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Review: Sustainable Periwinkle Shell Powder Applications in Enhancing Water-Based Drilling Mud Properties for High-Pressure, High-Temperature Drilling Operations

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Abstract: *The paper explores the potential benefits of utilizing periwinkle shell powder (PSP) as a sustainable additive to optimize water-based drilling fluid performance. PSP, primarily composed of calcium carbonate ($CaCO_3$), exhibits multifunctional properties that improve critical mud parameters such as filtration loss control, loss circulation control, rheological behavior modification, pH enhancement, and weighting capability. The review critically analyzes the performance of PSP in comparison to conventional synthetic additives, highlighting its capacity to maintain desirable mud characteristics under varying operational conditions, including its influence on plastic viscosity, yield point and gel strength. The findings indicate PSP offers both economic and environmental advantages over commercial substitute drilling fluid additives. Economically, PSP offers a cost-effective alternative to synthetic additives like Poly Anionic Cellulose (PAC), reducing reliance on expensive imports and curbing capital flight in drilling operations. Environmentally, the adoption of PSP promotes sustainable waste management by repurposing the periwinkle shells, which is commonly discarded as waste material in coastal regions. The utilization of PSP not only mitigates environmental pollution but also presents a strategic advantage for energy companies to leverage on locally available resources. Furthermore, this approach has the potential to boost indigenous revenue generation in Nigeria by establishing an indigenous supply chain for drilling fluid additives, thereby reducing dependence on foreign chemicals. The paper emphasizes the dual benefits of PSP as both a technical and economic solution, with promising implications for the future of sustainable drilling operations.*

Keywords—periwinkle shell powder, drilling mud, additives, high-pressure, high-temperature

1. Introduction

Over the past few decades, global energy demand has substantially increased, with fossil fuels maintaining dominance [16], [28]. Despite ongoing efforts to diversify energy resources, the world is expected to rely on petroleum for several more decades. Compared to traditional fossil fuels, renewable energy sources like biomass, geothermal, wind, solar, and nuclear energy are presently more costly [37], [22]. To ensure the economical and successful exploitation of oil and gas asset especially in deep formation, it is crucial to enhance various aspects of drilling to overcome its challenges associated. Deep and unconventional formations introduce unique challenges related to well engineering and operations, such as high pressure, high temperature, friction, uncertainties, and risks [28]. The productivity of the drilling fluid performs a significant role in addressing these challenges [55], requiring the selection of properly designed and efficient drilling fluids. High Pressure High Temperature (HPHT) wells. Enhanced properties are required in drilling fluid for HPHT formations including fluid loss control, loss circulation prevention, high thermal stability, and favorable rheological properties [72], [40]. The choice of drilling fluid strongly depends on the conditions of the drilling operation [58].

Oil-based muds (OBM can be hazardous and potentially pollute the cuttings, posing a risk to the immediate vicinity [45]. The potential consequences of contaminated drill cuttings include altered seabed composition, increased turbidity and sedimentation, and elevated toxicity and bioaccumulation levels, prompting costly treatment and disposal measures. On the other hand, water-based drilling fluids (WBMs) are effective due to their low preparation and maintenance costs, as well as their environmentally friendly characteristics. However, WBMs encounter serious challenges when utilized in HPHT wells. Notably HPHT wells, WBMs are prone to thermal problems Drilling operations are compromised by temperature-related gelation, heightened CO2 contamination risk, and enhanced solids sensitivity at elevated temperatures [50. Ensuring temperature stability in drilling fluid design is crucial. The temperature stability of drilling fluids must be evaluated to ensure optimal rheological performance in HPHT applications [43]. Physical and chemical stability are paramount characteristics, significantly impacting drilling operations. Testing for temperature stability is particularly valuable for identifying indicators of high-temperature flocculation in water-based muds [42]. Establishing baselines through such tests is instrumental in gauging the drilling fluid's ability to withstand high-temperature conditions. Techniques to minimize temperature gelation include eliminating lignite and lignite derivatives from WBM formulations, reducing bentonite concentration, and incorporating polymers and co-polymers into high-temperature WBM systems [43]. Drilling fluid chemical stability is the ability to maintain composition and performance despite chemical interactions with contaminants and internal components [63]. Meanwhile, physical stability refers to the drilling fluid's capacity to resist alteration due to physical downhole conditions, including elevated pressures and temperatures [27].

WBMs used in HPHT wells must overcome additional problems including loss circulation, fluid loss. Filtration loss control is a special area of concern in HPHT drilling conditions [72]. Filtration loss refers to the seepage of the liquid component of the drilling fluid into the formation through the filter cake that forms on the wellbore walls [64]. To optimize filter cake quality and minimize fluid loss, specialized additives are integrated into the mud formulation for HPHT drilling operations [72]. Excessive mud filtrate loss into the formation can have detrimental consequences on both drilling fluid performance and wellbore stability [71]. Water-based mud drilling operations often employ fluid loss additives to control filtration [12]. The drilling industry utilizes various polymers, including biopolymers, natural, modified, and synthetic polymers. Commercially prevalent additives such as polyanionic cellulose (PAC), hydroxyethyl cellulose (HEC), and xanthan gum (XG) are chosen for their outstanding rheological and filtration properties.

Loss circulation refers to the unintended and substantial fluid migration into the surrounding geology, resulting in reduced returns to the surface. This happens when the drilling fluid flows into fractures, vugs, or highly permeable zones in the formation [39]. Exceeding the formation's pressure tolerance through excessive mud pressure (overbalanced drilling) can induce fracture opening, facilitating mud invasion [70]. Lost circulation necessitates zone sealing, barring unusual geological environments that permit blind drilling, a scenario that rarely occurs [44]. While prevention is key, the prevalence of lost circulation necessitates equal emphasis on effective treatment solutions. Lost circulation treatments often incorporate conventional materials such as paper pulp, sized calcium carbonate, ground nutshells, cellophane fibers, mica flakes, and cottonseed hulls. With varying textures (fine, medium, coarse), these materials are added to drilling mud to seal loss-prone zones and are typically categorized as flaked, fibrous, granular, or combined [59], [70]. Despite their affordability, traditional lost circulation materials (LCMs) have limitations, including thermal instability, water absorption, premature gelation, and challenges in precise placement. Also, these materials can migrate into the formation, and their ecological implications are unfavorable.

The incorporation of local materials as additives aims to decrease drilling fluid expenditures and alleviate ecological concerns [32]. These additives are particularly advocated for use in WBMs to enhance their properties for HPHT drilling [3]. The selection of local materials for WBM formulations is based on their performance and desired properties. Several local materials, including bio-materials and seashells, have been investigated to augment WBMs. This research explores the feasibility of utilizing periwinkle shells as a supplementary component in drilling fluid formulations, specifically for HPHT applications. This paper offers an in-depth review of the requirements, considerations, and performance characteristics of utilizing periwinkle shells in WBM formulationsThis template, modified in MS Word 2007 and saved as a "Word 97-2003 Document" for the PC, provides authors with most of the formatting specifications needed for preparing electronic versions of their papers. All standard paper components have been specified for three reasons: (1) ease of use when formatting individual papers, (2) automatic compliance to electronic requirements that facilitate the concurrent or later production of electronic products, and (3) conformity of style throughout a conference proceedings. Margins, column widths, line spacing, and type styles are built-in; examples of the type styles are provided throughout this document and are identified in italic type, within parentheses, following the example. Some components, such as multi-leveled equations, graphics, and tables are not prescribed, although the various table text styles are provided. The formatter will need to create these components, incorporating the applicable criteria that follow.

2. The Need of Bio-materials in Drilling Fluid Formulation

Drilling fluids with non-decomposable chemical ingredients poses substantial environmental and health risks, necessitating the development of alternative, eco-friendly additives to minimize harmful waste release [11]. The environmental hazards of traditional additives, such as potassium chloride and polyamine, necessitate the development of biodegradable, eco-friendly drilling fluid solutions [10. Bioproducts and various waste materials are particularly promising in this regard. They offer comparable performance to conventional additives while being widely available and cost-effective. Utilizing these alternatives can lead to significant savings in terms of cost, energy, and time [13], [12]. Environmentally friendly alternatives, including carboxymethyl cellulose, polyanionic cellulose, xanthan gum, and partially hydrolyzed polyacrylamide, enhance drilling fluid properties while minimizing ecological harm [40].

2.1 Utilizing Periwinkle Shell Powder as a Local Material Additive in Drilling Fluid

Periwinkles are marine snails classified as gastropod mollusks. The species comprise Littorina littorea, Nodilittorina radiata, Tympanostomus fuscatus, and Pachmellania aurita, which flourish in aquatic settings, specifically intertidal zones [18]. The edible portion of periwinkles is soft and encased in hard, brittle shells, which owe their strength to a high concentration of calcium oxide (CaO). These shells are typically dark and sometimes banded, featuring an ovate, thick covering with 6 to 7 whorls of fine threads or wrinkles [5].

Periwinkles are predominantly found in the brackish wetlands of the Niger Delta, inhabiting areas between lagoons and mudflats. Their distribution in these regions is influenced Influenced by various parameters, including salinity levels, sediment composition, water depth, and hydrodynamic forces [20]. As mollusc shellfish, periwinkle shells are by-products left after extracting the edible part, with the shells accounting for up to 70% of the total body weight, depending on the species. This results in significant waste disposal challenges, as the shells are often dumped in open areas or landfills, where they cause foul odors and become breeding grounds for pathogens [73].

At maturity, periwinkle shells range from 10 to 12 mm in width, the dimensions of the shells exhibit variability, with lengths spanning 16-38 mm and heights reaching 30 mm, 43 mm, or 52 mm across different species [23]. Micro-structural studies by [23] revealed that reducing the sieve size of periwinkle shells from 350 μm to 100 μm enhanced their bonding, hardness, density, and compressive strength properties.

In major cities of the Niger Delta, such as Port Harcourt, Uyo, Calabar, Yenagoa, Warri, and Oron, periwinkle shells are often discarded in large quantities, contributing to environmental pollution [49]. The sheer volume of abandoned shells at seashores and waste receptacles highlights the limited use of this resource. According to De Angelisa et al. (2017),Global eggshell waste generation reaches approximately 8 million tons per year, highlighting the necessity for improved waste management practices. As noted by Jung et al. [35], finding beneficial and environmentally safe applications for periwinkle shells is essential.

Utilizing periwinkle shells can address environmental issues related to waste disposal while offering technical and economic benefits in various industries. Frequently, the shells are subjected to additional processing steps, including pulverization and thermal treatment, to yield periwinkle shell powder [5]. This powder is widely used, particularly in cement production and other applications within the oil and gas industry. A visual representation of periwinkle shells is provided in Figure 1. First, confirm that you have the correct template for your paper. Download the template from the website www.ijeais.org.

Figure 1: Periwinkle Shells

Periwinkle shell powder (PSP) has long been utilized in civil engineering, particularly for enhancing the strength and other critical properties of cement used in building and construction [1]. PSP has also found applications in the formulation of drilling mud, particularly as an agent of fluid loss control. A study by Igwilo et al. [30] explored the use of PSP and Mucuna solannie to improve the fluid loss properties of Nigerian bentonite. Through comprehensive analyses, including elemental oxides, scanning electron microscopy (SEM), and X-ray diffraction (XRD) tests, they demonstrated that local additives like PSP and Mucuna solannie significantly enhanced the performance of Nigerian bentonite.

PSP has emerged as a promising solution for the challenges posed by high-temperature and high-pressure conditions in drilling operations. It enhances the thermal stability of drilling mud, improves viscosity, and boosts filtration properties [57]. The nanoparticle concentration in PSP contributes to minimal or even zero free water during cementing operations. As a result, periwinkle shell powder provides excellent strength in concrete and is recommended as a supplementary additive in drilling fluids, enhancing multiple properties of the mud [60

2.2 Properties of Periwinkle Shell Powder

Periwinkle shells are primarily composed of calcium carbonate. A distinction must be made between pulverized and calcined seashells, as the former comprises primarily calcium carbonate in its ground state. However, when subjected to thermal degradation in the absence of air, the seashells undergo a chemical transformation that produces calcium oxide, releasing carbon dioxide (CO_2) in the process [5]. Notably, calcium oxide is the predominant constituent in traditional Portland cement [68]. This reaction is illustrated in Equation (1).

$$\boldsymbol{CaCO_3 \xrightarrow{heat\ (>700^oC} CaO + CO_2} \qquad 1$$

Periwinkle shells are heated to high temperatures, transforming them into ash, which is then ground into a fine powder [68]. When periwinkle shell powder is reduced to nanoparticle size, it exhibits enhanced surface area, reactivity, and structural properties that boost drilling mud functionality. The primary nanoparticle properties of PSP include [5]:

1. High Surface Area: The nanoscale transformation of PSP enhances surface area, thereby strengthening fluid-particle interactions, improving the stability and dispersion of the particles in the mud.

2. Surface Reactivity: Nanoparticles have increased surface energy, which makes them more reactive compared to their larger counterparts. PSP nanoparticles can form stronger bonds with the fluid matrix, refining its rheological behavior and fluid loss control.

3. Mechanical Strength: The nanostructure of PSP retains the mechanical properties of calcium carbonate ($CaCO_3$), the primary component of periwinkle shells. Incorporating PSP nanoparticles into drilling fluid enhances its rheological properties, forming a resilient matrix that boosts suspension and hole cleaning efficiency.

4. Thermal Stability: Nanoparticles typically exhibit better thermal stability than larger particles. This property allows PSP nanoparticles to withstand elevated temperatures encountered during deep drilling operations, maintaining the effectiveness of the mud over a wide temperature range.

5. Low Density: As a natural material, PSP has a relatively low density compared to conventional weighting materials. When used in nanoparticle form, it provides the dual benefit of controlling fluid properties without significantly increasing the overall weight of the drilling fluid.

2.2 Elemental Composition Measurements of Periwinkle Shell Powder

The chemical characterization of periwinkle shell powder (PSP) involves determining its predominant elements and chemical compounds. This is commonly done through scanning electron microscope (SEM) testing, which provides insights into the energy dispersion spectrum. The primary elements found in PSP include calcium (Ca), silicon (Si), calcium oxide (CaO), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3). While CaO significantly enhances the strength of drilling mud, SiO_2 and Al_2O_3 are effective nanoparticles for controlling fluid loss [14].

Aku et al. [8], periwinkle shell ash was found to have a density of 1.24 kg/cm³, indicating that periwinkle shell particles are well-suited for use as mud cake material. Another study by Obot, Yawas, and Aku [47] Studies demonstrated calcium oxide is the primary component of periwinkle shell grains, granting them outstanding abrasive capabilities and wear resistance. With a composition of 87% by weight, along with 12% resin and 0.5% methyl ethyl ketone peroxide hardener, as well as cobalt naphthenate, the material demonstrated impressive hardness and compressive strength, making it suitable for applications requiring abrasive properties.

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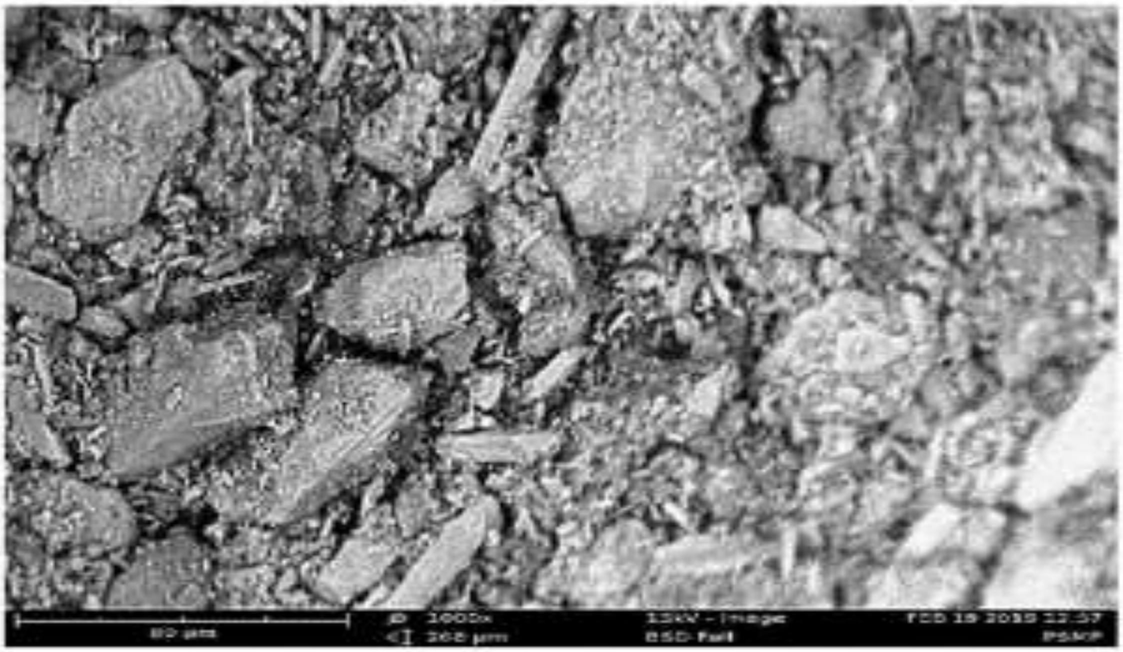

Figure 2: SEM image of PSP [1]

Table 1: Elemental composition of PSP from various researchers

Refences	Temperature, ºC	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O
Etim, Attah & Bassey (2017)	1000	42.32	29.54	11.6	5.13	0.42	0.43	0.11
Etuk, Etuk& Asuquo (2012)	800	55.53	26.26	8.79	4.82	0.4	0.25	0.2
Nnochiri (2017)	1000	41.35	35.37	9.6	4.84	0.5	0.21	0.2
Offiong and Akpan (2017)	600	38.62	23.32	9.62	5.01	0.36	0.24	0.13
Offiong and Akpan (2017)	800	40.63	33.85	10.24	6.25	0.83	0.15	0.26
Offiong and Akpan (2017)	1000	46.39	30.8	10.84	5.58	0.73	0.27	0.27
Umoh and Olusola (2012)	800	40.84	33.84	10.2	6.02	0.48	0.24	0.14
Onuoha et al. (2017)	800	40.8	33.8	10.2	6	0.5	0.2	0.1

Table 1 presents the elemental compositions of periwinkle shell powder (PSP) as reported by various researchers. Offiong and Akpan [48] demonstrated that the silicon dioxide (SiO_2) content of PSP varies with calcination temperatures. PSP calcined at 800°C showed the highest SiO_2 content, followed by samples calcined at 1000°C and 600°C. The specific gravity of PSP ranges from 2.08 to 2.56 [75]. In terms of strength development, PSP achieves 78% of its strength within 7 days and 80% by 14 days [53].

The pozzolanic properties of PSP, attributed to the presence of reactive silica, are also noteworthy [2]. While PSP has little or no binding capacity on its own, it forms a hardened compound when combined with lime and water. At a 10% weight proportion, PSP exhibits average stiffness strength, with a Modulus of Rupture (MOR) of 25.8 MPa and a Modulus of Elasticity (MOE) of 108.8 MPa. These values indicate optimal particle coating at 10–15% weight, with minimal or no contact between particles [2]

2.4 Utilization of periwinkle shells in wellbore drilling activities

To minimize mud filtration loss, various industries employ common polymers like carboxymethyl cellulose, hydroxyethyl cellulose, polyanionic cellulose, sodium polyacrylate, xanthan gum, and starch. Adding these polymers thickens the water-based continuous phase, reducing fluid loss (API, 2001). However, these polymers have limitations, including high costs, thermal instability, and susceptibility to bacterial degradation [29]. The thermal degradation temperatures of these polymers are outlined in Table 2.

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Table 2: Average cost of additive and their degradation temperatures

Fluid Loss Control Additive	Temperature of degradation, ^{O}C	Average Cost of Additive ($/kg)
CMC	252	3.54
HEC	205	6.4
PAC	>149	4.76
Starch	275	1.83
$CaCO_3$ (Fine)	>750	0.35

Temperature stability ensures optimal drilling fluid and additive performance [38]. Given the limitations of conventional fluid loss additives, such as high cost, Vulnerability to thermal decomposition, and bacterial attacks, researchers have long sought alternative materials to overcome these challenges. In this pursuit, biomaterials have gained attention as potential replacements. Agwu and Akpabio [4] provide a comprehensive review of the Harnessing biomaterials to reduce fluid loss in drilling. Despite progress in using agro-based materials, recent studies have explored the potential of periwinkle shells as effective fluid loss control agents.

One justification for using periwinkle shells as fluid loss additives lies in the findings of Dantas et al. (2014), who explained that calcium carbonate ($CaCO_3$), the primary component of periwinkle shells, can act as a sealant for mud cake pores, reducing permeability and preventing fluid loss. Schlumberger [61] also supports this view, stating that sized $CaCO_3$ particles, and the combination of polymers ensures optimal fluid loss management in diverse fluid applications, including brines, drill-in fluids, and completion/workover fluids. The advantages of incorporating calcium carbonate into drilling mud, include its sealing properties and ability to enhance mud cake consistency.

Agwu et al. [5] conducted a comprehensive study to examine the impact of periwinkle and oyster shells as supplementary components in drilling fluids and well cementing applications through a series of laboratory tests. The shells were pulverized to specific particle sizes—125 µm for oyster shells and 250 µm for periwinkle shells before being incorporated into the formulation of sixteen different samples of water-based mud and oil well cement. The research uncovered evidence that combined addition of both shells optimized the mud's filtration properties. However, the oyster shells demonstrated superior filtration control compared to the periwinkle shells. Additionally, the research emphasized the significance of additive concentration on mud filtration characteristics. Overall, the findings suggest that using periwinkle and oyster shells as alternative additives to conventional materials could be more cost-effective, potentially lowering drilling costs while also reducing environmental impact.

Berg [17] emphasizes the advantages of using periwinkle shells due to their safety, affordability, adaptability, and widespread availability. Their applications extend beyond just fluid loss control but also to maintain wellbore stability in cementing operation. According to Schlumberger (2019), the acid-soluble nature of calcium carbonate ($CaCO_3$) makes it a superior alternative to barite for production zone cleaning, using hydrochloric acid. $CaCO_3$ is favored as a bridging agent due to its chemical and mechanical stability and high solubility in acid, which contributes to a more consistent mud cake and effective restoration of reservoir rock permeability [76], [9].

Despite the gradual progress in using periwinkle shells as fluid loss agents, their field application remains unrecorded. A comprehensive review of existing studies has been conducted to understand this area better. One seminal study in this field was conducted by [56], whose work on periwinkle shells as filter loss materials was patented and has served as a foundational reference for subsequent research. Since then, various studies have advanced the understanding of periwinkle shells, testing different types of shells and refining their applications.

Research investigations have elucidated the mechanisms by which periwinkle shells mitigate filter loss:

a. Integration with Conventional Additives

Research indicates that periwinkle shells, or their derived calcium carbonate ($CaCO_3$), are often blended with traditional fluid loss modifying agents, including carboxymethyl cellulose (CMC). These traditional additives enhance viscosity and improve the modification of fluid loss in drilling muds. The integration of periwinkle shell-derived $CaCO_3$ with these additives exploits the complementary properties of both materials. Specifically, the periwinkle shell powder helps seal mud cake pores and reduce permeability, while the conventional additives further refine fluid loss control and overall mud performance [5]. This synergistic approach optimizes the effectiveness of drilling fluids, particularly in challenging drilling environments where enhanced filtration control is critical.

b. Application in Water-Based Muds

Most experimental studies involving periwinkle shells have focused on water-based muds. The benefits of water-based muds, encompassing cost, simplicity, and disposal, contribute to their widespread use in drilling. These muds consist primarily of water, supplemented with additives to manage properties such as viscosity, density, and fluid loss. Research on periwinkle shells in this context helps evaluate their performance under typical drilling conditions, providing insights into how these materials can enhance the efficiency and effectiveness of water-based muds. This makes periwinkle shells a promising alternative or supplement the traditional fluid loss control agents [5].

c. Particle Size Considerations

The particle size of calcium carbonate used in these experiments typically ranges up to 63 micrometers. Particle size is a critical factor influencing the interaction of the material with the drilling mud and its effectiveness in controlling fluid loss. Finer particles, in the micrometer range, offer a larger surface area and can more effectively fill the pores in the mud cake, thereby reducing permeability and fluid loss. By optimizing particle size, researchers aim to enhance the performance of periwinkle shell-derived $CaCO_3$ in fluid loss control applications and improve the overall quality of the drilling mud [21].

4. Versatility of Derived Products

Periwinkle shells yield various valuable products, including (CaO) and ($Ca(OH)_2$), which have potential applications in the mud and cement industries. Calcium oxide, obtained through the calcination of periwinkle shells, serves as a reactive additive in cement, enhancing its properties and performance. Calcium hydroxide, formed by the hydration of calcium oxide, is useful in several industrial processes additives [5]. The diverse applications of these derived products underscore the versatility of periwinkle shells, making them valuable not only as fluid loss control agents but also in improving the quality of cement and other construction materials.

2.4.2 Use as a weighting agent

Calcium carbonate ($CaCO_3$) is majorly utilized in petroleum sector in various capacities, surpassing its traditional role in the process of formation isolation and filter cake consolidation [65]. Calcium carbonate serves as an effective weighting material in drilling fluids, increasing density to mitigate sub-surface pressure (Sali, 2015). With a specific gravity of 2.7, calcium carbonate is well-suited for formulating drilling muds with reduced density [17]. To compensate for its lower density, salt is sometimes added to enhance the density of the aqueous phase [66].

For horizontal wellbores, $CaCO_3$ is a preferred choice for adjusting mud weight due to its minimal risk of plugging formations. The practical maximum mud weight achievable with $CaCO_3$ is reported to be 14.0 pounds per gallon (ppg). Phansalkar and Popham [56] confirmed that under certain conditions, $CaCO_3$ can effectively serve as a weighting agent.

While barite remains the dominant weighting material, $CaCO_3$ is gaining a modest share of the market, particularly for applications requiring low-density muds [69]. This is supported by [62], who noted a 16% increase in $CaCO_3$ consumption over a year. Conversely, Fattah and Lashin [74] optimization of drilling operations involves reducing barite application.

Agwu [5] Summarizes research outcomes regarding calcium carbonate's efficacy as a densifying agent. The data indicate that while the achievable density with $CaCO_3$ as a weighting agent is limited, high-purity $CaCO_3$ can achieve the desired density with smaller quantities. Compared to conventional barite, $CaCO_3$ offers the advantage of easier filter cake removal, making it a valuable alternative in certain drilling operations.

2.4.3 Use as Lost Circulation Agent

Drilling operations often face a major challenge known as lost circulation, where drilling fluids unintentionally seep into formation fractures or voids. Lost circulation occurs when the pressure of the drilling fluid exceeds the formation's capacity, leading to fluid invasion into fractures, voids, or permeable rock [7]. The financial and operational impact of lost circulation is significant, necessitating the design of drilling fluids that minimize fluid invasion into formations. To address lost circulation, Lost Circulation Materials (LCMs) are employed to seal fractures and reduce fluid loss. The potential of periwinkle shells has been applied to prevent loss circulation during WBM drilling [3].

Exceeding the formation's fracture resistance with wellbore pressure leads to lost circulation, particularly in formations with high permeability, natural fractures, or vugular structures [24]. Natural fractures, prevalent in most formations, and induced fractures, resulting from tensile failure near the wellbore, contribute to the problem. Caverns and vugs, particularly in limestones and dolomites, present additional challenges. Agwu et al. [5] have highlighted the effectiveness of periwinkle shells, in mitigating lost circulation in water-based muds (WBM). The positive results from these tests suggest that periwinkle shells could serve as a cost-effective substitute for imported LCMs. To maximize their potential, efforts should be made to increase the collection and utilization of Oyster Sea-shells, potentially by integrating shell waste collection into oyster consumption practices for use as an LCM.

2.4.4 Use of PSP as pH Enhancer

Periwinkle shell powder (PSP) improves stability and efficiency of water-based muds, specifically as a pH enhancer [52]. Maintaining the correct pH level in drilling fluids is crucial for optimizing mud properties, including viscosity, fluid loss control, and overall stability [6]. A higher pH prevents corrosion of drilling equipment and stabilizes clay particles in the wellbore. The calcium carbonate in periwinkle shells, when added to drilling mud, reacts with water to form calcium ions (Ca^{2+}) and carbonate ions (CO_3^{2-}). These carbonate ions help neutralize any acids present in the mud, raising the pH of the solution. In addition, under certain conditions, $CaCO_3$ can undergo further reactions to form calcium hydroxide ($Ca(OH)_2$), which is a stronger base and more effective at increasing the pH. This makes PSP a potential alternative to traditional alkaline additives, like (NaOH) or (KOH), in maintaining or adjusting the pH of water-based muds [18].

Subsequent to PSP addition to a water-based mud, the calcium carbonate dissolves and dissociates, leading to an increase in the pH through the following reaction:

$$CaCO_3 \ (s) + H_2O \ (l) + CO_2 \ (aq) \longrightarrow Ca^{2+} \ (aq) + HCO_3^- \ (aq) \quad (2)$$

Under drilling conditions where CO_2 may be present due to organic material in the wellbore, the release of carbonate ions can neutralize acidic components, increasing the pH. Additionally, in high-temperature conditions, $CaCO_3$ may decompose to form CaO (calcium oxide), which further reacts with water to produce calcium hydroxide, a potent base:

$$CaO \ (s) + H_2O \ (l) \longrightarrow + CO(OH)_2 \ (aq) \quad (3)$$

This reaction leads to an even more significant increase in pH, enhancing the effectiveness of PSP in controlling the mud chemistry.

Studies comparing the use of PSP to conventional pH enhancers, such as lime ($Ca(OH)_2$) or soda ash (Na_2CO_3), have indicated that PSP can achieve similar pH control in water-based muds without adversely affecting other critical properties like viscosity and fluid loss. In some cases, PSP has been shown to have a more sustained impact on pH due to its gradual solubility and extended reactivity, making it particularly suitable for longer drilling operations.

Lamin et al. [41] explored the potential of using locally sourced materials, specifically Periwinkle Shell Ash (PSA), as a substitute for imported chemicals to enhance drilling mud properties. The primary objective was to raise the mud pH to meet the API standard (9.5–12.5) while reducing the overall cost of drilling operations. The study focused on extracting calcium hydroxide ($Ca(OH)_2$) from periwinkle shells using two distinct process routes: calcination of PSA and a non-calcined method. Characterization tools were employed to identify the functional groups and elemental composition of the periwinkle shells. Various laboratory experiments were conducted to observe the effects of the synthesized additives on key mud properties, including pH, mud weight, filtration characteristics, and rheological behavior. The results indicated that as the mass of $Ca(OH)_2$ derived from calcined PSA, uncalcined PSA, and commercially available $Ca(OH)_2$ increased, the pH of the mud samples also rose significantly. The pH of the base mud increased by 20.9%, 15.1%, and 10%, respectively, for each additive source. This demonstrated that the extracted $Ca(OH)_2$, particularly from the calcined PSA, effectively functioned as a pH enhancer.

Olawale et al. [52] explored the use of periwinkle shells; a gastropod sea snail, in an investigation, as a pH booster in water-based drilling muds, aiming to reduce reliance on imported chemicals in Nigeria's energy industry. The study examined the performance of calcined periwinkle shells as a pH adjuster and mud weight controller in water-based mud systems. The mud samples were prepared using bentonite clay and distilled water, with varying amounts of calcined periwinkle shells (1g to 4g). pH and mud weight measurements were recorded at 25 °C. The results demonstrated a significant increase in pH, ranging from 64.3% to 92.8%, corresponding to the incremental addition of calcined periwinkle shells. However, the mud weight showed minimal change, with only a 0.56% increase. This indicates that periwinkle shells have a strong potential as pH enhancers in water-based muds, with minimal impact on mud weight, offering a viable alternative to traditional chemicals.

2.4.5 Use of Periwinkle Shell Powder (PSP) as Rheology Control Agents in Water-Based Muds

The rheology of drilling fluids plays a critical role in the efficiency and safety of drilling operations. In particular, water-based muds (WBM) must maintain optimal plastic viscosity (PV), yield point (YP), and gel strength to ensure effective cuttings transport, suspension of solids, and overall wellbore stability. The Bingham plastic model effectively characterizes the rheological properties of drilling fluids [18]. According to this model, PV signifies the fluid's opposition to flow resulting from mechanical friction between solid particles and liquid, while YP reflects electrochemical interactions between particles. Gel strength, on the other hand, indicates the strength of the fluid's structure when it is static, which prevents solids from settling during drilling pauses [21].

Several studies [21]; [5] have analyzed the rheological behavior of drilling mud when Periwinkle Shell Powder (PSP) is added to the formulation. These studies indicate that adding PSP to water-based muds improves PV, YP, and gel strength. The smaller the particle size of the PSP and the higher its concentration, the more pronounced the effect on these properties. The surge in rheological properties stems from the higher specific surface area of finer PSP particles, which facilitates bonding with the mud's liquid phase, thereby enhancing its viscosity.

PSP primarily consists of calcium carbonate ($CaCO_3$), a compound known for its wide-ranging applications in the petroleum sector. The fine particles of PSP, when added to water-based muds, create a structured network that improves the fluid's flow behavior [31]. This network interacts with the base fluid through electrochemical forces, which enhances the mud's shear-thinning properties. At high shear rates—such as when the mud is being circulated through the drill pipe—the fluid exhibits low viscosity, allowing it to flow easily. At low shear rates, such as during drilling pauses, the fluid's gelation properties intensify, preventing the settling of cuttings and solids. The $CaCO_3$ in PSP also contributes to its effectiveness as a rheology control additive by stabilizing the mud structure. This reduces the reliance on synthetic polymers and other chemical additives, making PSP a more sustainable and cost-effective alternative [30].

One of the key advantages of using PSP as a rheology control additive is its thermal stability. Drilling operations often encounter a wide range of temperatures, particularly in deep wells [51]. Synthetic polymers, which are commonly used as rheology control agents, tend to degrade at high temperatures, compromising the mud's performance. In contrast, PSP exhibits strong thermal stability, maintaining its rheological properties across a broad temperature range [30]. This makes it suitable for both shallow and deep drilling operations, where temperature fluctuations can impact mud performance. Compared to traditional rheology control agents like bentonite and synthetic polymers, PSP offers several advantages including cost effectiveness, sustainability, improved performance and thermal stability.

2.5 Economics Aspects of Periwinkle Shell Powder Application in WBM Drilling

The petrolatum sector has seen a rising demand for eco-friendly solutions, focusing on cost savings and minimizing environmental impacts during drilling. Conventional commercial additives, such as Poly Anionic Cellulose (PAC) and Carboxy Methyl Cellulose (CMC), are widely used as fluid loss control agents. However, these additives are typically imported, leading to a significant surge in operational costs. Every year, Saudi Arabia spends roughly $50 million on importing additives to control filtration [15]. The search for local, eco-friendly, and cost-effective alternatives has thus gained momentum. Periwinkle Shell Powder (PSP) presents a viable substitute for these expensive commercial additives. Derived from discarded periwinkle shells, which are waste materials, PSP offers a sustainable solution with a much lower environmental impact. By leveraging periwinkle shells as a waste resource, costs associated with raw materials can be substantially reduced. However, there are logistical and processing costs that must be considered when incorporating PSP into drilling operations.

2.5.1 Cost Considerations of PSP Production

1. Collection and Transportation Costs

While periwinkle shells are essentially waste materials, collecting them from individual locations such as restaurants, eateries, and private households can be both time-consuming and expensive. Transportation cost to gather shells from multiple areas would replace the otherwise negligible cost of the periwinkle shells themselves. To minimize these costs, a centralized collection system could be established, reducing the need for frequent trips to different locations [5].

2. Cleaning and Preparation Costs

Another significant cost associated with PSP production is cleaning the shells. If the shells are not adequately cleaned, their performance characteristics decline, rendering them ineffective for mud and cement applications. Periwinkle shells from waste sources undergo a cleansing process involving saltwater boiling to remove bacteria and foul smells. While acids could be used for cleaning, this would likely dissolve the calcium carbonate ($CaCO_3$) in the shells, leading to the release of CO_2, which could compromise the integrity of the material [5].

To desalinate the shells after boiling, thorough cleaning with fresh water is essential, rotary washing machines provide the ideal solution for this application. These machines help mitigate rusting of processing facilities and ensure a higher concentration of calcium carbonate in the final product. However, this process requires a significant amount of water, and the wastewater generated must be treated before disposal. The procurement cost of rotary washing machines (shipping fee inclusive) is approximately $10,000 [67].

3. Crushing and Pulverizing Costs

The next step in PSP production involves crushing the shells to a uniform particle size effective for controlling fluid loss Since the shells vary in strength and size, this process is crucial for generating a consistent final product. Ball mills are typically used for this purpose, Costs vary: $3,500-$60,000 contingent upon machine specifications. Uniform particle size is essential for ensuring the effectiveness of PSP in drilling mud formulations. After the shells are crushed and pulverized, they are packaged in high-density polyethylene (HDPE) bags due to their durability and ability to protect the material during transport and storage [5]. The process in the preparation of PSP from periwinkle shell is illustrated in Figure 3

Table 3: Estimated average costs for periwinkle shell unit with a production rate of 11,452 t/month [5].

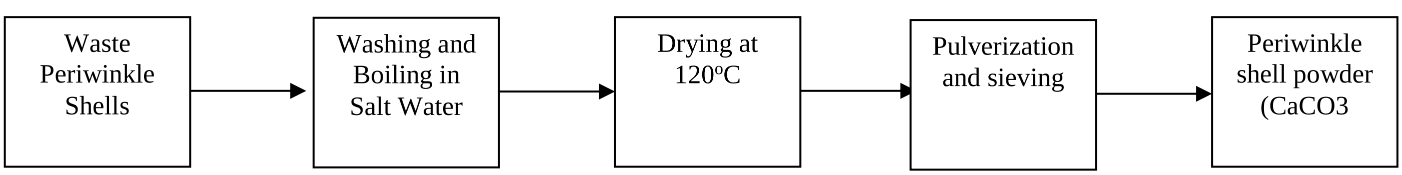

Figure 3: Steps for the process of obtaining PSP from periwinkle shells

2.5.2 Economic and Environmental Benefits of PSP

The use of locally sourced PSP possesses significant cost-saving potential for drilling operations unlike imported commercial additives, periwinkle shells are an abundant and renewable resource, particularly in regions where seafood consumption is high. Moreover, using PSP as a substitute for synthetic additives can contribute to minimizing the ecological footprint of drilling activities by reduction in reliance on non-biodegradable, petroleum-based chemicals [5]. Additionally, the use of natural waste materials like periwinkle shells reduces the amount of waste sent to landfills, contributing to a circular economy. By transforming waste into valuable products, the petroleum sector can employ more sustainable techniques while maintaining operational efficiency. Table 3 gives the estimated average cost of processing periwinkle shell into periwinkle shell powder (PSP) for commercial utilization in WBM drilling fluid preparations.

Table 3: Estimated average costs for periwinkle shell unit with a production rate of 11,452 t/month [5].

Component	Material Requirement	Unit Cost ($)	Annual Cost ($/year)
Transport for a trip	754 km	$2/km/month	$18,096
Cost of labour	10 workers	$2000 (twice the official minimum wage in Nigeria)	$20,000
Cost of electricity	19,774,288.26 kWh/yr	$0.2358/kWh	$4,662,777.17
Materials for Packaging	2,748,420 bag pieces	$0.05/piece	$137,421
Fuel for Calcination	52.05 t/y (44,242.5 L/y)	$1.32/L	$58,400
Propane as (oxidizer)	18.14 t/y (9,720.2 al/y)	$2.39/al	$23,231.3
Water Requirement	44,151 cum/y	$0.3963/cum	$17,496.6
Disinfection and cleansing (sodium chloride)	40,475	$0.031/kg	$1,254.7
Raw materials (shells) required	6,396 t/y		
Total CaCO3 expected output	137,421 t/y		
Overall Costs		$39.93/t	$4,938,676.77

The cost of transporting disposed periwinkle shells from source to end-use varies significantly depending on the distance traveled [34]. Location-specific factors influence loading and unloading costs, typically accounted for under labor expenses. Since the cost analysis presented here is simplified, the expenses related to acquiring machinery such as ball mills and rotary washing machines are not included. According to [5] as shown in the data in Table 3, Periwinkle shell processing costs are estimated at $39.93/ton, or roughly $0.04/kg. In comparison to the expenses associated with synthetic filtration control agents listed in Table 2, using periwinkle shell as an additive could lead to a reduction in overall drilling fluid costs. However, to determine whether these periwinkle shells offers a viable alternative to traditional filtration control agents like CMC, PAC, and HEC, further experimental testing is required. These tests would help assess the periwinkle shell's filtration loss capabilities.

2.6 Commercialization of Periwinkle Shell Powder Additives

Commercialization entails the introduction of marketable products into the industry, and for any product to achieve successful commercialization, it must align with specific market demands and potential. In the context of periwinkle shell powder (PSP) as a drilling additive in Nigeria, several critical steps must be taken to facilitate its entry into the oil and gas market. These steps involve processing, scaling up production, standardization, packaging, and skill development [5].

2.6.1 Processing and Transformation

The commercialization of periwinkle shell powder (PSP) for drilling applications requires efficient processing and transformation. The transformation process involves several steps, including washing to remove dirt and contaminants, drying, and grinding the shells into powder. Based on the required specifications and characteristics of the end product. Additional processing such as calcination may be employed. This helps to improve the calcium carbonate content of the shell powder, making it more suitable as a drilling fluid additive. Specialized machinery is essential to streamline these processes on a large scale, enabling the mass production of PSP to satisfy the requirements of the petroleum sector [36]. Sourcing periwinkle shells in commercial quantities also becomes crucial, requiring deliberate efforts to create efficient collection networks from restaurants, markets, and other locations where shells are discarded as waste.

2.6.2 Scale-up

For the successful commercialization of PSP, research must be conducted to develop efficient mass production techniques. This includes the optimization of processing methods, bulk packaging solutions, and logistical strategies to maintain product quality during transport and storage. Scaling up production from small-scale operations to industrial-scale levels will require careful planning and investment in infrastructure, such as factories and processing plants dedicated to periwinkle shell powder production. Moreover, maintaining temperature control during transport and managing distribution channels effectively will be key to ensuring that the PSP reaches the market in optimal condition [36].

2.6.3 Standardization and Documentation

Establishing standardized techniques and protocols for the production of periwinkle shell powder is critical for its commercialization. This involves documenting optimized methods for washing, drying, grinding, and possibly calcining the shells [5]. Standardization ensures that the quality of PSP remains consistent, regardless of the production scale or geographical location. Additionally, conducting comprehensive evaluations of the material’s properties under various conditions—such as temperature, pressure, and fluid interaction—is essential for product optimization. These standardized protocols will not only facilitate local use but also enable periwinkle shell powder to gain international recognition and meet the specifications required in global oil and gas markets [36].

2.6.4 Packaging and Transport

Proper packaging is essential for the successful commercialization of PSP. The packaging must protect the product from environmental factors such as moisture and contamination during transport and storage. Customized packaging solutions should be designed based on the product's expected shelf life, the conditions it may encounter during distribution, and the particular requirements of the petroleum sector [5]. Bulk packaging for large-scale industrial use, as well as smaller, more manageable units for specific applications, should be developed to cater to different market segments. By ensuring the preservation of both the quality and quantity of PSP during transportation, producers can maintain the integrity of the product until it reaches its final destination [36].

2.6.5 Skill and Entrepreneurship Development

The successful commercialization of PSP will also require significant investment in skill development and entrepreneurship. Establishing technical training programs for workers involved in the transformation of periwinkle shells into powder will not only create job opportunities but also contribute to human capital development. Such programs can be regulated by the Nigeria Content Management and Monitoring Board (NCDMB) to ensure adherence to industry standards. Additionally, fostering entrepreneurship in the production and commercialization of PSP will generate revenue for the government through taxes and foreign exchange earnings from potential exports. This initiative has the potential to reduce capital flight, increase GDP, and promote local content by encouraging the processing of resources within Nigeria, rather than relying on imported drilling fluid additives [36]. By focusing on these key areas processing, scaling up production, standardization, packaging, and skill development. Nigeria can capitalize on the abundance of periwinkle shells as a low-cost, sustainable drilling fluid additive. This approach will not only reduce the country's dependence on expensive imported materials but also contribute to its economic growth and environmental sustainability.

3. CONCLUSION

Research on the application of periwinkle shell powder (PSP) as a water-based drilling mud additive demonstrates its viability in enhancing key drilling fluid properties such as filtration loss control, loss circulation control, weighting capability, pH modulation, and rheological behavior. PSP, primarily composed of calcium carbonate ($CaCO_3$), exhibits unique nano-scale properties that contribute to its effectiveness in controlling fluid loss and improving mud stability, thereby enhancing drilling efficiency. As a filtration control agent, PSP shows comparable or superior performance to conventional synthetic additives, while its role as a pH enhancer and rheology modifier ensures improved mud system stability without significantly increasing mud weight.

From an economic perspective, PSP offers a cost-effective alternative to synthetic additives such as Poly Anionic Cellulose (PAC), which are imported at significant expense. Utilizing PSP locally can reduce drilling costs and decrease dependence on imported chemical additives, thus mitigating capital flight. Widespread utilization of PSP technology in the petroleum sector could also foster local economic development by creating jobs in the production and processing of shells, ultimately contributing to Nigeria's GDP.

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