Enhancing Lubricity and Filtration Control in Water-based Drilling Fluids Using Novel Silica Nanoparticles Derived from Rice Husk Ash

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***Abstract*—The low lubricity and high filtration loss of water-based drilling fluids (WBDFs) hinder the drilling industry and are the cause of high torque and drag, while also contributing to nuisance conditions such as wellbore instability. This study presents a new, environmentally friendly SiO_2 nanoparticle (NP) made from rice husk ash (RHA), one of the byproducts of agriculture, as a multifunctional additive for WBDFs. The RHA-SiO_2-NPs were produced by an alkaline extraction method and characterized using X-ray diffraction and scanning electron microscopy. RHA-SiO_2 NPs were incorporated (0.1–1.0 wt%) into a bentonite-based mud and evaluated for rheology, API fluid loss, and lubricity. The results showed that the addition of only 0.5 weight % RHA-SiO_2 resulted in a 60% reduction in fluid loss (16.8–6.8 mL) and a 39% improvement to the lubricity coefficient (0.28–0.17) in comparison to the base fluid. The presence of the RHA-SiO_2-NPs also increased the yield point and gel strengths when looking at the rheological properties, indicating improved hole-cleaning capabilities. RHA-SiO_2 NPs demonstrated multifunctional performance and potential for sustainable drilling applications.**

***Index Terms*—Drilling fluid, Nanotechnology, Rice husk ash, Fluid loss, Lubricity, Rheology, Sustainable additive.**

I. Introduction

The global energy landscape remains heavily reliant on hydrocarbons, making safe and efficient drilling of oil and gas wells a major discipline within petroleum engineering (IEA, 2023). As part of well construction, drilling fluids, or drilling muds, are absolutely critical in a multitude of aspects, including transporting drilled cuttings to the surface, counteracting pore pressures, lubricating and cooling the drill string, and producing filter cakes on the formation wall to prevent fluid infiltration into permeable formations (Fink, 2022; Caenn, Darley and Gray, 2017).

Water-based drilling fluids (WBDFs) remain the most commonly utilized drilling fluids, encompassing numerous engineering applications for an array of reasons. Compared to oil-based and synthetic-based muds, WBDFs are the least expensive, safest, and easiest to manage environmentally (Asad, et al., 2024). However, WBDFs have inherent challenges, such as fluid loss, insufficient lubricity, and ultimately, destabilizing the wellbore, pre-mature pipe sticking, and more torque and drag (Mohammed et al., 2020). In these WBDFs, some commonly used chemical and physical additives to address the challenges are ineffective due, basically, to thermal degradation (Ahmed, Kamal and Al-Harthi, 2019), costs, and render toxicity risk to the environment. Ultimately, there is a need for localized, sustainable, multi-functional solutions, cost-effective to supplement WBDFs to address both deficiencies of fluid loss and lubricity.

High surface areas and interactions at the colloidal level make nanoparticles (NPs) an excellent choice for drilling fluids. When used in drill fluids, silica NPs can plug nanopores to reduce fluid loss and improve lubricity by providing a rolling action (Sensoy, Chenevert and Sharma, 2009; Barry, et al., 2015; Nasser, et al., 2013). However, high commercial costs limit NPs' use in the drilling industry (Hoelscher, et al., 2012; Contreras, et al., 2014).

Rice husk ash (RHA) is a common by-product of farming that is made in large amounts when biomass is burned. It has many industrial uses, such as making cement and generating energy, but a lot of it is still not being used to its full potential in many areas. This opens up opportunities for developing materials that add value. RHA can also produce high-purity silica. Improper methods of disposal create environmental challenges with RHA as well; however, RHA can be turned into high-value materials, NPs. RHA-SiO_2 NPs as a WBDF could solve two problems: eliminate agricultural waste decommissioning methods, and ultimately use commercial NPs at no cost (Singh, Sharma and Sharma, 2021).

Bentonite is cheap compared to engineered NPs, but the economic viability of silica made from RHA should be judged on how well it works, rather than how much it costs to make. The NPs worked well even at very low concentrations (≤0.5 wt%), and they can be used to replace or reduce the

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need for traditional polymers, lubricants, and filtration additives all at once. Furthermore, RHA is a common agricultural waste that is cheap to get, and processing it on a large scale can save a lot of money on chemicals. Hence, once you compare the performance of RHA-derived NPs to that of regular additives, they can be equally effective.

Although RHA has been assessed for use as a filtration additive (Okon, Udoh and Bassey, 2014), there have not been sufficient studies on the use of RHA-derived nanosilica for increasing both lubricity and filtration. The purpose of this research is to synthesize silica NPs from RHA and assess the impact on the rheology, filtration, and lubricity of WBDFs to determine the best amount of RHA-derived nanosilica to use.

II. Literature Review

Drilling fluids are important in well construction because they can transport cuttings, maintain hydrostatic pressure, stabilize the borehole, control fluid invasion, and minimize mechanical friction (Mahto and Sharma, 2004; Ahmed, et al., 2024). Of the various drilling fluids, WBDFs have become most popular because they are inexpensive, widely available, and their environmental footprint is comparatively low. WBDFs are commonly limited by excessive fluid loss and limited lubricity (Alsaba, et al., 2014), which can result in wellbore instability, differential sticking (Excess fluid loss), and increased torque and drag on the drill string (Poor lubricity), which can lead to drill string failures and non-productive time.

Common additives such as polyanionic cellulose (PAC), carboxymethyl cellulose (CMC), starch derivatives and calcium carbonate ($CaCO_3$) are commonly used to enhance filtration and rheology (Abdullah, et al., 2022; Okon, Akpabio and Tugwell, 2020), but their performance decreases with the components of high temperature and high pressure (HTHP) conditions and/or when used in nanoporous formations (Ahmad, et al., 2020). Nanotechnology is one approach that has emerged for enhancing drilling fluids. It has been reported that various NPs, such as silica, titanium dioxide, graphene, and iron oxide, can improve fluid loss control, lubricity, and thermal stability (Vryzas and Kelessidis, 2017). Silica NPs (SiO_2 NPs) are appealing as they are readily available, can change morphology (different shapes and sizes), are multifunctional, and are less hazardous than some other options. They reduce fluid loss by producing stacked (compact) filter cakes and act as nano-ball bearings, reducing the lubricity coefficient (William, et al., 2014). However, commercial NPs are expensive to produce and acquire, hence preventing wider application possibilities (Abdo and Haneef, 2013). In addition, because of the environmental concerns associated with synthetic nanomaterials, there has been interest in biodegradable sources (Laurent, et al., 2008).

Agricultural waste materials can be considered as an environmentally sustainable source to produce NPs. RHA, a byproduct from the milling of rice, can have up to 90% amorphous silica depending on the combustion conditions (Zareei, Ameri and Dorostkar, 2017). Silica produced from RHA has been used in cement applications, polymer fillers, and for water treatment (Soltani, et al., 2015). In terms of drilling fluids, RHA without any treatment can function as a filtration control additive (Agwu, Akpabio and Archibong, 2019). RHA converted to nanoscale silica could potentially show even greater functional use because its smaller size increases surface area, dispersibility, better interaction with clay and polymers, and enhancement of lubricity due to rolling effects. The growing literature on agro-waste derived from nanomaterials also supports valorizing waste into products for the circular economy (Siddique and Cachim, 2018).

Studies conducted in the past few years have shown that both waste-derived silica NPs and synthetic silica NPs improve fluid rheology and reduce fluid losses up to 12–55% when tested in a laboratory (Yalman, et al., 2022; Zarei, et al., 2023; Yahya, et al., 2023). This research is unique because it compares the use of Silica nano materials obtained exclusively from the ash of rice husk to provide shelter and improve drilled hole fluids by filtering and having lubricity within the same base drilling fluid system that contains bentonite. This is different than most previous studies. Most of the previous studies concentrated on either untreated ash materials or solely on rheological enhancements, whereas the current research amalgamates NP synthesis, characterization, and multifunctional performance assessment in accordance with API testing standards.

Despite all potential advantages of using RHA-derived SiO_2 NPs, there is scant literature on all aspects of this particular NP in WBDFs. More specifically, very few studies have evaluated their efficacy in reducing fluid loss (for viscosity) and lubricity (wet/sliding friction) tests under API standard conditions. This research contributes to closing the gap on those existing studies by evaluating the use of RHA-SiO_2 NPs as a multifunctional, cheap, environmentally sustainable additive, compared to conventional materials and expensive nanomaterials, in WBDFs. The current study mainly focuses on laboratory-scale feasibility, and for it to be used in the field, it needs to be tested with industry partners to make sure it works in real-world drilling situations.

III. Materials and Methods

A schematic flowchart of the experimental design is illustrated in Fig. 1 for the purpose of giving an overview of the experimental design. The flowchart provides a summary of the stages of the research study, including the collection and preparation of RHA, production of silica NPs through alkaline extraction followed by acid precipitation, the characterization of silica NPs, incorporating silica NPs into drilling fluid formulations, and assessing the rheological, filtration, and lubricity characteristics.

A. Materials

The RHA utilized in this study was sourced from a nearby rice mill, where rice husk is incinerated in a regulated furnace environment for energy production. The combustion

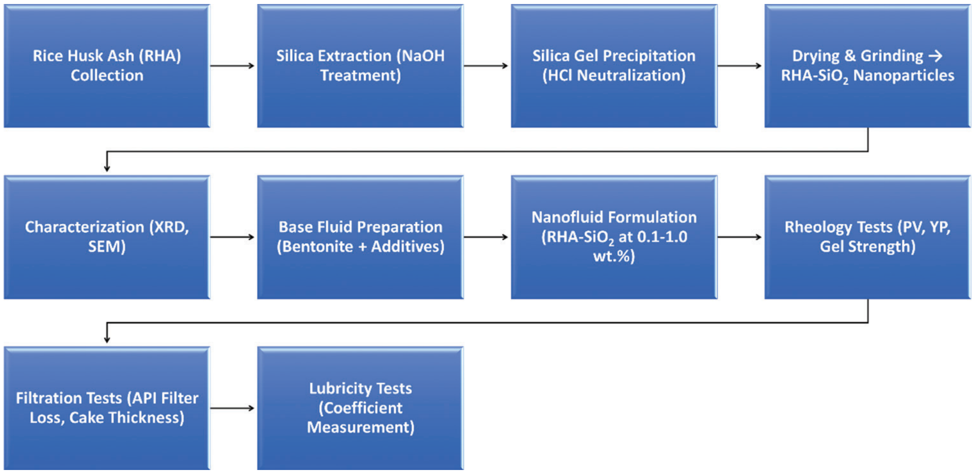

Fig. 1. Experimental workflow for the synthesis, characterization, and application of rice husk ash (RHA)-derived silica nanoparticles (NPs) (RHA-SiO_2 NPs) in water-based drilling fluids.

process has better temperature control compared to burning items outside and produces less carbon allowed to enter the material through the combustion gas, resulting in less carbon being deposited within the final structure. The temperature of the combustion process was consistent with the temperature range required for creating amorphous silica, as determined by X-ray diffraction (XRD) analysis, which showed that the temperatures were between 600°C and 700°C. The ash obtained was gray and was sieved through a 100-mesh screen to remove any coarser materials, unburned residues, and contaminants. The ash was kept in airtight containers until being used in order to prevent atmospheric contamination and moisture absorption. After burning, raw rice husk usually makes about 18–22 wt.% ash. Hence, the 20 g of RHA used in this study is about the same as 90–110 g of the original raw rice husk.

Analytical grade reagents were used in this study. Sodium hydroxide (NaOH, ≥97%), hydrochloric acid (HCl, 37%), and sodium carbonate (Na_2CO_3, ≥99.5%) were sourced from Sigma-Aldrich (Germany) and used without any further treatment; these were the primary chemicals used for the dissolution of silica, precipitation, and pH management in the synthesis process. To make a salt-free hydrogel, all chemical by-products were neutralized and washed with deionized (DI) water. This made sure that the process was safe for the environment.

API grade additives were used as drilling fluid ingredients to ensure adherence to API Recommended Practices. Standard bentonite (Baroid IDP, USA) was used as the main clay material, as it is commonly used in WBDFs. Properties, including increases in viscosity and fluid loss control, were achieved through the use of PAC-R and xanthan gum (XCD), which were obtained in powdered form and functioned as viscosity or fluid loss control agents. DI water was used throughout all phases of the experimental work, both as an aid for chemical reactions and for the preparation of the various drilling fluid formulations. DI water was synthesized in the lab using a Millipore purification system to ensure that ions and impurities that may interfere with the experimental results were removed.

B. Synthesis of Silica NPs from RHA

Silica NPs were produced from RHA following an alkaline extraction–acid precipitation method, which has overall been modified from previous procedures. The method was changed purposefully to improve both yield and purity. The extraction yield from RHA to silica NPs was about 65–75%, which means that about 13–15 g of silica powder was made from the 20 g of ash.

After producing silica NPs, 20 g of pre-sieved RHA (~100 mesh) was reacted with 200 mL of 2.5 M NaOH solution in a round-bottom flask equipped with a reflux condenser. The flask was placed in a sand bath, heated to 90 ± 2°C. The reaction was sealed and heated with a constant magnetic stirring speed of 600 rpm for 2 h at reflux. The reaction resulted in the SiO_2 in RHA reacting with NaOH to form soluble sodium silicate (Na_2SiO_3) that was removed during the filtration step.

At the 2-h mark, the hot reaction mixture was vacuum-filtered through a Whatman No. 42 filter paper to remove excess unreacted material and carbonaceous impurities. The olive green/transparent filtrate rich in sodium silicate was neutralized back to silica by being titrated with a 1 M HCl solution. A peristaltic pump was used to control the acid addition during vigorous stirring. The titration was stopped when a neutral pH (7.0 ± 0.1) was reached, and white silica hydrogel precipitate came out of solution.

The hydrogel was aged for 12 h, washed with DI water until chloride-free ($AgNO_3$ test), dried at 110°C for 24 h, and ground into nanopowder. Fig. 2 shows a schematic diagram of the process for making silica NPs from RHA. This makes it easier to understand the chemical treatment steps that were used.

Even though NPs may seem more expensive to make in a laboratory than bulk bentonite, they need much less and offer many benefits, which could mean that you do not need to add more specialty additives. Using agricultural waste to make things on an industrial scale is likely to cut costs by a lot.

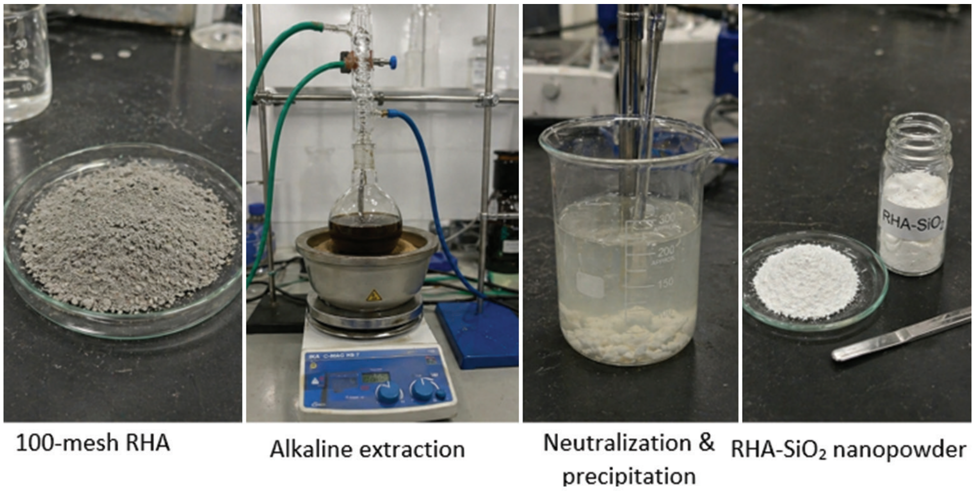

Fig. 2. Synthesis of silica nanoparticles from rice husk ash.

C. Characterization of RHA-SiO_2 NPs

The crystalline structure of synthesized RHA-SiO_2 NPs was investigated by XRD, Bruker D8 Advance using Cu Kα radiation (λ = 1.5406 Å). Samples were scanned from 10° to 80° in a 2θ range at a scan rate of 2°/min to detect crystallinity and amorphous phases of silica.

The morphology, size distribution, and surface texture of NPs were investigated using scanning electron microscopy (SEM, JEOL JSM-IT200). The powders were sputter-coated with a very thin layer of gold for conductivity before SEM analysis. Images were taken between magnifications of 5,000× and 50,000×. The mean particle size was estimated by measuring several particles using ImageJ software, to make a size distribution statistical.

While characterization methods such as Brunauer–Emmett–Teller surface area, Fourier transform infrared Spectroscopy, energy dispersive X-ray Elemental Analysis, and Zeta potential testing can provide more information on dispersion stability and surface chemistry, this research focuses on the performance of the functional drilling fluids. Additional research could include these characterization analyses for a better understanding of NP properties.

D. Drilling Fluid Formulation

The base clay material in Baroid's API-Graded Sodium Bentonite Study was API-Graded sodium bentonite, as it expands significantly, retains moisture well, and is a frequently employed clay for classic WBDFs. Sodium bentonite was determined to be superior to calcium bentonite for use as a reference material in testing new additives made from NPs because it promotes viscosity growth and enables excellent filtration control. A base fluid (BF) drilling was formulated according to API standards. In a Hamilton Beach high-speed mixer, 22.5 g of bentonite was slowly dispersed into 350 mL of DI water. To aid hydration and improve bentonite dispersion, 1.5 g of sodium carbonate (Na_2CO_3) was added to the suspension. The mixture was stirred at 12,000 rpm for 20 min and then left to age for 16 h at room temperature to ensure complete clay swelling and hydration.

Nanofluids (NFs) were synthesized by adding the RHA-SiO_2 NPs into the BF at different loadings, which are 0.1, 0.3, 0.5, 0.7, and 1.0 wt%. The RHA-SiO_2 nanopowders were pre-dispersed by ultrasonically dispersing them in 50 mL of DI water for 15 min to minimize agglomeration before adding them to the BF. The final NF was mixed in a high-shear mixer for 30 min to achieve uniform dispersion of NPs into the drilling fluid. In this study, I didn't test how stable NPs are in the long term while they are being used for drilling or the conditions of drilling over time. Future studies should look at things like how NPs behave under field-relevant conditions by measuring their stability with sedimentation studies, zeta potential measurements, and aging studies.

E. Rheological and Filtration Measurements

Rheological properties, including plastic viscosity (PV), yield point (YP), and gel strength (10-s and 10-min), were obtained using a Fann VG Meter (Model 35) at 25°C. API Recommended Practice 13B-1 procedures were followed. PV was calculated as the difference between the 600 rpm and 300 rpm dial readings. YP was obtained by subtracting that value from the 300-rpm reading. Gel strength values were recorded after rest periods of 10 s and 10 min.

Filtration properties were measured using an API filter press (OFITE Model 140-100). All tests were conducted at 100 psi pressure and 25°C, lasting 30 min. The volume of the filtrate collected was reported as the API fluid loss, and the thickness of the filter cake was measured after the test using a digital caliper. The filter cakes were assessed qualitatively to assess compactness, finished quality (smoothness), and permeability. All experimental measurements were performed in triplicate, and average values are reported to ensure data reliability and reproducibility.

F. Lubricity Measurement

The lubricating performance of the drilling fluids was measured using an OFITE lubricity tester (Model 120-00). The OFITE lubricity tester model simulates the sliding contact between the drill string and the wall of the wellbore.

It features rotating steel rings that contact a stationary steel block while under a fixed load. The lubricant (the drilling fluid) is located between the two surfaces where the sliding occurs, and the torque to maintain rotation is measured. The lubricity coefficient (C_v) is calculated by taking the ratio of the torque measured in the fluid to the torque of a dry reference test, as in equation (1).

$$C_v = \frac{\tau_{fluid}}{\tau_{dry}}$$

where C_v is the lubricity coefficient, T_{fluid} is the measured torque when the drilling fluid is present between the contact surfaces, and T_{dry} is the torque measured under dry contact conditions without lubrication.

This means the lower the lubricity coefficient, the better the lubrication with less metal-to-metal contact friction between surfaces. Each test was run three times, and an average value was reported. To limit the effects of temperature, all tests were done at 25 ± 1°C, and the surfaces were pre-cleaned with ethanol and dried before each run.

IV. Results and Discussion

A. Characterization of RHA-SiO_2 NPs

The XRD pattern of the synthesized RHA-SiO_2 NPs (Fig. 3) revealed a broad halo around ~22° (2θ), which is characteristic of amorphous silica. The absence of sharp crystalline peaks suggests the extracted silica did not contain an amount of crystal impurities (e.g., quartz, cristobalite), which verifies this was high-purity, amorphous silica extracted from RHA, with desirable amorphous qualities for use in drilling fluid applications of silica (i.e., larger specific surface area, greater reactivity than crystalline silica, which is generally more inert). The classification of high-purity silica in this study is corroborated by the lack of crystalline impurity peaks in the XRD spectrum and the prevalence of the amorphous silica halo, suggesting that the majority of inorganic contaminants were eliminated during the alkaline extraction and precipitation phases. Previous research has indicated that the silica content in adequately processed RHA exceeds 85–95%, corroborating the assertion that the synthesized NPs are primarily composed of SiO_2.

The SEM micrograph (Fig. 4) showed that the particles are mostly spherical in shape; however, some agglomeration is evident, as is to be expected due to the surface energy of NPs, which interacts to promote agglomeration. Image analysis for average particle size demonstrated an average of 45 ± 15 nm, which is within the range of nanoscale and suitable for both pore-plugging and lubricity enhancement. NPs of this size are small enough to seal and permeate precipitated nano- and micro-scale pore throats in the filter cake, but not so small that they can migrate into the formation containing micro-fractures and nanoporous media such as shale formations, tight sandstone, and depleted reservoirs where fluid invasion control is critical. This combination improves their performance as fluid loss additives.

The results, based on structural and morphological analyses, correlate with previous studies of RHA-derived silica, which showed that amorphous nanosilica has considerable capability as a mechanical reinforcement and sealing agent (Zareei, Ameri and Dorostkar, 2017; Soltani, et al., 2015). The current results, therefore, confirm that the RHA-SiO_2 NPs synthesized have the necessary traits for drilling fluid applications.

B. Rheological Properties

Summary of rheological properties for the WBDFs containing RHA-SiO_2 NPs is shown in Table I and Fig. 5. The BF, consisting of bentonite and standardized additives, had a PV of 12 cP, YP of 10 lb/100 ft², gel strength 10″ of 4 Ib/100 ft² and gel strength 10′ of 6 Ib/100 ft² which is consistent with a typical unenhanced, API-compliant WBDFs.

The addition of NPs caused a moderate increase in the PV. This result is likely due to the higher solid content in the system and the higher number of frictional interactions between suspended particles. Nevertheless, the increase was still moderate, indicating that the NPs were mostly well-dispersed throughout the fluid and did not add extra viscosity.

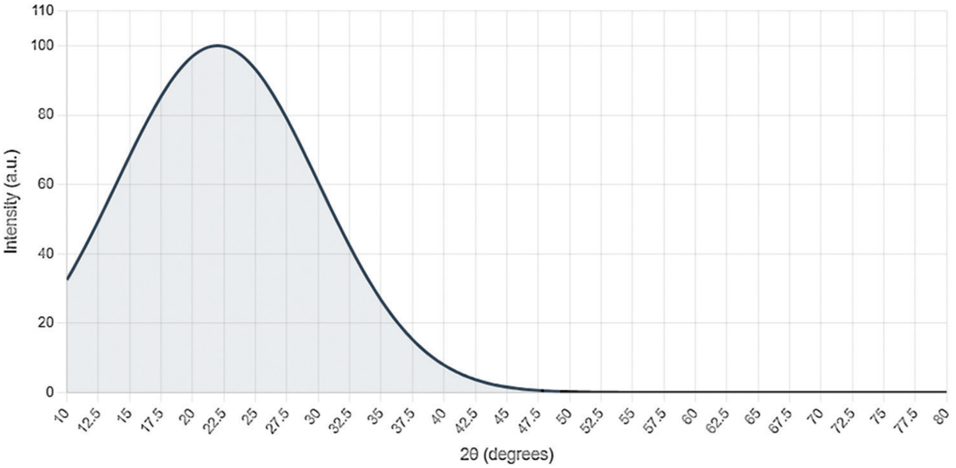

Fig. 3. X-ray diffraction pattern of the synthesized rice husk ash-SiO_2 nanoparticles.

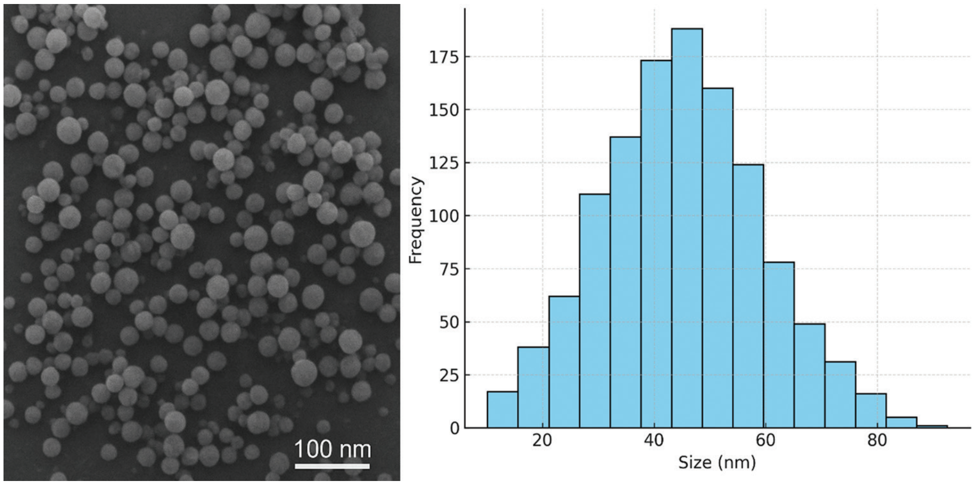

Fig. 4. Scanning electron microscopy image of rice husk ash-SiO$_2$ nanoparticles. Inset: Particle size distribution histogram.

Of noteworthy interest, the YP and gel strength showed a pronounced increase with increased NP loading, up to 0.5 wt.%. The increase may be attributed to the strong electrostatic and hydrogen-bonding interactions between the silica NPs, the bentonite platelets, and the polymer chains (PAC, XCD). These three components can create a stronger three-dimensional network structure within the fluid, thereby improving suspension of cuttings and weighting materials. Providing structural support is important for preventing barite sag and improving the wellbore cleaning ability of the fluid under static conditions.

Rheological properties increased with NP loadings above 0.7 wt.%, but at a lower rate, in line with lower returns in performance. The likely reason for this is that some agglomeration of NPs is resulting in a less per unit effective surface area, and decreased contact with bentonite and polymers. Therefore, the most effective NP loading appears to be 0.5 wt.%, which would be the level that would increase gel strength with limited commensurate viscosity. This line of analysis aligns with previous work establishing the range for an optimal concentration of NPs with regard to rheological enhancement (Vryzas and Kelessidis, 2017; Abdo and Haneef, 2013).

C. Filtration Properties

The effect of RHA-SiO$_2$ NPs on fluid loss control was much greater than anticipated. For the BF, the filtrate volume was measured at 16.8 mL, which is quite high and indicates inferior filter cake quality. After NPs were introduced, the filtrate volume quickly declined to a minimum of 6.8 mL at the 0.5 wt.% NP concentration (Table II and Fig. 6). This is a ~60% decrease in fluid loss compared to the BF, and it indicates the NPs were effective in sealing.

The mechanism of improvement can be associated with the smaller particle size being nanoscale, so the RHA-SiO$_2$ was able to penetrate the interstitial volumetric spaces between bentonite plates in the filter cake and ultimately fill them. In principle, this would produce a denser structure that reduces the filtrate because it would create a less permeable structure. Furthermore, NPs can also synergistically with bentonite

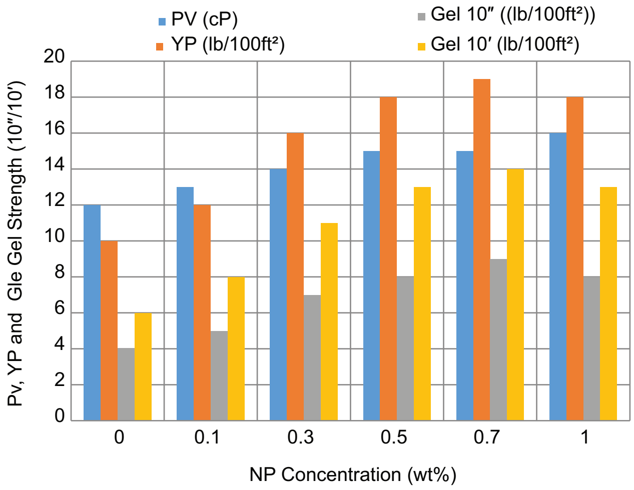

Fig. 5. Effect of rice husk ash-SiO$_2$ on rheological properties.

TABLE I
RHEOLOGICAL PROPERTIES AND API FILTER LOSS OF BASE FLUID AND NANOFLUIDS

Additive Concentration (wt%)	PV (cP)	YP (lb/100ft^2)	Gel Strength (10″/10′) (lb/100ft^2)
Base Fluid (0.0)	12	10	4/6
0.1	13	12	5/8
0.3	14	16	7/11
0.5	15	18	8/13
0.7	15	19	9/14
1.0	16	18	8/13

PV: Plastic viscosity, YP: Yield point

TABLE II
API FILTER LOSS OF BASE FLUID AND NANOFLUIDS

Additive concentration (wt%)	API FL (mL)	Mud cake thickness (mm)
Base Fluid (0.0)	16.8	2.5
0.1	13.5	2
0.3	9.8	1.6
0.5	6.8	1.1
0.7	7.9	1.3
1.0	8.1	1.4

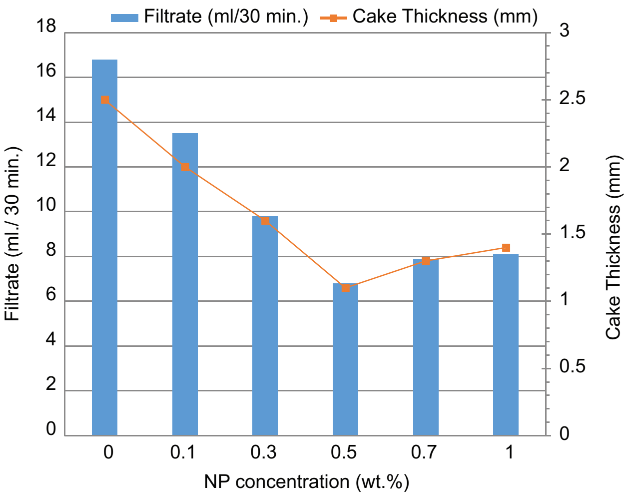

Fig. 6. Effect of rice husk ash-SiO_2 nanoparticles concentration on API fluid loss.

create a barrier that is more compact and denser, hence less permeable. This evidence is also noted by the tabulated sample of the filter cake at 0.5 wt.%, which had a change in thickness from 2.5 mm (BF) to 1.1 mm, indicating an overall change in effective sealing potential. Having a thinner yet denser cake is an advantage because it considerably decreases the risk of differential sticking and allows an effective seal to remain, thus, minimizing filtrate invasion.

At the higher NP concentrations (>0.7 wt.%), they did not show any significant improvements when their concentration increased, which could have resulted from particle aggregation and therefore a decrease in dispersion efficiencies, and that could also interfere with the overall structure of the filter cake. These observations are consistent with other documented NP-enhanced WBDF studies where the most filtration improvements were made with optimal concentrations using lower dosages and avoiding negative aspects of higher dosages (William, et al., 2014).

The NPs' enhanced ability to control filtration ultimately helps stabilize the wellbore by preventing fluids from entering reactive shale formations. NPs may be able to penetrate into nanopores and micro-fractures, which could contribute to reducing the swelling and dispersion of shales.

D. Lubricity Properties

The lubricity of the drilling fluids is found in Fig. 7. The base had a lubricity coefficient of 0.28, which was a reasonable value for bentonitic fluids but not enough for extended-reach or horizontal wells. The NPs showed consistent improvements in lubricity, with the maximum being at 0.5 wt.% NP concentration showing a coefficient of 0.17, which is a 39% improvement over the BF lubricity, and therefore this would likely give large reductions in torque and drag when drilling.

The mechanism of the improvements is associated with the unique role of the silica NPs with respect to tribology and their shape. It can be suggested that the NPs are spherical and at the interface between the rotating drill string and the static casing (or formation wall), the silica NPs are able to promote a form of rolling and/or minimize the coefficient of sliding friction due to the minimum contact area. In addition, the nature of the NPs from the adsorptive standpoint allows for their adsorption to metallic surfaces, which means it behaves like a lubricant and therefore mitigate both adhesive wear and contact friction.

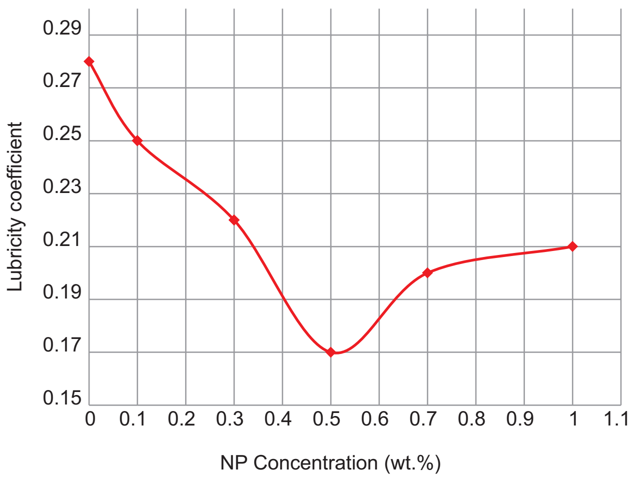

Fig. 7. Effect of rice husk ash-SiO_2 nanoparticles concentration on lubricity coefficient.

Further, the simultaneous reduction in fluid loss and improved lubricity represent two functions occurring at the same time with RHA-SiO_2 NPs as a possible next-generation additive to drilling fluids, where few of the more standard additives are capable of delivering sufficient benefits in either area of concern. RHA-SiO_2 NPs also have much reduced negative qualities of thermal degradation and environmental contaminant (e.g., Salam, Al-Zubaidi and Al-Wasiti, 2019) in comparison to oil-based lubricants. All of which is much more sustainable than oil-based fluids rather than metallic friction. Further evaluation under HTHP conditions is required for field validation.

E. Comparative Performance with Conventional Additives

In order to contextualize the performance of RHA-SiO_2 NPs, it is helpful to compare their performance against common fluid loss and lubricity additives more commonly used in WBDFs, polymers (i.e., CMC, PAC), and bridging agents (i.e., $CaCO_3$).

Filtration control

Conventional polymeric materials (e.g., polyacrylate or starch derivatives) can reduce the amount of fluid loss during a well-drilling project by swelling and forming gel-like filter cakes. However, this technique will be less effective when temperatures exceed approximately 120–150°C (>120–150°C), thus limiting their use under HTHP conditions (Abdullah, et al., 2022; Ahmad, et al., 2020). In comparison, the thermal stability of RHA-SiO_2 NPs allows these inorganic materials to control fluid loss through two mechanisms: nanoscale pore plugging and densification of the filter cake. When using 0.5 wt.% of RHA-SiO_2 NPs, they would produce a 60% reduction in fluid loss compared to the conventional polymeric additives tested at the same concentration level, demonstrating a higher degree of sealing capability than polymer additives used for similar applications.

Lubricity improvement

Mineral oils and fatty acid derivatives are typical types of lubricants and work by forming thin films on the surface of metal to decrease friction. However, these products can experience problems related to thermal stability, emulsification, and environmental impact (Salam, Al-Zubaidi and Al-Wasiti, 2019). In comparison, lubricity coefficients are reduced by 39% with the use of RHA-SiO_2 NPs due to their ability to act as nano-ball bearings between surfaces; therefore, providing an environmentally friendly and thermally stable replacement, while not negatively impacting mud stability.

Filter cake properties

$CaCO_3$ is a common and inexpensive bridging agent, but because of its particle size, it has difficulty sealing nano-sized pore spaces in tight formations (Okon, Akpabio and Tugwell, 2020). Conversely, nanosilica (45 ± 15 nm) can be used to effectively plug micro- and nano-sized pore throats. In this investigation, the use of RHA silica dioxide (RHA-SiO_2) produced thinner and denser filter cakes (1.1 mm at 0.5 wt.%) as compared to those produced with conventional $CaCO_3$ systems, thereby reducing the likelihood of differential sticking and enhancing the integrity of the wellbore.

Multifunctionality

RHA-SiO_2 NPs offer a distinct advantage in that they have multiple functions or uses. Traditional additive materials used in enhanced oil recovery processes (polymers for filtration, lubricants for reduced friction, bridging agents for sealing) are specifically made to be used for their intended function or purpose; however, RHA-SiO_2 NPs can enhance rheological properties, fluid loss control properties, and lubricity properties at the same time. This multifunctional property should enhance the ability of the operator to formulate fluids and reduce the amount of chemicals used in the overall operations, which reduces costs.

It is important to note that this study was done in a controlled laboratory setting using API standard testing methods. The results show that drilling fluid performance has improved a lot, but to fully understand the operational and economic benefits of these changes in real drilling conditions, pilot well tests or numerical drilling simulations would need to be done on a larger scale. Consequently, subsequent research should concentrate on field implementation studies in partnership with drilling companies.

In conclusion, RHA-SiO_2 NPs showed performance advantages over traditional WBDF additives with respect to thermal stabilities, pore-plugging capacity, lubricity improvement, and multifunctional use. Although added environmental benefits demonstrate RHA-SiO_2 potential as a sustainable next-generation option for drilling fluid development due to its environmental viability and low cost from its bio-waste origin.

V. Conclusion

The study demonstrates the successful synthesis, characterization, and use of silica NPs generated from RHA (RHA-SiO_2 NPs) as a multifunctional additive to WBDFs. The key highlights are summarized below:

A. Successful Synthesis and Characterization

The conversion of RHA to amorphous nanosilica was accomplished using an alkaline extraction–acid precipitation method. The particles obtained were mostly spherical, with an average size of 45 ± 15 nm as demonstrated by SEM, and had an amorphous state as verified by XRD, two physicochemical properties that are highly desirable for drilling fluid use.

B. Rheological Improvements

RHA-SiO_2 NPs did provide some modest increases in PV but more substantial increases in YP and gel strength to about 0.5 wt.%. The extent of improvement was a function of NP–clay–polymer interactions that likely contributed to strengthening the fluid's three-dimensional network, therefore improving suspension properties and hole cleaning behavior. The agglomeration effects post 0.7 wt.% NP loading affected performance efficiency and further illustrated that an optimal loading existed.

C. Filtration Control Performance

The addition of the NPs produced a drastic decrease in API fluid loss - approximately from 16.8 mL in the BF to approximately 6.8 mL at a 0.5 wt.% loading (60% improvement). The thickness of the filter cake also decreased simultaneously from 2.5 mm to 1.1 mm, which confirmed that a less permeable and denser barrier formed. The main performance mechanism was attributed to nanoscale pore-plugging of the NPs.

D. Lubricity Improvement

The improvements in lubricity caused by the NPs were notable, with the lubricity coefficient dropping from 0.28 (BF) to 0.17 at 0.5 wt.% NP loading (39% improvement). The mechanism of improvement was attributed to the nano-ball bearing effect of the spherical silica particles and their ability to form protective tribofilms on metallic surfaces.

E. Multifunctionality and Sustainability

The RHA-SiO_2 NPs improved rheology, fluid loss, and lubricity, unlike traditional single-function additives (e.g., PAC, oils, $CaCO_3$). The agro-waste "waste" improved cost-effectiveness and broadened sustainability (e.g., sustainability) for more sustainable technologies in the industry.

In conclusion, this study demonstrated the applicability of RHA-SiO_2 NPs as a low-cost, environmentally friendly, multifunctional additive to drilling fluids - a sustainable substitute to use instead of traditional materials and commercial nanomaterials. The use of RHA-SiO_2 NPs in drilling operations could improve wellbore stability while simultaneously improving drilling performance and enhancing environmental responsibility in oil and gas operations.

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