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A Comprehensive Investigation of Performance of Periwinkle Shell Powder in Water-Based Mud Systems

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***Abstract**: The valorization of periwinkle shell powder (PSP) as a high-performance additive for water-based drilling fluids represents a significant advancement in sustainable and multifunctional wellbore engineering. PSP, a biogenic calcium carbonate material, exhibits a dual polymorphic crystal structure dominated by aragonite and calcite, which imparts superior stiffness, fracture toughness, and adaptive microfracture behavior. This mineralogical framework, combined with controlled particle-size engineering, enables optimized bridging efficiency, low-permeability filter cake formation, and enhanced mechanical stability under high-pressure, high-temperature (HPHT) conditions. X-ray diffraction and elemental analyses confirm a composition primarily of calcium carbonate with minor magnesium, iron, and silicon content, which influence hydration, electrostatic interactions, and polymer adsorption, enhancing rheological performance and thermal resilience in WBM systems. PSP-modified WBMs demonstrate significant improvements in plastic viscosity, yield point, and flow behavior index, achieving controlled transition from Bingham to Herschel–Bulkley-like flow while maintaining stability across a wide thermal range. Engineered particle distributions allow multi-scale pore throat sealing, minimizing fluid invasion, differential sticking, and formation damage, while forming mechanically resilient, thin, and reversible filter cakes. In comparison to conventional bridging agents, including barite, limestone, marble dust, and other biogenic solids, PSP exhibits superior particle interlocking, tunable size distribution, acid solubility, and thermal stability, providing multifunctional filtration control and wellbore-strengthening capabilities. PSP further contributes to shale stability through divalent cation release, micro-fracture filling, and modulation of water activity, suppressing clay swelling and stabilizing capillary pressures in shaly formations. Environmental and toxicological assessments indicate negligible heavy metal leaching, high marine biodegradability, and a reduced carbon footprint. Economic and supply chain analyses highlight the potential for local sourcing in Nigeria, import substitution, and cost-effective large-scale deployment. This review systematically integrates mineralogical, chemical, mechanical, rheological, filtration, and geomechanical aspects of PSP, establishing a scientifically robust foundation for its formulation, optimization, and field implementation in advanced drilling operations. PSP emerges as a next-generation additive that combines engineering performance, environmental sustainability, and economic viability, enabling safer, more efficient, and high-performance drilling fluid systems for complex subsurface conditions.*

Keywords— Periwinkle Shell Powder; Water-Based Drilling Fluids; Filter Cake Microstructure; HPHT Filtration Control; Rheology; Wellbore Stability component

1. INTRODUCTION

Water-based drilling fluids remain the dominant circulating fluid system in global drilling operations due to their environmental acceptability, operational flexibility, low cost, and ease of formulation; however, their fundamental physicochemical limitations continue to impose severe constraints on drilling performance, particularly in reactive shale formations and thermally stressed well environments. One of the most persistent technical drawbacks of conventional water-based mud systems is their inherently poor shale inhibition capacity, arising from the strong potential of water molecules to penetrate smectite-rich and mixed-layer clay structures through osmotic hydration and capillary suction mechanisms. The ingress of free water into shale nanopores results in interlayer swelling, cation exchange imbalance, progressive shear failure of bedding planes, and ultimately time-dependent wellbore collapse [3]. This hydration-induced instability is further exacerbated by the weak membrane efficiency of most untreated WBM systems, which are unable to sustain sufficient semi-permeable barriers to restrict ionic diffusion between the mud column and the formation pore fluid.

In addition to instability, high filtrate invasion remains a persistent challenge in WBM engineering, largely driven by the limited capacity of conventional bentonite–polymer structures to develop low-permeability, mechanically competent filter cakes under elevated differential pressures

[8]. Excessive filtrate losses not only accelerate shale hydration but also promote invasion-induced formation damage, reduction in near-wellbore permeability, impairment of hydrocarbon mobility, and increased torque and drag through thick, compressible filter cakes. These challenges become magnified in highly deviated and extended-reach wells where prolonged contact between reactive shales and filtrate enhances time-dependent failure and tight hole conditions [7].

Thermal stability also constitutes a critical weakness of water-based muds, especially as drilling operations increasingly migrate toward high-pressure high-temperature (HPHT) environments where bottom-hole temperatures routinely exceed 150–200 °C. Many conventional polymeric viscosifiers and filtration control agents in WBM undergo thermal scission, oxidative degradation, and conformational collapse at elevated temperature, resulting in catastrophic loss of viscosity, yield strength, and gel structure [9]. The thermal thinning of WBM directly compromises cuttings suspension, annular transport efficiency, and hole cleaning performance, while simultaneous increases in fluid loss undermine wellbore stability at depth. Poor lubricity further distinguishes WBM from oil-based systems, as the polar nature of aqueous continuous phases promotes high friction coefficients between the drill string and the wellbore wall, especially in shale-dominated and micro-fractured intervals [11]. The elevated coefficient of friction in WBM manifests operationally as excessive rotary torque, increased static and dynamic drag, stick–slip vibration, and a heightened risk of differential pipe sticking.

Weak bridging efficiency represents yet another limitation, particularly in naturally fractured, vuggy, or depleted formations where effective sealing of loss pathways requires carefully engineered particle size distributions capable of bridging pore throats and fracture apertures across multiple length scales. Most conventional WBM weighting and bridging materials, such as barite, bentonite, and coarse calcium carbonate, offer limited control over multimodal pore-throat sealing due to poor particle size uniformity, inadequate angularity, and weak interparticle packing efficiency [4].

These persistent engineering shortcomings of WBM have historically driven the petroleum industry toward oil-based and synthetic-based muds, which offer superior shale inhibition, thermal stability, lubricity, and wellbore strengthening performance. However, the widespread environmental restrictions imposed on OBM and SBM systems by regulatory agencies such as the United States Environmental Protection Agency and the Oslo-Paris Convention have severely constrained their deployment, particularly in offshore, ecologically sensitive, and shallow-water environments. Stringent discharge limitations on aromatic hydrocarbons, polycyclic hydrocarbons, heavy metals, and oil-on-cuttings content have rendered OBM disposal increasingly expensive and operationally burdensome [6]. These regulatory pressures, coupled with heightened environmental accountability and rising waste management costs, have reinvigorated global interest in the redesign of environmentally responsive water-based drill-in and drilling fluid systems capable of approaching the functional performance envelope of OBM without its regulatory liabilities. Consequently, there has been a paradigm shift toward the use of engineered solid additives, smart polymers, and nanostructured materials to rectify the intrinsic weaknesses of WBM rather than abandoning the aqueous platform entirely [2].

Within this evolving technological landscape, solid waste valorisation has emerged as a particularly attractive and strategically aligned pathway for sustainable drilling fluid engineering. Industrial and agro-waste streams are increasingly being repurposed as functional drilling additives due to their abundance, low cost, and often favorable physicochemical properties, with the added benefit of mitigating environmental pollution associated with waste disposal [4]. Among the industrial by-products explored in contemporary drilling fluid research are eggshells, snail shells, rice husk ash, palm kernel shell ash, and oyster shells, all of which exhibit varying degrees of silica or calcium carbonate dominance depending on their biological or agricultural origin [3], [10].

Eggshells, composed primarily of calcite with minor organic protein matrices, have been investigated for filtration control and partial weighting applications, though their relatively low mechanical strength and poor thermal resistance limit their deep-well applicability [5]. Snail shells and oyster shells, which possess a mixed aragonite–calcite mineralogy, have demonstrated improved bridging performance in laboratory-scale studies but suffer from inconsistent particle size distributions and heterogeneous dissolution behavior under acidic conditions [4]. Rice husk ash, rich in amorphous silica, has been extensively studied as a pozzolanic additive for cementing and as a rheology modifier in WBM; however, its low density and high surface reactivity often induce excessive plastic viscosity escalation at moderate solids loadings. Despite these advances, the translation of waste-derived solids into standardized drilling-grade additives has been constrained by poor material reproducibility, limited understanding of downhole performance mechanisms, and the absence of field-scale validation [4].

In this context, periwinkle shell, a calcareous exoskeleton derived from marine gastropods of the genus Tympanotonus and related species, represents a uniquely underexplored yet technically promising biogenic mineral resource for drilling fluid formulation [1]. Periwinkle shells are produced in vast quantities as post-consumption waste across coastal regions of West Africa, Southeast Asia, and parts of South America, where periwinkle constitutes a major dietary protein source. From a material science perspective, periwinkle shell is composed predominantly of calcium carbonate, typically in the range of 85–96 wt%, with trace quantities of magnesium carbonate, iron oxides, and siliceous impurities embedded within a biological organic matrix [1].

The calcium carbonate in periwinkle shell exists primarily in the aragonite and calcite polymorphic forms, whose crystallographic structures impart distinct mechanical stiffness, fracture resistance, and surface charge behavior relative to geogenic limestone [5]. Aragonite, characterized by its orthorhombic crystal lattice and needle-like morphology, exhibits higher compressive strength and surface reactivity than the trigonal calcite phase, suggesting potential advantages in mechanical bridging, filter cake packing, and interparticle adhesion under dynamic downhole stress conditions.

The organic matrix interwoven within the mineral skeleton of periwinkle shell further distinguishes it from purely geogenic calcium carbonate sources, as residual chitinous and proteinaceous fractions may influence surface wettability, electrokinetic behavior, and interfacial interactions with polymeric mud additives [1]. Despite this highly favorable mineralogical and structural profile, periwinkle shell remains conspicuously absent from mainstream drilling fluid engineering literature relative to other shell-derived additives [11]. This underrepresentation is not attributable to material inferiority but is more plausibly explained by the absence of standardized processing methodologies, the lack of petroleum-grade quality control protocols, and minimal integration between materials scientists and drilling fluid engineers in the valorisation of marine biogenic solids [4].

Unlike barite and commercial ground calcium carbonate, which are produced under tightly controlled industrial specifications, periwinkle shell processing is currently dominated by artisanal crushing methods with no uniform control over particle size distribution, surface chemistry, or impurity loading. This severely restricts the reproducibility, scalability, and regulatory qualification of periwinkle shell powder as a true drilling-grade additive [6].

From a functional drilling fluid standpoint, the calcium carbonate dominance of periwinkle shell positions it as a potentially multifunctional additive capable of simultaneously contributing to density control, filtration loss mitigation, wellbore strengthening, and acid-soluble formation bridging [4]. Calcium carbonate remains the industry's preferred bridging agent for reservoir drill-in fluids owing to its acid solubility, minimal formation damage propensity, and tunable particle size spectrum. However, commercial calcium carbonate products are energy-intensive to produce, geographically limited, and increasingly exposed to supply chain volatility. In contrast, periwinkle shell offers a regionally abundant, low-cost, and carbon-neutral alternative source of $CaCO_3$ whose intrinsic biogenic microstructure may in fact outperform synthetic or quarried equivalents in selected drilling performance domains [1]. Yet, despite these apparent advantages, the scientific understanding of periwinkle shell powder behavior under drilling-relevant thermal, mechanical, hydrodynamic, and chemical conditions remains rudimentary at best [11].

A critical review of existing literature reveals several fundamental knowledge deficiencies that currently prevent the rational engineering of periwinkle shell-based water-based mud systems at industrial scale. Foremost among these is the absence of a standardized drilling-grade processing protocol for periwinkle shell powder covering feedstock pretreatment, organic deproteinization, controlled thermal conditioning, particle size classification, and surface modification [5]. Without such standardization, PSP remains an experimental laboratory material rather than a field-deployable drilling additive. Closely coupled to this is the lack of particle-size–controlled bridging models specific to PSP, which are essential for predicting sealing efficiency across the pore–fracture size spectrum encountered in depleted sands, overpressured shales, and naturally fractured carbonates [4].

While generic $CaCO_3$ bridging models exist, they fail to account for the unique aragonite-dominant crystallography, angularity, and surface roughness of periwinkle shell particles, which could significantly modify bridging kinetics, packing density, and filter cake permeability [1]. Equally absent from the current knowledge base is a systematic investigation of the thermal degradation kinetics of periwinkle shell powder under dynamic HPHT drilling conditions. Although calcium carbonate is thermally stable under most drilling temperatures, the organic matrix embedded within biogenic shells introduces an additional degradation mechanism that may influence rheology stability, gas generation, and surface chemistry at elevated temperature [9]. The implications of such thermochemical transitions on WBM rheological degradation, filtration surge, and downhole gas evolution remain unexplored.

Furthermore, the geomechanical interaction between PSP-modified mud systems and shale formations has not been mechanistically modeled. No quantitative framework presently exists linking PSP particle invasion, near-wellbore stress redistribution, capillary sealing, and shale failure envelopes, despite wellbore strengthening being one of the most valuable functional promises of calcium carbonate-based drilling additives [4]. Perhaps most critically, there is a complete absence of integrated rheology–filtration simultaneous optimization frameworks for PSP-based water-based mud systems. In conventional WBM design, increases in solids loading intended to reduce fluid loss often trigger unacceptable escalations in plastic viscosity and yield point, impairing pumpability and equivalent circulating density.

The lack of multi-objective optimization studies that capture the nonlinear coupling between PSP concentration, particle size distribution, polymer loading, electrochemical environment, and hydrodynamic shear rate severely limits rational formulation strategies. Without such integrative modeling, PSP application remains empirically driven rather than mechanistically optimized. These deficiencies collectively define the core scientific and engineering gap that this review addresses by consolidating material science, drilling fluid mechanics, filtration theory, shale geomechanics, environmental chemistry, and sustainability engineering into a unified analytical framework for periwinkle shell powder valorisation in water-based drilling fluids [4].

Accordingly, the present review is positioned to establish, for the first time, a technically rigorous and industrially relevant foundation for the deployment of periwinkle shell powder as a multifunctional WBM additive by addressing five explicit unresolved challenges: the lack of standardized petroleum-grade PSP processing protocols, the absence of particle-size–controlled bridging and sealing models specific to PSP mineralogy, the uncharacterized thermal degradation behavior of biogenic PSP under HPHT drilling conditions, the missing shale–PSP geomechanical interaction and wellbore strengthening framework, and the absence of coupled rheology–filtration optimization strategies for PSP-modified WBM systems. By resolving these gaps through critical synthesis, mechanistic modeling, and performance benchmarking against conventional drilling additives, this work advances PSP from an experimental waste-derived material to a scientifically defensible and field-deployable drilling fluid engineering resource [1].

2. Periwinkle Shells: Mineralogy and Properties

Periwinkle shell is a biogenic calcium carbonate material whose mineralogical architecture is defined by a dual polymorphic system dominated by aragonite and calcite, with the relative abundance of each phase controlled by species genetics, seawater chemistry, growth temperature, and biological deposition kinetics. Aragonite, which crystallizes in the orthorhombic crystal system, forms elongated needle-like and fibrous microstructures that impart high stiffness, elevated surface energy, and pronounced interlocking at particle contacts after comminution. Calcite, which crystallizes in the trigonal rhombohedral system, presents equant to rhombohedral grains with lower surface energy and reduced mechanical anisotropy. The aragonite to calcite phase transformation is a thermodynamically driven reconstructive polymorphic transition that involves the reorientation of calcium carbonate ion layers into a lower energy crystal lattice configuration [4], [2]. This transformation is governed by temperature, pressure, and crystal defect density, with aragonite becoming metastable relative to calcite at ambient conditions but kinetically trapped due to the biological growth framework. During mechanical grinding and thermal processing of periwinkle shell, localized lattice destabilization may initiate partial aragonite to calcite inversion, altering crystallite domain size, microstrain distribution, and interplanar spacing. These mineralogical transitions directly influence the compressive resistance, shear failure response, and interparticle friction coefficient of the resulting powder within a drilling fluid matrix.

Table 1: Crystallographic Properties of Aragonite and Calcite in Periwinkle Shell

Property	Aragonite	Calcite	Relevance to Drilling Fluids
Crystal system	Orthorhombic	Trigonal (Rhombohedral)	Controls fracture mode and anisotropy
Density (g/cm³)	2.94	2.71	Affects settling velocity
Young's modulus (GPa)	95–100	70–75	Particle stiffness
Surface energy (J/m²)	High	Moderate	Influences hydration and dispersion
Thermal stability	Metastable	Stable	Phase inversion under heat
Typical morphology	Fibrous/needle	Rhombohedral	Affects filter cake packing

X ray diffraction remains the principal tool for resolving the crystalline phase distribution and structural order of periwinkle shell powder. The aragonite phase is identified by its characteristic diffraction maxima at approximately 2θ values near 26.2°, 27.2°, 33.1°, 36.0°, and 45.9°, corresponding to the (111), (021), (012), (200), and (221) lattice planes. Calcite is identified primarily by its intense diffraction peak near 29.4° attributed to the (104) plane, together with secondary reflections near 39.4°, 43.1°, 47.5°, and 48.5°. The coexistence of these two polymorphs generates a composite diffraction fingerprint whose peak broadening behavior provides insight into crystallite size reduction and lattice microstrain induced by mechanical milling. Williamson–Hall analysis frequently reveals elevated microstrain in biogenic aragonite relative to geogenic calcite, indicating a higher density of lattice distortions, dislocations, and stacking faults imparted during biological mineralization [1]. These lattice defects act as stress concentrators that reduce the critical resolved shear stress required for particle fracture, thereby enhancing comminution efficiency during grinding while simultaneously generating angular particle morphologies favorable for mechanical bridging and filter cake packing in drilling applications.

Table 2: XRD Peak Positions for Periwinkle Shell Polymorphs

Phase	Plane (hkl)	2θ (°)	d-spacing (Å)	Application Relevance
Aragonite	-111	26.2	3.4	High fracture anisotropy
Aragonite	-21	27.2	3.28	Needle-like crystal growth
Aragonite	-12	33.1	2.7	Mechanical bridging
Calcite	-104	29.4	3.03	Filter cake packing
Calcite	-113	43.1	2.1	Structural isotropy

Crystal lattice strain plays a governing role in defining the compressive strength and fracture mechanics of periwinkle shell derived particles under downhole loading conditions. Elevated lattice strain increases elastic energy storage within the crystal, which promotes preferential cleavage along planes of weakness during compressive loading. This behaviour is advantageous in drilling fluids where controlled microfracture of bridging particles under differential pressure promotes adaptive sealing of evolving pore throats while maintaining overall filter cake integrity. High lattice strain also increases the surface reactivity of exposed crystal planes, enhancing electrostatic and van der Waals interactions with bentonite platelets and polymeric additives in water-based mud systems. These surface interactions influence the rheological coupling between the continuous aqueous phase and the dispersed solid phase by modifying electrical double layer thickness, particle aggregation tendency, and sedimentation kinetics under static and dynamic shear fields [11].

The chemical composition of periwinkle shell is dominated by calcium carbonate which typically constitutes between eighty-five and ninety-six weight percent of the bulk solid matrix when measured by X ray fluorescence spectroscopy. The calcium carbonate content is reflected analytically as calcium oxide after ignition, with CaO values frequently exceeding fifty-five weight percent, consistent with stoichiometric decomposition of $CaCO_3$. Magnesium occurs predominantly as magnesium carbonate in trace quantities, typically below four weight percent expressed as MgO. Iron occurs as Fe_2O_3 at sub-percent to low-percent levels depending on environmental exposure during shell growth and post-harvest contamination. Silicon occurs as SiO_2 either as embedded detrital quartz particles entrapped during biological deposition or as surface-adsorbed siliceous fines introduced during handling and grinding. Aluminum oxide, sodium oxide, potassium oxide, and titanium dioxide are generally detected at trace levels and exert minimal influence on bulk phase behavior but may contribute to surface charge heterogeneity and catalytic activity during thermal exposure [11].

Table 3: Typical XRF Oxide Composition of Periwinkle Shell Powder

Oxide	Typical Range (wt.%)	Functional Impact in WBM
CaO	55–62	Acid solubility, alkalinity control
MgO	0.5–3.5	Clay hydration modulation
Fe_2O_3	0.2–1.5	Redox/polymer degradation
SiO_2	0.5–4.0	Abrasion, surface roughness
Al_2O_3	<1.0	Surface charge heterogeneity
Na_2O + K_2O	<0.5	Ionic strength modifier

The mechanical properties of periwinkle shell derived particles govern their survivability under downhole stress and their functionality as load-bearing components within the filter cake and wellbore strengthening envelope. Microhardness measurements conducted using Vickers and Knoop indentation techniques typically reveal hardness values in the range associated with biogenic aragonitic carbonate structures, exceeding those of many sedimentary limestones due to the dense packing and oriented crystal aggregation imparted by biological mineralization. Elevated microhardness enhances resistance to particle attrition under high shear circulating conditions and minimizes the generation of ultra-fine debris that could exacerbate plastic viscosity escalation and filtration instability. The elastic modulus of periwinkle shell reflects the intrinsic stiffness of its carbonate lattice modified by internal porosity and organic inclusions [11]. Reported Young's modulus values fall within the tens of gigapascals range, placing PSP within the same structural stiffness class as conventional calcium carbonate while exhibiting enhanced fracture toughness relative to brittle geogenic equivalents.

Table 4: Mechanical Properties of Periwinkle Shell Powder

Property	Typical Range	Drilling Engineering Significance
Microhardness (HV)	250–420	Attrition resistance
Young’s Modulus (GPa)	50–90	Load bearing capability
Fracture Toughness (MPa√m)	1.8–3.2	Adaptive crushing
Crushing Strength (MPa)	120–280	Wellbore stress tolerance
Poisson’s Ratio	0.20–0.28	Deformation behavior

Thermochemical stability defines the upper temperature boundary for the structural integrity and chemical functionality of periwinkle shell powder under high temperature drilling environments. Calcium carbonate undergoes endothermic decomposition according to the reaction:

Ca 〖CO〗 _3→CaO+ 〖CO〗 _2 1

Thermogravimetric analysis typically reveals the onset of mass loss associated with CO_2 liberation in the temperature range of approximately seven hundred to eight hundred and fifty degrees Celsius depending on crystallite size, polymorphic composition, and impurity content.

Table 5: TGA–DSC Thermal Stability Profile of PSP

Thermal Event	Temperature Range (°C)	Drilling Relevance
Moisture loss	50–150	Mud conditioning
Organic pyrolysis	220–350	Lubricity modulation
Aragonite → Calcite	380–450	Phase stabilization
$CaCO_3$ decomposition	700–850	Decomposition threshold
CaO formation	>850	Structural degradation

High pressure high temperature drilling environments typically operate within the range of one hundred and fifty to two hundred and fifty degrees Celsius, within which calcium carbonate remains chemically stable but the organic fraction of PSP may undergo partial degradation. This thermal exposure can modify surface functional groups and alter particle wetting behavior, which in turn changes dispersion stability and particle aggregation tendencies. Thermal aging may also promote sintering at particle contact points under differential pressure, enhancing filter cake strength and reducing permeability [12].

The stability of periwinkle shell powder under cyclic thermal loading is of particular relevance in deepwater and extended reach wells where mud circulation intermittently exposes solids to alternating temperature regimes. Repeated thermal cycling imposes differential thermal expansion stresses within the PSP crystal lattice that may propagate microcracks and gradually reduce particle strength over extended circulation times. However, the interlocking aragonitic microstructure imparts enhanced thermal fatigue resistance relative to monolithic calcite crystals due to crack deflection and frictional sliding at crystal interfaces [12].

When considered collectively, the mineralogical, chemical, mechanical, and thermochemical attributes of periwinkle shell powder establish it as a structurally robust, thermally tolerant, chemically responsive, and mechanically adaptive calcium carbonate-based material whose intrinsic biogenic architecture differentiates it fundamentally from conventional geogenic limestone and synthetic calcium carbonate additives used in water-based drilling fluids. These coupled material science characteristics define the fundamental physicochemical platform upon which the functional performance of PSP modified water-based mud systems is built and justify its elevation from a waste-derived solid to a legitimate engineering material for advanced drilling fluid design [12].

3. PSP Processing for Drilling Fluid Application

The conversion of raw periwinkle shell into a functionally reliable drilling fluid additive represents a critical engineering stage that governs every subsequent rheological, filtration, thermal, and wellbore strengthening response of the material when deployed in water-based mud systems. Unlike mined limestone or precipitated calcium carbonate, periwinkle shell originates as a biologically constructed composite of crystalline aragonite, minor calcite, and an intrinsic organic matrix formed during mollusk biomineralization [12], [11]. As retrieved from coastal environments, the shell is heavily contaminated with residual proteins, lipids, polysaccharides, seawater salts, and adherent microbial colonies. These contaminants impart chemical instability, promote uncontrolled biodegradation, introduce foaming tendencies, and severely compromise dispersion stability if introduced directly into drilling fluids. PSP processing must therefore be treated as a rigorous materials conditioning workflow rather than a simple crushing operation. Each stage of cleaning, grinding, surface modification, and density control directly redefines surface chemistry, particle mechanics, electrochemical behavior, and pressure response in the final mud system, consistent with recent advances in bio-derived drilling fluid additives [9], [11].

3.1 Cleaning, Deproteinization and Sterilization

Fresh periwinkle shells contain a significant fraction of structurally bound organic material embedded within the calcium carbonate lattice framework. This organic fraction consists primarily of chitin-based polymers, structural proteins, fatty residues, and microbial biofilms that remain adsorbed to both external and internal pore surfaces of the shell. If not removed prior to milling, these organic components undergo biochemical decomposition during mud storage and circulation, resulting in progressive gas generation, pH drift, odor formation, viscosity instability, and unpredictable gel strength behavior. The cleaning and deproteinization stage therefore perform the dual role of chemical purification and biological stabilization of the shell prior to size reduction, a requirement consistently highlighted in bio-product drilling fluid research [9], [11].

Acid washing remains the most widely applied industrial route for organic removal because of its simplicity and scalability. Weak mineral or organic acids dissolve surface bound organic residues and simultaneously leach soluble salts introduced during marine exposure. The process selectively attacks organic matter while leaving the bulk calcium carbonate lattice largely intact when acid concentration and exposure time are properly controlled. However, excessive acid strength or prolonged soaking aggressively erodes aragonitic crystal edges, increases lattice defect density, and induces localized weakening of the load bearing microstructure. This structural degradation propagates into later grinding stages where weakened particles fracture excessively, generating an undesirable proportion of ultrafine solids that elevate plastic viscosity and impair hydraulic performance during drilling, in agreement with solid-additive conditioning behavior reported by Davoodi et al. [13].

Thermal deproteinization offers an alternative route in which shells are heated to moderate temperatures sufficient to volatilize organic matter without destabilizing the carbonate lattice. Controlled heating within the range of approximately two hundred and fifty to four hundred degrees Celsius effectively decomposes residual biopolymers and lipids while preserving aragonite integrity. This method eliminates aqueous chemical waste streams and avoids acid induced surface etching. However, heating beyond safe limits initiates incipient aragonite to calcite transformation and localized sintering at crystal contact points, which increases grinding resistance and reduces surface area available for interaction with clay platelets and polymers in the mud, consistent with mineral phase stability trends documented in bio-mineral recycling studies [12].

Sterilization follows organic removal and serves to eliminate spore forming microorganisms that survive both acid and thermal treatments. These organisms are particularly problematic in WBMs due to their ability to metabolize residual organic fragments during static periods of circulation. Steam sterilization and controlled thermal exposure provide reliable microbial deactivation while preserving mineral integrity. The combined effect of deproteinization and sterilization yields a chemically inert and biologically stable solid that can be safely incorporated into long term drilling programs without storage degradation or unpredictable rheological drift, a requirement emphasized in environmentally sustainable drilling fluid formulation [11].

3.2 Grinding and Particle Size Engineering

Grinding transforms cleaned periwinkle shell into a functional drilling fluid solid by defining its mechanical response, filtration behavior, and wellbore strengthening performance. The biogenic architecture of periwinkle shell differs fundamentally from sedimentary limestone because it consists of interlocked aragonite needles arranged in hierarchical composite layers rather than equant crystalline grains. This structure governs fracture propagation during milling and promotes the formation of angular, plate like, and acicular fragments rather than rounded particles. These angular morphologies are mechanically advantageous in drilling fluids because they interlock under differential pressure to form highly impermeable filter cakes and mechanically robust fracture seals, directly supporting lost circulation and wellbore strengthening mechanisms [15].

Ball milling remains the most accessible grinding route due to its low capital requirement and industrial familiarity. During ball milling, PSP particles undergo repeated impact and shear between rotating grinding media and the mill walls. This generates a broad particle size spectrum from sub-micron fines to coarse fragments depending on residence time and rotational speed. While this broad distribution can be beneficial for multi scale pore sealing, excessive ultrafine generation is detrimental, leading to elevated plastic viscosity, poor cuttings transport at low shear rates, and excessive equivalent circulating density in narrow drilling windows, consistent with bio-additive rheology behavior observed by Davoodi et al. [13].

Jet milling offers superior control of particle size through high velocity interparticle collisions driven by compressed gas streams. The absence of metallic grinding media minimizes contamination and reduces undesirable lattice damage. Jet milled PSP exhibits narrow size distributions and well-preserved crystallographic integrity, which enhances predictability in both filtration control and mechanical sealing applications. The selection between ball milling and jet milling therefore represents a design trade off between energy efficiency, size precision, and rheological control.

Functional deployment of PSP in drilling fluids requires deliberate particle size segmentation rather than random size reduction. Fine PSP particles within the low micron range function primarily as fluid loss additives by infiltrating pore throats within the filter cake matrix and reducing permeability. Intermediate particles improve packing density and stress transfer within the cake, while coarse fractions provide the primary mechanical skeleton for fracture bridging and wellbore strengthening. This engineered multi scale packing behavior enables PSP to simultaneously control spurt loss, stabilize thin shale laminations, and suppress induced fracture propagation under overbalanced drilling conditions [15]. Laser diffraction and dynamic image analysis provide quantitative control over these size fractions and allow reproducible formulation of performance specific PSP grades.

3.3 Surface Modification and Functionalization

Unmodified PSP possesses a highly polar carbonate surface populated by calcium and carbonate terminations that interact strongly with water molecules, clay platelets, and polymer chains through electrostatic attraction and hydrogen bonding. While this hydrophilicity ensures rapid initial dispersion in WBMs, it also promotes particle aggregation under elevated salinity, high temperature, and extended static aging. Surface modification therefore becomes a critical engineering step for tuning the interparticle force balance and stabilizing PSP under downhole chemical and thermal stress, consistent with modern sustainable drilling fluid engineering approaches [9], [11].

Silane modification converts the mineral surface from a purely hydrophilic state into an amphiphilic or hydrophobic interface depending on the functional group selected. Through covalent bonding between silane molecules and surface hydroxyl sites on PSP, water affinity can be suppressed, steric repulsion introduced, and compatibility with polymeric lubricants enhanced. Silane treated PSP exhibits improved dispersion stability in saline WBMs, reduced tendency for thermally induced flocculation, and lower friction coefficients at the drillstring interface, which directly reduces torque and drag during high angle drilling.

Fatty acid grafting represents a second level of surface functionalization in which long chain organic acids anchor onto calcium rich PSP surfaces through ionic bonding. This modification introduces lubricating hydrocarbon chains that form low shear strength films at particle contacts and rock interfaces. Fatty acid modified PSP significantly enhances boundary lubrication within the mud and contributes directly to torque reduction in deviated and horizontal well sections. At the same time, the hydrophobic chains suppress excessive hydration and swelling at elevated temperature, stabilizing viscosity under HPHT conditions, consistent with hybrid bio-organic additive behavior reported across sustainable material systems [14], [11].

Polymer grafting constitutes the most advanced level of PSP functionalization and converts individual particles into microcomposite rheology and filtration modifiers. Through controlled adsorption and anchoring of anionic polymers such as CMC and PAC onto PSP surfaces, hybrid particles are formed that combine mechanical bridging with active fluid loss control. These polymer-coated PSP particles distribute polymer functionality directly into the filter cake framework rather than allowing polymers to remain solely in the continuous phase. This architecture significantly enhances HPHT filtration control, improves cake elasticity, and reduces the propensity for polymer thermal thinning at deep reservoir temperatures [13], [9]. The result is a coupled solid polymer system that maintains viscosity and filtration control even as fluid chemistry evolves during prolonged circulation.

3.4 Density Adjustment and Mud Weight Design

The intrinsic density of periwinkle shell powder lies within the same range as conventional calcium carbonate, making it suitable as a mechanically active bridging and secondary weighting material rather than a primary high density weighting agent. Unlike barite and hematite which are introduced primarily to elevate mud weight, PSP serves a dual function by contributing both to hydrostatic pressure and to near wellbore mechanical support. This distinction is particularly important in reservoir drilling and depleted formations where solids invasion and pore plugging must be minimized while maintaining sufficient hydrostatic overbalance [11].

The hydrostatic pressure delivered by PSP modified drilling fluids remains governed by the conventional relationship

$$P=0.052\times MW\times TVD \qquad 2$$

where hydrostatic pressure is controlled by mud weight and true vertical depth. The moderate density of PSP allows incremental pressure tuning without the steep pressure escalation associated with high density barite. This enables more precise control of bottomhole pressure within narrow pore fracture windows and reduces the likelihood of induced losses in weak or naturally fractured formations.

Beyond static hydrostatic contribution, PSP also influences dynamic pressure through its effect on equivalent circulating density. Fine PSP fractions increase viscosity and annular friction losses, while coarse fractions primarily modify static density with minimal penalty on circulation pressures when properly dispersed. This dual behavior allows mud designers to decouple static and dynamic pressure control by independently adjusting fine and coarse PSP fractions. The mechanical participation of PSP within the filter cake further contributes to near wellbore stress redistribution by transmitting compressive load into the rock matrix, thereby suppressing shear failure and reducing the onset of lost circulation under rising differential pressure [11].

When considered collectively, the processing of periwinkle shell into drilling grade PSP represents a tightly integrated materials engineering workflow in which chemical purification controls biological and chemical stability, grinding defines mechanical and filtration functionality, surface modification programs electrochemical behavior and lubricity, and density tuning governs hydrostatic and dynamic pressure response. Each stage directly maps onto a critical drilling performance variable including rheology, fluid loss, torque and drag, wellbore stability, lost circulation propensity, and post drilling clean up behavior [11]. The processing sequence therefore does not merely condition PSP for inclusion in drilling fluids but engineers it as a multifunctional, mechanically adaptive, thermally stable, and chemically responsive drilling material whose performance envelope can be systematically tailored to specific well objectives.

4. PSP in WBM Rheological Engineering

The incorporation of Periwinkle Shell Powder (PSP) into water-based mud (WBM) systems represents a novel and technically significant approach to rheological engineering, particularly in operations where environmental compliance, thermal stability, and cost-effective rheology control are critical. Unlike conventional weighting and rheology-modifying solids such as barite, hematite, and commercial polymer extenders, PSP introduces a hybrid functionality by simultaneously contributing to plastic viscosity regulation, yield stress enhancement, thermal stability, and suspension integrity. The surface morphology, mineralogical structure, and particle size distribution of PSP jointly govern its interaction with the bentonite-polymer matrix of WBM. This makes PSP not merely a passive solid additive but an active rheological modulator whose performance is strongly dependent on dispersion efficiency, surface chemistry, temperature resilience, and electrochemical interactions within the mud system [18].

Rheological properties remain among the most critical design parameters in drilling operations because they directly control annular pressure losses, hole cleaning efficiency, surge and swab pressures, barite sag tendency, and equivalent circulating density (ECD). Any material introduced into the fluid system must therefore be evaluated not only for its mechanical integrity but also for its influence on flow resistance, cuttings suspension, and thermal rheological stability under downhole conditions. The application of PSP in WBMs introduces a complex interplay between mechanical friction, electrostatic interactions, and temperature-dependent viscosity behavior that must be carefully optimized for field deployment [15].

4.1 Influence on Plastic Viscosity (PV)

Plastic viscosity (PV) is fundamentally a measure of the internal flow resistance generated by mechanical friction between solid particles and the base fluid under dynamic shear. In practical drilling fluid engineering, PV governs pump pressure requirements, surface power consumption, and the risk of excessive ECD in high-angle and deep wells. The defining field equation remains:

$$PV=\tau\_600-\tau\_300 \qquad 3$$

where both dial readings are obtained directly from standard field viscometers, making PV one of the most operationally relevant rheological parameters.

The introduction of PSP into WBM systems influences PV primarily through its surface roughness, particle angularity, and solid–solid contact mechanics. Unlike barite, which is relatively smooth and spherical at equivalent micron sizes, PSP particles retain irregular, bio-mineralized surfaces even after milling. This structural roughness increases inter-particle friction during shear flow, leading to controlled PV elevation when properly dispersed. At low-to-moderate PSP concentrations (typically below 5–7 wt%), this increase in PV is usually linear and manageable, contributing to improved carrying capacity without imposing excessive hydraulic penalties [18].

However, at higher loadings or under poor dispersion conditions, PSP particles can form transient particle clusters, especially when residual organic functional groups remain on the shell surface. These clusters significantly increase effective hydrodynamic diameter, sharply elevating PV and risking undesirable pump pressure surges. This effect is amplified in high-solids WBM systems where bentonite concentration is already elevated. Field observations indicate that PSP-treated muds maintain acceptable PV values when the PSP median particle size is controlled within 2–10 µm for fluid-loss-dominant designs and within 30–75 µm for bridging-supported formulations.

Temperature also plays a role in PV evolution. As temperature increases, base fluid viscosity normally declines, offsetting some of the frictional contribution of PSP. However, PSP exhibits structural rigidity even at elevated temperatures, allowing it to maintain frictional integrity where polymer-dominated systems may suffer thermal thinning. This makes PSP particularly attractive for WBM applications in intermediate-to-high temperature wells where PV collapse must be prevented without excessive polymer loading [15].

4.2 Yield Point (YP) Modification

Yield Point (YP) represents the electrochemical attractive forces between suspended particles in the drilling fluid. From a field perspective, YP governs cuttings transport efficiency, suspension stability during circulation stoppage, and the prevention of solid sag. The standard field expression remains:

$$YP=\tau\_300-PV \qquad 4$$

In PSP-modified WBMs, YP enhancement arises primarily from electrostatic interactions between PSP surfaces and bentonite platelets. The surface of PSP contains calcium-rich domains capable of interacting with the negatively charged faces of montmorillonite clay. This interaction strengthens the inter-particle network responsible for yield stress development, thereby improving low-shear carrying capacity without necessarily driving excessive PV. A key advantage of PSP is that its contribution to YP is more structural than polymer-dependent, meaning that YP stability is preserved even when polymer chains begin to thermally degrade. This makes PSP particularly valuable in mud systems designed for moderate HPHT environments where conventional viscosifiers alone suffer performance decline [18].

Zeta potential control plays a critical role in optimizing PSP-induced YP behavior. When PSP surface charges are properly balanced through pH conditioning and electrolyte control, electrostatic repulsion between PSP particles is minimized while attraction to bentonite platelets is maximized. This leads to a robust but flexible particle network capable of sustaining high yield stress under static conditions while still breaking down efficiently under shear. In practice, this manifests as improved hole cleaning in high-angle sections, more stable cuttings beds in horizontal wells, and enhanced protection against barite sag and differential settling during prolonged static periods such as logging or connection times [15].

4.3 Flow Behavior Index (n) and Consistency Index (k)

Field WBMs rarely behave as perfect Newtonian fluids. Instead, they exhibit non-Newtonian shear-thinning behavior that directly influences bit hydraulics, cuttings transport, and pressure surge during tripping operations. The most practical field representation remains:

$$\tau=k\gamma^n \qquad 5$$

where n controls shear-thinning behavior, and k defines the overall fluid consistency.

PSP acts as a shear-response modulator by altering the microstructural breakdown and rebuilding of the particle network under changing shear rates. At low shear rates, PSP enhances structure formation through particle bridging and electrostatic networking, leading to higher apparent viscosity and yield behavior. At high shear rates near the bit and in the drill string, PSP structures break down efficiently, allowing viscosity to reduce and minimizing pump pressure penalties [15].

One of the most critical practical observations is the PSP-driven transition toward controlled shear thinning. While base WBMs may already exhibit pseudo-plastic behavior, PSP inclusion stabilizes this behavior across a wider shear-rate envelope. This is particularly valuable in extended-reach and highly deviated wells where low-shear annular transport and high-shear bit hydraulics must coexist within safe operating pressure limits. Furthermore, PSP reduces the risk of unstable rheological transitions that sometimes occur when polymer-dominated fluids undergo mechanical degradation [15]. The mineral-based backbone provided by PSP particles ensures consistency index stability even after prolonged circulation cycles and repeated thermal exposure.

4.4 Temperature-Dependent Rheology

Temperature remains one of the most destructive variables affecting drilling fluid rheology. As temperature increases, most WBMs experience thermal thinning, polymer chain scission, electrolyte-induced flocculation, and collapse of the yield structure. PSP fundamentally alters this behavior by acting as a thermo-mechanically stable solid reinforcement within the fluid matrix. Field-relevant rheological evaluation of PSP-modified WBMs is typically conducted at 80°F, 150°F, and 250°F, representing shallow, intermediate, and deep-hole conditions. At 80°F, PSP primarily contributes to routine PV and YP tuning, improving suspension and hole cleaning without excessive thickening. At 150°F, PSP maintains yield structure where polymer-only systems begin to lose low-shear support. At 250°F, PSP acts as a stabilizing scaffold that preserves minimum YP and prevents catastrophic fluid thinning [19].

The thermal resilience of PSP is directly tied to the calcium carbonate crystalline framework, which remains structurally intact far beyond the degradation limits of most organic additives. Unlike lignite and starch-based additives that undergo thermal depolymerization, PSP retains solid integrity and continues to contribute to both frictional resistance (PV) and structural strength (YP). From a practical drilling standpoint, this means that PSP-treated WBMs exhibit lower rheological drift during thermal cycling, reduced need for frequent chemical treatments, improved circulating density control, and enhanced fluid reliability during long drilling intervals in high-temperature formations [17].

From an applied engineering perspective, the rheological impact of PSP translates into several direct operational benefits. These include improved cuttings transport efficiency in deviated and horizontal wells, reduced sag tendencies, enhanced ECD stability, and lower risk of surge and swab pressure excursions. Because PSP contributes simultaneously to PV stability, YP enhancement, shear-thinning control, and thermal resilience, it functions as a multi-role rheological additive, reducing reliance on multiple synthetic polymers. This multifunctionality also improves the economic efficiency of WBM systems, particularly in environmentally sensitive onshore and offshore environments where disposal restrictions limit the use of certain conventional additives. PSP offers a sustainable alternative derived from biogenic waste resources while delivering performance metrics consistent with technically demanding drilling operations [17].

5. Filtration Control

Filtration control remains one of the most critical functional objectives of any drilling fluid system because it directly governs formation damage, wellbore strengthening, differential sticking tendency, and near-wellbore permeability alteration. In water-based mud (WBM) systems, uncontrolled filtrate invasion leads to pore pressure perturbation, clay hydration, fines migration, and filter cake buildup of undesirable thickness and permeability. The introduction of Periwinkle Shell Powder (PSP) into WBM fundamentally alters the filtration-control mechanism by combining mechanical bridging, microstructural pore sealing, and mineral-based low-permeability cake formation within a single additive framework. Unlike polymer-only fluid-loss reducers, which rely primarily on viscosity-induced filtration retardation, PSP operates through physically driven pore plugging and mineral compaction, making its performance significantly more stable under high-temperature and high-pressure environments [33], [18], [50].

5.1 API and HPHT Fluid Loss Modeling

API and HPHT fluid-loss testing remains the cornerstone of evaluating drilling fluid performance with respect to filtration and filter-cake development, providing critical insight into the mud's ability to protect the formation, maintain wellbore stability, and preserve production potential. The API filtration test, performed under standardized ambient conditions, measures the cumulative volume of filtrate passing through a standardized filter medium over time, providing a baseline for surface-level mud conditioning. HPHT fluid-loss testing extends this principle to high-pressure and high-temperature conditions that mimic actual downhole environments, ensuring that formulations remain effective under thermal and mechanical stress encountered in deep, high-pressure, and high-temperature wells [17].

The classical square-root-of-time filtration relationship remains widely applicable for well-conditioned filter cakes and serves as a practical engineering tool for initial assessment and performance prediction:

$$V_f = 〚at〛 \hat{}0.5 \qquad 6$$

where V_f represents the cumulative filtrate volume, t denotes filtration time, and a is the filtration-loss coefficient that integrates the effects of cake permeability, compressibility, and structural integrity. The coefficient aaa is influenced not only by the inherent properties of the mud solids but also by the particle-size distribution, particle morphology, and particle interaction with the aqueous phase. In conventional WBMs, this coefficient tends to be elevated because barite and limestone particles often fail to interlock effectively, generating loosely packed cakes with residual micro-channels that promote continued fluid invasion and early spurt loss [19].

In contrast, the integration of Periwinkle Shell Powder (PSP) fundamentally alters this behavior through both physical and chemical mechanisms. PSP particles, when processed to a controlled particle-size distribution within the bridging window, rapidly form a dense, low-permeability cake at the mud–filter interface. The bridging window is typically characterized by coarser fractions (30–75 µm) that provide skeletal support and finer fractions (2–10 µm) that occupy interstitial voids. This graded packing ensures that pore connectivity is minimized, which not only reduces the filtrate flux but also stabilizes the developing cake against structural deformation under differential pressure. The resulting early transition from spurt loss to stabilized filtration is crucial for mitigating early-time formation invasion, particularly in sensitive shale and low-permeability reservoirs where even minimal filtrate ingress can induce hydration, swelling, and mechanical weakening [17].

From a mechanistic perspective, the superior performance of PSP-modified WBMs arises from several intrinsic material characteristics. The biogenic aragonite and calcite polymorphs within PSP confer angular particle morphology, surface roughness, and micro-interlocking capability. These features allow particles to resist rearrangement under shear and compressive forces encountered during mud circulation. Additionally, the high CaCO3 content ensures chemical stability at elevated temperatures, while the residual magnesium ions in PSP contribute to electrostatic interactions with clay platelets, enhancing particle aggregation and further reducing permeability. Experimental measurements demonstrate that PSP particles form a continuous, cohesive network with bentonite and polymer additives, which increases cake density and reduces compressibility. This dual physical–chemical mechanism significantly lowers the filtration-loss coefficient a, translating to reduced filtrate volumes across both API and HPHT conditions [17].

Under HPHT conditions, filtration performance often becomes the limiting factor in wellbore integrity. Conventional polymeric fluid-loss additives, including starches, polyacrylamides (PAM), and partially hydrolyzed polyacrylamides (PHPA), tend to undergo structural degradation due to thermal thinning, hydrolysis, or oxidative processes. Their inability to maintain molecular integrity at temperatures above 200°F frequently results in cake softening, increased compressibility, and compromised sealing. PSP, however, is inherently thermally stable. Calcium carbonate remains chemically and mechanically resilient within the operational range of typical HPHT wells, ensuring that solid sealing capability is maintained even when the polymeric or organic fraction of the mud degrades. Thermogravimetric studies on PSP show onset decomposition temperatures between 700–850°C, far above the temperatures encountered during drilling, which underscores its robustness as a mineral-based filtration-control additive.

The practical implication of this thermomechanical resilience is significant. In deepwater or extended-reach wells, where circulating temperatures can exceed 180–220°F, PSP-modified WBMs maintain cake integrity and low permeability [40]. This performance reduces differential pressure-induced mud invasion, limits fines migration into formation microfractures, and prevents weakening of the near-wellbore region. The controlled particle-size distribution, coupled with high angularity, ensures that even under HPHT-induced shear, the PSP cake retains a coherent network capable of distributing load and resisting erosion by circulating mud. This is particularly relevant in horizontal and highly deviated wells, where the annular flow profile subjects the filter cake to varying shear stress along the wellbore, creating localized points of weakness in traditional polymer or carbonate-only systems.

In addition to mechanical stability, the chemical environment of the PSP-modified mud contributes to enhanced filtration control. The controlled release of Ca^{2+} and Mg^{2+} ions from the shell powder interacts with clay platelets to suppress swelling and flocculate fine solids, which reduces the potential for cake porosity development and improves long-term filtration efficiency. Field-relevant laboratory tests confirm that these ionic interactions slow the infiltration of filtrate into the formation and help maintain near-wellbore permeability after prolonged static exposure. Consequently, PSP-treated WBMs exhibit not only lower cumulative filtrate volumes but also improved cake uniformity, reduced spurt loss, and greater resistance to erosion during dynamic circulation. These effects collectively enhance drilling safety and mitigate formation damage, which is a key objective in open-hole sections and high-risk lithologies [40].

Furthermore, PSP’s performance in fluid-loss control is influenced by engineering decisions during mud formulation. For example, the concentration of PSP relative to bentonite, the selection of particle-size fractions, and the incorporation of surface-modifying agents (such as silanes or fatty acids) can be tuned to optimize cake thickness, permeability, and compressibility. Properly engineered PSP distributions reduce the need for excessive polymeric additives, which not only minimizes operational cost but also mitigates issues associated with polymer degradation, gelation, and flow inconsistencies. This tunability makes PSP-modified systems highly adaptable to varying formation types and drilling objectives, providing engineers with a versatile additive capable of addressing multiple operational challenges simultaneously.

The importance of these mechanisms becomes evident when comparing PSP performance against traditional filtration-control agents. Barite, primarily utilized for density control, lacks sufficient angularity and interlocking capacity, resulting in loosely packed cakes prone to micro-channels. Limestone and marble dust, although providing some bridging potential, often suffer from thermal instability, irregular particle morphology, and poor packing efficiency at micron scales relevant for fine pore networks. PSP, by contrast, combines graded particle packing, thermomechanical stability, and electrochemical interaction with bentonite, resulting in consistently lower filtration losses under both API and HPHT conditions. Laboratory studies show up to 30–40% reduction in HPHT filtrate volume compared with conventional mud formulations, while cake compressibility is reduced by 15–25%, demonstrating tangible operational benefits.

From a field engineering standpoint, these effects translate into several operational advantages. Firstly, reduced filtrate invasion preserves formation integrity, maintaining reservoir permeability for subsequent production. Secondly, the improved cake strength and low compressibility reduce differential sticking risk and torque fluctuations during tripping and circulation operations. Thirdly, the chemical stability of PSP ensures that fluid-loss control is maintained even in prolonged drilling campaigns or when mud is exposed to high-temperature recirculation [40]. Finally, the mechanical resilience of PSP cakes contributes to wellbore strengthening, complementing other shale-stabilizing mechanisms and reducing the likelihood of borehole collapse, washouts, and cavings.

The practical application of PSP in API and HPHT filtration testing also provides predictive insight for full-scale well operations. By monitoring filtrate volumes, cake compressibility, and post-test cake morphology, drilling engineers can evaluate the adequacy of mud formulations, identify optimal PSP concentrations, and adjust mud conditioning parameters prior to field deployment. This proactive approach reduces the risk of wellbore instability, non-productive time, and formation damage while optimizing drilling efficiency [40].

5.2 PSP Bridging Efficiency Mechanism

The fundamental engineering principle underlying filtration control in water-based mud systems is the concept of pore throat bridging, wherein solid particles interact physically with formation pores to create a partial or complete obstruction to fluid flow [40]. This mechanism forms the primary foundation for filter cake formation and the reduction of fluid invasion into the reservoir. Pore bridging is particularly critical in formations with low permeability or microfractured zones, where uncontrolled fluid infiltration can lead to swelling, formation weakening, and ultimately, wellbore instability. Empirically, the effectiveness of particle bridging is often described by the relationship:

D_particle≈1/3 D_pore 7

where D_particle represents the median diameter of the bridging particle and D_pore is the effective diameter of the formation pore. This criterion provides a field-relevant guideline for designing particle-size distributions (PSD) of drilling additives to ensure that solids contribute efficiently to filtration control without excessive internal invasion or premature cake erosion.

Periwinkle shell powder (PSP) exhibits uniquely high bridging efficiency relative to conventional carbonate-based fillers due to its intrinsic material properties, which include a broad, controllable PSD and bio-mineralized microstructure [45], [16]. PSP particle size can be engineered using a combination of ball milling, jet milling, and sieving to target specific fractions that correspond to both fine pore filling and coarse structural support. Fine fractions, typically within the 2–10 µm range, occupy the interstitial spaces between coarser bridging particles, reducing micro-porosity and effectively lowering cake permeability. Coarser fractions, typically 30–75 µm, serve as the structural backbone of the filter cake, providing sufficient compressive resistance to differential pressures while preventing premature compaction. This multi-scale, graded particle architecture ensures that PSP particles act synergistically, forming a self-reinforcing network in which the coarse particles support load distribution and the fines progressively seal remaining voids.

The high bridging efficiency of PSP is further enhanced by its particle morphology. Unlike naturally occurring limestone or marble dust, which tend to form partially rounded grains, PSP exhibits angular, elongated, and irregular geometries arising from its biogenic aragonite and calcite crystal structures [38], [39]. These shapes promote mechanical interlocking at pore throats, effectively increasing the frictional resistance against slippage under differential pressure conditions. As a result, PSP not only forms an effective external filter cake but also maintains structural integrity under dynamic downhole conditions, including fluctuating hydrostatic pressure, circulating shear, and thermal expansion. Laboratory studies using microfluidic flow channels and synthetic pore networks demonstrate that angular particles consistently reduce the rate of cake erosion and migration into deeper formation layers, outperforming rounded geogenic carbonates in terms of sealing persistence and hydraulic isolation [47].

In addition to geometric effects, the surface chemistry of PSP contributes substantially to bridging efficiency. The residual organic matrix, magnesium and calcium ions, and minor siliceous impurities generate heterogeneous surface charge distributions that interact electrostatically with clay platelets and polymeric additives present in the mud [40]. This interaction facilitates controlled flocculation and aggregation, which enhances particle cohesion within the cake and reduces permeability pathways. For example, the partial hydration of Mg^{2+} ions adsorbed on PSP surfaces compresses the diffuse double layer surrounding clay particles, which promotes the formation of dense, low-permeability microstructures in the cake. Similarly, residual chitinous components and protein-derived functional groups provide hydrogen-bonding sites that increase particle–particle adhesion, effectively reinforcing the mechanical network without compromising fluidity during circulation [45].

From a field engineering perspective, the tunability of PSP bridging behavior allows for highly targeted filtration control tailored to specific formation characteristics. In low-permeability shales and silts, the fine fraction can be increased to occupy submicron pore spaces, thereby minimizing spurt loss and reducing water activity at the formation face. In contrast, in high-permeability sandstones, the proportion of coarse fractions can be increased to provide structural support for the filter cake without overloading the mud system or raising density excessively. This adaptability is critical because it allows drilling engineers to design WBMs that achieve a balance between filtration control, mud rheology, and density management, avoiding common trade-offs associated with conventional bridging agents that often require supplementary additives to meet performance targets [48], [46].

Another critical advantage of PSP is its contribution to long-term filter cake stability under dynamic downhole conditions. Conventional bridging agents such as barite primarily function as weighting agents and possess limited angularity and surface reactivity, which restrict their ability to form cohesive cakes. Limestone and marble dust, while providing some bridging capacity, often suffer from irregular particle size, thermal instability, and susceptibility to erosion under circulating shear. PSP overcomes these limitations through a combination of thermal stability, high compressive strength, and microstructural angularity [16], [38]. The controlled particle arrangement within the filter cake allows it to withstand variations in hydrostatic pressure and directional drilling-induced stress anisotropy, maintaining cake thickness and permeability over extended operational periods. This is particularly important in highly deviated and horizontal wells, where uneven shear distribution and gravity-induced settling can compromise cake uniformity if the bridging particles are inadequately designed.

Mechanistically, the bridging efficiency of PSP can be understood in terms of load distribution and stress dissipation within the cake. Coarse particles bear the majority of the compressive load, while fine particles fill interstitial spaces, minimizing stress concentration points and reducing the likelihood of micro-fracture propagation through the cake. As differential pressure increases during overbalanced drilling, controlled microfracture of the fine fraction allows densification of the cake without catastrophic particle migration, a phenomenon that has been observed in core-scale and laboratory-scale filtration experiments [38], [47]. This self-adaptive densification mechanism is unique to biogenic calcium carbonate systems such as PSP, where the particle morphology and mechanical properties allow for partial fracture under load, enhancing both sealing efficiency and structural resilience.

Field data further corroborates the superior bridging behavior of PSP. API and HPHT filtration tests conducted with PSP-modified WBMs show consistently lower filtrate volumes, thinner yet denser cakes, and reduced spurt loss compared with limestone or marble dust systems. Scanning electron microscopy of post-filtration cakes reveals tightly packed angular particles interspersed with fine filler fractions, forming a micro-architecture that effectively bridges pore throats across a range of formation types [49]. In addition, the acid solubility of PSP allows for controlled removal after drilling, minimizing the risk of long-term formation damage and ensuring that the bridging layer does not compromise subsequent production operations.

5.3 Filter Cake Thickness and Permeability

The functional quality of a drilling fluid’s filter cake is determined not solely by the volume of filtrate lost during circulation, but by a combination of physical parameters including cake thickness, intrinsic permeability, mechanical integrity, and ease of post-drilling removal. Each of these parameters directly affects wellbore stability, the risk of differential sticking, and overall drilling efficiency. A filter cake that is excessively thick may exacerbate annular friction, increase torque and drag, and hinder tripping operations, while a cake that is too thin or weak may fail to adequately isolate the formation, allowing filtrate invasion and formation damage. Therefore, the engineering goal in advanced water-based mud (WBM) design is to generate a filter cake that is both mechanically robust and hydraulically effective, minimizing thickness while maintaining low permeability [49].

From engineering perspective, the intrinsic permeability of the filter cake can be approximated using a modified form of Darcy's law, expressed as:

$$k=Q\mu L/A\Delta P \qquad 8$$

where k represents the cake's intrinsic permeability, QQQ is the volumetric flow rate of filtrate, μ is the dynamic viscosity of the filtrate, L is the measured thickness of the deposited cake, AAA is the effective filtration area, and ΔP is the differential pressure driving the filtration. This relationship enables engineers to correlate laboratory-measured filtrate volumes and cake thicknesses with predicted hydraulic performance under downhole conditions. In practical drilling scenarios, achieving low permeability with minimal thickness is essential for limiting the hydrostatic pressure differential across the cake, thereby reducing the risk of differential sticking and maintaining operational control of the mud column.

Periwinkle shell powder (PSP), due to its distinctive material properties, enables the formation of filter cakes that meet these engineering objectives more effectively than conventional barite or carbonate-based systems. The biogenic microstructure of PSP, consisting of angular aragonite needles and rhombohedral calcite grains, promotes dense particle packing and interlocking at multiple scales. When the particle-size distribution is engineered to include fine fractions (2–10 µm) for void filling and coarse fractions (30–75 µm) for skeletal support, the resulting cake exhibits a highly compact microarchitecture with minimal interstitial voids. This compact packing reduces permeability substantially, even at reduced cake thicknesses, because the flow pathways for filtrate are disrupted and tortuosity within the cake is increased. Experimental studies using core-scale filtration cells show that PSP-modified WBMs produce cakes that are 20–40% thinner than comparable barite or limestone systems, yet exhibit 25–35% lower permeability. This represents a significant improvement in hydraulic isolation without excessive mud loading. Comparable trends have been reported in studies on engineered nano-additives, where microstructural densification leads to sharp reductions in filtrate mobility [23]; [24].

Mechanical integrity is another critical aspect of PSP-derived filter cakes. Drilling fluids must maintain cake stability under the dynamic shear conditions induced by circulating mud, particularly in deviated and horizontal wells. PSP cakes retain structural coherence during circulation because of the mechanical interlocking of angular particles and the cohesive interactions mediated by surface ions and residual organic fractions. Unlike polymer-dominated filter cakes, which often deform plastically under stress and leave behind gummy residues during clean-up, PSP cakes exhibit controlled mechanical breakdown. Under backflow or washing operations, the cake can partially disintegrate in a reversible manner, allowing for easy removal without leaving persistent residues that could damage the formation or impede production. This behavior is critical for maintaining near-wellbore permeability in open-hole completions, shale-rich intervals, and low-permeability formations, where conventional polymeric cakes often result in irreversible damage and formation plugging. This reversible breakdown mechanism aligns with recent studies emphasizing the need for filter cakes that balance structural robustness with ease of removal, a principle also highlighted in research on geopolymers and engineered sealing materials designed for zonal isolation [25].

The ability of PSP to produce thin, low-permeability cakes also directly impacts drilling performance by reducing differential sticking risk. Differential sticking occurs when the drill string becomes immobilized due to an excessive pressure differential across the filter cake. Thick or compressible polymer-rich cakes exacerbate this effect by increasing the contact area and adhesive forces at the pipe–cake interface. In contrast, PSP cakes achieve the dual objective of low permeability and minimal thickness. The reduced thickness minimizes the exposed contact area between the filter cake and drill string, while the mechanical rigidity and smooth interparticle contacts reduce adhesion, collectively lowering the likelihood of differential sticking. This is particularly advantageous in extended-reach wells, highly deviated sections, and offshore drilling operations where the combination of torque, drag, and annular friction presents a persistent operational challenge. The importance of such mechanically stable but minimally thick cakes is reinforced by HPHT fluid-loss research, where emerging additives—including those derived from pharmaceutical waste—have shown similar benefits in maintaining low-permeability barriers under extreme thermal gradients [26].

Thermal and mechanical stability under high-pressure, high-temperature (HPHT) conditions further distinguishes PSP-based cakes. Calcium carbonate derived from periwinkle shells exhibits high compressive strength and resistance to microfracture, ensuring that cake permeability remains low even as mud temperature fluctuates during circulation. At elevated temperatures, the fine PSP fractions maintain their structural packing due to limited thermal expansion and minimal organic decomposition, while the coarse fractions preserve the skeletal framework of the cake. Laboratory HPHT filtration tests demonstrate that PSP cakes remain mechanically intact at temperatures exceeding 200°F, whereas starch- or PAC-dominated cakes tend to soften, thin, or develop micro-channels that compromise hydraulic isolation. This thermal resilience enhances operational reliability and allows for prolonged circulation in challenging formations without loss of filtration control. Thermal stability of mineral-based additives has long been documented as a prerequisite for deep and ultra-deep drilling, consistent with earlier field-engineered systems specifically designed for hot-hole environments [29].

Additionally, the surface chemistry of PSP contributes to cake consolidation and permeability reduction. Magnesium and calcium ions present on particle surfaces interact with clay platelets and polymeric additives to promote controlled flocculation and minimize microchannel formation. Hydrogen bonding from residual organic fractions reinforces particle–particle cohesion, creating a mechanically interlocked network that resists erosion from mud circulation. The combined effects of particle morphology, chemical interactions, and PSD engineering result in cakes that achieve optimal thickness, low permeability, and reversible mechanical behavior – a combination that is difficult to replicate with geogenic carbonates or synthetic fillers. These interactions are further supported by recent investigations into modified carbonate systems and nanoparticle-enhanced mud chemistries, which confirm that ionic surface activity plays a critical role in optimizing fluid loss control [28].

In deviated and horizontal wells, where axial drag, torque, and annular pressure fluctuations are magnified, PSP-derived cakes provide additional operational advantages. The combination of thin cake profile, low permeability, and mechanical coherence reduces pipe–cake adhesion and mitigates torque and drag escalation. This translates into smoother tripping operations, reduced wear on drill string components, and lower risk of stuck pipe incidents. Moreover, the acid solubility of PSP ensures that any remaining cake material can be removed effectively during post-drilling clean-up, preserving near-wellbore formation integrity and preventing long-term production impairment. Acid-soluble biogenic additives derived from periwinkle shells have recently gained traction not only for filtration control but also for mud conditioning and pH enhancement, reflecting their broad functional compatibility with WBM chemistries [27].

5.4 Comparative Performance with other Additives

The engineering performance of periwinkle shell powder (PSP) in water-based mud systems becomes particularly evident when benchmarked against conventional filtration-control and bridging materials, including barite, limestone, marble dust, and other biogenic additives such as oyster shells or generic mollusk shells [11], [21]. Comparative evaluation requires consideration of multiple interdependent factors, including particle-size distribution, particle morphology, mechanical strength, thermal stability, acid solubility, and interaction with clay and polymeric components in drilling fluids [17], [23]. Across these metrics, PSP consistently exhibits superior characteristics that translate into field-relevant improvements in filter cake quality, hydraulic isolation, and wellbore stability [13, [19].

Barite ($BaSO_4$) has long been the standard weighting agent in drilling fluids due to its high density, chemical inertness, and cost-effectiveness. However, when assessed as a filtration-control material, barite exhibits significant limitations. Its large median particle size, often exceeding 30–40 µm for standard grades, reduces bridging efficiency in fine-pored formations such as shales, siltstones, and microfractured sandstones [15]. The angularity of barite particles is typically lower than biogenic carbonates, resulting in limited mechanical interlocking at pore throats. Consequently, barite tends to form thick, loosely packed cakes with significant interstitial voids, leading to higher cake permeability and increased filtrate invasion. In extended reach or highly deviated wells, the excessive thickness of barite cakes contributes to elevated annular friction, higher torque and drag, and an increased likelihood of differential sticking. Laboratory and field studies consistently demonstrate that barite-modified WBMs exhibit higher spurt loss and less stable cake formation compared to PSP-modified systems, particularly under high-pressure high-temperature (HPHT) conditions where polymeric components may degrade [17], [29].

Limestone and marble dust, both naturally occurring calcium carbonate materials, provide improved filtration-control capability relative to barite due to their chemical solubility and finer particle-size fractions. Limestone typically contains high-purity calcite and exhibits greater particle angularity than barite, which enhances mechanical bridging at pore throats. Marble dust, being derived from metamorphic limestone, also provides reasonably fine fractions and moderate surface roughness conducive to cake compaction. However, both materials present limitations in particle-size tunability and mechanical interlocking efficiency. The particle populations are often dominated by equant, partially rounded grains, which under sustained differential pressure facilitate micro-channel formation within the filter cake. These micro-channels increase effective permeability over time, allowing slow but progressive fluid invasion, particularly during static or low-circulation periods. Furthermore, the crystalline structure of geogenic limestone and marble dust is comparatively less resistant to thermal and mechanical stress. Under HPHT conditions, microfracturing and particle rearrangement can occur, reducing cake integrity and long-term filtration control [17]. In contrast, PSP combines both angularity and controlled multi-scale PSD, producing dense, interlocking cakes with minimal void spaces and lower permeability even at thinner cake thicknesses, mitigating many of the operational challenges associated with conventional carbonate fillers [13], [18].

Biogenic calcium carbonate sources, including oyster shells, snail shells, and other mollusk-derived materials, have been investigated as sustainable and environmentally friendly alternatives for WBM formulation [12], [21]. These materials offer several advantages, including acid solubility, partial PSD tunability, and intrinsic porosity. However, PSP demonstrates a superior balance of physicochemical properties that enhances both filtration control and wellbore strengthening [18], [19]. One critical differentiating factor is the calcium-to-organic residual ratio, which affects thermal stability, biodegradation potential, and long-term integrity of the filter cake. PSP typically exhibits a higher $CaCO_3$ content (85–96%) with controlled trace Mg^{2+} incorporation, resulting in improved lattice stability, reduced organic decomposition, and enhanced HPHT performance (Lamin et al., 2023). Oyster shells and other mollusks often retain higher residual protein fractions after conventional cleaning and deproteinization, which can lead to increased organic degradation under thermal exposure. This degradation may introduce fines, gas evolution, and localized pH changes within the mud, adversely affecting rheology, polymer stability, and mud–rock interactions. PSP, by contrast, undergoes optimized cleaning, deproteinization, and sterilization protocols that minimize residual organics, preserve lattice integrity, and ensure consistent performance across a wide range of temperatures and pressures [12], [21].

The mechanical attributes of PSP further reinforce its superiority over conventional additives. Microhardness, Young's modulus, and compressive strength measurements indicate that PSP particles withstand hydrostatic, overburden, and differential pressures without premature fracture, while still exhibiting controlled microfracturing that enhances pore-throat sealing [13], [25]. In contrast, limestone and marble dust particles often fail under comparable stress due to lower intrinsic toughness and reduced lattice defect density. Barite, being primarily dense and brittle, can crush under high-pressure zones, producing fines that increase mud plastic viscosity and disrupt cake formation. PSP's dual-phase aragonite–calcite structure, combined with angular particle morphology, creates a synergistic mechanical system where the coarse fraction bears load and the fine fraction fills interstitial voids, producing a stable, low-permeability cake capable of resisting erosion and maintaining filtration control over extended circulation periods [17].

Thermal stability is another key area where PSP demonstrates field-relevant advantages. High-temperature drilling operations in deepwater or HPHT environments expose drilling fluids and filter cakes to temperatures ranging from 150–250°C. Conventional polymeric fluid-loss additives, as well as geogenic carbonate fillers, often experience thermal degradation, plasticization, or particle rearrangement under these conditions [23], [24]. PSP maintains structural integrity due to the high crystallinity of the aragonite–calcite phases, with onset decomposition of $CaCO_3$ occurring only at 700–850°C, far above operational ranges. Additionally, the minor residual organic content in PSP contributes positively by improving lubricity and interparticle cohesion without introducing deleterious effects on cake permeability. Laboratory HPHT tests indicate that PSP-modified filter cakes retain low permeability, minimal thickness, and mechanical coherence at elevated temperatures, outperforming barite, limestone, and marble dust systems, which often exhibit increased cake compressibility and microfracture formation under similar conditions [17], [13].

Acid solubility provides an additional functional advantage for PSP relative to conventional fillers. Post-drilling clean-up and formation stimulation operations frequently require removal of the filter cake to restore near-wellbore permeability and avoid long-term formation damage. PSP dissolves efficiently in mild hydrochloric acid treatments without leaving insoluble residues, whereas barite, limestone, and marble dust may require stronger acids or extended exposure, risking unintended formation alteration or scaling issues. Moreover, the dissolution of PSP is controllable, ensuring that selective removal is achieved without destabilizing the surrounding mud column or inducing unwanted fines generation. This characteristic enables PSP to function not only as a high-performance filtration-control material but also as a strategic component in wellbore strengthening and production-preserving operations [15], [19].

From a fluid-mechanical perspective, the interaction of PSP particles with the aqueous phase, clay platelets, and polymeric additives contributes to superior rheological control compared with conventional materials [20]. The surface chemistry of PSP, including Mg^{2+} and residual functional groups, enhances particle flocculation, electrostatic stabilization, and mechanical interlocking. This contrasts with barite, which primarily acts as an inert weighting agent with minimal surface interaction, and with geogenic carbonates, whose limited surface roughness and chemical reactivity reduce the efficiency of particle network formation within the filter cake. The enhanced particle–particle cohesion of PSP allows for consistent formation of a uniform, thin, low-permeability cake that can withstand high shear rates and dynamic downhole conditions while minimizing the risk of annular friction escalation [17].

Finally, PSP's versatility extends to multi-scale and multi-functional applications. Beyond filtration control, its mechanical and chemical attributes contribute to near-wellbore strengthening, shale stabilization, and wellbore lubricity enhancement [15]. The ability to engineer PSD, surface properties, and particle morphology enables PSP to bridge pore throats of varying diameters, densify the filter cake, and interact synergistically with mud polymers to provide shear-thinning behavior, yield stress control, and thermal resilience. When compared against barite, limestone, marble dust, and other biogenic materials, PSP emerges not merely as a viable alternative but as a next-generation multifunctional solid additive capable of addressing the intertwined challenges of filtration control, mechanical wellbore support, and HPHT operational reliability [11], [17].

6. Wellbore Stability & Shale Interaction

Wellbore instability remains one of the most persistent sources of non-productive time in drilling operations, particularly in shale-dominated formations where chemical, mechanical, and hydraulic mechanisms act simultaneously [15]. Traditional WBM systems often fail to adequately suppress shale hydration, osmotic swelling, capillary suction, and near-wellbore mechanical weakening. The integration of PSP into WBM introduces a new stabilization pathway combining water activity suppression, capillary pressure regulation, micro-fracture sealing, and mechanical strengthening of the near-wellbore stress zone [13]. Unlike purely chemical inhibitors such as KCl and PHPA, PSP operates through a hybrid physicochemical and geomechanical mechanism that directly modifies stress transfer, pore pressure diffusion, and crack propagation behavior in the near-wellbore region.

The stability of shales during drilling operations is fundamentally governed by the interplay between chemical, mechanical, and capillary processes, all of which influence the migration of water, pore pressure evolution, and near-wellbore stress distribution. Central to these processes is the concept of water activity, which defines the thermodynamic driving force for moisture movement between drilling fluids and shale formations. Water activity in the drilling context is commonly expressed as the ratio of the vapor pressure of the drilling fluid to that of pure water, providing a direct indicator of the chemical potential gradient that drives hydration into expandable clay lattices. In conventional water-based muds, high water activity promotes rapid water influx, leading to swelling of smectitic clays, softening of the shale matrix, and subsequent mechanical instability manifesting as caving, washouts, and differential sticking [15]. The integration of periwinkle shell powder (PSP) into water-based mud systems introduces a dual chemical and mechanical control mechanism that effectively reduces water activity and its associated deleterious effects [18], [27].

The reduction in water activity conferred by PSP arises primarily from the release of divalent calcium and trace magnesium ions into the mud filtrate. These ions increase the ionic strength of the solution, compressing the diffuse double layers around clay platelets and diminishing the osmotic potential for water migration into shale pore networks. Unlike potassium chloride, which relies solely on monovalent cation exchange, or partially hydrolyzed polyacrylamide, which operates primarily through molecular encapsulation of clay surfaces, PSP provides a persistent ionic buffering effect that is maintained even under high-temperature circulation conditions. The robust thermal stability of the biogenic calcium carbonate lattice ensures that the ionic release mechanism remains operational while polymeric inhibitors degrade, extending the effective protection of the near-wellbore environment into the high-temperature zones commonly encountered in deepwater or extended-reach wells [17], [24]. By lowering the chemical potential gradient between the mud and shale, PSP-treated systems minimize water absorption, retard pore pressure build-up, and suppress shale softening, thereby delaying the onset of mechanical failure and promoting stable borehole geometry.

Shale swelling, the principal driver of wellbore instability, arises from the intercalation of water molecules into the interlayer spaces of smectitic clays, resulting in volumetric expansion and mechanical weakening. Traditional chemical inhibitors such as KCl mitigate swelling through monovalent cation exchange, replacing sodium ions in the clay lattice and reducing interlayer expansion. Similarly, polymeric inhibitors like PHPA achieve stabilization by adsorbing onto clay platelet surfaces and forming a protective hydrophobic shell that limits hydration. PSP, however, introduces an additional stabilization pathway through a dual chemical–mechanical mechanism. The calcium-rich surface of PSP promotes strong divalent cation exchange with expandable clay lattices, creating more robust electrostatic binding and reducing interlayer expansion more effectively than monovalent potassium ions. Concurrently, the finely ground PSP particles penetrate nano-scale pores, micro-fractures, and weak bedding planes within the shale, establishing physical confinement that mechanically restricts volumetric expansion. This dual mechanism is particularly advantageous under HPHT conditions where polymer inhibitors alone exhibit thermal degradation and reduced efficacy, enabling PSP-modified muds to maintain shale stability at elevated temperatures exceeding 250°F (Davoodi et al., 2018; Gautam et al., 2022).

The control of capillary pressure is another critical aspect of shale stabilization, as capillary suction governs the spontaneous movement of water into micro- and nano-scale pore systems. Capillary pressure is inversely proportional to the pore radius and is modulated by the surface tension of the fluid and the wettability of the solid matrix. PSP influences capillary dynamics through two principal mechanisms. First, the physical blocking of pore throats and micro-fractures by strategically sized PSP particles reduces the effective pore radius, thereby diminishing the driving force for spontaneous filtrate imbibition. Second, surface modification of PSP, including silane or fatty-acid coatings, can alter wettability towards neutral or weakly hydrophobic behavior, reducing the effective contact angle term in the capillary pressure relationship. The combination of reduced effective pore radius and tailored surface energy limits deep filtrate penetration, preserving near-wellbore mechanical integrity and reducing the likelihood of hydration-induced microfracturing [15], [13]. This effect is particularly significant in highly laminated or micro-fractured shales, where conventional chemical inhibitors fail to prevent rapid pressure diffusion and localized instability.

Beyond chemical and capillary effects, PSP contributes directly to mechanical strengthening of the near-wellbore zone. Fine PSP particles infiltrate induced micro-fractures and bedding-plane weaknesses, where they become mechanically interlocked under differential pressure. This particle–rock coupling effectively redistributes hoop stress around the borehole, mitigating localized stress concentrations that could otherwise lead to shear failure or tensile breakout [25]. The presence of PSP within these microstructural gaps forms a composite mud–rock interface that behaves as a load-bearing shell, capable of sustaining transient overpressure events while providing controlled compliance to dynamic drilling loads. Laboratory and field studies have shown that PSP-enhanced mud–shale systems reduce micro-fracture propagation, limit bedding-plane slippage, and maintain borehole gauge, even under high torque and drag conditions [15]. Moreover, the mineral content of PSP promotes localized cementation under downhole temperature and pressure, further increasing near-wellbore stiffness and contributing to a mechanically stabilized annular region that resists collapse and cavings [27].

The integration of PSP into drilling fluids therefore produces a multiphase stabilization effect: the mud exhibits reduced water activity and controlled ionic strength, the shale matrix experiences limited interlayer expansion and mechanical confinement, and the capillary forces driving spontaneous infiltration are diminished. These effects combine to produce measurable improvements in operational performance, including reduced volume of caved materials, lower torque and drag fluctuations, and improved maintenance of borehole gauge and structural integrity. Additionally, the mechanically and chemically stabilized near-wellbore environment improves the quality of logging data, enhances the success rate of completions, and facilitates the deployment of advanced drilling technologies, such as managed pressure drilling and extended reach operations [29], [15].

Another field-relevant aspect of PSP is its ability to provide long-duration stabilization under cyclic thermal and mechanical loading. In deepwater and high-angle wells, drilling fluids repeatedly cycle between surface and downhole temperatures, imposing differential thermal expansion stresses on both mud solids and formation matrices. PSP’s interlocking aragonitic and calcitic crystal microstructure exhibits enhanced thermal fatigue resistance compared with monolithic calcite or polymeric additives. This resilience ensures that the combined chemical–mechanical stabilization effect of PSP is maintained over extended circulation periods, preventing fines generation, preserving rheological control, and maintaining filter cake integrity despite repeated thermal cycling [17], [24].

From a design and engineering standpoint, the selection of PSP particle size distribution, surface modification, and dosage can be tailored to match formation characteristics, including shale clay content, pore size distribution, and formation sensitivity. Coarse PSP fractions bridge larger pore throats to provide structural support, while fine fractions penetrate micro-pores to reduce effective permeability and capillary suction. Surface treatments can be applied to enhance compatibility with polymers, adjust wettability, and further suppress filtrate invasion. This tunability ensures that PSP-modified WBMs can be optimized for both conventional and challenging well environments, providing a versatile solution that addresses both chemical and mechanical instability simultaneously [19], [13].

Overall, the inclusion of PSP in drilling fluids establishes a synergistic stabilization platform that merges chemical inhibition, capillary pressure modulation, and mechanical strengthening into a single additive system. The persistent release of divalent cations controls water activity, the dual chemical–mechanical bridging reduces swelling, and the physical blockage of micro-pores attenuates capillary suction, while the mineral-mediated mechanical coupling reinforces near-wellbore stress distribution. The cumulative impact of these mechanisms is a demonstrably improved borehole integrity under high-temperature, high-pressure, and highly deviated well conditions. Operators benefit from reduced non-productive time due to caving and stuck pipe incidents, enhanced drilling efficiency from lower torque and drag fluctuations, and improved wellbore quality that facilitates subsequent completions, stimulation, and production operations [15], [17].

7. Environmental Assessment

The environmental, toxicological, and regulatory performance of drilling fluid additives constitutes a critical determinant of their field adoption and sustainability credentials [11]. As the oil and gas industry faces increasingly stringent environmental regulations, particularly in offshore and ecologically sensitive regions, drilling engineers are compelled to evaluate not only the functional performance of additives but also their potential impacts on ecosystems, human health, and regulatory compliance [28]. Periwinkle shell powder (PSP), as a biogenic calcium carbonate material, provides a unique opportunity to reconcile drilling performance with environmental stewardship, yet it requires a rigorous assessment of potential heavy metal leaching, biodegradability, and carbon footprint across its life cycle [21].

The leaching potential of PSP, particularly for heavy metals, is a primary concern in both regulatory and operational contexts. Standardized leachate assessments such as the Toxicity Characteristic Leaching Procedure (TCLP) provide a framework to quantify the mobilization of environmentally sensitive elements, including lead, cadmium, chromium, and mercury [11]. In the context of PSP, the native calcium carbonate matrix generally exhibits low intrinsic heavy metal content; however, trace incorporation of metals can occur during biological growth or environmental exposure, particularly from contaminated seawater or sediment deposition. TCLP tests of PSP-modified drilling fluids reveal that leachate concentrations of Pb, Cd, Cr, and Hg consistently remain below internationally recognized regulatory thresholds, often by several orders of magnitude [28]. This is attributable to both the strong chemical stability of the carbonate lattice and the limited solubility of trace metal ions under neutral to mildly alkaline mud conditions. Unlike synthetic mineral additives or waste-derived carbonates, PSP does not require additional chemical stabilization to achieve regulatory compliance, reducing the risk of unanticipated mobilization during storage, transport, or downhole disposal.

Marine biodegradability is another key consideration for the adoption of PSP in offshore drilling operations. Conventional water-based muds often rely on synthetic polymers or starch-based additives to achieve fluid-loss control and rheological modification. These components, while functionally effective, present variable degradation profiles in marine environments and may contribute to oxygen demand, microbial activity, or the accumulation of recalcitrant organic matter [23]. In contrast, PSP is an inorganic biogenic material with minimal residual organic content following standardized deproteinization and thermal treatment [12]. Laboratory biodegradability studies demonstrate that the residual organic fraction, predominantly composed of chitinous and protein-derived molecules, undergoes gradual microbial mineralization under both aerobic and anaerobic conditions, without producing persistent or toxic intermediate compounds [21]. The dissolution of calcium carbonate under slightly acidic conditions further enhances its benign environmental profile by promoting localized alkalinity buffering, which can neutralize minor acidic discharges.

The carbon footprint of drilling fluid additives is increasingly scrutinized under life-cycle assessment (LCA) methodologies, particularly as operators seek to reduce Scope 3 emissions associated with upstream and midstream operations. In the case of PSP, the environmental benefit is derived from both the substitution of high-energy, mined mineral additives such as barite and limestone, and the utilization of a low-value biogenic waste product that would otherwise require disposal [11], [12]. Quantitative LCA indicates that the production of one ton of PSP-modified drilling fluid solids consumes significantly less energy than equivalent tonnage of barite or synthetic calcium carbonate, primarily because it bypasses high-temperature calcination and extensive chemical purification steps. Transportation emissions are also reduced due to the lower effective bulk density of PSP compared with barite, which reduces fuel consumption per unit volume transported to offshore rigs or remote onshore operations. Furthermore, the end-of-life scenario for PSP, involving reintegration into sediments or controlled pit disposal, produces minimal greenhouse gas emissions relative to both synthetic additives and unprocessed mined minerals.

Toxicological assessment of PSP extends beyond heavy metal leaching to encompass potential acute and chronic hazards associated with inhalation, dermal exposure, and accidental ingestion. In laboratory trials simulating mud handling conditions, the fine fraction of PSP exhibits low respirable particulate concentrations, and standardized cytotoxicity assays indicate negligible adverse effects on mammalian epithelial cells [28]. The primary hazard associated with PSP handling is mechanical irritation typical of fine mineral dusts; standard occupational safety measures, such as respirators and dust control during storage and milling, effectively mitigate these risks. Unlike certain synthetic or industrial by-products that may carry embedded organic solvents, residual monomers, or reactive species, PSP presents a chemically inert profile, reducing regulatory and operational concerns regarding worker exposure, environmental contamination, and long-term liability.

The regulatory landscape for drilling fluid solids is diverse, spanning multiple jurisdictions and incorporating limits on heavy metals, total suspended solids, biodegradability, and ecotoxicological thresholds. PSP’s favorable chemical and physical properties facilitate compliance across this regulatory spectrum [11]. Its low leachable metal content meets TCLP and equivalent leachate testing requirements. Its gradual mineralization and low organic content satisfy marine biodegradability criteria. Its origin from natural biogenic shells allows classification as a non-hazardous solid under multiple international regulatory frameworks.

The combined environmental and regulatory advantages of PSP also support circular economy objectives by valorizing shell waste that would otherwise contribute to environmental burden [12], [21]. Coastal regions generating significant periwinkle shell waste face disposal challenges, often leading to uncontrolled dumping, eutrophication, or local contamination. By redirecting these shells into drilling fluid applications, the material achieves an engineered value stream, converting low-value biowaste into a high-performance, environmentally benign drilling additive.

The comparative evaluation of PSP against conventional additives, such as barite and limestone, reinforces its environmental and regulatory superiority. Barite, while functionally adequate for mud weighting, exhibits higher embodied energy, limited biodegradability, and higher potential for particulate discharge and aquatic accumulation. Limestone and marble dust, although acid-soluble and moderately effective as bridging agents, require energy-intensive processing and present a higher carbon footprint. By contrast, PSP demonstrates a unique combination of low toxicity, controlled particle size tunability, acid solubility for post-drilling removal, and sustainable sourcing [11], [28].

Beyond regulatory compliance, PSP adoption has implications for long-term ecological stewardship and corporate environmental responsibility. By minimizing heavy metal introduction, reducing biodegradable polymer load, and lowering greenhouse gas emissions associated with production and transport, PSP contributes to the reduction of drilling operations’ cumulative environmental impact. The predictable and reproducible environmental profile of PSP facilitates environmental impact assessments, post-drilling monitoring, and stakeholder reporting, which are increasingly demanded in international projects and high-profile offshore developments. The alignment of technical performance with environmental stewardship enhances corporate reputation, supports ESG targets, and provides a measurable pathway toward greener drilling practices.

8. Economic and Supply Chain Analysis

The economic feasibility and supply chain implications of deploying periwinkle shell powder (PSP) in water-based mud systems represent a critical pillar for its adoption in both local and offshore drilling operations. While technical performance is essential for wellbore stability, filtration control, and rheology optimization, practical deployment requires a thorough evaluation of cost efficiency, material availability, logistics, and potential for import substitution. This section examines the comparative economics of PSP relative to conventional weighting and bridging materials, the supply potential from local Nigerian sources, and the operational advantages conferred by establishing a domestic PSP supply chain. The motivation for alternative materials is further strengthened by the increasing emphasis on lost circulation mitigation and wellbore strengthening, where calcareous and particulate additives play critical roles in sealing microfractures and strengthening weak formations [30].

The unit cost of drilling fluid additives directly influences overall mud system economics, particularly for high-volume wells and extended reach operations. Barite, the conventional weighting agent in Nigeria and globally, is predominantly imported for offshore operations, incurring both material costs and shipping premiums. Recent market assessments indicate landed costs for barite in Nigerian ports range between $400–$600 per metric ton, depending on grade, particle size distribution, and shipping distance from primary exporters such as India, China, or the Middle East. In contrast, PSP, derived from locally abundant periwinkle shells, has an intrinsic cost advantage. Initial collection and primary processing costs are relatively low, as shells are often treated as agricultural or fishery waste, consistent with the characterization of shell-based materials as low-cost, underutilized calcareous resources [42]. With centralized milling, deproteinization, and classification facilities, the unit cost of PSP powder suitable for drilling applications is estimated between $150–$250 per metric ton, representing a potential 50–65% reduction compared with imported barite. This cost differential is amplified when considering offshore logistics, where transportation of imported barite to rig-side facilities can further increase delivered cost due to specialized handling, port congestion, and risk management premiums. Furthermore, the replacement of imported additives with local shell-derived materials aligns with previously documented findings on the economic and technical viability of native biomineral-based products in drilling muds [34], [35].

A critical component of the PSP economic proposition is the local supply advantage, particularly within the Niger Delta region, which hosts extensive artisanal and semi-industrial periwinkle harvesting operations. Studies indicate that the aggregate annual collection of periwinkle shells from estuarine and coastal fisheries exceeds several thousand tons, far surpassing current industrial demand for processed additives. Similar observations have been made in civil engineering applications, where periwinkle shell ash has demonstrated substantial availability and mechanical stability when processed for geotechnical improvement [32]. By channeling this material into drilling fluid production, operators can establish a domestic raw material base, reduce foreign exchange exposure, and minimize vulnerability to international commodity price fluctuations. The supply chain is further reinforced by the relative simplicity of PSP processing, which does not require energy-intensive calcination, extensive chemical treatment, or high-temperature synthesis. Primary processing can be implemented near collection points, thereby reducing bulk transport costs associated with shipping unprocessed shells over long distances. Secondary processing, including milling to target particle size distributions and optional surface modifications, can be concentrated near industrial hubs or directly at drilling service depots to optimize logistical efficiency. This model mirrors previous recommendations for integrating locally sourced additives into drilling fluid management systems to enhance economic and environmental resilience [36].

An import substitution index provides a quantitative metric for the potential reduction in foreign dependency achieved by PSP adoption. Considering that Nigeria imports the majority of its barite requirement for offshore operations, the substitution of even a fraction of high-value mud solids with locally sourced PSP represents a substantial reduction in national foreign exchange outflow. For example, replacing 50% of barite in a typical offshore drilling program consuming 20,000 tons of mud solids could conserve approximately $4–$5 million in import expenditure per well program. Over multiple years and across multiple rigs, the cumulative economic impact becomes significant, effectively creating a new domestic industrial niche while simultaneously enhancing energy security and material resilience. This substitution potential is also consistent with the global shift toward environmentally benign and regionally sourced additives, particularly in environmentally sensitive offshore environments where water-based mud discharge and cuttings dispersion are scrutinized [31].

The logistics of shell collection and processing represent a non-trivial but manageable component of PSP adoption. Shells must be collected, washed, sorted, and deproteinized to ensure consistent chemical composition and minimal residual organic content. Acid washing or thermal treatment removes surface-bound organics and potential microbial load, while controlled milling produces particle size distributions optimized for bridging, filtration, and rheology functions. These treatment pathways are similar to those documented for other biomineral powders used in drilling fluids and composite materials, where proper preconditioning significantly influences performance [42], [35]. The cost structure of these operations is highly sensitive to scale. At small artisanal scales, unit costs may rise due to labor intensity and energy inefficiency. However, centralized processing facilities that aggregate shell input from multiple collection sites achieve economies of scale, reducing unit production costs and enabling consistent quality control. Investment in semi-automated washing, milling, and classification lines further enhances productivity and ensures that particle size, surface morphology, and residual moisture are tightly controlled, all of which are essential for reliable mud system performance. Previous experimental studies on additives such as polypropylene–silica nanocomposites have shown that the consistency of particle processing directly affects rheological and filtration outcomes, reinforcing the necessity of strict quality control in PSP production [37].

Beyond processing, storage and transport logistics are critical for operational continuity. PSP, being a calcareous powder, is mechanically robust and chemically stable, permitting standard bulk storage in silos or enclosed containers without risk of chemical degradation. Unlike barite, which may segregate during transport due to broad particle size distributions, PSP can be engineered with narrow PSD windows to maintain uniformity throughout storage and handling. Transport to rig sites is simplified by the lower specific gravity of PSP (≈2.65–2.75 g/cm³), reducing loading, hoisting, and rig-side handling requirements relative to barite. In offshore applications, where lift cost per ton-meter is a key operational parameter, the lower density and higher bridging efficiency of PSP directly reduce mud system tonnage requirements without compromising wellbore support. These efficiencies are particularly relevant in deep-water and ultra-deep-water operations, where dynamic loading, material transport, and handling contribute significantly to operational cost and equipment stress [41].

The potential economic benefits of PSP are further enhanced when considering integrated supply chains and local industrial participation. By establishing partnerships with local fisheries, cooperatives, and processing firms, drilling operators can create stable procurement networks that reduce price volatility and enhance social license to operate. This approach not only supports regional economic development but also aligns with corporate social responsibility mandates, which increasingly emphasize local content and value addition. In addition, the circular economy dimension of PSP use—transforming shell waste into a high-value drilling additive—provides a demonstrable environmental and sustainability benefit, further strengthening the business case for its adoption. The environmental compatibility of such materials also enhances their suitability for use in WBM systems deployed in sensitive offshore ecosystems [31].

A comparative analysis of the full cost of mud solids incorporating PSP versus traditional barite is instructive. Table 1 presents an indicative cost breakdown for mud solids in a standard offshore program, illustrating the combined effect of material, processing, transport, and logistical factors.

Table 6: Comparative Cost Analysis of PSP vs Barite in Drilling Mud Solids

Component	Barite ($/ton)	PSP ($/ton)	Notes
Raw Material	350	50–80	PSP sourced locally from shell waste
Processing & Milling	30	60–100	Milling, classification, optional surface modification
Transport & Handling	100–200	40–70	Includes offshore rig lift and bulk delivery
Quality Control & Storage	20	15–25	PSD and chemical composition monitoring
Total Delivered Cost	500–600	150–250	50–65% cost savings achievable

Table 1 demonstrates the potential for substantial cost savings, with PSP reducing the total delivered cost of mud solids by more than half in typical scenarios. These savings are compounded over extended drilling campaigns, particularly in remote offshore environments where logistical surcharges on imported materials are significant.

The adoption of PSP enhances supply chain resilience. Reliance on imported barite exposes operators to international market volatility, shipping disruptions, and geopolitical risks. By contrast, a domestic PSP supply chain, leveraging local shell resources and centralized processing, mitigates these vulnerabilities. Operators gain predictability in material availability, improved responsiveness to drilling program changes, and reduced exposure to foreign currency fluctuations. Additionally, the ability to tailor PSD and optional surface modifications on-site permits real-time adaptation of mud properties to changing wellbore conditions, offering both technical and economic flexibility [43]. In addition to cost and supply considerations, the PSP supply chain presents opportunities for process optimization and local industrial development. Investments in modular processing units, which combine washing, milling, classification, and optional functionalization, enable scalable production and reduced lead times. Centralized quality control laboratories can monitor mineralogical composition, particle size distribution, residual organics, and density, ensuring consistent additive performance. This level of control is particularly critical for offshore HPHT wells, where mud system reliability directly impacts non-productive time, completion success, and overall drilling program economics.

9. Field Application

The translation of laboratory-scale performance of periwinkle shell powder (PSP) into field-scale applications represents the ultimate validation of its utility as a multifunctional additive in water-based drilling fluids. While bench-top evaluations of rheology, filtration control, and shale inhibition provide critical mechanistic understanding, field deployment encompasses additional complexities, including high-temperature high-pressure (HPHT) environments, extended circulation times, complex lithologies, and operational constraints such as lost circulation, wellbore tortuosity, and dynamic mud weight management. In this context, PSP offers a unique combination of chemical, mechanical, and thermochemical attributes that collectively support improved drilling outcomes in challenging Nigerian Niger Delta shale wells and analogous reservoirs worldwide.

The Niger Delta presents one of the most technically demanding drilling environments for water-based mud systems, particularly in the deep offshore and onshore shaly formations characterized by high smectite content, laminated bedding, and pervasive natural fractures. Shale instability in this region often manifests as hole collapse, wellbore enlargement, differential sticking, and increased torque and drag during drilling, with consequent delays in drilling programs and elevated non-productive time. Conventional inhibitors, including potassium chloride (KCl) and partially hydrolyzed polyacrylamide (PHPA), provide partial mitigation by controlling water activity and restricting clay hydration. However, these chemical inhibitors are limited by thermal degradation, insufficient mechanical confinement, and inability to address pore-scale fractures, particularly under HPHT conditions where polymer breakdown and ion exchange inefficiency reduce effectiveness [44]. PSP bridges this performance gap by offering dual chemical–mechanical inhibition mechanisms. The controlled release of Ca^{2+} and trace Mg^{2+} ions reduces water activity, compresses the diffuse double layer of smectitic clays, and stabilizes the shale matrix electrochemically [45]; [39]. Concurrently, fine and coarse PSP particles physically invade micro-fractures and pore spaces, forming a mechanically interlocked network that reinforces the near-wellbore stress shell, thereby enhancing hoop strength and reducing the propensity for borehole collapse [38].

In HPHT formations, typically encountered in deep offshore wells of the Niger Delta where bottomhole temperatures range between 150°C and 250°C and pore pressures may exceed 10,000 psi, PSP demonstrates significant advantages over conventional additives. Laboratory simulations and HPHT filtration tests indicate that PSP maintains structural integrity, thermal inertness, and bridging efficiency under temperatures that degrade polymeric inhibitors [49]. The thermochemical stability of calcium carbonate ensures that the solid sealing function is preserved, while controlled pyrolysis of the residual organic matrix minimally modifies surface chemistry, providing lubricity benefits and reducing torque and drag on the drill string [47]. This operational robustness is critical for HPHT formations where drilling fluid failure can rapidly escalate into severe wellbore instability, loss of circulation, or stuck pipe incidents. By integrating PSP into WBMs, operators can maintain a predictable rheology profile, minimize differential pressure penetration into weak shales, and sustain effective wellbore support over prolonged circulation periods.

Lost circulation zones represent another operationally critical application for PSP-modified muds. In these scenarios, the challenge is to maintain hydrostatic pressure and mud circulation while preventing mud loss into highly permeable or fractured formations. Conventional bridging agents such as barite or limestone are often too coarse or insufficiently interlocking to arrest fluid migration at the micro- and meso-fracture scale. PSP's broad particle size distribution, which can be engineered from 2–10 µm for pore filling to 30–75 µm for structural bridging, allows it to form multi-scale sealing networks that adapt to the formation permeability profile. This graded packing approach facilitates early bridging, reduces the extent of mud invasion, and promotes the formation of a thin but mechanically robust filter cake that both supports the wellbore and maintains hydraulic isolation [43]. Field deployment logic dictates that PSP be combined with conventional lost circulation materials where macro-fractures exist, enabling a synergistic approach in which fine PSP fills micro-fractures while coarse fibers or granular LCMs provide bulk sealing. Such integrated strategies have the potential to reduce lost circulation events, limit mud volume consumption, and improve overall drilling efficiency.

Wellbore strengthening through PSP addition is not limited to physical plugging. The intercalation of PSP particles within micro-fractures and bedding planes creates a composite mud–rock interface that redistributes stress concentrators and enhances near-wellbore stiffness. By mechanically reinforcing the annulus, PSP reduces the likelihood of tensile breakout, shear slippage, and cavings generation during directional drilling or extended-reach well operations. Field-scale modeling indicates that a properly engineered PSP-modified WBM can increase the effective hoop stress around the borehole by several hundred psi, providing a margin that is particularly valuable in shales with low unconfined compressive strength [16]. This stress redistribution is complemented by the ionic stabilization provided by Ca^{2+} and Mg^{2+}, which suppresses clay hydration and prevents progressive weakening of the shale matrix. Together, these chemical and mechanical effects translate into measurable improvements in gauge hole quality, reduced torque and drag fluctuations, enhanced mud circulation efficiency, and improved success rates for logging and completion operations [46].

Operational integration of PSP in Niger Delta wells also highlights practical considerations for field-scale adoption. The logistics of additive preparation, including localized milling, classification, and optional surface modification, can be accommodated at central service facilities near drilling sites. Real-time monitoring of mud properties, including rheology, filtrate volume, and solids content, allows engineers to adjust PSP concentration dynamically, optimizing bridging and wellbore support while minimizing over-dosing and associated cost implications [48]. The modular nature of PSP addition—whereby coarse and fine fractions can be blended to meet formation-specific permeability profiles—permits field engineers to tailor the mud system to lithological variations encountered during multi-lateral or extended-reach drilling campaigns. Additionally, the use of PSP reduces dependency on imported materials, enhances local content utilization, and contributes to sustainable waste valorization, aligning operational efficiency with corporate social responsibility objectives [39].

From a performance validation standpoint, field trials of PSP-modified WBMs in deep offshore Niger Delta wells demonstrate consistent improvements in key metrics. For example, well sections drilled with PSP-enhanced muds exhibit reduced cumulative mud losses, lower filtrate invasion depth, and improved stability in intermediate shaly intervals where differential sticking risk is highest. Comparative analyses with conventional polymer-inhibited muds show that PSP not only maintains equivalent or lower mud densities for equivalent wellbore support but also reduces the need for reactive addition of weighting materials to counteract hole instability. In horizontal and extended-reach well trajectories, the mechanical reinforcement provided by PSP mitigates borehole enlargement and maintains gauge diameter, facilitating smoother tool conveyance, improved logging tool response, and higher-quality well completions.

The versatility of PSP is further evident in its capacity to support complex wellbore engineering strategies. For instance, in wells with alternating shale and sandstone sequences, PSP can function as both a bridging agent and a partial filtration controller, limiting water loss into permeable sands while stabilizing adjacent shaly zones. Its acid solubility also allows for post-drilling remedial treatments, such as low-impact flushes to remove filter cakes, minimizing long-term formation impairment and improving ultimate hydrocarbon recovery. In deepwater or HPHT wells, PSP's thermal stability ensures continuous performance during extended circulation periods, while its ability to maintain mechanical integrity under cyclic loading addresses the thermal fatigue challenges associated with repeated fluid movement between surface and bottomhole environments.

Moreover, the field-scale application of PSP opens opportunities for integration with other advanced drilling technologies. Its particle size engineering enables compatibility with hybrid water-based mud formulations containing polymers, nanoparticles, or biopolymers for enhanced rheology and filtration control. PSP can be blended with conventional weighting agents to fine-tune density profiles without compromising bridging efficiency. Additionally, PSP's dual chemical–mechanical inhibition allows for reduced reliance on environmentally sensitive polymeric inhibitors, aligning operational objectives with increasingly stringent regulatory frameworks governing offshore drilling fluids.

10. Conclusion

Periwinkle shell powder (PSP) is demonstrated to be a multifunctional and high-performance additive for water-based mud (WBM) systems, offering significant advancements in drilling fluid design through its intrinsic mineralogical, chemical, mechanical, and thermochemical properties. The biogenic nature of PSP, defined by a dual polymorphic structure of aragonite and calcite, provides a robust crystalline framework that imparts high stiffness, fracture toughness, and controlled microfracture behavior. These characteristics enable efficient bridging and formation of low-permeability, mechanically resilient filter cakes under dynamic downhole stress conditions. X-ray diffraction and elemental analyses confirm that PSP is predominantly composed of calcium carbonate with minor amounts of magnesium, iron, and silicon. These elements influence hydration behavior, electrostatic interactions with clay platelets, and polymer adsorption, establishing PSP as both chemically active and mechanically functional within WBM formulations.

Rheologically, PSP enhances plastic viscosity, yield point, and flow behavior index, enabling controlled transition from Bingham to Herschel–Bulkley-like fluid behavior while maintaining stability under elevated temperatures typical of HPHT environments. Engineered particle-size distributions of PSP, ranging from fine microfillers to coarse bridging fractions, provide multi-scale pore throat sealing and optimized filtration control. This results in thin, dense filter cakes with low permeability, reducing fluid invasion, differential sticking, and formation damage. Comparative evaluations show that PSP outperforms conventional bridging agents, including barite, limestone, marble dust, and other biogenic solids, due to its angular particle morphology, tunable size distribution, and acid-soluble nature, which ensures controlled removability during post-drilling operations.

PSP contributes directly to wellbore stability and shale inhibition. The release of divalent cations, combined with physical micro-fracture filling, reduces water activity, suppresses clay swelling, and stabilizes capillary pressures in shaly formations. This dual chemical–mechanical mechanism enhances near-wellbore stress support, redistributes hoop stress, and seals micro-fractures, improving hole quality, reducing torque and drag fluctuations, and mitigating shale instability in high-pressure, high-temperature, and complex lithology wells, such as those encountered in the Niger Delta.

Environmental evaluations indicate negligible heavy metal leaching, enhanced biodegradability in marine environments, and a reduced carbon footprint compared to conventional mineral additives. Economically, PSP offers cost advantages, potential import substitution, and a sustainable local supply chain in Nigeria, leveraging waste valorization and minimizing logistics costs. These factors make PSP a viable alternative for large-scale deployment in operational drilling programs without compromising performance or regulatory compliance. PSP provides a structurally robust, chemically active, and mechanically adaptive platform for WBM formulation, addressing critical challenges in filtration control, rheology, wellbore strengthening, and shale stabilization. The integration of mineralogical characterization, particle engineering, rheological performance, filtration mechanisms, and mechanical interactions with formations establishes PSP as a next-generation additive for high-performance, environmentally sustainable, and economically viable drilling fluid systems. This review establishes the technical foundation for rational PSP formulation, process optimization, and field-scale implementation, supporting safer, more efficient, and sustainable hydrocarbon extraction operations.

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