

Article

Feasibility Study of Rice and Bread Waste as Sustainable Fluid Loss Additives in Water-Based Drilling Fluids

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Abstract

Drilling fluids are essential in oil and gas operations for wellbore stability, cuttings transport, pressure control, and fluid-loss reduction. Water-based drilling fluids (WBDFs) are widely used because of their cost-effectiveness and lower environmental impact compared with oil-based systems; however, they often suffer from fluid loss into the formation and lower rheological performance. This laboratory-scale study investigates the feasibility of using rice and bread waste powders as bio-based additives for WBDFs to mitigate fluid loss. The collected food wastes were dried, milled, and sieved into three particle sizes of fine (150 μm), very fine (75 μm), and ultrafine (45 μm). The prepared powders were characterized using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX). A total of 18 drilling-fluid formulations were prepared using rice and bread powders at concentrations of 1 wt%, 2 wt%, and 3 wt%. Filtration tests were conducted under low-pressure low-temperature (LPLT) conditions of 100 psi and 25 °C and high-pressure high-temperature (HPHT) conditions of 1500 psi and 70 °C, while rheological properties were measured using a rotational viscometer. The results showed that additive type, particle size, and concentration strongly influenced WBDF performance. The best-performing formulation was WBDF with added rice powder at 45 μm and 3 wt% (RC45-3), which reduced fluid loss from 19.5 mL to 6.1 mL, corresponding to a reduction of approximately 68.7% at LPLT. Under HPHT conditions, the same formulation reduced fluid loss from 36.5 mL to 11.4 mL, corresponding to a reduction of approximately 68.8%. RC45-3 also produced the thinnest measured filter cake, reducing filter-cake thickness from 5.0 mm for the base mud to 0.52 mm. The formulation maintained shear-thinning behavior and produced suitable gel strength values, indicating improved suspension capacity. The improved performance of rice powder is attributed to its fine particle size, favorable morphology, and ability to form a compact, low-permeability filter cake. Overall, the findings indicate that processed rice waste powder has potential as a low-cost, bio-based fluid-loss-control agent for WBDFs, although further testing in field-representative mud systems is required before practical application.



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1. Introduction

Drilling fluids are essential to the successful construction of oil and gas wells, serving multiple mechanical, hydraulic, and chemical functions throughout the drilling process. These fluids, commonly referred to as drilling muds, carry drilled cuttings to the surface, stabilize the wellbore, counterbalance formation pressures, cool and lubricate the drill string, protect productive formations from damage, and transmit hydraulic energy to the bit for more efficient rock breaking [1]. Drilling fluid is necessary to prevent pressure build-up from rock formations, remove bits of rock from the hole, and hold them in place when the mud is not moving. Moreover, it prevents leaks in the rock layers, reduces friction, and keeps the drill tools cool [2].

To achieve these functions, drilling fluids are formulated with various additives that modify their density, viscosity, pH, filtration properties, and lubrication characteristics. A wide range of additives is routinely employed to optimize drilling-fluid performance. Weighting materials such as barite and hematite increase fluid density to maintain wellbore pressure control [3]. Miscodifying agents like bentonite and xanthan gum enhance carrying capacity and suspension of solids. Alkalinity regulators, including caustic soda and lime, maintain chemical stability. Fluid loss agents reduce fluid invasion into permeable formations by forming a thin, low-permeability filter cake [4]. Additional additives, including corrosion inhibitors, biocides, and defoamers, are incorporated to suppress corrosion, microbial activity, and foam generation, respectively. Together, these components ensure that the drilling fluid performs reliably across dynamic downhole conditions. WBDFs are popular due to the lower cost and fewer harmful substances compared to oil-based drilling fluids [5]. However, they suffer from fluid loss during the operations, which requires the fluid-loss agents to be added to mitigate the problem.

Conventional WBDF additives often present environmental concerns and high costs. This has driven increasing interest in developing sustainable, bio-based alternatives capable of delivering comparable or improved performance. Food waste represents a promising resource in this regard due to its abundance, low cost, and bio-based nature. Global food-waste volumes have risen significantly in recent decades, and valorizing such waste into industrial additives supports circular-economy principles while reducing environmental burdens. Furthermore, since bio-based economic growth naturally influences ecosystems, there must be clear evidence demonstrating that these bio-products are more environmentally friendly than products made from fossil fuels in terms of greenhouse gas emissions, water use, soil health, and biodiversity [6]. Table 1 provides a consolidated summary of these bio-based additives, showcasing their effectiveness and reinforcing the viability of biowaste utilization in WBDFs.

Table 1. The list of previous experiment food-waste samples that were used before.

Author(s) and Year	Reference	Material	Combination	Purpose	Summary
Madu et al., 2024	[3]	Coffee and watermelon rind waste	1, 2, and 3 g added to conventional WBDF	Reduction in the fluid loss	Improve water-based drilling fluid rheology, with optimal performance at around 3 wt% concentrations.
Saengdee and Terakulsatit, 2017	[4]	Sugar cane bagasse ash	API RP13B-1, the analysis is conducted at 25, 50, and 80 °C at concentrations of 1, 3, and 5%	Fluid loss	At 25–80 °C, sugarcane bagasse ash (1–5% wc%) enhances drilling mud filtration with optimal performance at 1%, resulting in minimum fluid loss and thinner filter cakes. As a result of higher concentrations, filtrate volume and thickness increase despite high SiO ₂ (88.37%) and quartz content (73.412%).

Table 1. Cont.

Author(s) and Year	Reference	Material	Combination	Purpose	Summary
Hossain and Waijheuddin, 2016	[5]	Grass (300 µm, 90 µm, and 35 µm particle sizes)	0.25, 0.50, 0.75, and 1.0 g of grass with different particle sizes added to WBDF	Control fluid loss	Enhance the viscosity, yield point, and gel strength in water-based drilling fluids by 0.75 ppb (300 and 35 m) and 1 ppb (90 m).
Amadi et al., 2018	[6]	21 types of food and green waste	Between 0 and 10 ppb concentration of different green and food-waste materials added to the WBDF	Control fluid loss	A 1% concentration of food-waste additives (banana peels, potato peels, gum arabic) reduced fluid loss by 78 percent and decreased the thickness of the filter cake, demonstrating effective control of fluid loss and improved rheological characteristics.
Sauki et al., 2019	[7]	Eggshell waste	15 g added to the total WBDF mud	Control fluid loss	Eggshell additives provided stable rheology, a thin filter cake (only 1/32 inch), and controlled fluid loss equivalent to standard CaCO ₃ materials.
Al Hameedi et al., 2019	[8]	Grass powder (GP)	1% and 2% GP added to the WBDF	Control fluid loss	By increasing critical shear stress to 10.45 Pa and forming a dense, low-permeability filter cake, natural rubber latex (0.5 w/v%) improved rheological performance.
Olaniyan and Sarah, 2024	[9]	black sunflower seeds' shell powder	N/A	Fluid loss control	This transesterification-enhanced BSO ester-based mud demonstrated superior rheological and filtration performance, achieving 10 ppb without additional rheology modifiers, demonstrating high thermal stability, biodegradability, and lower environmental toxicity than diesel-based mud.
Yaseer et al., 2020	[10]	Wheat Husk Powder (WHP)	Concentrations of 1, 2, 3, and 4 wt% WHP were added to the WBDF	Control fluid loss	A WHP mud may reduce filtration loss by up to 81.42 wt% at 4% concentration (versus 64.28% for a CMC mud), while retaining similar filter cake thickness, negligibly affecting mud weight, and having stable performance up to 100 °C.
Akmal et al., 2020	[11]	Waste banana peels	Various percentages were added to the WBDF	Control fluid loss	As eco-friendly LCMs, banana peel and sugarcane bagasse additives demonstrated superior rheological and filtration properties, and thermal stability tests indicated that temperature had a significant effect on mud stability.
Zhou et al., 2021	[12]	Wild Jujube Pit Powder (WJPP)	0.5, 1, 2, 3, and 5 wt% WJPP were added to WBDF	Control fluid loss	It has enhanced viscosity, yield point, shear-thinning, and thixotropy, and reduces filtration loss and lubrication coefficient with greater performance at smaller particle sizes and higher concentrations, with temperature tolerance up to 273.9 °C.
Novrianti et al., 2021	[13]	Cassava starch	0 to 10 g were added to the WBDF	Control fluid loss	In addition to reducing fluid loss and filter cake thickness, cassava starch also significantly improved plastic viscosity, yield point, and gel strength, with strong correlations ($r = 0.994\text{--}0.996$).

Table 1. Cont.

Author(s) and Year	Reference	Material	Combination	Purpose	Summary
Medved et al., 2022	[14]	Waste Mandarin Peel as	Different concentrations (0.5, 1, 1.5, and 2 wt% were added to the WBDF	Control fluid loss	Mandarin peel powder ($\leq 0.1\text{--}0.16$ mm) significantly reduced API filtration and PPT filtration by up to 61.54%, while spurt loss decreased by up to 75% at concentrations of 1.5–2%, improving rheological properties within acceptable limits.
Ali et al., 2023	[15]	wheat nano-biopolymers	2 wt% added to WBDF	Fluid loss control	There was no expansion of wheat nano-biopolymers over 48 h, improved rheological behavior at pH >10, and a minimum fluid loss of 11.5 mL (vs. 8 mL for CMS-modified mud).

Previous studies have shown that several bio-based and waste-derived materials can improve the filtration and rheological performance of water-based drilling fluids. Madu et al. [3] investigated coffee grounds and watermelon rind waste as WBDF additives at LPLT and reported improved rheology and fluid-loss control, with the best performance observed at approximately 3 wt% concentration. Saengdee and Terakulsatit [4] studied sugarcane bagasse ash at 1, 3, and 5 wt% over a temperature range of 25–80 °C. They found that 1 wt% provided the most effective filtration performance, while higher concentrations increased filtrate volume and filter-cake thickness. Hossain and Wajheeuddin [5] examined grass powder with different particle sizes and showed that it could improve viscosity, yield point, and gel strength in WBDFs. Amadi et al. [6] evaluated several food and green-waste materials, including banana peels, potato peels, and gum arabic, and reported that a 1% concentration reduced fluid loss by up to 78% while also decreasing mud-cake thickness. Sauki et al. [7] investigated eggshell waste and found that it provided stable rheology, formed a thin filter cake, and controlled fluid loss in a manner comparable to conventional calcium carbonate materials.

Al-Hameedi et al. [8] studied grass powder as a water-based drilling-fluid additive and reported improvements in rheological performance and filter-cake quality. Yaseer et al. [10] investigated wheat husk powder at concentrations of 1–4 wt% and found that it reduced filtration loss by up to 81.42% at 4 wt%, while maintaining stable performance up to 100 °C. Akmal et al. [11] examined banana peels and sugarcane bagasse as lost-circulation material additives and showed that these materials improved rheological and filtration properties, although temperature had a significant effect on mud stability. Zhou et al. [12] evaluated wild jujube pit powder at concentrations of 0.5–5 wt% and reported improvements in viscosity, yield point, shear-thinning behavior, thixotropy, filtration loss, and lubrication coefficient, with better performance at smaller particle sizes and higher concentrations. Novrianti et al. [13] investigated cassava starch and reported reductions in fluid loss and filter-cake thickness, together with improvements in plastic viscosity, yield point, and gel strength. Medved et al. [14] studied mandarin peel powder at 0.5–2 wt% and reported reductions in API/PPT filtration of up to 61.54%, with spurt loss reduced by up to 75%. Abbas et al. [15] examined wheat nano-biopolymers and found improved rheological behavior and reduced fluid loss, although the filtration performance remained lower than that of CMS-modified mud. Overall, these studies confirm that bio-based and waste-derived additives can improve fluid-loss control, filter-cake quality, and rheological behavior in WBDFs.

Although rice-derived materials such as rice husks have previously been investigated as fluid-loss-control additives in WBDFs [16], the use of processed rice food-waste pow-

der and bread waste powder as comparative WBDF additives remains underexplored. In particular, no previous study identified in the reviewed literature has systematically compared rice and bread waste powders across different particle sizes and concentrations while linking their filtration and rheological performance to FTIR, SEM, and EDX characterization. This provides the core novelty of the present study. Therefore, this study investigates the effects of different concentrations and particle sizes of bread and rice waste powders on the filtration loss and rheological properties of WBDFs. Moreover, this study demonstrates a direct correlation between material structure and fluid performance by integrating rheological, filtration, and microstructural analyses (FTIR, SEM, and EDX). Compared to previous studies, this combined approach offers a better understanding of bio-based additive behavior. Various waste-derived materials, such as rice husks, coffee grounds, and banana peels, have demonstrated fluid loss reductions ranging from 30% to over 80%, depending on concentration and temperature conditions. However, most studies focus on single materials and limited particle sizes. In contrast, the present study provides a systematic evaluation using multiple particle sizes and concentrations. Further, rice and bread waste are widely available and inexpensive, which provides a practical advantage over other materials.

The aim of this study is to develop environmentally friendly additives based on food waste to enhance the filtration and rheological properties of WBDF. To this end, two materials from food waste, including rice and bread, have been chosen that will be discussed briefly hereafter. Food waste has greatly influenced questions in the twenty-first century. According to research conducted by the Food and Agriculture Organization of the United Nations (FAO), food is produced at a rate of 1.3 billion metric tons annually. A UN study indicates that 931 million tons of food are wasted each year by households, retail outlets, and the food service industry, raising the likelihood that the real quantity of food lost globally is more than double earlier estimates. In truth, waste is determined by a variety of factors along the supply chain. According to the UN Environment Programme's (UNEP) Food Waste Index Report, homes account for 61% of food waste, followed by food service (26%), and retail (13%). Rice accounts for more than half of wasted cereals in Japan, China, and South Korea, as well as 72% of lost or discarded grains throughout South and Southeast Asia, a total of 149.7 million tons, according to the United Nations. That lost rice produces greenhouse gas emissions equivalent to 610.5 million tons of CO₂ every year. Rice is primarily composed of carbohydrates, which make up more than 80% of its total dry weight. According to [16], using rice husk at a concentration of 350 mL per 20 pounds per barrel resulted in a 64.89% fluid loss reduction, and filter cakes were reduced by 3.03% and 8.57%. Bread has been one of the most wasted food categories. Given the fact that bread is a basic item, estimates show that 100 million tons of bread are produced each year globally, resulting in hundreds of tons wasted per day [17].

There has been extensive research conducted on the use of biodegradable additives in water-based drilling fluids; however, most of the available studies concentrate on a single type of waste material or operate under limited conditions [18]. As food-waste sources, particle sizes, and concentration levels are not systematically compared, it is difficult to gain a comprehensive understanding of their performance [19–25]. Therefore, this study presents a novel and systematic examination of rice and bread wastes as drilling fluid additives utilizing multiple particle sizes (150 µm, 75 µm, and 45 µm) and concentrations (1%, 2%, and 3%). Furthermore, this research combines rheological characterization, density analysis, and microstructural analysis (SEM, FTIR, and EDX) to establish a direct connection between material structure and drilling fluid performance [26]. Subsurface fluid behavior is governed by multiple interacting factors, including flow path, permeability, pressure conditions, and transport behavior [27]. A recent study has shown that seepage pathways,

injection conditions, and permeability evolution can significantly influence fluid migration and storage performance in porous media [28–30]. Similarly, the performance of the drilling fluid is a function of several important parameters, including viscosity, density, yield point, gel strength, filtration loss, filter-cake thickness, lubricity, inhibition performance, and thermal stability [31]. Therefore, this study evaluates both rheological properties and filtration behavior, including apparent viscosity, plastic viscosity, yield point, gel strength, fluid loss, and filter-cake thickness, to provide a more comprehensive assessment of the effects of rice and bread waste powders on WBDF performance.

There have been several studies investigating waste-based additives for improving drilling fluid performance, but most of these studies have concentrated on a single material or a limited range of particle sizes. Furthermore, there are few studies that compare different waste types at varying particle sizes and concentrations. Therefore, this study aims to fill this gap by analyzing rice and bread waste at various particle sizes and concentrations. A more comprehensive understanding of their performance in water-based drilling fluids is provided by this research.

2. Materials and Methods

The experimental method based on API RP 13A [18] was designed to evaluate rice and bread waste powders as biodegradable additives for water-based drilling fluids. Two additive types, rice powder and bread powder, were prepared at three particle sizes of fine (150 μm), very fine (75 μm), and ultrafine (45 μm). Each additive was incorporated into the reference water-based mud at three concentrations of 1 wt%, 2 wt%, and 3 wt%. In total, 18 additive-containing drilling-fluid formulations were prepared and compared with the reference base mud without additives. The prepared muds were evaluated through density, rheological, and filtration tests. Filtration performance was assessed under LPLT conditions of 100 psi and 25 °C and HPHT conditions of 1500 psi and 70 °C. The main measured outputs were filtrate volume, filter-cake thickness, apparent viscosity, plastic viscosity, yield point, and gel strength. The experimental run was repeated twice for reliability and repeatability of the tests. Figure 1 summarizes the overall experimental workflow. Table 2 also summarizes the detailed description of the materials, methods, and the purpose of each step taken in the study.

Table 2. The detailed preparation of the materials and experiments in this study.

Category	Studied Cases/Conditions	Purpose
Base fluid	Reference water-based mud: 700 mL deionized water, 40 g bentonite, 1 g NaOH	Control sample for comparison
Additive type	Rice powder and bread powder	Evaluate food-waste-derived additives
Particle size	150 μm , 75 μm , 45 μm	Investigate particle-size effect on filtration and rheology
Concentration	1 wt%, 2 wt%, 3 wt%	Determine the effect of additive loading
Number of formulations	18 additive formulations + 1 reference mud	Systematic comparison of all cases
Characterization	FTIR, SEM/FESEM, EDX	Identify functional groups, morphology, and elemental composition
Rheological tests	Apparent viscosity, plastic viscosity, yield point, gel strength	Assess flow and suspension behavior
Filtration tests	LPLT: 100 psi, 25 °C; HPHT: 1500 psi, 70 °C	Assess fluid-loss control and filter-cake formation
Filtration outputs	Filtrate volume over 30 min; filter-cake thickness after 30 min	Compare filtration-control performance

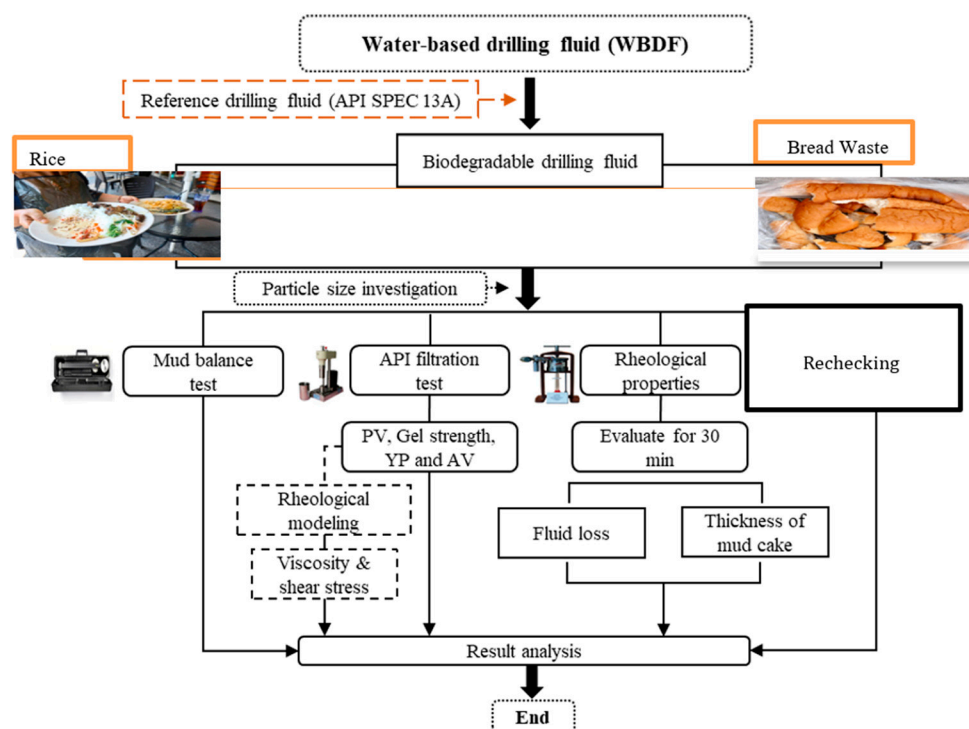


Figure 1. Processing route for converting rice and bread waste into powder additives and incorporating them into water-based drilling fluids.

2.1. Preparation of Biodegradable Materials and Drilling Fluids

Figure 2 depicts the synthesis and characterization of bio-based materials, as well as their application as WBDF additives. Rice and bread trash from local restaurants and supermarkets are dehydrated in an oven for 24 h at 110 °C. The dried bits were then crushed into powder using an electric grinder. Various particle sizes (150 µm, 75 µm, and 45 µm) were selected according to their relevance to drilling fluid performance and prior studies on fluid loss agents. Research has demonstrated that smaller particle sizes enhance packing efficiency within the filter cake, reducing permeability and improving fluid loss control. Due to this, the selected size range allows a systematic evaluation of the transition from coarse to ultrafine particles, as well as their combined effects on rheological behavior and filtration. In earlier studies of bio-based and conventional drilling fluid additives, it was determined that particle size played a critical role in the performance of these additives [14]. The elemental composition and morphological structure of the extremely tiny materials were determined using a Hitachi S-3400N microscope equipped with EDX and SEM (Tokyo, Japan). Furthermore, the functional groups found in each material were identified using FTIR spectroscopy on the Perkin Elmer Spectrum 100 series (Waltham, MA, USA), with spectra ranging from 650 to 4000 cm⁻¹ and 64 scans per sample to achieve a high spectral resolution of 1 cm⁻¹. A water-based drilling base mud (BM) was created in compliance with American Petroleum Institute requirements [19]. This included combining 700 mL of deionized water with 1 g of caustic soda (NaOH) and 40 g of bentonite. The mixture was homogenized for 10 min with a 3-speed Type GM20 Hamilton Beach Commercial mixer (Glen Allen, VA, USA) before being allowed to settle for 24 h, as specified by the API. The settling period provides adequate hydration, viscosity stabilization, chemical reaction completion, and the release of trapped gases and air [19,20].

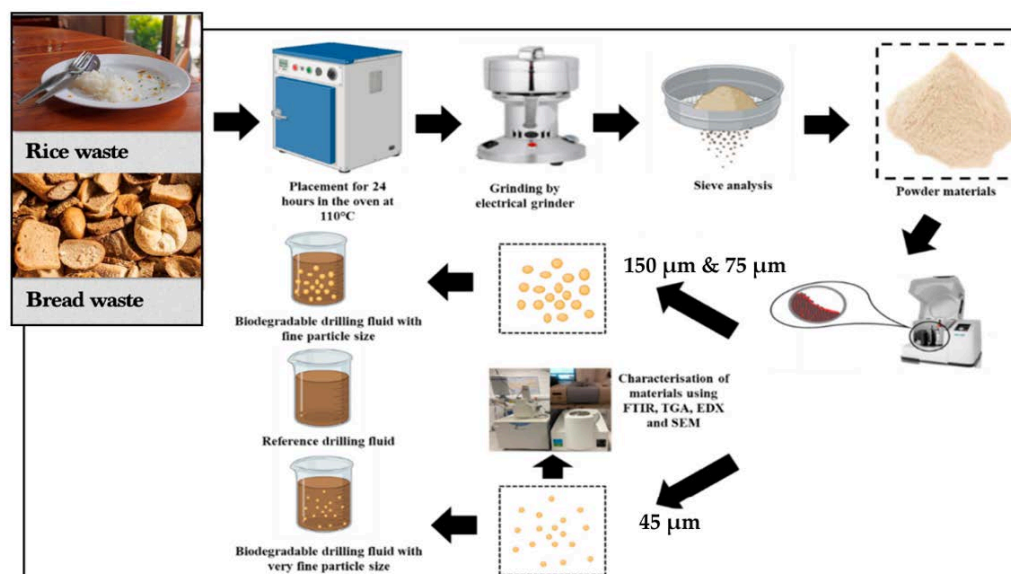


Figure 2. Process flow diagram for the synthesis and characterization of biodegradable drilling fluid additives from household food-waste rice and bread.

Subsequently, 18 bio-based drilling muds were formulated, each incorporating fine, very fine, and ultrafine particles of the prepared materials as additives. To the reference drilling fluid, 7 g (1%), 14 g (2%), and 21 g (3%) of these additives were added. The mixtures were blended into the water-based mud (WBM) for 30 s using an electric mixer to ensure thorough homogenization, followed by a series of tests. The base mud used in this study was prepared as a simplified API-based laboratory reference WBDF. The recommended formulation was selected to provide a controlled system in which the individual effects of rice and bread waste powders on filtration and rheological properties could be evaluated. However, it should be noted that field drilling fluids usually contain additional additives, including filtration-control polymers, lubricants, shale inhibitors, salts, and biocides. Therefore, the present results should be interpreted as an initial feasibility assessment, and further compatibility testing with conventional additives such as low-viscosity polyanionic cellulose (PAC-LV) is required.

The study assessed filtering parameters, such as fluid loss and filter cake development, using a Series 300 LPLT filter press (OFITE Instruments, Houston, TX, USA) at a pressure of 100 psi at 25 °C and an HPHT filter press (OFITE Instruments, Houston, TX, USA) at 1500 psi and 70 °C. The operation started with carefully placing filter paper into the cell of the filter press, followed by loading the sample material. A graduated cylinder was placed below the filtrate tube to collect the filtered material.

After the setup was complete, the testing phase began with the activation of a timer for 30 min. Throughout this time, the amount of filtrate collected was reported at regular intervals. At the end of the test, the thickness of the filter cake was measured and recorded. This approach allowed for the measurement of filter cake thickness after 30 min and the tracking of fluid loss at certain 5 min time intervals during the same timeframe.

2.2. Mud Preparation with Biomaterials

To determine whether biodegradable additives influence WBDFs, three concentrations (7 g, 14 g, and 21 g) of each powder were added to the base mud. The amounts selected represent 1%, 2%, and 3% of the weight of the sample. It was determined that 700 mL of deionized water was required for each formulation, which was measured into separate beakers labeled with the type and concentration of the additive. Bentonite is a relatively rich source of resources. With further research, organic bentonite modifications will be syn-

thesized. This will replace the current drilling fluid treatment products [22]. Figure 3 shows papered water-based drilling fluid (WBDF) samples containing different bioadditives. The standard method was consistent with API RP 13B-1 protocols [18].



Figure 3. The prepared drilling fluid muds with various concentrations of bio-based materials.

2.3. Characterization of the Materials

There was a consistent recipe for each formulation: 700 mL of deionized water, 40 g of bentonite, and 1 g of NaOH, with varying concentrations shown in Table 2 of environmentally friendly additives. The table below summarizes the different formulations prepared using bread and rice powder, along with the particle size ranges and weight percentages used. As a baseline for evaluating performance, the table also includes a reference mud without additives. An examination of the morphology, functional groups, and elemental composition of each additive (bread and rice powders) was conducted.

To provide a clear understanding of the experimental program, three particle sizes (150 μm , 75 μm , and 45 μm), and at three concentrations (1 wt%, 2 wt%, and 3 wt%) were used. We developed 18 formulations and compared them with a reference base mud (BM). It was assessed that each formulation performed well in rheological tests (viscosity, yield point, gel strength) as well as filtration tests (fluid loss and filter cake thickness) under standard API conditions in LPLT and HPHT. EDX and FTIR analyses were used to determine the chemical composition of two waste materials: rice waste and bread waste. EDX and FTIR are important for identifying unknown compounds of the selected materials and their effect on fluid loss and rheological properties [21]. The EDX results revealed significant amounts of oxygen (O) and potassium (K), followed by phosphorus (P), chlorine (Cl), magnesium (Mg), calcium (Ca), and silicon (Si) in all three tested materials. Three sizes of fine (150 μm), very fine (75 μm), and ultrafine (45 μm) were measured using high-resolution imaging in SEM.

2.4. Rheological Measurement

The rheological properties of the prepared water-based drilling fluid samples were measured using a rotational viscometer at ambient temperature, following API RP 13B-1 procedures. Before each measurement, the mud sample was mixed thoroughly to obtain a homogeneous suspension and then transferred into the viscometer cup. The rotor sleeve was immersed to the required level, and dial readings were recorded at rotational speeds of 600, 300, 200, 100, 6, and 3 rpm. The measured dial readings were used to calculate the main rheological parameters, including plastic viscosity (μP), apparent viscosity (μa), and

yield point (YP). Plastic viscosity and apparent viscosity were calculated using the 600 rpm and 300 rpm dial readings as follows:

$$\mu_P \text{ (cP)} = \theta_{600} - \theta_{300} \quad (1)$$

$$\mu_a \text{ (cP)} = \theta_{600}/2 \quad (2)$$

where θ_{600} and θ_{300} are the viscometer dial readings at 600 rpm and 300 rpm, respectively. The yield point, expressed in lb/100 ft², was calculated using

$$YP = \theta_{300} - \mu_P \quad (3)$$

Gel strength was measured after allowing each mud sample to remain static for 10 s and 10 min. After each static period, the maximum dial deflection required to break the gel structure was recorded as the initial gel strength and final gel strength, respectively. Gel strength is an important parameter because it indicates the ability of the drilling fluid to suspend drill cuttings when circulation is stopped and to maintain wellbore stability. Further analysis of the drilling fluids' rheological behavior was performed to assess shear-thinning characteristics, which are critical for efficient cutting transport and optimal pumping performance during drilling [22].

Further rheological analysis was performed to assess the shear-thinning behavior of the formulated drilling fluids. This behavior is important during drilling because the fluid should provide sufficient viscosity at low shear rates to suspend and transport cuttings, while maintaining lower viscosity at high shear rates to reduce pumping resistance. All rheological measurements were performed twice, and the reported values represent the average of three independent measurements [32].

2.5. Filtration and Filter Cake Measurement

The filtration behavior of the drilling fluid samples was evaluated using API filter-press tests in accordance with API RP 13B-1. LPLT filtration tests were conducted at 100 psi and 25 °C for 30 min. HPHT filtration tests were conducted at 1500 psi and 70 °C for 30 min. For each test, the drilling fluid sample was placed in the filter-press cell, and pressure was applied under the selected test condition. The filtrate was collected in a graduated cylinder, and the filtrate volume was recorded at 5 min intervals over the 30 min test period. The total filtrate volume after 30 min was reported as the fluid-loss value. After completion of the filtration test, the filter cake formed on the filter paper was carefully removed. Excess surface fluid was gently removed without disturbing the filter cake structure, and the filter-cake thickness was measured using a Vernier caliper. Lower filtrate volume and thinner filter-cake thickness were considered indicators of improved filtration-control performance, as they suggest reduced fluid invasion and the formation of a denser, less permeable filter cake. All filtration and filter-cake measurements were performed twice, and the average values were reported. Repeat testing was used to confirm the reliability and repeatability of the measured filtration performance.

3. Results and Discussion

3.1. Characterization of Rice and Bread Waste Powders

3.1.1. EDX and SEM Analysis

The EDX analysis was carried out to determine the elemental composition of the bread and rice waste powders. The results are presented in Table 3. Both materials were mainly composed of carbon and oxygen, which is expected for starch- and carbohydrate-based food-waste materials. For the bread powder, carbon and oxygen were detected in

the ranges of 55.29–55.48 wt% and 42.43–42.90 wt%, respectively. For the rice powder, carbon and oxygen were detected in the ranges of 55.80–56.87 wt% and 42.63–43.67 wt%, respectively. The dominance of carbon and oxygen confirms the organic and carbohydrate-rich nature of both waste powders. This is important for drilling-fluid performance because oxygen-containing groups can contribute to water interaction and hydrogen bonding with bentonite particles, which may influence viscosity, yield point, gel strength, and filter-cake formation. Minor elements, including sodium, phosphorus, sulfur, chlorine, potassium, and copper, were also detected. These elements were present in small quantities and may originate from the natural composition of the food materials, processing history, or residual mineral content. A comparison between the two additives shows that rice powder contained slightly higher carbon content and similar oxygen content compared with bread powder. Bread powder showed slightly higher levels of sodium, chlorine, and potassium, which may be related to salt and other ingredients used during bread preparation. The relatively simple carbon–oxygen-dominated composition of rice powder, together with its particle morphology, may help explain its better filtration-control performance compared with bread powder. In particular, the oxygen-rich surface may support interaction with the aqueous bentonite system, while the fine rice particles contribute to denser filter-cake packing and reduce filtrate invasion. Overall, the EDX results support the interpretation that both rice and bread waste powders are organic, oxygen-rich materials capable of interacting with the water-based mud system. However, the slightly different elemental composition of rice and bread may contribute to their different rheological and filtration behavior.

Table 3. EDX elemental composition of bread and rice waste powders.

Sample	C	O	Na	P	S	Cl	K	Cu	Total
Bread	55.48	42.43	0.55	0.16	0.17	0.73	0.33	0.15	100
Bread	55.29	42.66	0.50	0.14	0.20	0.70	0.34	0.17	100
Bread	55.35	42.90	0.36	0.17	0.14	0.71	0.30	0.07	100
Rice	56.22	43.35	0.00	0.10	0.13	0.00	0.13	0.07	100
Rice	55.80	43.67	0.03	0.08	0.12	0.01	0.13	0.17	100
Rice	56.87	42.63	0.04	0.10	0.11	0.01	0.09	0.15	100

SEM analysis was used to examine the morphology of the prepared rice and bread waste powders, as shown in Figure 4a,b. The SEM micrographs reveal clear differences between the two materials, which are related to their composition and processing history. The rice powder mainly consisted of fragmented and granular starch particles with relatively sharp edges and a compact structure. These particles appeared more brittle and grain-like, with smaller particles distributed across the sample. This morphology is beneficial for drilling-fluid performance because fine rice particles can fill void spaces within the bentonite matrix, improve particle packing, and contribute to the formation of a denser and less permeable filter cake. In contrast, the bread powder showed a more irregular, rough, and partly agglomerated morphology. Its structure was more porous and sponge-like, which is likely related to fermentation, baking, starch gelatinization, and the formation of a gluten/protein network. The presence of pores, broken crumb structures, and agglomerated particles may reduce uniform packing within the filter cake. Therefore, the SEM observations help explain why the rice-based formulations, particularly at smaller particle size and higher concentration, showed better fluid-loss reduction and filter-cake control than the bread-based formulations.

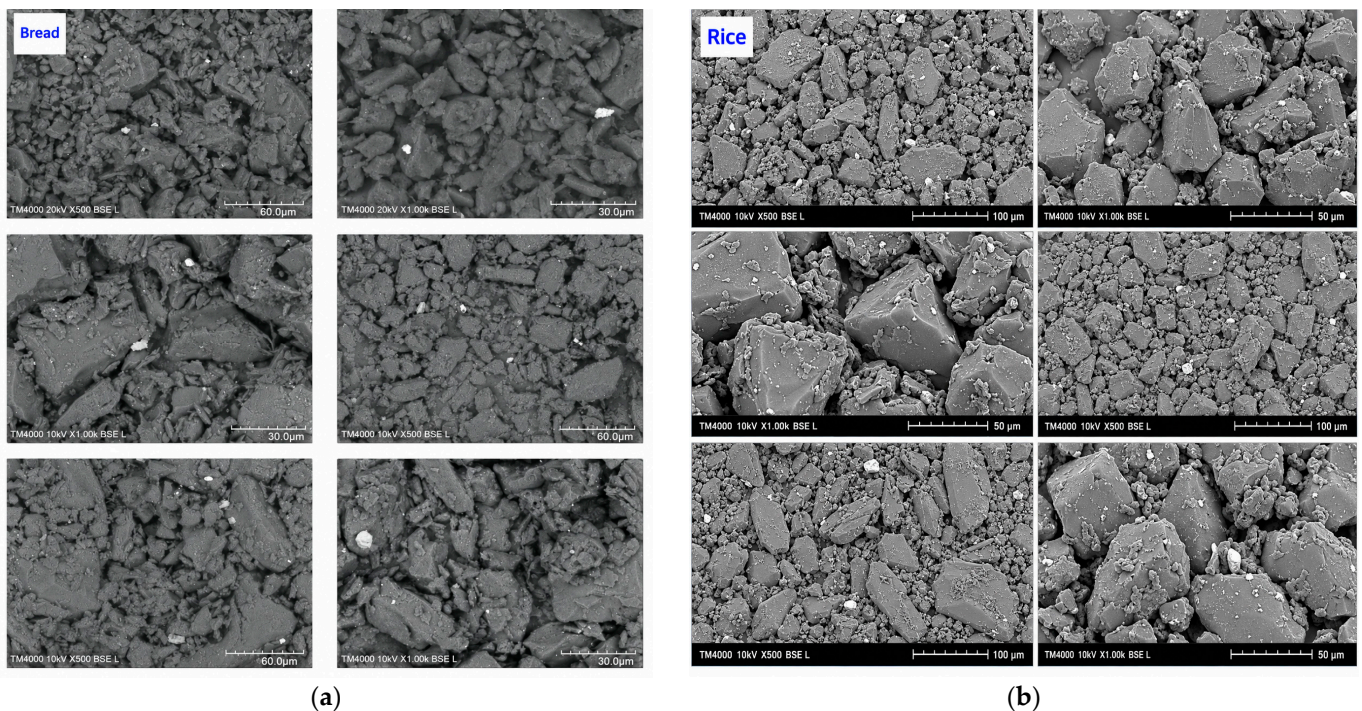


Figure 4. SEM micrographs of bread powder (a) and rice powder (b) waste particles prepared at different particle sizes. The images show the differences in particle morphology, surface roughness, and particle distribution between the two additives.

3.1.2. Fourier Transform Infrared Spectroscopy (FTIR)

Based on the FTIR spectra obtained for bread and rice samples (Figure 5a,b), the characteristic functional groups associated with starch-based foods can be identified. On both spectra, there is a broad absorption band around 3300 cm^{-1} , consistent with O–H stretching vibrations. Typically, this occurs when polysaccharides and moisture are retained within the samples. There is a small peak at 2900 cm^{-1} that can be attributed to the stretching of aliphatic groups found in carbohydrate structures. There are significant differences between the two samples in the $1600\text{--}1700\text{ cm}^{-1}$ region. The bread spectrum exhibits a clearer and more intense absorption band in this region. This band is likely attributable to amide I vibrations associated with proteins, particularly gluten. Rice, on the other hand, exhibits a weaker response, which is consistent with the fact that rice contains a relatively low amount of protein. There are prominent features in both spectra in the $1000\text{--}1200\text{ cm}^{-1}$ fingerprint region. A starch molecule's C–O and C–C stretching vibrations are reflected in this formula. However, the bread sample displayed a slightly more complex pattern in this region, likely due to structural changes in starch granules during baking (e.g., gelatinization and retrogradation). In general, the FTIR results indicate that both bread and rice particles are dominated by carbohydrate-based functional groups, while variations in the amide region and fingerprint complexity are due to differences in protein content and processing history. Strong absorption in the fingerprint region at 1000 cm^{-1} is a complex structure. A more defined and intense peak shape than in (a), indicating more purity or crystallinity.

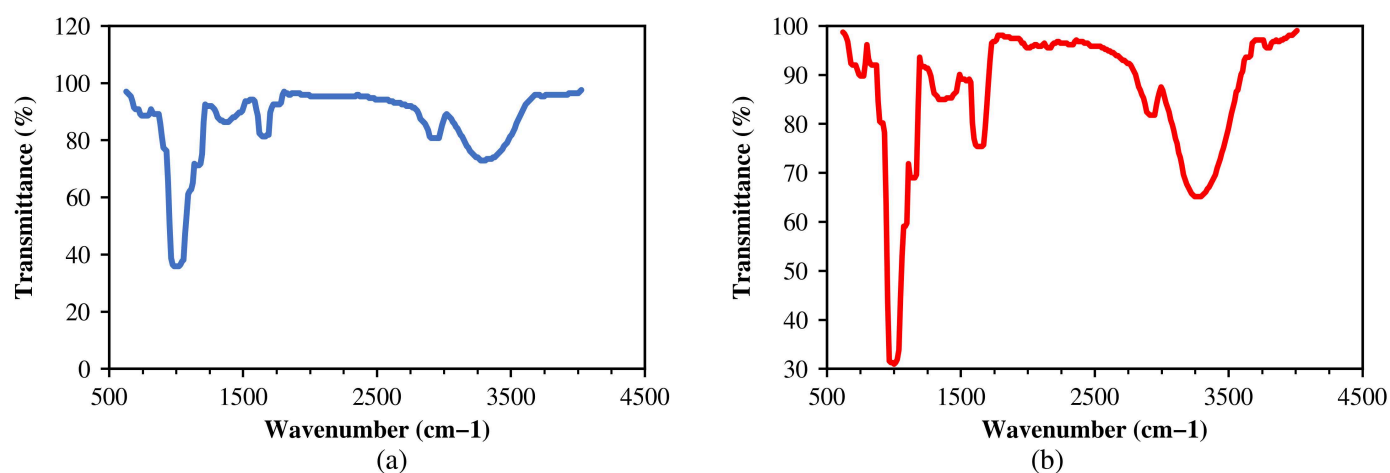


Figure 5. FTIR spectra of bread and rice waste powders showing the main functional groups associated with hydroxyl, aliphatic, amide, and carbohydrate structures.

The spectra were analyzed to identify the main functional groups present in the two starch-based waste materials. Both samples showed a broad absorption band around 3300 cm^{-1} , which is associated with O–H stretching vibrations. This indicates the presence of hydroxyl groups from polysaccharides and retained moisture within the samples. These hydroxyl groups are important because they can promote water retention and hydrogen bonding with bentonite particles in the water-based drilling fluid system. A smaller absorption band was observed around 2900 cm^{-1} , corresponding to C–H stretching vibrations from aliphatic groups in carbohydrate structures. Both bread and rice powders also showed strong absorption bands in the $1000\text{--}1200\text{ cm}^{-1}$ fingerprint region, which are associated with C–O and C–C stretching vibrations in starch-based materials. These results confirm that both additives are mainly carbohydrate-rich organic materials. Some differences were observed between the bread and rice spectra. The bread powder showed a more pronounced absorption band in the $1600\text{--}1700\text{ cm}^{-1}$ region, which may be related to amide vibrations from protein content, particularly gluten. The bread sample also showed a more complex fingerprint region, likely due to starch gelatinization and retrogradation during baking. In comparison, the rice powder showed a simpler carbohydrate-dominated spectrum, which is consistent with its relatively lower protein content and less-processed structure. A comparison of the two graphs shows that the wavenumber on (a) increases from left to right, while on (b) it is reversed. The transmittance scale (a) reaches 120%, while (b) reaches 100%. Depending on the baseline noise level, it is possible that (b) displays sharper, deeper peaks. Both spectrums indicate O–H and C–H stretches, but (b) displays higher fingerprint peaks, which suggest additional functional groups (such as carbonyl). To investigate the mechanism of extraction, FTIR spectroscopy was employed to investigate electrostatic interaction, hydrophobic interaction, and hydrogen-bonding interaction.

The FTIR results help explain the rheological behavior of the modified drilling fluids. The presence of hydroxyl and carbohydrate-related functional groups can increase particle–water and particle–bentonite interactions through hydrogen bonding. These interactions may contribute to the observed changes in viscosity, yield point, and gel strength after the addition of rice and bread waste powders. Therefore, the FTIR analysis supports the interpretation that both additives can interact with the aqueous bentonite-based mud system, while the differences in their functional groups and processing history may partly explain their different drilling-fluid performance.

3.2. Relationship Between Shear Rate, Viscosity, and Shear Stress

Before discussing the rheological behavior of the formulated WBDFs, the characterization results should be considered because the chemical functionality and microstructure of the rice and bread waste powders may influence their interaction with the bentonite-based mud system. The FTIR results indicated the presence of hydroxyl and carbohydrate-related functional groups, which may promote water retention and hydrogen bonding between the waste particles, water, and bentonite. This can contribute to the changes observed in viscosity, yield point, and gel strength after the addition of rice and bread powders. In addition, the SEM and EDX results suggest that differences in particle morphology and elemental composition may affect particle interaction and structural stability within the mud. Therefore, the rheological trends discussed in this section are considered together with the material characteristics of the additives [23,24].

The performance of drilling fluid can be greatly influenced by the shear stress and shear rate it experiences. The use of bentonite in drilling fluids is a result of its special properties due to its charge. A structure is created when these charged particles stick together. As soon as the pressure or force is applied, it cannot prevent the structure from breaking apart, and the fluid ceases to flow. This specific level of pressure or force at which the fluid stops moving is known as the yield stress of the fluid [25]. For base mud, viscosity increases with decreasing shear rate, from 9.99 cP at a shear rate of 1021.38 s⁻¹ to 27.59 cP at 170.23 s⁻¹. According to the observed decrease in viscosity with increasing shear rate, the drilling fluid exhibits pseudoplastic (non-Newtonian) behavior. Drilling operations benefit from this characteristic because it facilitates cutting transport at low shear rates while reducing pumping resistance at high shear rates. This behavior is typical for non-Newtonian fluids used in drilling operations, where viscosity increases as the shear rate decreases to the surface and maintains hole cleaning. This finding is in line with [16], showing that wheat particles can enhance the viscosity and yield stress of drilling fluids, improving their ability to suspend and transport cuttings.

The effects of shear rate and shear stress on drilling fluid performance are critical. As drilling fluids are subjected to shear stress, their viscosity may significantly drop, affecting their ability to transport drill cuttings and provide necessary lubrication to drill bits [3]. A decrease in fluid viscosity may impair the fluid's ability to convey drill cuttings to the wellbore's surface, potentially resulting in cuttings collection and obstructions. Furthermore, low-viscosity fluids' lower lubrication might increase drill bit wear and damage, thereby influencing drilling operations [3]. To assess experimental data relating to shear stress, viscosity, and shear rate, the techniques provided in [19] are followed, with the Fann 35 viscometer. According to API guidelines, the apparent viscosity, shear rate, and shear stress are determined using the equations below:

$$\mu_a = (\text{shear stress})/(\text{shear rate}) \times 100 = \tau/\gamma \times 100 \quad (4)$$

$$\text{Shear rate} = K_1 N \quad (5)$$

where K_1 is the shear rate constant of 1.7023 S⁻¹, and N is the viscometer speed in rpm. The shear stress can be determined using

$$\text{Shear stress} = K_2 K_3 \theta \quad (6)$$

According to the shear rate, shear stress, and apparent viscosity, 18 experiments were made for two samples of rice and bread, including RC150-1, RC150-2, RC150-3, RC75-1, RC75-2, RC75-3, RC45-1, RC45-2, RC45-3, BD150-1, BD150-2, BD150-3, BD75-1, BD75-2, BD75-3, BD45-1, BD45-2, and BD45-3. In this study, indices one, two, and three indicate the

levels of weight concentration of the added material. Based on a weight-by-weight analysis, these levels correspond to 1%, 2%, and 3% of the total sample. By adding BD150-1 to the base mud, the shear rate increases from 46 cP for $\Theta 3$ to a maximum of 163cP for $\Theta 600$. For the BD45-3, the viscosity becomes 40 cP for $\Theta 3$ and 120 cP for $\Theta 600$, respectively. Overall, the highest shear rate occurs at 178 cP when B150-3 is added to the bread sample for $\Theta 600$, and the lowest rate of 33.19 occurs in BD45-1. The highest viscosity occurs when adding BD15-3 to the base mud, increasing to 178 cP for $\Theta 600$. The lowest point of 33 cP appears at the addition of B45-1 at $\Theta 3$. For the rice sample, by adding R150-1 to the base mud, the shear rate increases from 12 cP for $\Theta 3$ to a maximum of 107 cP for $\Theta 600$. It is a lot lower than the result of the bread sample for the same amount of additive and the same processes. For the RC45-3, the viscosity becomes 30 for $\Theta 3$ and 209 cP for $\Theta 600$, respectively. Overall, the highest shear rate occurs at 209 cP when adding RC45-3 to the rice sample for $\Theta 600$, and the lowest rate of 33.19 occurs in BD45-1. The highest viscosity occurs when adding BD15-3 to the base mud, increasing to 178 cP for $\Theta 600$. The lowest point of 12 cP appears at the addition of B150-1 at $\Theta 3$.

For the appearance viscosity, the base mud has 399, 234, 27, 18, 15, and 9 for $\Theta 3$, $\Theta 6$, $\Theta 100$, $\Theta 200$, $\Theta 300$, and $\Theta 600$. The numbers are inversely proportional to Θ values according to the calculation in the formula for viscosity. By adding BD150-1 to the base mud, the base mud's viscosity increases from 899 for $\Theta 3$ to a minimum of 16 for $\Theta 600$. For the BD45-3, the viscosity becomes 783 for $\Theta 3$ and 11 for $\Theta 600$, respectively. Overall, the highest viscosity of 1199 occurs in adding BD75-3 for the bread sample for $\Theta 3$, and the lowest of 10 in BD45-1. For the rice sample, by adding R150-1 to the base mud, the viscosity decreases from 400 to 250 for $\Theta 3$ compared to the mud sample, and gets nearly the same result of around 10 when adding for $\Theta 600$. It shows there is no formal trend for the increasing and decreasing of the apparent test for the samples. For the RC45-3, the viscosity increases to 783 for $\Theta 3$ and 11 for $\Theta 600$, respectively. Overall, the highest shear rate occurs in 1199 when adding RC75-3 for the rice sample for $\Theta 3$, and the lowest is 9.7 in BD45-1. If we compare both rice and bread samples, the highest viscosity occurs when RC45-1 is added at $\Theta 3$, and the lowest one occurs when BD45-1 is added at $\Theta 600$. Notably, it shows the highest increase in viscosity with the decrease in shear rate, suggesting a superior thickening effect at lower shear rates.

Figures 6 and 7 demonstrate that the shear response of both bread- and rice-based samples increased as the applied shear rate/ x -axis value increased from 0 to 1100. In the bread-based samples, most particle size–concentration combinations increased from approximately 0–50 at the initial stage to around 150–200 at the highest shear-rate point. The lower-concentration samples generally ended closer to 100–130, while the higher-concentration modified samples clustered around 150–180. A similar trend was observed for the rice-based samples, although the increase was more pronounced, with several curves reaching approximately 180–220 at the highest shear-rate value. This was particularly evident at 3% concentration, where the rice samples showed a stronger shear response than the corresponding 1% and 2% formulations [26,27].

The BM sample showed the lowest shear response in both graphs, reaching approximately 80–120, but it still followed an increasing trend with shear rate. Overall, the rice-based formulations showed slightly higher final shear values than the bread-based formulations, suggesting a stronger resistance to increasing shear forces. These results indicate that the tested formulations behave as non-Newtonian shear-dependent fluids, with the modified samples showing enhanced shear resistance compared with the base material. The stronger response at higher concentrations suggests that particle concentration contributes to the development of a more resistant internal structure under applied shear [32].

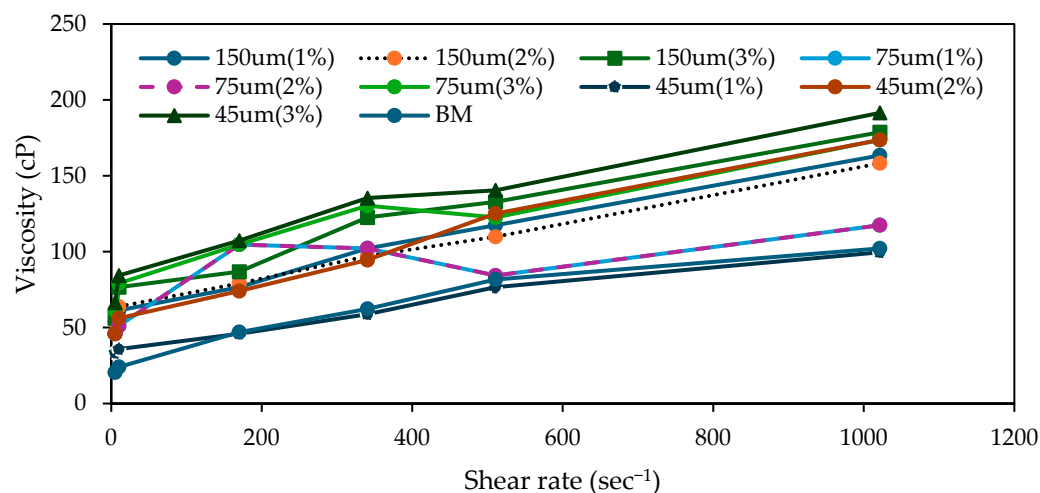


Figure 6. The shear rate calculation results for the bread sample for the different particle sizes (150, 75, and 45 μm for 1%, 2%, and 3%).

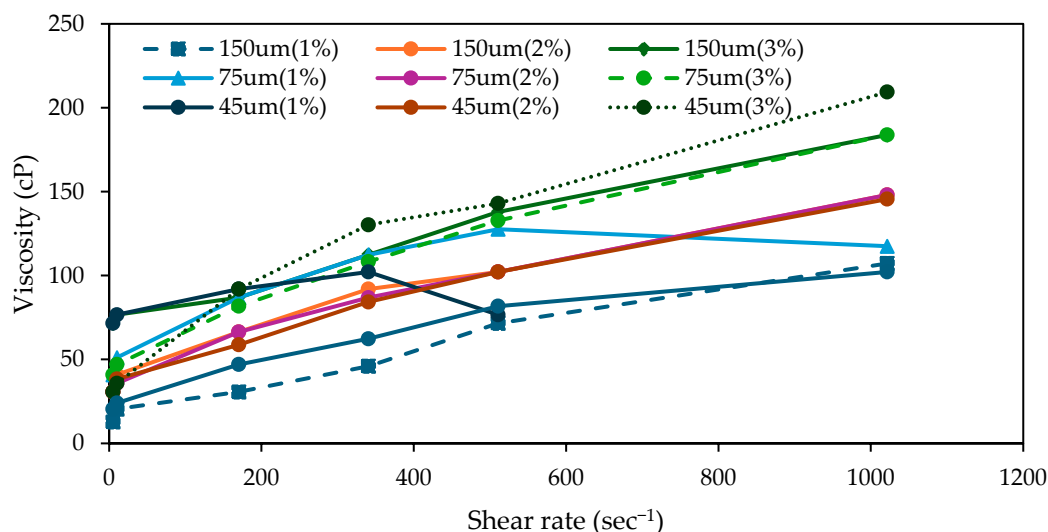


Figure 7. The shear rate calculation results for the rice sample for the different particle sizes (150, 75, and 45 μm for 1%, 2%, and 3%).

3.3. Rheological Property

The impact of adding the bio-based bread and rice waste particles on rheological properties and gel strength of WBDF is experimentally investigated and shown in Figure 8a–c. Viscosity of the drilling mud, which represents the ability of the mud to flow, is a critical parameter that needs to be tested. Two types of apparent and plastic viscosity are measured and presented in this section. The apparent viscosity represents the viscosity of the mud at the specified shear rate. On the other hand, the number of solid contents in the mud is determined by the plastic viscosity. The WDBM or base mud (BD) sets a baseline with a plastic viscosity of 4 cP, an apparent viscosity of 10 cP, and a yield point of 12 lb/100 ft². The gel strength rises from 7 lb/100 ft² at 10 s to 15 lb/100 ft² after 10 min. Adding 1% of 150 μm rice particles changes the plastic viscosity to 7 cP, apparent viscosity and yield point to 10.5 cP and 7/100 ft², respectively, and the minimum and maximum gel strength become 9 lb/100 ft² at 10 s and 28 lb/100 ft² at 10 min. And for the addition of 3% of 45 μm rice particles, the plastic viscosity is 13 cP, apparent viscosity and yield point are 20.5 cP and 15/100 ft², respectively; also, the minimum and maximum gel strength become 7 lb/100 ft² at 10 s and 19 lb/100 ft² at 10 min. For the bread sample testing, mixing 1% of 150 μm rice particles changes the plastic viscosity to 9 cP, apparent viscosity

and yield point to 16 cP and 14/100 ft², respectively; also, the minimum and maximum gel strength become 13 lb/100 ft² at 10 s and 34 lb/100 ft² at 10 min. For 3% of 45 µm of bread particles, the plastic viscosity is 10 cP, the apparent viscosity and yield point are 18.75 cP and 17.5/100 ft², respectively, and the minimum and maximum gel strength become 17 lb/100 ft² at 10 s and 38.5 lb/100 ft² at 10 min. According to the 18 experiments for two samples for three sizes (45, 75, and 150 µm for 1%, 2%, and 3%), the best result is achieved by adding the rice sample of size RC45-3 to the formal mud sample. Supporting these findings, the recent literature on biodegradable materials as drilling mud additives aligns with the observed improvements. Ref. [28] reports that Cupressus cones powder enhances the plastic viscosity, yield point, and gel strength, which supports the beneficial impact of vegetable-based additives. These improvements with the broader research trend support the use of biodegradable additives for their environmental benefits and ability to enhance drilling fluid performance. Such materials can provide an environmentally friendly alternative to conventional additives, often associated with higher toxicity and disposal issues. The use of biodegradable additives not only aligns with the increasing environmental regulations but also offers potential cost savings and improved biocompatibility in drilling operations. There was a similar trend in rheological properties, where an increase in additive concentration and a decrease in particle size were associated with an improvement in viscosity, yield point, and gel strength.

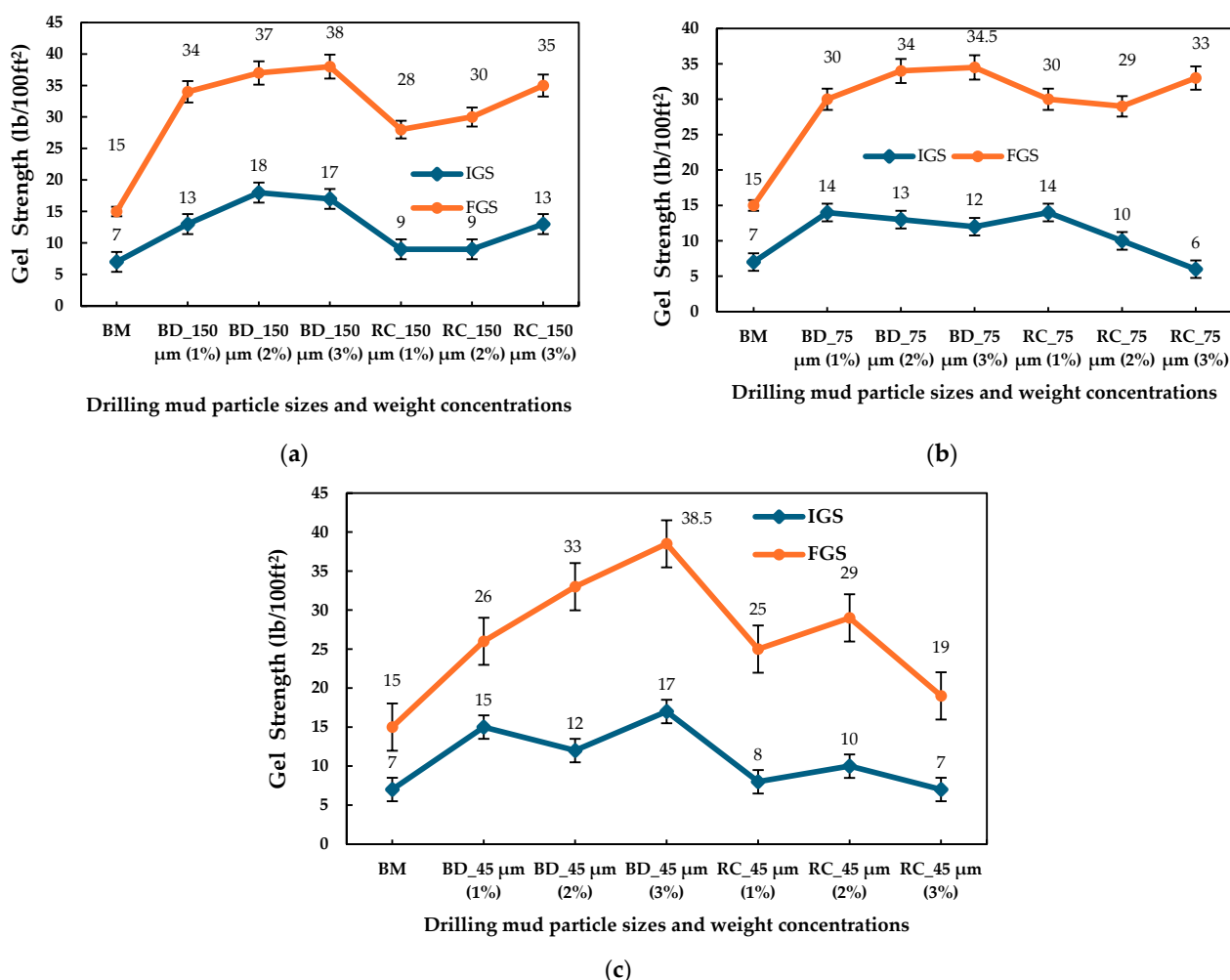


Figure 8. Initial (blue) and final (orange) values of gel strengths for BM and biodegradable drilling fluids prepared by adding bread and rice at various concentrations and sizes: (a) fine (150 µm), (b) very fine (75 µm), and (c) ultrafine (45 µm).

As shown in Table 4, the viscosity of the bread-powder-based mud formulations varied with particle size, additive concentration, and rotational speed. In general, increasing the additive concentration from 1 wt% to 3 wt% increased the dial readings, indicating stronger particle interaction within the mud system. The highest viscosity values for the bread-based formulations were observed at higher additive concentration, particularly for the 45 μm and 75 μm samples. This suggests that both concentration and particle size influence the rheological response of the modified WBDFs.

Table 4. Rheological results for bread-based WBDF formulations at different particle sizes and concentrations.

Particle Size (μm)	Viscosity (cP)								
	150			75			45		
	Weight Fraction			Weight Fraction			Weight Fraction		
RPM (Shear Rate)	1%	2%	3%	1%	2%	3%	1%	2%	3%
③3	9	10.5	11	9	12	12	6.5	9	13
③6	12	12.5	15	10	15.5	15.5	7	11	16.5
③100	15	15.5	17	20.5	20.5	20.5	9	14.5	21
③200	20	19	24	20	25.5	25.5	11.5	18.5	26.5
③300	23	21.5	26	16.5	24	24	15	24.5	27.5
③600	32	31	35	23	34	34	19.5	34	37.5

Figure 8 also presents the initial gel strength (IGS) and final gel strength (FGS) of the biodegradable drilling fluids prepared with bread and rice waste powders at different concentrations and particle sizes. In all cases, the FGS values were higher than the corresponding IGS values, indicating that the formulated muds developed stronger gel structures after static aging. Figure 8a shows the results for the 150 μm particle size. The FGS values increased with additive concentration and reached a maximum value of 38 lb/100 ft² for BD_150 μm at 2 wt%, before slightly decreasing at 3 wt%. The IGS values varied between 7 and 18 lb/100 ft². Figure 8b presents the results for the 75 μm particle size. The FGS values showed a moderate variation, with the highest value of 34.5 lb/100 ft² recorded for BD_75 μm at 2 wt%. The IGS values were within a similar range to those observed for the 150 μm samples, varying from 6 to 14 lb/100 ft². Figure 8c shows the results for the 45 μm particle size. The highest FGS value was 38.5 lb/100 ft² for BD_45 μm at 3 wt%, while the IGS values remained comparatively lower, ranging from 5 to 17 lb/100 ft². The results show that the final gel strength was consistently higher than the initial gel strength for all formulations. This indicates improved particle interaction and gel-structure development in the modified drilling fluids, which can enhance suspension capacity and help maintain drill cuttings in suspension when circulation is stopped.

There is a consistent difference between FGS and IGS across all cases, which indicates that the strength of the gel increases over time. In general, smaller particle sizes (45 μm) and higher concentrations (3%) produce the strongest FGS values, which suggests that smaller particles and higher levels of additives are essential to enhancing gel strength. As per Figure 8, the presence of smaller particles and higher concentrations of additives enhances the gel strength, and the final gel strength (FGS) consistently exceeds the initial gel strength (IGS), indicating that finer additives and increased dosage enhance drilling fluid stability.

SEM analysis (Figure 4) supports the better performance of rice powder compared with bread powder. Rice particles showed a more fragmented and granular structure with a wider distribution of smaller particles, allowing them to fill voids within the bentonite filter cake and produce a denser, less permeable sealing layer. In contrast, bread particles

were more irregular, rough, and partly agglomerated, which may reduce uniform packing and weaken filter-cake compaction. This explains why the RC45-3 formulation produced the lowest fluid loss and thinnest filter cake among all formulations [29].

Figure 9 shows that the addition of bread and rice waste powders influenced the rheological behavior of the water-based drilling fluids, with changes depending on particle size and additive concentration. In general, both apparent viscosity (μ_a) and plastic viscosity (μ_p) increased compared with the base mud, indicating improved solids interaction and better carrying capacity. The yield point (YP) also increased for several formulations, particularly at higher additive concentrations, suggesting improved ability of the mud to suspend and transport drilled cuttings under low-shear conditions. This is important in drilling operations because a suitable increase in viscosity and yield point can improve hole cleaning, reduce cuttings accumulation, and support wellbore stability.

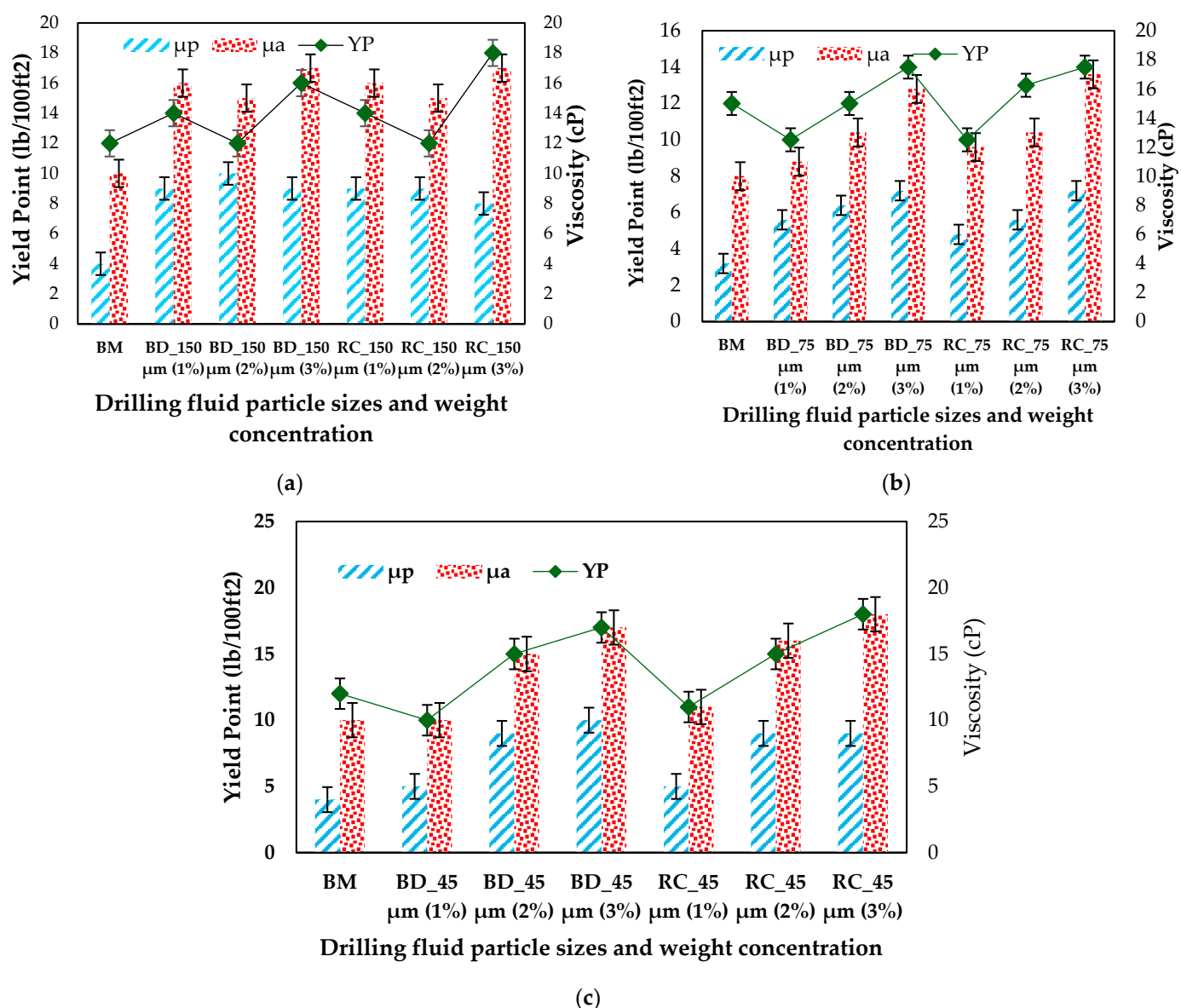


Figure 9. The results of apparent viscosity (μ_a), yield point (YP), and plastic viscosity (μ_p) for the BM and drilling fluids prepared with bread and rice at various concentrations and sizes: (a) medium (150 μ m), (b) very fine (75 μ m), and (c) ultrafine (45 μ m).

The effect was more noticeable for the finer particle sizes, especially the 45 μm formulations shown in Figure 9c. At this particle size, both bread- and rice-based additives produced higher viscosity and YP values than the base mud, with the rice-based formulation at 45 μm and 3 wt% showing one of the most favorable rheological responses. This behavior can be attributed to the ability of finer particles to disperse more effectively within the bentonite-based mud and increase particle–particle interactions. The starch-rich composition and compact morphology of rice powder may further enhance gel-structure development and improve the suspension capacity of the fluid. Therefore, the rheological results support the filtration findings by showing that the optimum rice-based formulation not only reduces fluid loss but also provides suitable viscosity and yield point values for cuttings transport and drilling-fluid stability. However, the viscosity increase remains moderate, which is important because excessively high viscosity could increase pumping pressure and reduce hydraulic efficiency [30].

Figure 10 illustrates the density measurement of drilling fluids using various biodegradable materials. Among the samples, rice exhibits the highest density at nine, followed closely by BM at 8.5, indicating that rice-based muds can match or slightly exceed conventional formulations.

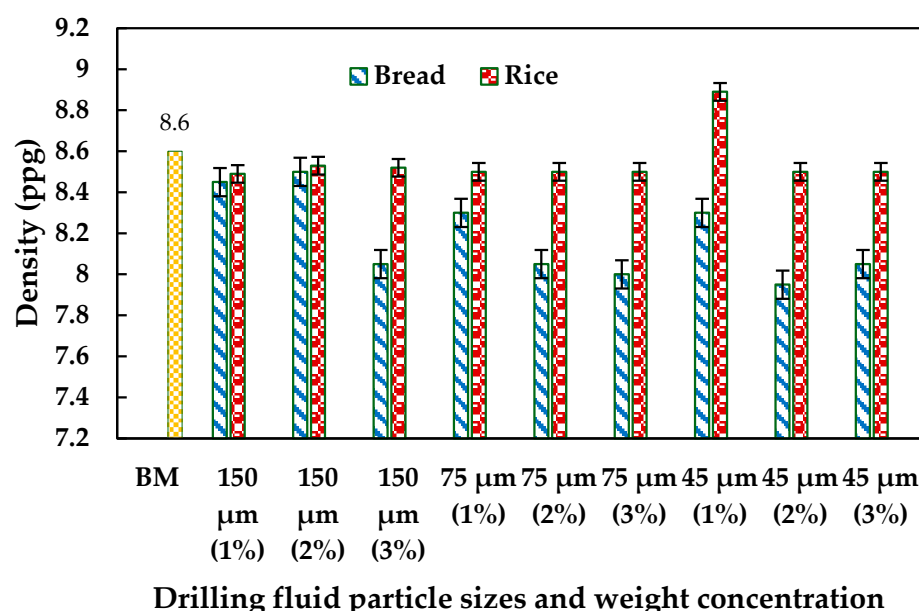


Figure 10. The density measurement comparison for the bread and rice samples for the different particle sizes (150, 75, and 45 μm for 1%, 2%, and 3%) vs. the base mud.

3.4. Filtration Property

The fluid-loss performance of the water-based drilling muds modified with bread and rice waste powders was evaluated after 30 min under both LPLT and HPHT conditions, as shown in Figures 11 and 12. The base mud exhibited the highest filtrate volume, with 19.5 mL under LPLT and 36.5 mL under HPHT, indicating poor fluid-loss control in the absence of biodegradable additives. The addition of both bread and rice waste powders reduced fluid loss, confirming their potential as filtration-control additives for water-based drilling fluids.

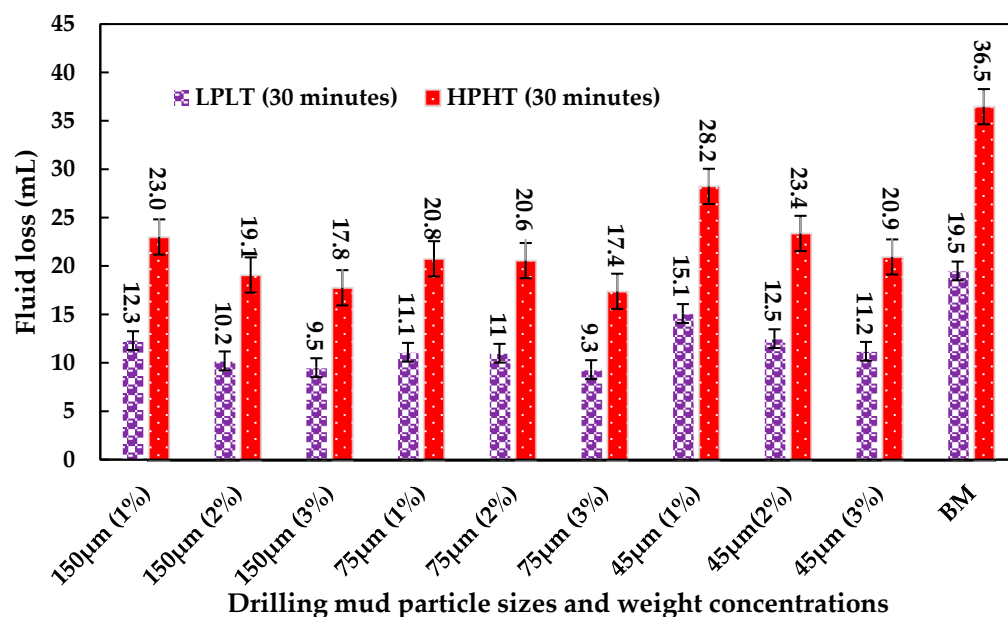


Figure 11. The fluid loss of the WBDM with added bread waste powder as an additive with various concentrations and particle sizes over 30 min period.

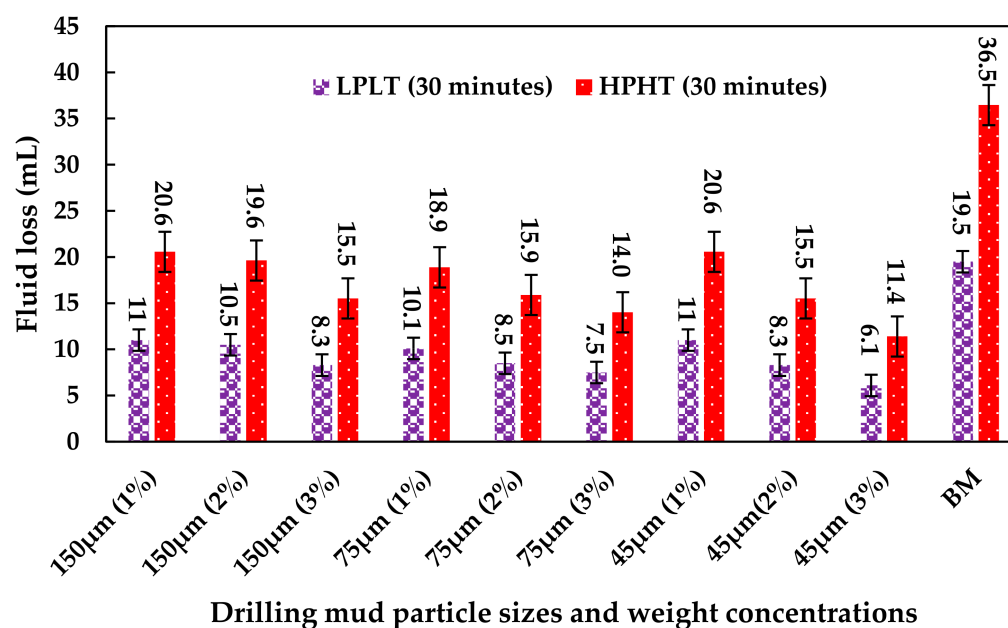


Figure 12. The fluid loss of the WBDM with added rice waste powder as an additive with various concentrations and particle sizes over 30 min period.

For the bread-based formulations, fluid loss generally decreased as the additive concentration increased from 1 wt% to 3 wt%, indicating improved filtration control at higher additive loading. At a particle size of 150 µm, the LPLT fluid loss decreased from 12.3 mL at 1 wt% to 9.5 mL at 3 wt%, while the HPHT fluid loss decreased from 23.0 mL to 17.8 mL over the same concentration range. A similar trend was observed for the 75 µm formulations. The best bread-based performance was achieved at 75 µm and 3 wt%, where fluid loss decreased to 9.3 mL under LPLT conditions and 17.4 mL under HPHT conditions. Compared with the base mud, these values correspond to fluid-loss reductions of approximately 52.3% under both test conditions. However, the 45 µm bread-based formulations did not follow the same improvement trend, particularly at lower concentrations. At 1 wt%, the 45 µm bread formulation showed fluid loss values of 15.1 mL under LPLT conditions and

28.2 mL under HPHT conditions, which were higher than those obtained for the 150 μm and 75 μm bread formulations at the same concentration. This suggests that excessive particle-size reduction did not necessarily improve the performance of bread powder. The lower effectiveness of the 45 μm bread samples may be associated with less uniform dispersion, possible particle agglomeration, or the more porous and irregular structure of bread particles. These factors could limit the formation of a compact, low-permeability filter cake and reduce the overall fluid-loss-control efficiency.

The rice-based formulations showed stronger and more consistent fluid loss reduction than the bread-based formulations. At 150 μm , the LPLT fluid loss decreased from 11.0 mL at 1 wt% to 8.3 mL at 3 wt%, while the HPHT fluid loss decreased from 20.6 mL to 15.5 mL. At 75 μm , fluid loss was further reduced to 7.5 mL under LPLT and 14.0 mL under HPHT at 3 wt%. The best overall performance was achieved by the rice formulation with 45 μm particle size and 3 wt% concentration, where fluid loss decreased to 6.1 mL under LPLT and 11.4 mL under HPHT. Compared with the base mud, this represents reductions of approximately 68.7% and 68.8%, respectively. These results indicate that rice powder, particularly at finer particle size and higher concentration, provides the most effective fluid-loss control among all tested formulations.

The systematic comparison of the results in Table 5 indicates that additive type, particle size, and concentration all influence filtration performance. Increasing concentration generally improved fluid-loss control because a greater amount of solid additive was available to participate in filter-cake formation. Rice-based additives outperformed bread-based additives at comparable concentrations, which may be related to the denser and more compact particle morphology of rice powder. Finer rice particles are more likely to fill void spaces within the bentonite filter cake, producing a denser and less permeable barrier that limits filtrate invasion. This interpretation is consistent with the SEM observations, which showed differences in the microstructure of rice and bread particles, and with the EDX results, which indicated oxygen-rich and mineral-containing components that may contribute to particle interaction and filter-cake stability. Therefore, the RC45-3 formulation can be considered the optimum formulation for fluid-loss reduction in this study.

In addition to fluid loss, the filter-cake thickness of the base mud and the formulated muds were measured, as shown in Figure 13. The base mud produced the thickest filter cake, approximately 5.0 mm, indicating poor filtration control and greater solid deposition in the absence of additives. In drilling operations, a thinner and compact filter cake is generally preferred because it reduces filtrate invasion into the formation and helps maintain wellbore stability.

The addition of both bread and rice waste powders significantly reduced filter-cake thickness compared with the base mud. For the bread-based formulations, the filter-cake thickness generally decreased with decreasing particle size and increasing additive concentration. At 150 μm , the filter-cake thickness decreased from 1.55 mm at 1 wt% to 1.31 mm at 3 wt%. At 75 μm , it decreased from 1.48 mm to 1.18 mm, while at 45 μm it decreased from 1.44 mm to 1.07 mm. The best bread-based result was therefore obtained at 45 μm and 3 wt%, showing that finer particles and higher concentration improved the sealing ability of the mud.

The rice-based formulations showed a stronger reduction in filter-cake thickness than the bread-based formulations. At 150 μm , the thickness decreased from 1.05 mm at 1 wt% to 0.97 mm at 3 wt%. At 75 μm , the values were further reduced, ranging from 0.85 mm to 0.81 mm. The best overall result was achieved with the rice formulation at 45 μm and 3 wt%, where the filter-cake thickness decreased to 0.52 mm. Compared with the base mud, this corresponds to an approximate reduction of 89.6%, calculated from 5.0 mm to 0.52 mm.

Table 5. Fluid-loss performance of WBDF formulations containing bread and rice waste powders at different particle sizes and concentrations under LPLT and HPHT conditions. The percentage reduction was calculated relative to the base mud fluid loss of 19.5 mL under LPLT and 36.5 mL under HPHT after 30 min.

Additive	LPLT Fluid Loss (mL)	LPLT Reduction (%)	HPHT Fluid Loss (mL)	HPHT Reduction (%)
BM	19.5	—	36.5	—
BD150-1	12.3	36.9	23.0	47.7
BD150-2	10.2	47.7	19.1	47.7
BD150-3	9.5	51.3	17.8	51.2
BD75-1	11.1	43.1	20.8	43.0
BD75-2	11.0	43.6	20.6	43.6
BD75-3	9.3	52.3	17.4	52.3
BD45-1	15.1	22.6	28.2	22.7
BD45-2	12.5	35.9	23.4	35.9
BD45-3	11.2	42.6	20.9	42.7
RC150-1	11.0	43.6	20.6	43.6
RC150-2	10.5	46.2	19.6	46.3
RC150-3	8.3	57.4	15.5	57.5
RC75-1	10.1	48.2	18.9	48.2
RC75-2	8.5	56.4	15.9	56.4
RC75-3	7.5	61.5	14.0	61.6
RC45-1	11.0	43.6	20.6	43.6
RC45-32	8.3	57.4	15.5	57.5
RC45-3	6.1	68.7	11.4	68.8

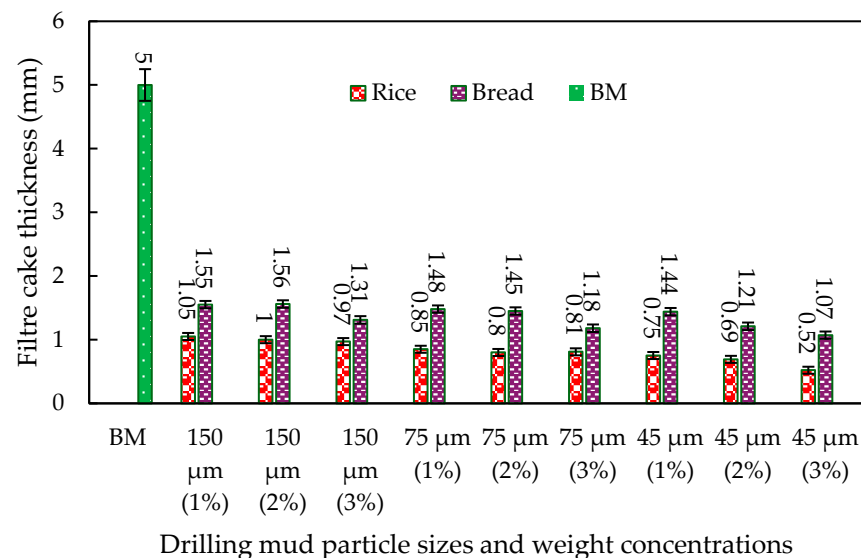


Figure 13. Mud thickness comparison for the bread and rice samples vs. base mud for the different particle sizes (150, 75, and 45 μm for 1%, 2%, and 3%).

The results show that rice waste powder was more effective than bread waste powder in producing a thinner filter cake across all particle sizes and concentrations. This improvement is likely due to the finer and more compact morphology of rice particles, which can fill the void spaces within the bentonite matrix and form a denser, less permeable

filter cake. The trend also agrees with the fluid-loss results, where the rice 45 μm –3 wt% formulation showed the lowest filtrate volume. Therefore, the combined fluid-loss and filter-cake-thickness results confirm that RC45-3 is the optimum formulation for improving the filtration performance of the water-based drilling fluid [31].

Table 6 compares the performance of the optimum formulation identified in the present study with selected natural, waste-derived, nanoparticle, and biopolymer additives reported in previous studies. The best-performing formulation in this study was rice waste powder with a particle size of 45 μm and a concentration of 3 wt% (RC45-3). This formulation reduced fluid loss by approximately 68.8% after 30 min and produced the thinnest filter cake among all tested formulations. Compared with the base mud, the filter-cake thickness decreased from 5.0 mm to 0.52 mm, corresponding to an approximate reduction of 89.6%. These results indicate that RC45-3 formed a compact, low-permeability filter cake, which effectively limited filtrate invasion. Compared with previously reported additives, including broad bean peel powder, potato peel powder, grass powder, pistachio shell powder, palm tree leaves powder, rice husk ash, wild jujube pit powder, CuO nanoparticles, and Rhizophora-based biopolymer, the RC45-3 formulation showed competitive or superior filtration-control performance [31]. Grass powder and wild jujube pit powder also showed notable reductions in fluid loss, while rice husk ash exhibited the lowest performance and was reported to increase filter-cake thickness.

Table 6. Comparison of the percentage reduction in fluid loss after 30 min and filter-cake thickness for the optimum rice-waste formulation in the present study and selected natural, waste-derived, nanoparticle, and biopolymer additives reported in the literature.

Material	Reduction in Fluid Loss After 30 min (%)	Reduction in Filter Cake Thickness (%)	Reference
Best-performed additive (very fine particle rice waste powder RC45-3)	68.8	89.6	Current study
Broad bean peel powder	31.86	28.57	[19]
Potato peel powder	30	40	[8]
Grass powder	42	33.33	[8]
Nanoparticle (CuO)	30.20	27.60	[20]
Pistachio Shell Powder	38.57	20.54	[21]
Palm Tree leaves powder	28	36.67	[22]
Rice husk ash	10	Increased	[23]
Wild Jujube Pit Powder (WJPP)	42.5	Not provided	[12]
Biopolymer (Rhizophora, Mucronate Tannin)	33.33	3.33	[24]

The improved filtration and rheological behavior can be explained by the combined effects of particle size, concentration, and material composition. Finer particles, particularly the 45 μm rice powder, can fill void spaces within the bentonite filter cake more effectively than larger particles, producing a denser and less permeable barrier. Increasing the additive concentration to 3 wt% provides more solid particles for pore filling and filter-cake compaction. In addition, the starch-rich and oxygen-containing composition of rice powder may promote particle interaction and gel-structure development, which helps explain the improved viscosity, yield point, gel strength, and fluid-loss control. Therefore, the superior performance of RC45-3 is attributed to the combined effect of fine particle size, compact morphology, and favorable chemical composition.

3.5. Mechanism of the Drilling Mud

Figure 14 illustrates the proposed mechanism of filter-cake formation on the borehole wall for the base mud and the mud systems containing rice and bread waste powders. In the base mud, the absence of an effective biodegradable sealing additive results in a relatively thick and more permeable filter cake. This allows a greater amount of filtration to pass into the formation, leading to higher fluid loss. When rice and bread waste powders are incorporated into the water-based drilling fluid, the solid particles participate in the formation of a denser sealing layer on the filter medium or borehole wall [18].

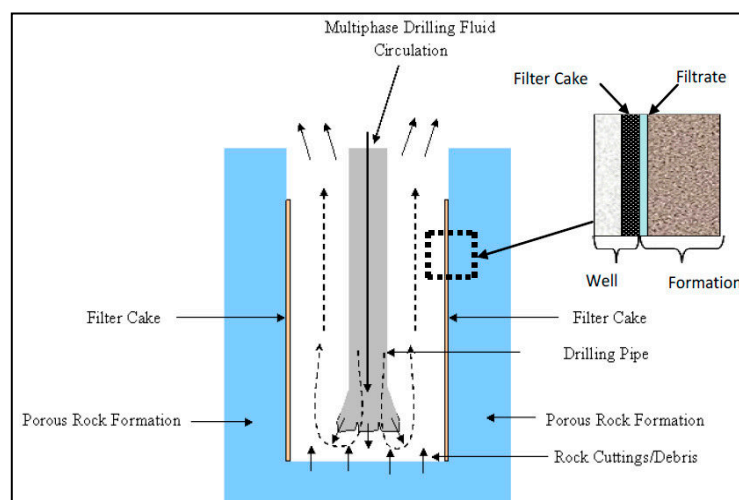


Figure 14. Proposed mechanism of filter-cake formation for base mud and water-based drilling fluids containing rice and bread waste powders at different particle sizes and concentrations.

The effectiveness of this sealing mechanism depends strongly on particle size and additive concentration. Larger particles, such as 150 μm , can contribute to initial bridging across pore spaces, but they may leave larger voids within the filter cake. In contrast, finer particles, particularly 45 μm , can more effectively fill the spaces between bentonite and larger additive particles. This improves particle packing, reduces pore connectivity, and decreases filter-cake permeability. As the additive concentration increases from 1 wt% to 3 wt%, more solid particles become available to build a compact barrier, which further reduces filtrate invasion.

The experimental results support this mechanism. The base mud produced the highest fluid loss and the thickest filter cake, whereas the rice- and bread-modified muds showed improved filtration control. Among all formulations, the rice waste powder at 45 μm and 3 wt% produced the lowest fluid loss and the thinnest filter cake. This suggests that fine rice particles were more effective at filling voids and forming a compact, low-permeability filter cake compared with bread particles. The improved performance of rice-based formulations may also be associated with their more compact particle morphology and starch-rich composition, which can enhance particle interaction and filter-cake stability [32].

Therefore, the proposed mechanism indicates that biodegradable food-waste additives improve water-based drilling-fluid performance by enhancing bridging, pore filling, and filter-cake compaction. The combined effect of smaller particle size and higher additive concentration produces a thinner, denser, and less permeable filter cake, thereby reducing fluid loss and improving wellbore stability.

Although rice and bread powders are food-waste-derived materials with potential sustainability advantages, their full environmental and field performance was not directly evaluated in this study. In particular, biodegradability, ecotoxicity, lubricity, shale-inhibition behavior, and salt/calcium tolerance were outside the scope of the present feasibility

investigation. Future work should include standard biodegradation testing, lubricity measurements, inhibition tests, and salt/calcium contamination studies to confirm the field applicability and environmental performance of these additives under more representative drilling conditions.

4. Conclusions

This study evaluated rice and bread waste powders as biodegradable additives for improving the filtration and rheological performance of water-based drilling fluids. Eighteen formulations were prepared using two waste materials, three particle sizes of 150 μm , 75 μm , and 45 μm , and three concentrations of 1 wt%, 2 wt%, and 3 wt%. The results showed that drilling-fluid performance was strongly influenced by additive type, particle size, and concentration.

The base mud showed the poorest filtration control, with fluid-loss values of 19.5 mL under LPLT conditions and 36.5 mL under HPHT conditions after 30 min. All rice- and bread-based formulations reduced fluid loss compared with the base mud, but rice powder showed more consistent and effective performance. The optimum formulation was rice powder at 45 μm and 3 wt% (RC45-3), which reduced LPLT fluid loss from 19.5 mL to 6.1 mL, corresponding to a 68.7% reduction. Under HPHT conditions, it reduced fluid loss from 36.5 mL to 11.4 mL, corresponding to a 68.8% reduction.

The filter-cake results followed the same trend. The base mud produced the thickest filter cake of approximately 5.0 mm, while RC45-3 produced the thinnest filter cake of 0.52 mm, representing an 89.6% reduction. This improvement is attributed to the ability of fine rice particles to fill voids within the bentonite filter cake and form a compact, low-permeability sealing layer. Bread powder also improved filtration performance, with the best bread-based formulation obtained at 75 μm and 3 wt%; however, its performance was less consistent, probably due to the more porous and irregular structure of bread particles. The rheological results also supported the suitability of rice powder as a drilling-fluid additive. The RC45-3 formulation maintained shear-thinning behavior and produced suitable gel strength values of 7 lb/100 ft² after 10 s and 19 lb/100 ft² after 10 min, indicating improved suspension capacity for carrying drill cuttings and maintaining wellbore stability.

Overall, rice waste powder at 45 μm and 3 wt% was identified as the most effective formulation under the laboratory conditions used in this study. However, this work should be considered a laboratory-scale feasibility investigation, as the experiments were conducted using a simplified water-based mud formulation under controlled LPLT and HPHT laboratory conditions. Therefore, the findings should not be directly generalized to field drilling operations without further validation. Future work should evaluate RC45-3 in field-representative mud systems containing conventional additives such as PAC-LV, lubricants, shale inhibitors, salts, and biocides. Further studies should also examine dynamic filtration, aging stability, biodegradation behavior, lubricity, shale inhibition, salt/calcium tolerance, and long-term HPHT performance before practical field application.

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Abbreviations

The following abbreviations are used in this manuscript:

WBDF	Water-based drilling fluid
BP	Bread powder
RP	Rice powder
HPHT	High pressure and high temperature
LPLT	Low pressure and low temperature
API	American Petroleum Institute
SEM	Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Spectroscopy
EDX	Energy-Dispersive X-ray Spectroscopy
RC	Rice powder
BD	Bread powder
C	Carbon
Na	Sodium
O	Oxygen
P	Phosphorous
K	Potassium
S	Sulfur
Ca	Calcium
Mg	Magnesium
Al	Aluminum
Si	Silicon
Cl	Chloride
Cu	Copper
µm	Micrometer
s	Second
min	Minute
wc%	Weight concentration percentage

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