatic association may cause the coil to contract; upon addition of salt, small ions screen the internal charge pairs and the chain segments instead expand, which is the so-called anti-polyelectrolyte effect. For high-salinity drilling fluids, this behaviour can partially offset the salt-induced coiling of ordinary anionic polymers. The zwitterionic sites can also anchor onto clay surfaces through multi-point adsorption and remain adaptable as the surface charge of different minerals changes.

In a high-density saturated brine system, Huang et al. combined a weakly crosslinked zwitterionic fluid-loss additive, a flexible polymer microsphere nano-plugging agent and a comb-shaped lubricant to build a water-based drilling fluid with a density of 2.0 g/cm³. The system gave a filtrate volume below 15 mL at 200 °C and high pressure, a sag factor below 0.52 after 5 d of high-temperature static aging, and simultaneously balanced plugging, lubrication and a cuttings rolling recovery close to that of oil-based drilling fluids [7]. This result highlights the importance of a “material package” rather than a single additive: the amphoteric polymer maintains colloidal and filtration stability in brine, the flexible microspheres regulate pore-throat grading, and the low-molecular-weight comb-shaped lubricant reduces friction. Correspondingly, the performance of the whole system cannot be attributed entirely to any one polymer.

Another difficulty in high-density systems is excessive structuring. Weighting materials and clay form a strong particle network after high-temperature exposure, which may cause abnormally high viscosity and shear stress. The amphoteric polymer thinner ZPT-3 prepared by Lv et al. regulates weighted water-based mud through adsorption and dispersion; at a 2 wt% dosage it achieved a viscosity-reduction rate of 66.3% in complex weighted polymer mud after aging at 200 °C, outperforming the commercial thinners compared, and a multi-output machine-learning model was further built to predict rheological parameters at different concentrations and aging temperatures [9]. This shows that amphoteric polymers can be used not only to “maintain viscosity”, but also to restore rheology to a controllable window by breaking down an excessively strong particle network.

4.3 Comb-Shaped Side Chains and Hydrophobically Associating Networks

Comb-shaped polymers consist of an adsorbing or charged backbone and long side chains; the side chains form a thick hydration/steric layer on the particle surface, which can suppress

aggregation induced by high salinity and contamination. The restorative effect of DN-1 on CO₂-contaminated systems derives precisely from the steric repulsion of such radially extended side chains [8]. Compared with purely electrostatic dispersants, steric hindrance is less sensitive to ionic strength; however, excessive side-chain density and length may reduce the chance of adsorption sites reaching the clay surface and increase synthesis complexity.

Hydrophobically associating polymers, by contrast, introduce a small number of hydrophobic groups onto a hydrophilic backbone. The hydrophobic microdomains form reversible physical crosslinking points that strengthen the network at low shear and dissociate at high shear, thereby balancing suspension and shear thinning. P-DADL combines zwitterionic character with hydrophobic association, using charge/hydration to maintain conformation in salt while building a spatial network through hydrophobic microdomains; it still exhibited low fluid loss and high suspension stability at 180 °C and 35 wt% NaCl [10]. This phenomenon of “salt-synergised fluid-loss reduction” may be related to salt-enhanced hydrophobic association and chain-conformation changes, but its generality still requires verification under different salt types, weighting materials and shear histories.

4.4 Poly(ionic liquid)s, Cyclodextrin and Supramolecular Structures

Poly(ionic liquid)s combine a polymer backbone with ionic liquid units, offering strong ionic interactions, thermal stability and tunable hydrophilicity/hydrophobicity. Liu et al. introduced poly(ionic liquid) structures into a β -cyclodextrin backbone; after hot rolling at 180 °C for 16 h, the treated system gave an API filtrate volume of 2.8 mL, whereas Driscal-D, PAC-LV and CMC in the same study gave 10.4, 12.4 and 14.8 mL respectively. Particle size, Zeta potential and filter-cake analysis indicated that a low-permeability, thin and dense filter cake was the main reason [13]. This result suggests possible synergy among the rigid cyclodextrin backbone, ionic sites and polyhydroxy interface, but the synthesis steps, environmental impact of monomers and scale-up cost still need to be compared with conventional polymers.

Supramolecular materials rely on reversible non-covalent interactions such as hydrogen bonding, hydrophobic interactions and host–guest inclusion. Their advantage is not absolute strength, but the ability to reorganise after damage and to adapt to temperature, salinity or shear. The water- and oil-based systems reviewed by Yang and Ma show that supramolecular rheology modifiers can maintain a network in concentrated brine, that cyclodextrin-derived structures can improve filtration through high-temperature-induced transformation, and that self-healing gels can adapt to irregularly shaped loss channels [30]. However, reversible interactions may

also be weakened under long-term high shear, competing adsorbents and complex ionic environments, so “intelligence” must be demonstrated by cycling stability rather than a single triggering experiment.

4.5 Overall Assessment of the Synthetic Polymer Route

Synthetic polymers remain the route closest to engineering controllability, because monomer ratio, molecular weight, branching and crosslinking degree are adjustable and can be designed for a specific salt type, temperature and contaminant. However, the literature commonly suffers from thorough structural characterisation combined with insufficient engineering formulation information; many studies use FTIR and thermogravimetry to demonstrate “successful synthesis and high decomposition temperature” without quantitatively reporting molecular weight distribution, degree of substitution, adsorption amount or structural changes after prolonged shear. More importantly, a thermogravimetric decomposition temperature far above the downhole temperature is not equivalent to functional retention in aqueous solution: a polymer may already have hydrolysed, coiled, desorbed or lost its network function before the backbone decomposes to any significant extent.

Evaluating a synthetic polymer should therefore include at least four layers of evidence: evidence of chemical structure and molecular weight; conformation and stability in high-temperature, high-salinity solution; particle interfacial behaviour and the rheological/filtration response in a well-defined base mud; and system-level contamination cycling, static sag and wellbore/plugging performance. Only when these four layers form a causally coherent evidence chain can one move from “the new polymer has high thermal stability” to the engineering judgement “it is suitable for a specific deep-well condition”.

5 Nanomaterials and Organic-Inorganic Composite Systems

The key to particulate materials does not lie in pursuing the smallest possible particle size, but in combining rigid particle load-bearing, nanoparticle void filling and flexible polymer bridging to jointly reduce pore connectivity and improve filter-cake toughness. Figure 4 illustrates this logic of synergistic construction through multi-level particle size grading.

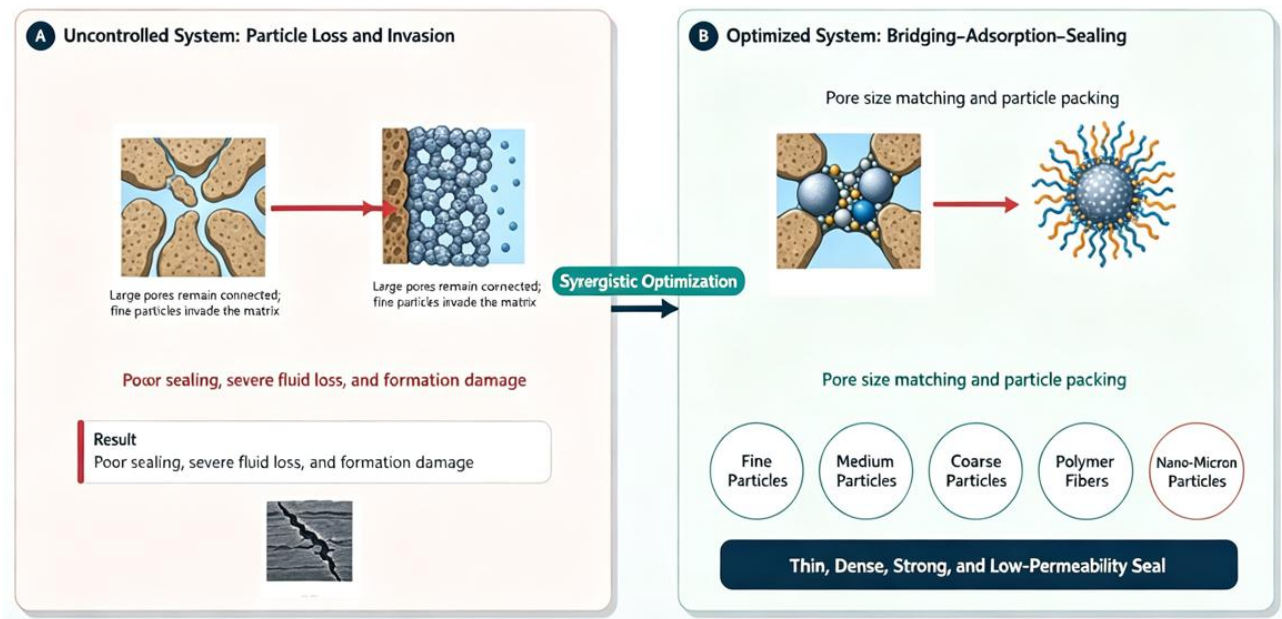


Figure 4 Synergistic construction of a low-permeability, tough filter cake by rigid particles, nano-sized filling units and polymer bridging (summarized from [14-20,25,34,35,37])

5.1 From the 'Nano Effect' Back to Particle Size Grading and Interfacial Interaction

Nanomaterials possess a high specific surface area, tunable surface chemistry and relatively good thermal stability, enabling them to enter micro- and nano-scale pores that conventional particles cannot easily cover, and to alter clay particle aggregation and filter-cake packing. However, the so-called nano effect does not mean that the smaller the material and the higher the dosage, the better the performance. When particles are excessively fine and lack larger bridging particles, they may invade the formation together with the filtrate; an excessively high surface energy leads to agglomeration in saline environments; and a high specific surface area may adsorb large amounts of polymer, thereby 'exhausting' the additives originally intended for dispersion or viscosification. Therefore, the design problem for nanomaterials should be framed as follows: under a given pore-throat scale, salt type and polymer background, how can a combined particle size distribution be obtained that provides stable dispersion, effective bridging and low-permeability filling?

The graphene oxide material prepared by Luo et al. adsorbs on the bentonite surface at a relatively low dosage and provides steric hindrance under conditions of 4 wt% bentonite, 10 wt% NaCl and 160 °C, suppressing particle aggregation and maintaining a smaller particle size together with the network structure; the study reported that it can improve the cuttings-carrying capacity of the system and reduce fluid loss, and further achieved a lost-circulation control rate of 91.7% with a composite plugging formulation [14]. Here the role of graphene is not only to

physically cover pores as a two-dimensional rigid sheet, but also to adsorb onto clay through surface oxygen-containing groups and to regulate the interparticle spacing. If this interfacial effect is ignored and the lost-circulation control performance is explained solely in terms of a 'high-strength two-dimensional material', then its influence on rheology at low dosage cannot be accounted for.

The micro- and nano- CaCO_3 -reinforced clay-based system further demonstrates the synergy between grading and network formation. The Ca-CBSLTPF reported by Li et al. forms a denser and higher-strength deposited layer through spatial embedding of rigid particles and a clay-polymer hydrogen-bonding network, achieving a thixotropic structure recovery of 115% while maintaining a water retention of more than 90% at high temperature; CT three-dimensional reconstruction and seepage simulation showed that it can inhibit fracture propagation and fluid permeation around the wellbore [34]. The filter cake of this system is relatively thick, but its strength is markedly increased, suggesting that a 'thin filter cake' is not the only objective in all wellbore scenarios: for soft coal seams and fractured formations, a reinforcing layer with load-bearing capacity may be more important than pursuing an extremely thin cake.

5.2 Metal Oxides and the Trade-off Between Different Performance Objectives

Metal oxide nanoparticles differ in surface hydroxyl groups, crystal structure and hydration reactions, so their effects on rheology and fluid loss should not be generalized. Goswami et al. compared Al_2O_3 , MgO and ZnO at the same dosage in a xanthan gum water-based drilling fluid; after aging at 250 °F, ZnO maintained a higher yield value and brought the low-temperature low-pressure (LPLT) fluid loss to 4 mL, but its HTHP fluid loss was 15 mL; MgO gave a lower HTHP fluid loss of 10.2 mL while maintaining relatively stable rheology [15]. SEM showed that the particles can improve filter-cake packing, but the macroscopic results indicate that the optimal particles for LPLT fluid loss, HTHP sealing and cuttings-carrying performance are not the same. This research design is more valuable than merely comparing 'with and without addition', because it reveals the objective conflicts arising from material chemistry and morphology.

Research on the valorization of waste aluminum wire to prepare Al_2O_3 links nanomaterial performance with sustainable manufacturing. Abbood and Al-Anssari prepared crystalline Al_2O_3 with a particle size of no more than about 40 nm via a chemical-thermal treatment and direct precipitation route; after addition to a bentonite water-based system, at the optimal dosage it reduced HTHP fluid loss by up to 33%, LPLT fluid loss by 40.5% and the friction coefficient

by 19%, and inhibited bentonite swelling by about 49% relative to the water control [37]. Its advantages lie in multifunctionality and waste valorization, but calcination at the 1000 °C level is itself energy-intensive; whether it truly lowers the life-cycle burden must be assessed by accounting for the energy source, yield, washing wastewater and transportation, and cannot be judged as a green advantage merely on the basis of a 'waste-derived' origin.

5.3 Polymer Microspheres and Organic-Inorganic Hybridization

Flexible polymer microspheres can deform under differential pressure to enter pore throats and form multi-level filling together with rigid particles. Their particle size, crosslinking density and surface chemistry determine whether they can retain their morphology after thermal exposure and whether they will over-expand. Li et al. reinforced AM/AMPS polymer microspheres with surface-modified SiO₂; 3 wt% of the material reduced the fluid loss of an API bentonite slurry after aging at 150 °C by 63.5%; when 1 wt% was added to a complete water-based system, the fluid loss before and after aging was about 5.2 and 5.0 mL, indicating good temperature and salt resistance [16]. The inorganic SiO₂ provides a thermally stable backbone and filling units, while the polymer phase provides hydration, adsorption and deformation capability; this rigid-flexible combination more readily forms a tough filter cake than nanoparticles alone.

Chitosan-nano-silica hybrid materials, in turn, reveal the importance of the preparation method. da Luz et al. prepared hybrids via different routes, and FTIR, UV, thermal analysis, particle size and zeta potential confirmed an interaction between silanol groups and chitosan amino groups; after use in water-based drilling fluids, the apparent viscosity increased by up to about 23% and the fluid loss decreased by about 60% [17]. However, the evaluation temperatures were mainly 25 and 90 °C, which cannot directly demonstrate applicability at ultra-high temperatures. The more reliable contribution of this study is that it establishes the linkage 'preparation route-interfacial structure-dispersion properties-rheology/fluid loss', providing a mechanistic basis for the design of organic-inorganic hybrids in high-temperature systems.

Cyclodextrin polymer microspheres demonstrate another unconventional pathway. Zhong et al. found that β -cyclodextrin polymer microspheres only significantly activate their fluid-loss-control capability above 160 °C, with temperature resistance up to 240 °C; the high-temperature hydrothermal reaction generates nano carbon spheres and composite structures that fill nano pores and form a dense filter cake [20]. Their subsequent long-term aging study further showed that after about 6 h at 200 °C the fluid loss of the system actually decreased and tended

to stabilize, outperforming the control polymer that continuously destabilized over time [18]. This implies that the 'post-service structure' of a material may be more important than its initial structure. Future evaluations should include analysis of the chemical composition, particle size evolution and reversibility of aged products, avoiding the blanket treatment of high-temperature-induced carbonization as either degradation or beneficial conversion.

5.4 Agglomeration, Dosage Window and Safety Boundaries

The main risks in the application of nanomaterials are agglomeration and a narrow dosage window. A low dosage may be insufficient to cover interfaces or fill pores, while a high dosage increases the solid content, plastic viscosity and filter-cake thickness, and disrupts the original formulation balance by adsorbing polymer. An increase in salt concentration compresses the electrical double layer on the particle surface, making surface-unmodified nanoparticles more prone to agglomeration; high temperature, in turn, accelerates collisions, desorption and chemical reactions. Therefore, studies should not report only the optimum point, but should provide dosage-performance curves, particle size distributions before and after aging, sedimentation stability, and compatibility with key additives.

The health, safety and recycling issues of nanomaterials are insufficiently discussed in existing drilling fluid literature. Once particles enter waste mud, drill cuttings and the formation, they may alter environmental fate; the dissolution and ecological effects of certain metal oxides differ from those of the bulk material. Even if a material can significantly reduce fluid loss, its preparation energy consumption, on-site dust exposure, waste liquid treatment and resource recovery must also be evaluated. On the basis of existing evidence, the nano/composite route can be regarded as having clear potential for interfacial and filter-cake regulation, but it cannot yet be generally concluded that its cost or environmental performance is superior to that of mature polymers.

Table 3 Functional windows and key boundaries of nano and organic-inorganic composite materials

Material type	Main function	Favorable conditions	Key evaluation metrics	Main risks
Graphene oxide and two-dimensional sheets	Interfacial adsorption, steric hindrance and sheet plugging	Brine-based muds and micro-fracture scenarios	Particle size, adsorption, fluid loss and lost-circulation control rate	Cost, dispersion and long-term environmental fate
Al ₂ O ₃ 、MgO、ZnO	Void filling, rheology regulation, filter-cake densification	Systems requiring a balance between fluid loss and cuttings transport	LPLT/HTHP fluid loss, PV, YP and leaching	Agglomeration in salt, reactivity and dust exposure
Polymer microspheres	Deformable filling and pressure adaptation	Micro-/nano pore throats and formations with pressure fluctuations	Particle size retention, compressibility, pressure bearing and flowback	Over-expansion and loss of morphological control after heating
Organic-inorganic hybrids	Synergy between rigid support and flexible film formation	Systems requiring a tough filter cake and multi-level filling	Interfacial bonding, cyclic fluid loss and filter-cake permeability	Complex preparation, component compatibility and dosage window
Hollow or thermally insulating particles	Formation of a low-thermal-conductivity filter cake and thermal barrier	High-heat-flow sections of ultra-deep wells	Thermal conductivity, fluid loss, filter-cake thickness and pressure resistance	Thermal insulation obtained at the cost of rheology or strength

6 Green Modification of Bio-Based Materials and Their Performance Boundaries

6.1 Bio-Based Does Not Mean Used As-Is

Starch, cellulose, xanthan gum, guar gum, chitosan and lignin are widely available and rich in functional groups, generally exhibit lower toxicity and better biodegradation potential, and constitute an important material library for the greening of water-based drilling fluids [24]; waste-derived materials such as coconut coir fiber and bagasse fly-ash zeolite have also been

used to regulate rheology, fluid loss and particulate structure [40,41]. However, natural structures often suffer from batch-to-batch variation, insufficient thermal stability, coiling or precipitation in salt, microbial degradation and storage stability problems. The key to high-temperature and high-salinity applications is not to prove that 'some agricultural waste can be added to mud', but to tune its molecular structure, particle size and interfacial behavior into a reproducible window through controllable modification, and to demonstrate that the modification process does not offset the environmental benefits.

Existing research has roughly formed four modification routes: introducing hydrophobic or ionic groups through etherification, esterification and the like; improving heat resistance and responsiveness through graft copolymerization; forming microspheres or networks through crosslinking; and compositing with inorganic particles, lignocellulosic fibers or other polysaccharides to construct multi-level filling structures. These routes are not sharply distinguished from synthetic polymers. A material that uses starch or chitosan as its backbone and is grafted with acrylic acid and polyether side chains is, in terms of performance mechanism, already a hybrid of a natural backbone and synthetic functional units. Evaluation should report the renewable content fraction, synthetic reagents, energy consumption and degradability simultaneously, rather than affixing a 'green' label solely on the basis of the backbone origin.

6.2 Starch and Cyclodextrin: from Readily Degradable Polysaccharides to Structured Fluid-Loss Additives

Native starch is low in cost and has relatively good film-forming and viscosifying capability, but at high temperature the cleavage of glycosidic bonds, gelatinization and degradation alter its viscosity, and salt and microorganisms also affect its stability. A review of modified starches shows that carboxymethylation, grafting, crosslinking and nano-sizing can extend their temperature resistance and fluid-loss-control range, but the economics and environmental burden differ markedly among modification routes [22]. Zhang et al. prepared a micro-/nano rod-like composite fluid-loss additive, SW, from hydroxypropyl starch and walnut shell powder via inverse emulsion polymerization; 3 wt% SW reduced the fluid loss of a 4 wt% bentonite dispersion after aging at 190 °C for 16 h from 49 mL to 8.4 mL, while maintaining a relatively low viscosity. Zeta potential, particle size and filter-cake morphology indicated that its action derives from colloidal stabilization, particle size optimization and pore filling [25]. This study shows that biomass fibers/particles can serve as structural units rather than merely inert fillers.

Cyclodextrin is a cyclic oligosaccharide derived from starch, with hydrophilic outer hydroxyl groups and a hydrophobic inner cavity, making it suitable for host-guest assembly, crosslinked microspheres and poly(ionic liquid) backbones. The high-temperature hydrothermal transformation of β -cyclodextrin microspheres [18-20] and the low fluid loss exhibited by poly(ionic liquid)-cyclodextrin systems [13] together indicate that the value of cyclodextrin derives not only from its natural origin, but also from its rigid cyclic backbone, abundant hydroxyl groups and the constructible cavity network. It should be noted that crosslinking agents, ionic liquid monomers and the emulsion polymerization process may increase the environmental burden, and related studies should provide data on residual monomers, degradability and wastewater treatment.

6.3 Xanthan Gum, Guar Gum and Cellulose: Rheological Function and Thermal-Saline Adaptation

Owing to its rigid helical conformation and pronounced shear thinning, xanthan gum is one of the most mature bio-based rheology modifiers for water-based drilling fluids. Its performance is governed jointly by concentration, pH, salinity, temperature, aging time and interactions with other polysaccharides [23]. A moderate amount of salt can sometimes screen charges along the chain and stabilize the ordered conformation, but prolonged high temperature still causes viscosity decay. Blending xanthan gum with natural gums can improve static gel strength but does not necessarily improve dynamic cuttings transport [39]; therefore, the goal of modification should not be to raise viscosity unconditionally, but to maintain the rheological window and recoverability at the target shear rate.

The cis-hydroxyl groups and long polymer chains of guar gum favor hydration and viscosification, but the native structure has limited salt and heat resistance. Pires Neto et al. introduced hexyl groups via etherification with 1-bromohexane; the hydrophobic modification increased the hydrodynamic size and induced association in water, giving better thermal aging stability and better rheology and fluid loss under high NaCl conditions than native guar gum, with a denser filter cake and performance approaching that of xanthan gum systems [21]. This demonstrates that a small number of hydrophobic groups can transform a natural polysaccharide from a mere hydration viscosifier into a reversibly associating multifunctional additive. At the same time, the use of organic halogenated reagents, control of the degree of substitution and treatment of residual reagents should be incorporated into the green assessment.

Cellulose is abundantly available and readily nano-sized. When cellulose nanoparticles derived from apricot shells were used in an 8.7 ppg water-based system, they increased the yield

value from 30 to 33 lb/100 ft² and reduced the 30-min fluid loss from 18 to 10 mL, improving suspension and filtration while maintaining flow behavior [26]. That study did not cover ultra-high temperature and high salinity, so it is better regarded as early evidence for a sustainable particulate platform. By contrast, grafting poly(ethylene glycol) methacrylate onto the surface of cellulose nanocrystals provides a tunable LCST and thermothickening behavior; beyond the LCST the grafted chains strengthen hydrophobic interactions and form clusters and networks with bentonite, endowing an oil/water Pickering emulsion drilling fluid with a water continuous phase with temperature-responsive rheology [31]. This composite design extends the role of cellulose from a passive particle to an intelligent interfacial stabilizer.

6.4 Chitosan and Lignin: from Adsorption and Film Formation to Wellbore Strengthening

Chitosan contains amino and hydroxyl groups and readily undergoes hydrogen bonding and electrostatic interactions with silanol, clay and negatively charged surfaces. Its hybridization with nano-SiO₂ can simultaneously increase apparent viscosity and reduce fluid loss [17]; after carboxymethyl chitosan is grafted with polyether and acrylic acid, it can form temperature-sensitive nano micelles and heated aggregates for adaptive plugging of microporous formations [27]. Together, the two studies indicate that the advantages of chitosan are its chemical modifiability and interfacial affinity, while its limitations are acid-base sensitivity, variability in molecular weight and degree of deacetylation, and insufficient thermal stability in the unmodified state.

Lignin possesses an aromatic backbone and various phenolic hydroxyl groups, making it a candidate that combines rigidity, adsorptivity and a renewable origin. Song et al. condensed dealkalized lignin with furfural in a deep eutectic solvent to prepare a lignin-based wellbore-strengthening adhesive for use in water-based drilling fluids for fractured shale; the core idea is for the material to produce bonding and structural reinforcement after entering fractures, rather than merely reducing fluid loss [28]. This route advances the concept from a 'green fluid-loss additive' to a 'renewable wellbore structural material', but data are still needed on deep eutectic solvent recovery, reaction scale-up, long-term formation compatibility and reversible plug removal.

6.5 The Evidence Boundary of Green Claims

The environmental advantages of bio-based materials should be disaggregated into at least five stages: feedstock renewability, synthesis process, dosage used, service life and end-of-life

disposal. Agricultural waste may reduce the feedstock burden, but washing, acid-base treatment, solvothermal reactions and high-temperature calcination bring energy consumption and waste liquid; biodegradable materials facilitate end-of-life disposal but may also reduce storage and long-term downhole stability; and the low toxicity of natural materials does not mean that the modification monomers and crosslinking agents are of low toxicity. Most current studies report only feedstock origin and laboratory performance, and lack life-cycle assessment, toxicity, chemical oxygen demand, residual monomer and on-site waste mud data [19,22,24].

Therefore, at the present stage it can reasonably be concluded that bio-based backbones provide a material basis for reducing dependence on petrochemical feedstocks, and that structural modification has already enabled some systems to reach laboratory performance at the 190-200 °C level; however, the strong claim of being 'greener and more economical' still requires life-cycle and scale-up evidence. In the future, green metrics should be placed on a par with rheological and fluid-loss metrics, rather than being used as qualitative embellishment in the introduction and conclusion of papers.

Table 4 Modification routes and evidence gaps for representative bio-based materials

Bio-based backbone	Common modification routes	Main function	Demonstrated advantages	Evidence still required
Starch and cyclodextrin	Carboxymethylation, grafting, crosslinked microspheres, poly(ionic liquid) compositing	Fluid loss control, void filling and host-guest assembly	Fluid loss control at the 190 °C level and in-situ material formation at high temperature	Residual monomers, degradability and scale-up cost
Xanthan gum and guar gum	Hydrophobic etherification, blending and associative modification	Shear thinning, suspension and fluid loss control	Tunable dynamic cuttings transport or salt-induced association	Long-term thermal-saline cycling and consistency of the degree of substitution
Cellulose	Nano-sizing, surface grafting and thermo-responsive modification	Particle stabilization, suspension and thermosensitive thickening	Renewable particulate platform and interfacial responsiveness	Ultra-high-temperature and high-salinity stability and emulsion compatibility

Bio-based backbone	Common modification routes	Main function	Demonstrated advantages	Evidence still required
Chitosan	Carboxymethylation, grafting and SiO ₂ hybridization	Adsorption, film formation and adaptive plugging	Chemically modifiable with interfacial affinity	Degree of deacetylation, pH sensitivity and thermal stability
Lignin and agricultural waste	Condensation, compositing, carbonization or zeolitization	Cementation enhancement, rheology and particulate filling	Renewable aromatic backbone and waste valorization	Solvent/calcinatio n energy consumption, batch variation and life cycle

7 Stimuli-Responsive Behavior and Wellbore Functionalization

For bio-based backbones and stimuli-responsive units to enter engineering systems, they must pass through four transitions: controllable modification, confirmation of the trigger window, evaluation under coupled conditions, and field feedback. Figure 5 unifies the evidence chain that must be completed between 'green feedstock' and 'engineering usability'.

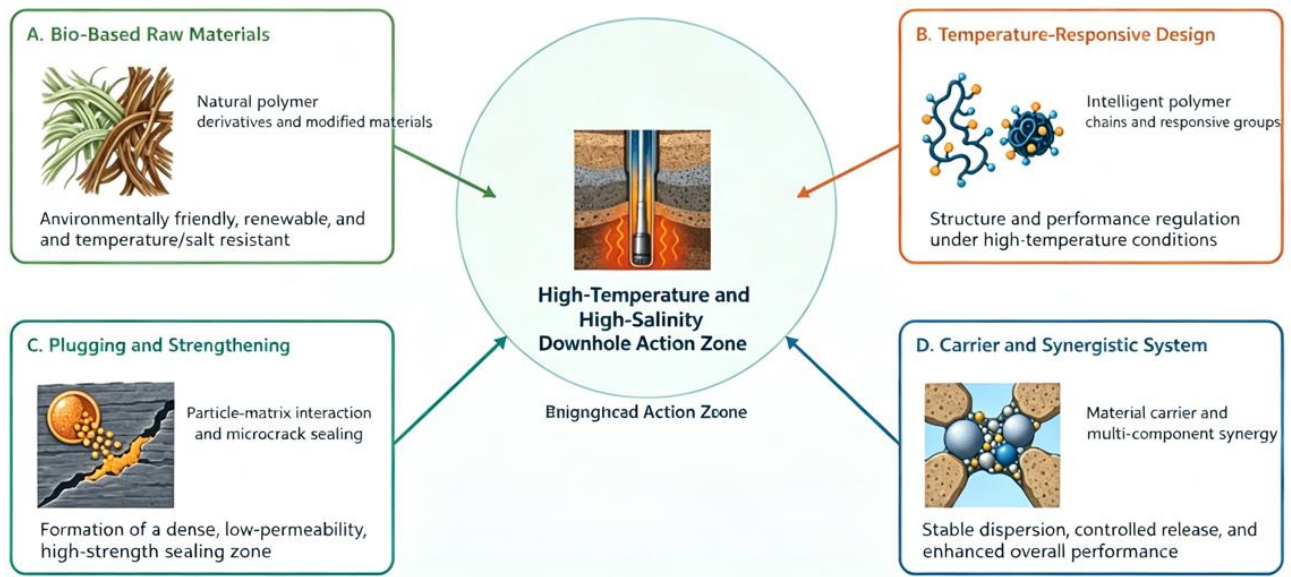


Figure 5 Green regulation mechanisms and engineering evaluation framework integrating bio-based functionalization, thermosensitive regulation, fracture self-healing and interfacial plugging (summarized from [21-33,35,39-41])

7.1 On-Demand Aggregation and Reversible Plugging of Thermosensitive Polymers

Thermosensitive polymers undergo a dissolution-aggregation transition near the LCST or UCST, so that the system presents different states at the wellhead and at the bottom hole. For LCST-type materials, the hydrophilic chain segments are fully hydrated and remain dispersed at low temperature; after heating beyond the transition temperature, dehydration of the chain segments and hydrophobic interactions are enhanced, forming micelles, clusters or networks that increase viscosity or plug pore throats. Wang et al. pointed out in a review that thermosensitive units can be used for rheology regulation, lost-circulation control, fluid loss reduction and viscosity reduction, but are still constrained by salt tolerance, mechanical strength, long-term integrity and cost [29].

Lei et al. grafted poly(ethylene glycol) methyl ether methacrylate and acrylic acid onto carboxymethyl chitosan and adjusted the acrylic acid ratio so that the LCST fell between 90 and 110 °C; after exceeding the trigger temperature, the original nano micelles aggregated into mesoscopic assemblies and plugged the pore throats of low- and medium-permeability cores, partially dissociating upon cooling, exhibiting a temperature switch and adaptivity [27]. The engineering value of such materials lies in reducing ineffective consumption in non-target well sections and in making subsequent plug removal possible. The key risk is that downhole salinity, shear and rock surface adsorption alter the LCST and its reversibility, so the transition temperature measured in laboratory pure water or simple brine cannot be used directly as the field trigger temperature.

The Pickering emulsion system stabilized by thermo-responsive cellulose nanocrystals, by contrast, is regulated jointly by interfacial adsorption and thermally induced association. Cellulose nanocrystals grafted with POEGMA adsorb at the oil-water interface, while bentonite reinforces the aqueous-phase network; beyond the LCST, hydrophobic interactions promote the formation of particle-clay clusters, producing thermothickening and lower API fluid loss [31]. This design integrates emulsion stabilization, rheology and thermosensitive function into a single system, but the emulsion type, the influence of the oil phase, the reversibility of thermal cycling and interfacial competition under high salinity still require further evaluation.

7.2 Self-Healing, Cementation and Film Formation, and Hydrophobic Inhibition

Wellbore instability in fractured and broken formations involves barrier failure and a reduction in rock mass strength, and simple particle filling is difficult to cope with fracture propagation and pressure fluctuations. Self-healing microcapsules rupture their shells under

temperature, pressure or mechanical damage, releasing reactive core material that polymerizes or bonds within fractures. Yan et al. constructed double-walled self-healing microparticles containing bisphenol A and luteolin epoxy monomers; after treatment in a 160-200 °C aqueous environment, the material brought the shear strength of shale coupons to 634-707 kPa, reduced the permeability of artificial cores from 0.95 to 0.162 mD, and achieved a plugging rate of 82.95%; the mechanism is that the microparticle shells rupture and release the core material, cementing loose rock fragments into a dense whole [32]. These results provide both seepage and mechanical evidence, but the completeness of the epoxy reaction, unreacted monomers, plug-removal capability and long-term embrittlement still warrant attention.

The cementation-film formation-hydrophobic route emphasizes the establishment of a continuous interface. Pore fractures in deep coal-rock span multiple scales, and a material of a single particle size is difficult to apply across the full range. Sun et al. proposed a system of 'efficient plugging of medium and large pore fractures + cementation and film formation in micro and small pore fractures + overall surface hydrophobic inhibition': flexible organic-inorganic microspheres adapt to pore throats through deformation, while an inhibitor containing strongly adsorbing and hydrophobic groups forms a cemented film on the rock surface and reduces its hydrophilicity; experiments and field application showed that the system balances rheology, fluid loss, lubrication, anti-collapse performance and cuttings transport [33]. Its significance lies in extending formulation design from the bulk properties of the mud to formation surface engineering, but the range of applicability to different coal-rock minerals and fracture structures still requires more well-site comparisons.

7.3 Thermal Management and Multifunctional Filter Cakes

The conventional strategy is mainly to make additives 'tolerant of high temperature', whereas another approach is to reduce the heat input from the wellbore into the drilling fluid. Research on nanomaterials that enhance the thermal conductivity or thermal insulation of drilling fluids has formed an independent direction of thermal management [36]; among these, hollow silica nanospheres reduce thermal conductivity through their hollow structure, mesoporous shell and phonon scattering, and form a continuous insulating network in the filter cake [35]. Such thermal management materials can slow the thermal degradation of additives and reduce the thermal load on downhole tools, but the added particles also change the plastic viscosity, yield value and filter-cake thickness. Their evaluation should incorporate thermal conductivity, fluid loss, rheology, pressure resistance and long-term cycling simultaneously, avoiding the sacrifice of hydraulic performance in exchange for localized thermal insulation.

From a broader perspective, an intelligent drilling fluid does not rely on a single 'responsive' molecule, but is composed jointly of a stable base fluid, triggerable functional materials, and monitoring and control. Responsive materials must have a well-defined trigger window, sufficient triggering speed, cycling reversibility and fail-safe behavior; the downhole temperature gradient, salt type, shear history and contaminants cause the laboratory trigger threshold to drift. Only by embedding the response curves into wellbore temperature-pressure models and operational procedures can intelligent materials move from proof of concept to operable technology.

8 Comparison of Representative Evidence, Controversies and Limitations

8.1 Benefits and Costs of the Different Routes

Taking the existing evidence together, the advantages of synthetic polymers are tunable structure, well-defined function and accumulated system-compatibility experience, making them suitable for providing the baseline high-temperature and high-salinity stability; the costs are complex synthesis, residual monomers and environmental disposal pressure, together with possible over-thickening or irreversible adsorption. Nano and organic-inorganic composite materials excel at interfacial regulation, micropore filling and filter-cake densification, and can also introduce functions such as thermal insulation and lubrication; their limitations are agglomeration, the dosage window, particle safety and scale-up cost. Bio-based materials possess renewable backbones and abundant functional groups, but without modification they lack temperature and salt resistance, and once modified they face the problem that their 'green attributes are diluted by the synthesis process'. Stimuli-responsive materials can act according to temperature or damage location and in principle reduce ineffective dosage, but they place higher demands on the trigger window, cycling stability and downhole models.

These routes are not in a relation of substitution, but are more likely to constitute a layered system: temperature- and salt-resistant polymers maintain the continuous phase and particle dispersion, rigid-flexible composite particles optimize grading and the filter cake, bio-based structures reduce dependence on some petrochemical feedstocks, and a small amount of responsive material addresses localized plugging, film formation or thermal management. Both the high-density saturated brine system of Huang et al. [7] and the deep coal-rock cementation and film formation system [33] support the engineering philosophy that 'synergy among

multiple additives is preferable to a universal single additive'. However, multiple components also increase the difficulty of formulation interactions and quality control, requiring orthogonal or response surface experiments, mechanism-constrained data models and long-term cycling verification.

Table 5 Multi-scale effects and evidence boundaries of the main material routes

Material route	Main length scale of action	Representative benefits	Main limitations	Representative refs.
Temperature- and salt-resistant synthetic polymers	Molecular conformation, interfacial adsorption, mesoscopic network	Tunable structure, suitable for maintaining rheology, dispersion and fluid loss	Complex synthesis, possible over-thickening or irreversible adsorption	[7-13]
Nano and organic-inorganic composite materials	Particle interfaces, particle size grading, filter-cake pores	Rigid-flexible synergy, suitable for micropore filling, plugging and thermal management	Agglomeration in salt, dosage window and particle safety	[14-20,34-37]
Bio-based and modified natural materials	Hydrated chains, reversible association, film formation and bonding	Renewable backbone, multiple functional groups and potentially low toxicity	Batch variation, insufficient intrinsic temperature and salt resistance, modification burden	[21-28,39-41]
Stimuli-responsive and wellbore functional materials	Thermosensitive assembly, damage triggering, wellbore interface	On-demand thickening, plugging and healing in the target temperature zone or fracture	Trigger drift, insufficient cycling and long-term field evidence	[27,29-33,35]

8.2 Why Performance Figures Are Often Not Directly Comparable

A value labeled as 'fluid loss after aging at 180 °C' may correspond to different bentonite sources and concentrations, different salt types and salinities, different aging times, static or rolling aging, API or HTHP tests, and different measurement temperatures and differential pressures. Some papers use the aging temperature as the HTHP test temperature, while others measure after cooling; some evaluate the heat resistance of a material in a freshwater base mud, while others evaluate it in saturated brine and high-density systems. Even when the fluid loss is the same, the filter-cake thickness, permeability, compressibility and formation damage may differ [3,4].

For example, a cyclodextrin poly(ionic liquid) gave an API fluid loss of 2.8 mL after 180 °C [13], P-DADL gave an API fluid loss of 6.4 mL at 180 °C and 35 wt% NaCl [10], and SMPU reported an HTHP fluid loss of 15.6 mL at 210 °C [11]. These three figures cannot be ranked simply, because the salinity, base mud, differential pressure, measurement temperature and target function differ. A reasonable comparison should first group by 'equivalent evaluation level': freshwater base mud screening, brine base mud, weighted complete systems, contaminated cycling systems, core/fracture plugging, and field application; then compare the performance retention, dosage, filter-cake quality and side effects within the same group.

8.3 The Hierarchy of Mechanistic Evidence

Many studies use FTIR to demonstrate the presence of functional groups, thermogravimetry to show a relatively high decomposition temperature, and SEM to display a denser filter cake, and then propose a complete mechanism. However, these pieces of evidence may only be correlated. Stronger mechanistic evidence should include: quantitative information on material structure; molecular weight or chemical changes before and after aging; variations of adsorption capacity, zeta potential and particle size with temperature and salinity; rheological frequency sweeps or thixotropic recovery; filter-cake porosity, permeability and elemental distribution; and, where necessary, molecular simulation or in-situ characterization to explain the pathway of action. The combination of multiple characterization techniques with molecular simulation by Liu et al. on the high-temperature failure of clay [2], and the tracking of aging time and newly formed carbon spheres by cyclodextrin microspheres [18,20], represent relatively complete cross-scale evidence.

Conversely, a single SEM image is easily affected by sampling, drying and field-of-view selection; an increase in the absolute value of the zeta potential generally supports enhanced dispersion, but cannot rule out polymer adsorption shifting the position of the shear plane; and a thermogravimetric decomposition temperature cannot substitute for functional stability in aqueous solution. This paper therefore rates the evidence strength of most primary studies as moderate, and does not upgrade it to strong merely because the performance figures are outstanding.

8.4 Extrapolation Limits of the Existing Literature

First, most studies test a single additive in a laboratory base mud and lack compatibility data with real multi-additive systems. Second, high temperature and salt contamination are often investigated separately, and are seldom combined with high density, CO₂/H₂S, drill-

cuttings invasion and repeated thermal cycling. Third, the evaluation duration is usually around 16 h, which is difficult to extend to long horizontal-section drilling, pump stoppages and multiple circulation cycles. Fourth, field evidence is scarce, and successful cases often lack contemporaneous controls, failure cases and complete cost data. Fifth, environmental assessment mostly stops at feedstock origin and qualitative 'low toxicity', lacking standard ecotoxicity, degradability and life-cycle analysis.

This paper itself also has scope limitations. The candidate pool consists of the 61 PDFs provided by the user; although the full-text coverage is high and recent materials research is well represented, no systematic search of external databases was performed, so classic literature, negative results, patents, standards and non-open-access studies may have been missed. The number of candidates does not meet the requirement of 150 references for a Grade A submission-level narrative review; therefore, the conclusions of this paper are suitable for establishing the research context of a specific topic and for a draft manuscript, and should not be described as an exhaustive judgment of the entire field.

8.5 Building a Reproducible Evidence Package Instead of Reporting Only the Optimal Formulation

Current papers often focus their research on the 'optimal dosage' and its percentage improvement relative to a blank, while providing relatively little data that would allow the results to be recomputed and transferred. A reproducible evidence package for a drilling fluid material should include at least the raw material batch and purity, synthesis feed and yield, molecular weight or particle size distribution, the complete base mud formulation, mixing order, shear energy, aging cell fill ratio, temperature-time curve, test instrument calibration, number of replicates and raw rheological readings. For polymers, the monomer molar ratio, residual monomers, molecular weight distribution and degree of substitution should be disclosed; for nanomaterials, the specific surface area, surface modification, agglomeration state and dispersion method; and for bio-based materials, the source, season/batch, pretreatment and compositional variability should be stated.

Statistical reporting also needs strengthening. Many materials studies present improvements of tens of percentage points based on a single representative value or a small number of replicates, without reporting variation, confidence intervals or experimental-day effects. Because drilling fluid preparation and fluid loss testing themselves involve operator and batch variation, independent preparation replicates should at least be performed, rather than only repeated readings on the same sample. Multifactor optimization should not merely select

the mathematical optimum, but should also test its robustness to feedstock fluctuations and operational error. If superiority over a commercial additive is claimed, the comparison should be made under reasonable conditions of equal effective solids content, equal cost or equal environmental burden, and the brand name and active ingredients of the commercial product should be stated.

Negative results and failure boundaries are equally important. The salinity at which a material begins to precipitate, the temperature at which irreversible thickening occurs, and the additive after which it loses its function often provide better field guidance than a single optimum value. It is recommended to report a three-dimensional temperature-salinity-dosage performance window and to identify explicitly the forbidden zone, transition zone and stable zone; for responsive materials, the trigger hysteresis, number of cycles and post-trigger residual performance should also be reported. Such an evidence package can enter a shared database directly and provide reliable input for cross-laboratory replication and physics-constrained machine learning.

9 Research Directions for Engineering Translation

9.1 Establishing Coupled-Condition and Tiered Evaluation Protocols

Future research should shift from single-factor 'heat resistance tests' to a condition matrix. At a minimum, the base mud mineral and concentration, polymer molecular weight/degree of substitution, salt type and salinity, pH, weighting material, aging method and duration, measurement temperature, HTHP differential pressure, number of replicates and error should be reported. A four-tier evaluation is recommended: the material solution level for chemical stability and conformation; the standard base mud level for screening interfacial behavior and fluid loss; the weighted/contaminated complete system level for formulation compatibility and cycling; and the core, fracture and field level for wellbore and formation effects. Proceeding to the next tier only after the performance at the previous tier is stable can reduce the accumulation of materials that 'perform excellently in a simple base mud but cannot enter an engineering system'.

Combined contamination should cover at least high temperature $\times$ NaCl/CaCl₂, high temperature $\times$ high-density solids, high temperature $\times$ CO₂/H₂S, and multiple thermal-contamination cycles. The five temperature-contamination cycles of DN-1 [8] provide an example closer to engineering disturbances than single aging; the 5-day static sedimentation

evaluation of a high-density brine system [7] also reflects ultra-deep well risks better than short-term rheology. In the future, shear history, pressure fluctuations and filter-cake destruction-recovery cycles should also be included.

Table 6 Recommended tiered evaluation protocol for engineering translation

Evaluation tier	Core purpose	Conditions to be reported	Key outputs	Criteria for advancing to the next tier
Material solution level	Assess chemical stability and conformational window	Temperature, salt type, pH, aging time	Molecular weight, turbidity, particle size, viscosity and structural changes	No precipitation and reproducible function within the target window
Standard base mud level	Verify clay interfaces and baseline fluid loss	Base mud mineral, salinity, shear and API/HTHP conditions	Full rheological curves, fluid loss, filter cake and interfacial characterization	Advantage independent of a single dosage point and no abnormal thickening
Complete system level	Examine multi-additive compatibility and sedimentation stability	Weighting agent, contaminants, thermal cycling and standing time	Rheological window, sedimentation factor, lubrication and cyclic fluid loss	Remains controllable in a real formulation with acceptable side effects
Core and fracture level	Verify formation plugging, wellbore and reservoir effects	Pore-throat/fracture scale, mineral composition and differential pressure cycling	Permeability, pressure bearing, rock strength, flowback and plug removal	Achieves the target well-section function and its recoverability meets the intended use
Pilot and field level	Verify scale-up, maintenance and economic-environmental performance	Long-duration cycling, real drill cuttings and wellbore temperature-pressure trajectory	Additive maintenance demand, complications, cost and waste mud load	Stable net benefit relative to a control or historical baseline

9.2 Developing In-Situ Multi-Scale Characterization and Falsifiable Mechanistic Design

Materials research needs to shift from 'endpoint comparison' before and after aging to process observation. High-temperature high-pressure in-situ rheology, in-situ small-angle scattering, NMR, microscopic imaging and on-line particle size/reflectance measurements can track changes in chain conformation, clusters and networks; micro-CT can reconstruct filter-cake and core pores, and combined with differential-pressure seepage can yield structure-permeability relationships; molecular dynamics and mesoscopic simulations should be calibrated with measurable adsorption, diffusion and interaction parameters. Mechanistic hypotheses should also be designed with falsifiable controls, for example by changing a single functional group, blocking a specific interaction, or comparing particles of equal size but different surface chemistry, rather than only comparing a new material with a blank base mud.

9.3 Data-Driven Formulation Optimization Must Embed Physical Constraints

High-temperature high-salinity drilling fluids are characterized by multiple objectives, multiple variables and strong interactions, making them suitable for machine-learning-assisted optimization. Existing studies have begun to use multi-output models to predict the rheology of high-density water-based mud [9], and reviews of HPHT drilling fluids also regard AI/ML as a direction for formulation and performance prediction [6]. However, small sample sizes, incomplete formulation records and differences in protocols across laboratories cause models to learn the data source rather than the material laws. Future databases should record monomers, molecular weight, dosage, base mud, temperature-salinity-pressure, aging and performance using unified fields, and retain negative results; models should incorporate physical constraints such as mass conservation, rheological constitutive relations, particle size grading and temperature dependence, and output uncertainty and the domain of applicability, rather than only a single-point optimal formulation.

9.4 Moving from 'Green Feedstock' to Full Life-Cycle Performance

Green assessment should be designed in parallel with technical performance. For starch, cellulose, chitosan, lignin and agricultural-waste-derived materials, the feedstock pretreatment, solvent, reaction temperature, yield, water consumption, residual monomers and degradability should be reported; for nanomaterials, the preparation energy consumption, dust safety, leaching and end-of-life fate should be reported. The unit of assessment should shift further from 'per kilogram of material' to 'the material and energy required to achieve an equivalent

well-section function', because a synthetic polymer with higher durability and lower dosage may have a lower full-cycle burden in some scenarios. Cost should also include preparation, maintenance, effects on rate of penetration, waste mud disposal and accident risk, rather than comparing only raw material prices.

9.5 Advancing Material-System-Formation Co-Design

The most promising direction for the future is not to continue stacking more functional groups, but to reverse-design material combinations based on formation pore fractures, minerals and the temperature-pressure trajectory. The continuous phase requires temperature- and salt-resistant polymers to maintain the rheological window; the particulate phase should be graded in a rigid-flexible multi-level manner according to the pore-throat distribution; the wellbore interface uses adsorption, film-forming or cementing units; and specific well sections are further equipped with thermosensitive, self-healing or thermally insulating materials. Formulation optimization objectives should simultaneously include pumping, cuttings transport, sedimentation, fluid loss, plugging, lubrication, reservoir protection and disposal, rather than minimizing a single metric. Field trials should define success and failure criteria in advance and record additive additions, maintenance frequency, downhole complications and long-term integrity, forming closed-loop evidence that can be used for model updating.

9.6 Building a Staged Verification Route from Laboratory to Well Site

Engineering translation can adopt a staged route of 'material screening-system compatibility-core/fracture-pilot circulation-field trial'. The material screening stage emphasizes structure and basic temperature-salinity stability; the system compatibility stage adds the candidate additive to a real complete formulation and examines its interactions with thinner, lubricant, weighting agent and shale inhibitor; the core/fracture stage evaluates invasion, pressure bearing and plug removal according to the pore-throat and mineral composition of the target formation; the pilot stage uses a circulation loop, heating and pressurization and real drill cuttings to simulate prolonged shear and contamination; and the field stage evaluates maintenance demand, hole enlargement, torque and drag, complications and waste mud cost against a well-section-matched control or historical baseline.

Each stage advancement should include 'stop conditions'. For example, if a material gives excellent fluid loss in a simple base mud but causes loss of control over the yield value after entering a weighted system, it should return to structural or dosage optimization rather than proceeding directly to core tests; if the plugging rate is high but permeability recovery after

flowback is poor, it is not suitable for reservoir sections; and if a bio-based material has acceptable technical performance but large batch variation, feedstock standards must first be established. A staged route allows limited resources to be concentrated on candidates that genuinely possess system compatibility and formation adaptability, and can also reduce failures after a material that only works under the optimal conditions of a paper enters the field.

9.7 Establishing Short-, Medium- and Long-Term Research Priorities

The focus of short-term work should be to improve the comparability of existing materials: establish shared testing protocols around commonly used base muds and representative salt types, conduct head-to-head comparisons of zwitterionic polymers, hydrophobically associating polymers, modified polysaccharides and nanocomposites, and disclose the raw data. In the medium term, materials showing stable performance should be placed in high-density, multi-contaminant and long-duration cycling systems, using core and fracture models to verify filter-cake toughness, plugging pressure bearing and reservoir recovery, while completing pilot scale-up, batch variation and preliminary toxicity evaluation. The long-term goal is to form a formulation platform that can be adjusted in real time according to the wellbore temperature-pressure trajectory and formation pore throats: sensor data are used to identify rheological and fluid loss risks, physics-constrained models predict additive requirements, responsive materials perform plugging, film formation or thermal management in the target well section, and flowback and waste mud data are used to evaluate full life-cycle performance.

These three stages should be connected by unified material identifiers, formulation data structures and failure records. If a short-term protocol cannot reproduce a material's advantage, the problem should not be concealed by adding functional monomers; if a medium-term complete system shows insufficient compatibility, priority should be given to redesigning the material combination rather than continuing to optimize the simple base mud; and if long-term intelligence lacks reliable sensing and model applicability domains, a manually controllable safe mode should be retained. The value of research prioritization lies in converting innovation from a performance peak in a paper into verifiable, scalable and maintainable engineering capability.

10 Conclusions

The failure of high-temperature and high-salinity water-based drilling fluids is the result of the continuous evolution of molecules, interfaces, mesoscopic networks and filter-

cake/wellbore structures. High temperature not only causes chemical degradation of polymers, but also alters clay interlayers, surface hydroxyl groups and hydrophilicity; high salinity not only compresses the electrical double layer, but also reshapes chain conformation, adsorption competition and hydrophobic association. Macroscopically, these changes jointly determine particle coalescence, shear thinning, suspension, filter-cake permeability and wellbore strength. Therefore, a single functional group, a single particle size or a single fluid loss metric is insufficient to define the merits of a material.

The existing evidence supports three overall judgments. First, the key to temperature- and salt-resistant synthetic polymers is the synergy of hydration, adsorption, steric hindrance, chain rigidity and reversible association, and zwitterionic groups, comb-like side chains and hydrophobic association provide relatively strong adaptability to complex salt contamination. Second, the effects of nano and organic-inorganic composite materials derive mainly from controllable interfaces and particle size grading, and the problems of agglomeration, dosage window and competitive adsorption with polymers must be addressed. Third, bio-based and stimuli-responsive materials are pushing water-based drilling fluids toward renewability, multifunctionality and on-demand regulation, but strong evidence is still lacking for their green advantages, long-term cycling and field reliability.

Research in the next stage should shift the focus of innovation from 'synthesizing a new material and reporting its optimum point' to 'demonstrating cross-scale mechanisms, performance boundaries and engineering translatability under a unified protocol'. Standardized coupled conditions, in-situ characterization, physics-constrained data models, life-cycle assessment and material-system-formation co-design will determine whether high-performance water-based drilling fluids can truly replace more oil-based systems and safely serve deep and ultra-deep oil and gas development.

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