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Feasibility study of biodegradable coffee ground waste and watermelon rind as water-based drilling fluid additives

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A R T I C L E I N F O

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A B S T R A C T

Addressing environmental concerns in extracting and producing hydrocarbon resources requires environmentally friendly water-based drilling fluid (WBDF) additives. These additives not only protect the environment but also offer operational benefits. One of the major challenges of WBDF is fluid loss into the formation and its degradability in high-temperature conditions, which induce cost, formation alteration and environmental pollution. This study explored the feasibility of wasted watermelon rind powder (WRP) and coffee ground waste powder (CGWP) as potential WBDF additives to regulate fluid loss and modify other rheological properties. WRP and CGWP were characterized using Energy Dispersive X-Ray (EDX) and Fourier Transform Infrared Spectroscopy (FTIR) tests. The thermal stability of the proposed additives was confirmed using a thermogravimetric analysis (TGA) test. Several experiments were conducted to investigate the impact of WRP and CGWP with different weight concentrations (wt.%) on the rheological and drilling fluid properties of conventional WBDF. The results show that at 3 wt%, the WRP improved the plastic viscosity by 75% and the CGWP increased the plastic viscosity by 100%. At the same time, the CGWP reduced the gel strength substantially, while WRP increased the gel strength. At an optimum 3 wt%, the CGWP reduced fluid loss by 53%, resulting in the thinnest filter cake thickness. These results demonstrate the potential use of the studied materials as multifunctional additives in drilling operations with WBDF.

1. Introduction

Hydrocarbon exploration and extraction activities have changed our world for good with the provision of energy for industrial use. However, these activities have adverse harmful environmental and health impacts on both the environment and humans (Antia et al., 2022; Orisakwe, 2021). Drilling fluid is a very important component of the oil industry and plays a vital role in the success or failure of drilling hydrocarbon reserves. The drilling fluid provides sufficient subsurface formation pressure, carries cuttings of rock to the surface, preserves borehole stability, mitigates damage to the productive zone and lubricates the drills during the drilling operation (Caenn and Chillingar, 1996). Abandoned drilling fluid is one of the largest sources of waste in the oil industry (Yang et al., 2023). Drilling fluid contains many chemicals-based additives that become pollutants during drilling. One of the significant challenges during the drilling operation is the loss of drilling fluid into the formation (Minakov et al., 2019). The loss of drilling fluid can affect the permeability, damage the formation, and contaminate groundwater reserves (Mehmood et al., 2016b). There are typically two types of drilling muds in the industry, including oil-based and water-based. In oil-based mud (OBM), mineral or low-toxicity oil is in a continuous phase. Due to the continuous phase of oil in OBM, they exhibit excellent penetration rate, shale inhibition, well-bore stability, high thermal stability, lubricity and high salt tolerance (Caenn et al., 2011). Despite many advantages of OBM environmental considerations restrain their usage in the industry (Amani et al., 2012). Therefore, the water-based drilling fluid (WBDFs) gained popularity due to lower cost of preparation and inherited environmentally friendly characteristics in compare to OBM (Kania et al., 2015). WBDF consists of an aqueous phase (e.g., freshwater or brine) and some chemical additives (e.g., ferro-chrome lignosulfonate, sodium asphalt sulfonate) to regulate mud filtration, alter the rheological properties and suspend solid particles (Akpan et al., 2019; Fink, 2015). Nevertheless, WBDFs suffer from poor lubricity, shale inhibition, lower thermal stability and mud loss during the fluid circulation (Mao et al., 2020). To tackle these deficiencies and enhance WBDF rheological and fluid properties such as viscosity, filtration ability and mud weight, various additives have been introduced into the industry. However, drilling fluid additives can have adverse effects, such as reducing fertility rates and increasing the

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Nomenclature

CC	Cubic centimetres (Millilitre)
CMC	Carboxy methylcellulose
CP	Centipoise
EDX	Energy dispersive X-ray spectroscopy
EPA	Environmental protection Agency
FTIR	Fourier transform infrared spectroscopy
CGWP	Coffee ground waste powder
NaOH	Sodium hydroxide (caustic soda)
pH	Potential of Hydrogen
ppg	Pounds per gallon
RPM	Revolution per minute
TGA	Thermogravimetric analysis
WBDF	Water-based drilling fluid
WRP	Watermelon rind powder
YP	Yield point
τ	Shear stress
μ	Viscosity
μ_a	Apparent Viscosity
μ_p	Plastic Viscosity
Υ	Shear rate
Θ_{300}	Viscometer reading at 300 rpm
Θ_{600}	Viscometer reading at 600 rpm

mortality rates of inhabitants (Pereira et al., 2022). An example of this is ferro-chrome lignosulfonate, which has been found to have a negative impact on fish eggs (Mehmood et al., 2016a). In recent years, specific efforts have predominantly focused on exploring the use of food and agricultural waste as viable options for the formulation of WBDFs, given their biodegradability, cost-effectiveness, and eco-friendliness (Ajithram et al., 2022; Al-saba et al., 2018). Previous research studies focusing on the impact of biodegradable materials on filtration characteristics and rheological properties of water-based drilling fluids are currently under consideration as shown in Table 1. Onuh et al. (2017) performed a study to examine the viability of utilizing coconut shells and corn cobs as WBDF loss control additives. They found that corn cobs performed very well in controlling fluid. In a separate study by Talukdar et al. (2018), the use of tannate extracted from used tea as WBDF additive was investigated. Their findings indicated that calcium tannate serves as a rheology modifier in drilling fluid. Amadi et al. (2018) conducted an empirical study to assess the effectiveness of gum Arabic, banana peels, and potato peels as WBDF additives in drilling fluid. The study revealed that potato peel powder acted as a multifunctional additive, significantly improving the drilling fluid's rheological and filtration properties. Banana peels was very effective in regulating the fluid loss into the formation. They also found that gum Arabic powder and potato peel powder, could reduce the mud weight and both can be used as drilling fluid density modifier agents. Similarly, Nik Ab Lah et al. (2019) investigated the feasibility of using eggshells as a fluid lost control material in synthetic-based drilling fluids. The study found that coarse-sized eggshell particles performed exceptionally well, displaying very low fluid loss and mud cake thickness. Furthermore, Al-Hameedi et al. (2019a) were conducted an experiment to investigate the capability of grass powder in regulating fluid loss and mud cake thickness. Their findings revealed that the grass powder outperformed conventional chemicals in controlling seepage, resulting in an impermeable and thinner filter cake and regulating mud loss. In addition, Akmal et al. (2020) found that banana peel outperformed sugar cane bagasse for circulation loss as it contains high amounts of cellulose, lignin, starch, and crude fibers. Yaseer et al. (2020) investigated the feasibility of using wheat husk powder as an environmentally friendly drilling fluid additive, aiming to replace the toxic Carboxymethyl Cellulose (CMC) additive. Their results demonstrated that wheat husk powder provided drilling fluid with properties comparable to CMC. Similarly, in 2021, Zhou et al. (2021) studied wild jujube pit powder (WJPP) as a potential substitute for chemical additives. The experimental findings showed that (WJPP) had the potential to increase viscosity, reduce filtration, and enhance lubrication while promoting the shear thinning of the drilling fluid. Medved et al. (2022) conducted an experimental study using mandarin peel powder in various concentrations and particle sizes as a biodegradable WBDF additive. They showed that increasing the concentration of mandarin peel powder led to reduced filtration, while adding particles size between 0.1 and 0.16 mm increased the rheological properties of the drilling fluid.

Drawing from the insights provided by the previous studies, this study aimed to investigate the feasibility of utilizing watermelon rind powder (WRP) and coffee ground waste powders (CGWP) to alter rheological properties and regulate mud loss of WBDF. Some of the applications of the WRP and CGWP are summarized in the following. The dried WRP is employed in the pharmaceutical industry as a neutral dietary fiber, in the bakery as an ingredient of flour, water content stabilizing agent for pasta and ice cream, in candy production, fertilizer and animal food, (Fabani et al., 2021; Ibrahim et al., 2006; Maletti et al., 2022; Souad et al., 2012). Petkowicz et al. (2017) showed interesting properties such as dynamic surface tension, foaming ability and very good emulsifying properties of WRP in extracting pectin. Despite the interesting properties of the WRP that attract scholars to investigate its suitability for different applications, using this material as a water-based drilling additive is scarce. Hence, this study marks the first-ever utilization of WRP as a water-based drilling fluid (WBDF) additive, expanding its potential applications. The water-based drilling mud typically consists of bentonite clay that performs as a viscosity modifier and caustic soda (NaOH) as a thinner to alter the high-yield point or reduce the gel strength. Liu et al. (2012) experimentally investigated the reactions between NaOH and watermelon rind powder and found that WRP makes an excellent solution with NaOH that is capable of removing heavy metals such as copper (Cu), zinc (Zn), and lead (Pb) in the process of water treatment. Moreover, WRP was irradiated and mixed with NaOH, successfully treating cadmium metal-contaminated and phosphate-contaminated water (Aryal et al., 2022; Husein et al., 2017). Another study showed that the WRP was pyrolyzed in the presence of NaOH at high temperatures of 250–450 °C and atmospheric pressure (Debbarma et al., 2021). The effect of bentonite on WRP was shown by increasing the pH of the solution for wastewater treatment (Muhammad et al., 2020).

In addition to WRP, in this study, we also employed CGWP as a potential WBDF biodegradable additive. Coffee is one of the most popular drinks around the world, with human consumption of 2 billion cups globally and 98 million cups in the UK (BCA, 2023). Subsequently, the amount of waste that is produced continues to boom around the world. Coffee by-products include coffee husks, silver husks, coffee pulps and spent coffee grounds (SCG) (Forcina et al., 2023). SCG, which we call coffee ground waste powder (CGWP) hereafter, is generated from coffee beverage preparation and instant coffee production, and contributes to 45% of the whole waste that directly goes into the landfill (Murthy and Naidu, 2012). Around 500,000 tonnes of waste coffee grounds are produced annually in the UK alone, which mainly end up in landfills (Ferreira and Ferreira, 2020). Hence the industry has a huge potential to supply the wasted products and repurpose them to another field such as oil and gas. CGWP has been used for production of biohydrogen and biogas, biochar, anti-aging lotion and biomass fuel cell (Emmanuel et al., 2017; Jang et al., 2015; Ribeiro et al., 2018; Vanyan et al., 2022). The characterization of CGWP in other studies has shown that it exhibits a coarse and very high textured surface with heterogeneous porosity,

Table 1
Summary of recent published research on developing WBDF biodegradable additives using waste material.

Source	Biodegradable material	Combination	Target
Onwuachi-Iheagwara (2015)	Banana peel powder	Various concentrations added to WBDF	pH modifier to replace conventional caustic soda
Moslemizadeh and Shadizadeh (2017)	Henna Extract	10 g/l and 30 g/l henna extract added to typical bentonite WBDF and aged for 4h at 105 °C in a rolling oven.	Increased lubricity of WBDF, decreased swelling properties and altered contact angle.
Amadi et al. (2018)	21 types of food and green waste used (e.g., Banana Peel Powder (BPP), Gum, Arabic Powder (GAP) and Potato Peel Powder (PPP), Sugar Cane, coconut shells, corn cub and etc,	Between 0 and 10 ppb concentrations of different green and food waste materials added to the WBDF.	Yield point and gel strength increased to 640% and 330%, reducing the fluid by 64%.
Talukdar et al. (2018)	Tea waste	0.5%–3% to total weight of tea waste added to the drilling mud.	viscosity, gel strength and yield point decrease while density increases due to higher tea waste concentration. No effect on fluid loss.
Nik Ab Lah et al. (2019)	Eggshell waste	15 g added to the total WBDF mud.	Minimizes fluid loss and has no effect on plastic and apparent viscosities.
Al-Hameedi et al. (2019a)	Grass powder (GP)	1% and 2% GP added to the WBDF.	Gel strength increased from 22 to 26 Ib/100 ft^2 and fluid loss reduced by 28%.
Al-Hameedi et al. (2019b)	Potato peel powder (PPP)	1%, 2%, 3% and 4% wt. of PPP added to the bentonite WBDF.	Enhancing mud weight (MW), plastic viscosity (PV), yield point (YP), the filtration characteristics and pH).
Al-Hameedi et al. (2020)	black sunflower seeds' shell powder	0.5%, 1.5%, 2.5%, and 3.5% weight percentage (wt %) added to WBDF.	Maximising yield point, viscosity and enhanced other rheological properties.
Yaseer et al. (2020)	Wheat Husk Powder (WHP)	Concentration of 1%, 2%, 3% and 4% WHP were added to the WBDF.	Fluid Loss Additive. Fluid loss reduced by 48.571%, 76%, 77.14% and 81.42% with concentration of 1%, 2%, 3%,4% respectively.
Akmal et al. (2020)	Waste banana peels	Various percentages were added to the WBDF.	Fluid loss control agent.
Zhou et al. (2021)	Wild Jujube Pit Powder (WJPP)	0.5, 1, 2, 3 and 5% concentrations of WJPP were added to WBDF.	improved the rheological, filtration and lubrication properties of WBDF.
Novrianti et al. (2021)	Cassava starch	0–10 g were added to the WBDF.	Fluid loss control agent.
Yalman et al. (2021)	Rice husk ash	Concentration within the range from 2 wt% to 15 wt% were added to WBDF.	Apparent viscosity and yield point increased by 60% and 183%, respectively using 15% of rice husk ash. Fluid loss decreased by 10% using 4% of the biodegradable additive.
Medved et al. (2022)	Waste Mandarin Peel as	Different concentrations (0.5, 1, 1.5, and 2% were added to the WBDF.	API filtration was reduced by 42%, and PPT filtration by 61.54%, with the optimum concentration of 1.5% of the volume of water.

resulting in a high surface area-to-volume ratio (Ballesteros et al., 2014; Lee et al., 2022). This characteristic is useful for any drilling mud as it helps to react with the solution as well as reduce the permeability of the filter cake, leading to a reduction of mud loss during the drilling (Beg et al., 2019; Hamad et al., 2019). Moreover, the chemical reaction between CGWP and the constituents of WBDM agent (NaOH) has been studied previously for pre-treatments of CGWP at a temperature of 50–121 °C (Wongsiridetchai et al., 2018). The results indicated that the solution of CGWP and NaOH at the optimum ratio of 1:2 and 50 °C would not break the CGWP enzymes. Furthermore, the chemical reaction of the NaOH with CGWP at ambient temperature showed a viable option for removing herbicides from wastewater (Lee et al., 2021). The above interesting properties of the CGWP and WRP and their availability and cost-effectiveness were the main reasons for their selection in this study. The ultimate goal of this study is to develop a highly efficient water-based drilling fluid using WRP and CGWP as biodegradable and environmentally friendly additives.

The article is structured as follows: section 1 provides an overview of the study's background and the relevant literature related to the topic. Section 2 summarized the materials, procedures, and equipment used in the study. Section 3 presents and discusses the results of the study. The study is concluded in section 4.

2. Material and methods

Fig. 1 illustrates the preparation of the water-based reference drilling fluid, and water-based drilling mud with added additives using CGWP and WRP. This section also discusses the composition of the natural biodegradable drilling fluid additive.

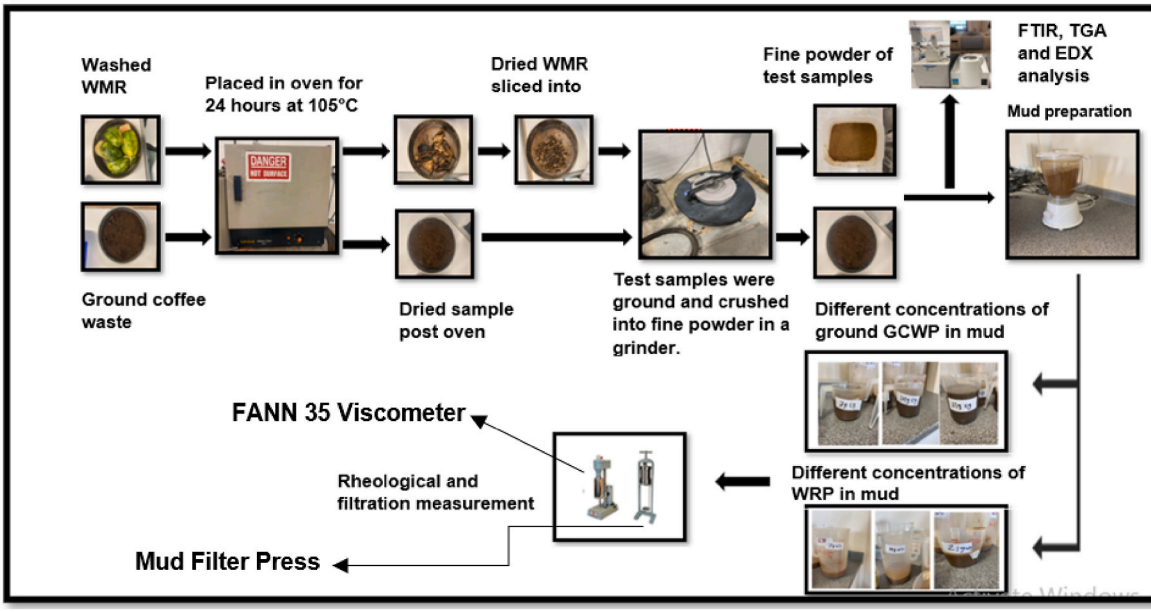

Fig. 1. Schematic of the experimental procedure of the study.

2.1. *Drilling fluid formulation*

2.1.1. *Reference drilling mud preparation*

The water-based mud, serving as the reference drilling fluid, was prepared following the recommendation of the American Petroleum Institute (API SPEC 13A, 1993). The constituents and their ratio included 40g of bentonite, 700 ml of deionized water, and 1g of caustic soda (NaOH). The bentonite was gradually added to the deionized water, while the caustic soda was combined into the solution. The mixture underwent thorough stirring to achieve a homogeneous blend. Subsequently, the formulated reference mud was allowed to rest for 24 h to ensure proper hydration, stabilize viscosity, and complete chemical reactions. This resting period also facilitated the release of trapped gases and air, API (API SPEC 13A, 1993).

2.1.2. *Adding WRP and CGWP to the WBDFs*

Three different concentrations of WBDF were prepared by adding varying amounts of watermelon rind powder additive: 7, 14 and 21 g. These three weight concentrations were added to the formulated water-based drilling mud. To prepare each drilling fluid, three separate beakers were filled with 700 ml of deionized water and labelled according to the corresponding WRP and CGWP additive concentration. Then, 40g of bentonite was carefully added to each beaker, followed by 1g of caustic soda (NaOH). Afterward, the specified amounts of WRP and CGWP additives (7, 14, and 21 g). These three concentrations contributed to each mud's 1, 2, and 3 wt concentration percentages (wt%). In total, six water-based drilling mud combined with WRP and CGWP and one water-based referenced mud were prepared. The contents in each beaker were thoroughly mixed using a mixer to achieve a homogenous solution. The mixing process was carried out for 5 min, after which the newly formulated drilling fluids were left to rest for 24 h before performing the tests, allowing for proper hydration and stabilization of the prepared mud. A similar approach was taken for the concentration of other biodegradable material drilling fluid by Ali et al. (2022) and Rafieefar et al. (2021). Table 2 summarizes the composition and concentrations of the additives and other materials for the preparation of referenced base mud as well as drilling fluid muds containing CGWP and WRP additives.

2.2. *Rheological measurement*

The rheological properties of the drilling fluids were measured using the FANN 35 viscometer at the ambient pressure and temperature, as shown in Fig. 1. To conduct the measurement, the samples were placed in the heating cup on the viscometer platform. The fluid level was checked to ensure it reached the marked circumferential groove on the rotating outer sleeve. The outer sleeve was then rotated to stir the drilling fluid sample at the ambient temperature. At this temperature, the 600 rpm speed was selected, and the dial reading was allowed to stabilize before recording the readings. Subsequently, while the motor was still running, the 300 rpm speed was selected, and the dial reading was again allowed to stabilize before recording the readings. To measure the gel strength of the prepared biodegradable drilling mud, the mud was stirred at 600 rpm for 15 s to break any gels. Then, a low speed was selected, and the viscometer was switched off for 10 s to allow the WBDF to settle before continuing the test. After 10 s, the viscometer was switched on again, and a speed of 300 rpm was selected. The maximum dial reading was recorded at this point, representing the initial gel strength. The drilling fluid test sample was stirred again at 600 rpm for 15 s to break any formed gels. The viscometer was then switched off, and the sample was left for 10 min. The waiting time of 10 s and 10 min is proposed by API standard procedure in the preparation of WBDM (API SPEC 13A, 1993). Many other scholars also showed the effectiveness of the 10 s waiting time to settle the WBDM and for eliminating potential air bubbles (Amani et al., 2012; Beg et al., 2019; Ezeakacha and Salehi, 2018; Nmegbu and Bari-Agara, 2014). After this waiting period, the

Table 2
Experimental drilling fluids composition.

Drilling fluid	Type	Deionized water	Bentonite	Caustic soda (NaOH)	WRP (gram)			GCWP (gram)		
Reference drilling fluid	WBM	700 ml	40 g	1 g	–	–	–	–	–	–
Drilling fluid with WRP	WBM	700 ml	40 g	1 g	7	14	21	–	–	–
Drilling fluid with CGWP	WBM	700 ml	40 g	1 g	–	–	–	7	14	21

viscometer was switched on again, and a speed of 300 rpm was selected. The maximum dial reading was recorded once more, and this value represents the final gel strength. Using the obtained measurements the plastic and apparent viscosities were derived utilizing the conventional drilling mud viscosity equation as follow (Ali et al., 2022; Caenn et al., 2011).

$$\mu_P(cP) = \varnothing_{600} rpm\ reading\ - \varnothing_{300}\ rpm\ reading \quad (1)$$

$$\mu_a(cP) = \frac{\varnothing_{600}\ rpm\ reading}{2} \quad (2)$$

where μ_P is plastic viscosity and μ_a is apparent viscosity in the unit of Centipoise (Cp). $\varnothing_{600}$ and $\varnothing_{300}$ represent viscometer reading at 600 rpm and 300 rpm. Then the yield point was derived using the following equation.

$$YP\left(\frac{lb}{100}ft^2\right) = \varnothing_{300} - \mu_P\left(\frac{Ib}{100\,ft^2}\right)$$

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

where YP represents yield point in (lb/100 ft^2).

2.3. Fluid loss & filter cake thickness measurement

Series 300 LPLT Filter Press (shown in Fig. 1) was utilized to measure the fluid loss and filter cake thickness of the various concentrations of the reference mud, with the addition of either WRP or CGWP as additives. The procedure used for these measurements is as follows. First, the filter press components were thoroughly checked for cleanliness, dryness, and any potential contamination. It was ensured that the rubber seal was securely fastened to the bottom of the filter press mud chamber. A gauze frame was then inserted, and the filter paper was placed on top of the gauze frame. A rubber gasket was placed over the filter paper, and the pin on the cylindrical body of the mud chamber was inserted into the slot on the bottom of the chamber and tightened to lock the assembly in place. Next, the mud chamber was filled with the drilling fluid while carefully minimizing voids. The filled mud chamber was then inserted into the filter press frame, and the lid of the mud chamber was locked and sealed by turning the screw on the filter press frame. A graduated cylinder was positioned under the mud chamber and adjusted in height to collect the filtrate from the drainpipe at the bottom of the mud chamber. The device was pressurized with a CO_2 cartridge, and a pressure of 100 psi was applied to the mud chamber. This pressure was maintained for 7.5 min, and after that duration, the pressure was released, and the amount of filtrate was recorded in the graduated cylinder. The values were recorded as fluid loss in millilitres. After completing the fluid loss measurement, the mud chamber was carefully removed from the filter press frame, and the chamber was disassembled while taking care not to damage the filter cake on the filter paper. The filter paper was then lightly rinsed to remove any mud on the surface of the filter cake. At this stage, the thickness of the filter cake was measured and recorded. This entire process was repeated for 10, 15, and 30 min, and the liquid loss and filter cake thickness were recorded accordingly.

3. Results and discussions

3.1. Energy Dispersive X-ray (EDX) spectroscopy and FTIR analysis

Energy Dispersive X-ray Spectrometer (EDX) and Fourier Transform Infrared (FTIR) analysis were used to conduct an elemental analysis of both WRP and CGWP. This is to determine the percentage weight of chemical compositions that are present on each material. Both EDX and FTIR are important to identify unknown compounds of WRP and CGWP (Bagum et al., 2022). FTIR is a powerful technique that attracts many researchers in search for new drilling fluid additives. The FTIR test can reveal the functional chemical groups and bonding between the constituents. This is to detect the unknown material or reveal any contamination in the material (Ballesteros et al., 2014; Lee et al., 2021; Singh et al., 2023).

These tests are introduced to many areas of petroleum industry such as core sample analysis in core flood experiments, identifying different types of oil and drilling fluid characterizations (He and Stephens, 2011). The EDX is associated with electron microscopy in that the presence of elements in the specimen is determined based on generating characteristics X-rays (Scimeca et al., 2018). The EDX analysis of both WRP and SCG revealed significant amounts of carbon and oxygen, represented by weight percentages of 33.84% and 58.19% for SCG, and 30.58% and 59.21% for WRP, respectively. Table 3 displays the presence of the elements found in the WRP and CGWP samples. WRP contains lower amounts of Chlorine (0.1%), Magnesium (0.78%), and Sodium (0.22%). On the other hand, CGWP contains lower amounts of Phosphorus (0.64%) and Potassium (0.79%). In terms of Calcium and Silicon content, both samples were almost similar, with percentages by weight of 1.4% and 1.52% for Calcium, and 0.57% and 0.51% for Silicon, respectively.

The results of the EDX of both SCG and WRP indicates the toxicity level of the materials are negligible.

Fig. 2 depicts the results of FTIR test of CGWP and WRP in the range of 600–4000 cm^{-1}. The results reveal the presence of specific functional groups within the vibration bands. The presence of the O – H functional group between 3000 and 3600 cm^{-1} indicates the existence of intramolecular hydrogen bonding compounds such as phenols, carboxylic acid alcohol (Chou et al., 2012). This indicates the presence of both hydroxyl group and carboxylic acid within this broad vibration band. Additionally, the band between 2800 and 2950 cm^{-1} shows the presence of the C–H functional group. The findings show that the sample may contain cellulose, lignin and pectin. Furthermore, the broad band between 1200 and 1800 cm^{-1} implies the existence of the C=O functional group, likely corresponding to carboxylic acid. Moreover, the broadband between 1200 and 1000 cm^{-1} indicates the presence of the C–O functional group, suggesting the existence of lignin and cellulose in the sample. In the other hand the FTIR results of WRP revealed broad bands between 3000 and 3650 cm^{-1}, indicating the presence of O–H groups, which suggest the existence of alcohol. Additionally, the presence of O–H functional groups signifies a major concentration of lignin and pectin in the material, likely due to the presence of carboxylic acids and phenols (Chou et al., 2012). Furthermore, the band between 2700 and 2900 cm^{-1} implies the presence of C–H functional groups, which are characteristic of alkanes. Additionally, the broad bands between 1600 and 1800 cm^{-1} and at 1500 cm^{-1} indicate the presence of C=O functional groups, likely corresponding to carboxylic acid. Moreover, the broad band at 1000 cm^{-1} indicates the existence of C–O functional groups, which could be attributed to the presence of cellulose and lignin in the WRP. In summary, the FTIR analysis provides valuable information about the functional groups present in the WRP and CGWP including hydroxyl groups, alkanes, carboxylic acids, and C–O and C–H

Table 3
EDX results of WRP and CGWP.

Element	Coffee ground waste powder (Weight %)	Watermelon rind powder (Weight %)
Carbon (C)	33.84	30.58
Oxygen (O)	58.19	59.21
Sodium (Na)	2.69	0.22
Calcium (Ca)	1.52	1.4
Potassium (K)	0.79	4.95
Silicon (Si)	0.51	0.57
Chlorine (Cl)	0.59	0.1
Magnesium (Mg)	1.23	0.78
Phosphorus (P)	0.64	2.19

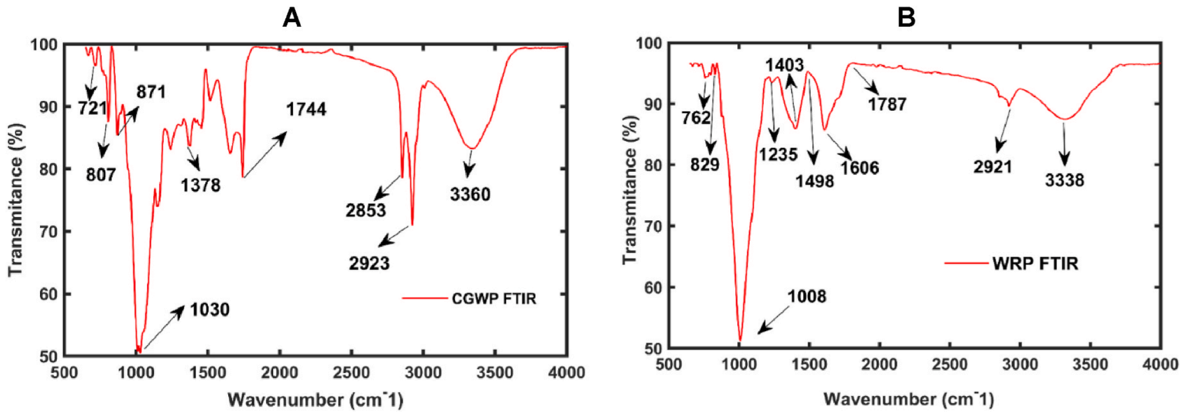

Fig. 2. FTIR analysis result of the spent coffee ground waste powder (CGWP) and watermelon rind powder (WRP).

bonds, shedding light on their composition and potential applications.

3.2. Thermogravimetric analysis (TGA)

To assess the resistance of the biodegradable drilling mud additives to heat, their thermal stability was investigated using thermogravimetric analysis (TGA). The TGA is a quantitative analytical technique that measures changes in the mass of a sample as a function of temperature/or time (Saadatkhah et al., 2020). A sample placed into a pan inside the furnace that can heating the sample isothermally up to 1000 °C. The sample pan is connected to a precise micro balance inside the device, which can accurately weigh the samples in a closed furnace (Vyazovkin et al., 2011). The initial weight of the samples are recorded by micro-balance and compared to the weight of the samples in various temperature. Further information about the principle of the TGA can be found in (Bach and Chen, 2017; Fateh et al., 2016; Saadatkhah et al., 2020). The WRP and CGWP samples were loaded to the thermogravimetric analyser and the temperature increased sequentially and held for a specific interval to see the effect on mass. Upon heating up both materials, three significant phases of weight loss were observed, as illustrated in Fig. 3. The weight loss at the end of each phase was calculated using the following relation. Similar approach was taken for the computation of weight loss in different stages of the TGA (Bensharada et al., 2022; Monteiro et al., 2010)

$$\textit{weight loss at each phase} = \frac{W_i - W_t}{W_i} \times 100\% \quad (4)$$

where w_i is the weight of the sample at the beginning of the phase, w_t is the weight of the sample at the end of the respective phase. The first phase known as the drying phase, involves the evaporation of free moisture from the sample, effectively removing any moisture content. In this phase, the WRP lost 4.73% while CGWP lost 6.02% of its weight. The second phase is the decomposition phase, which involves the breakdown of organic matter in the material, leading to the formation of volatile compounds (Saadatkhah et al., 2020). In this phase the rate of weight loss is very sharp and wight loss was 50.02% and 60.27% for WRP and CGWP, respectively. The final decomposition of the material occurs in the third phase, where the residue resulting from the second phase's decomposition is analysed. In this phase two decomposition stages were identified and the weight loss percentage of 68.86 and 86.32 for WRP, which indicates the WRP lost its weight by a substantial amount. Both the second and third phases have attributed to the degradation of the remained organic matters. Furthermore, the results show that CGWP weight reduction due to rising temperature in the first phase starts at about 350 °C, making it suitable for applications in high-temperature conditions. Nevertheless, there is an unusual rise in the data for CGWP in first phase. The rise could be attributed to several factors including the tendency of the sample to absorb the moisture, chemical reactions such as oxidation or decomposition, which lead to release of gases and the generation of new compounds. This also could be associated to the fact that some of the compound of CGWP might be volatilized that contribute to increase in mass and unexpected rise of the data (Safaei-Farouji et al., 2022). The higher weight loss observed in the TGA analysis of the CGWP indicates its significant thermal sensitivity. Findings support the notion that CGWP and WRP can serve as effective and viable options for high-temperature drilling applications in industry.

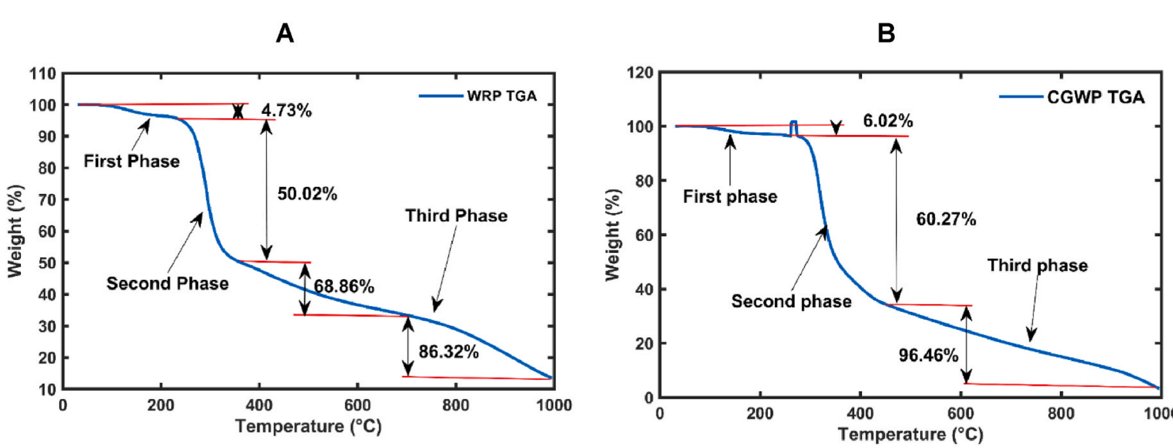

Fig. 3. TGA thermograms of A: watermelon rind powder (WRP), and B: coffee ground waste powder (CGWP).

3.3. Drilling mud fluid properties

As explained earlier the fluid properties of the biodegradable drilling mud as well as water-based drilling mud were measured during the experiment and were tabulated in Table 4. The properties include mud weight, pH, gel strength, thickness of filter cakes, filtration properties, apparent and plastic viscosities and the yield point. The effect of biodegradable CGWP and WRP on the rheological properties of the reference water-based drilling mud will be discussed in detail in the following.

3.3.1. Effect on mud weight (density)

Mud weight or mud density is an important parameter of drilling fluid required to ensure efficient well drilling operation and it also helps to maintain well control (Bridges and Robinson, 2020). The ideal mud weight required for any well drilling operation is slightly higher than the pore pressure but lower than the formation fracture pressure of the drilled wells (Denney, 2001). The mud weight ensures the stability of the well and efficient cutting removal. Increasing the mud weight will raise the hydrostatic pressure, leading to balance in the formation pressure, thereby maintaining the wellbore integrity. Moreover, it reduces the risk of kicks and blowouts, prevents gas, oil and water from going into the formation and reduces mud loss (Caenn et al., 2011).

Fig. 4A illustrates the impact of WRP and CGWP on drilling fluid density (mud weight) at different weight concentrations. At 1 wt% (7g), WRP had a negligible effect on the drilling fluid density, while CGWP had no effect. Similarly, at 2 wt% (14g), WRP had no effect, but CGWP showed a slight reduction in drilling fluid density. At 3 wt% (21g), WRP slightly increased the drilling fluid density, while CGWP had a minor reduction in drilling fluid density. In addition at both 1 and 3 wt%, WRP had a negligible effect on increasing the drilling fluid density. Similarly, at 2 and 3 wt% concentrations, CGWP led to a negligible reduction in drilling fluid density. These negligible effects are desirable as they demand less pump pressure to circulate the mud within the system (Awl et al., 2023). Lastly, at 1 and 2 wt% concentrations, neither WRP nor CGWP had any significant effect on the drilling fluid density.

Table 4
Measured and derived fluid properties of WBDF and proposed biodegradable muds.

Properties	Reference Mud	Watermelon rind powder			Coffee ground waste powder		
Weight (grams)		7	14	21	7	14	21
Percentage (%)		1	2	3	1	2	3
Density (ppg)	8.6	8.7	8.6	8.7	8.6	8.5	8.5
pH	11.33	10.5	9.6	8.9	11.2	10.1	9.7
Initial gel strength (lb/100 ft^2)	9.3	10	11	12	5	6	7
Final gel strength (lb/100 ft^2)	15	15	17	17	8	8.5	9
Thickness of filter cake (mm)	1.75	1.56	1.41	1.35	1.43	1.28	1.03
Filtration 7.5 min (cc)	10	7.6	7.3	6	5.9	5.6	5.2
Filtration 10 min (cc)	11.6	8.9	8.4	6.8	6	6.5	6
Filtration 15 min (cc)	14.9	11.2	9.4	8.6	8.4	8	7.4
Filtration 30 min (cc)	20.4	15	13.8	12	12.1	10.5	9.5
Apparent Viscosity	10	8.5	10	11	8.5	10	11.5
Plastic viscosity (Cp)	4	5	6	6	5	7	8
Yield Point (lb/100 ft^2)	12	7	8	10	7	6	7

3.3.2. Effect on apparent and plastic viscosities

Viscosity refers to the resistance of a drilling mud to flow. There are two types of apparent and plastic viscosities that are measured in any drilling fluid experiment. Apparent viscosity measures the fluid's viscosity at the shear rate specified by the API. Apparent viscosity is very important as it helps to prevent drilling problems and improves well cleaning (Al-Khdheeawi and Mahdi, 2019). Very high apparent viscosity will result in increased friction, thereby making it difficult for the mud to flow and hence reducing the pump's performance (Li, 2000). The apparent viscosity of the mud needs to be monitored and controlled within the acceptable range.

On the other hand, the plastic viscosity of the mud is an indicator of the amount of solid content in the mud (Abdelrahman et al., 2019). The apparent viscosity results in Fig. 4B show a clear trend when WRP and CGWP are added to the WBDF. As the concentration of these additives increases, the apparent viscosity of the fluid also increases. This observation suggests that higher concentrations of the additives, especially above 3%, can significantly enhance the cutting carrying capacity of the drilling fluid. While adding 1% WRP and CGWP exhibits a lower apparent viscosity of 8.5 cp, increasing the additives to 2 wt% and 3 wt% linearly increases the apparent viscosity to 10cp and 11cp and 10cp and 11.5cp for WRP and CGWP, respectively. The apparent viscosity of the base mud was recorded as 10 cp. Notably, adding 1 wt% of both biodegradable additives exhibits shear thinning, in which the viscosity decreases with increasing shear rate. At 1 wt% additive, the WBDM shows the thixotropy behavior, where it becomes less viscous under the effect of applied shear force and then steadily regains the original viscosity (Livescu, 2012). This change might be due to two competing factors the breakdown and build-up of the mud structure. The breakdown is due to the flow stresses, and the build-up is due to collisions of the particles in the mud in a later stage (Mewis and Wagner, 2009).

It is evident from Fig. 4C, that both WRP and CGWP increased the plastic viscosity of the drilling fluid at all concentrations. As the concentration of the additives increases, the plastic viscosity will also increase. For instance, at 1 wt% concentration, both additives raised the plastic viscosity from 4cp to 5cp, marking a 25% increase in viscosity. At 2 wt% and 3 wt% concentrations, WRP had a consistent effect on the reference mud, elevating the plastic viscosity from 4cp to 6cp, resulting in a 50% increase in viscosity. On the other hand, at 2 wt%, CGWP increased the plastic viscosity from 4cp to 7cp, indicating a significant increase of 75%. At 3% concentration, the CGWP boosted the plastic viscosity from 4cp to 8cp, doubling the viscosity with a 100% increase. These findings suggest that CGWP and WRP additives at concentrations of 1, 2, and 3 wt% can effectively enhance the viscosity of the drilling fluid, making them valuable options for improving fluid properties in drilling operations.

3.3.3. Yield point

The electrochemical forces between the liquid, solids, and liquid and solids in chemical reactions in dynamic conditions will be measured by yield point (Novrianti et al., 2021). The yield point is an important property of the drilling mud that needs to be understood. In general, a higher yield point of drilling mud is desirable for carrying the cuttings from the wellbore to the surface (Mohammadsalehi and Malekzadeh, 2011). However, the optimal value of the YP depends on the size of the cutting and drilling conditions. Fig. 4D illustrates the yield point of referenced water-based drilling mud (RBM) as well as biodegradable CGWP and WRP. The RBM yield point is calculated as 12 Ib/100 ft^2. Adding 1 wt% WRP additive to the RM would decrease the yield point by 41.6% to the value of 7 Ib/100 ft^2. Increasing the concentration of WRP to 2 wt% and 3 wt% would decrease the yield point to a lesser degree of 33.3% and 16.7%. The results obey the general rule that indicates adding a higher concentration of additives will increase the yield points (Ali et al., 2023).

Furthermore, similar to WRP, adding 1 wt% and 3 wt% r CGWP reduced the yield point by 41.6% (7 Ib/100 ft^2). Moreover, adding 2 wt

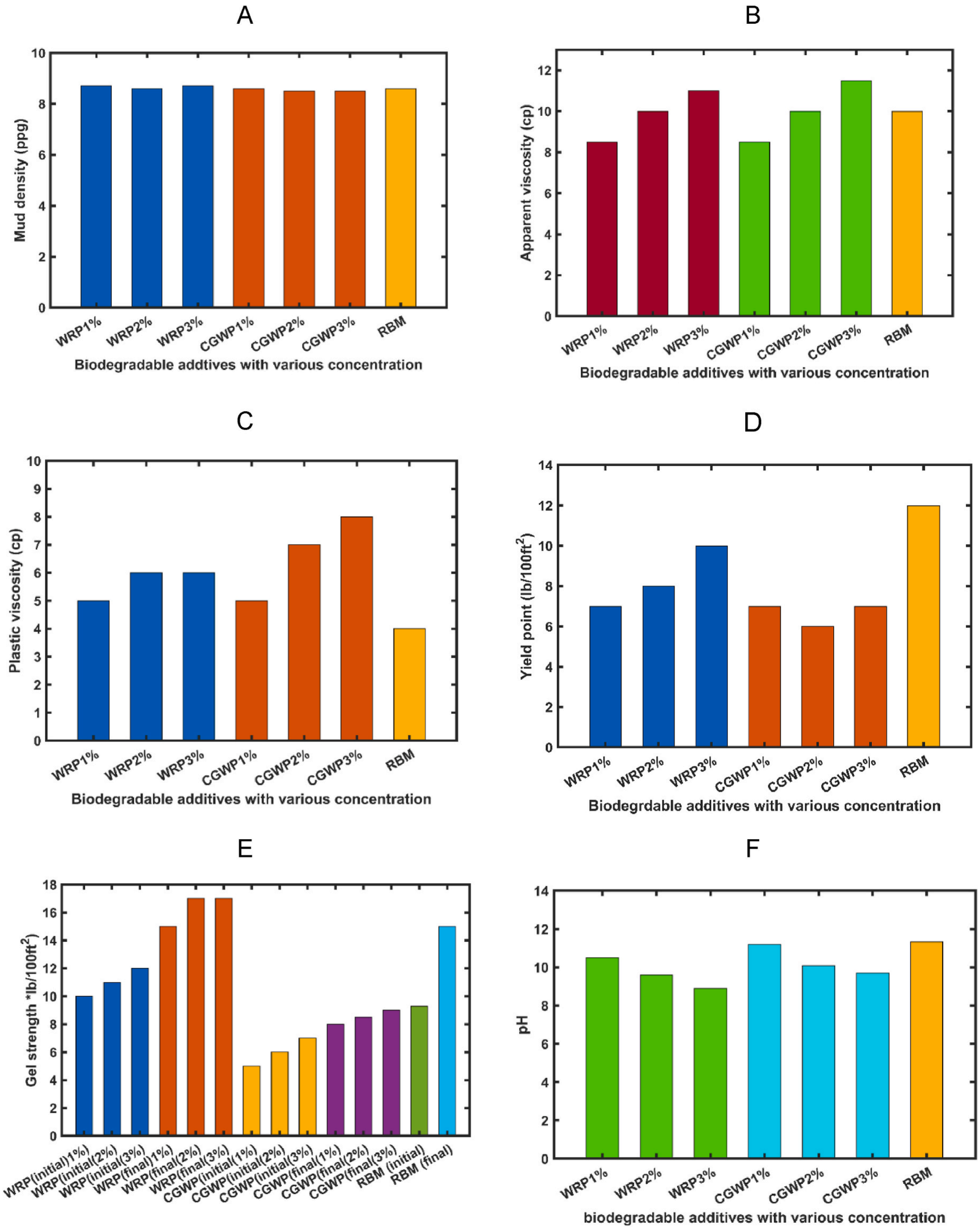

Fig. 4. The impact of watermelon rind powder (WRP) and coffee ground waste powder (CGWP) biodegradable additives on WBDF properties (A: mud density, B: apparent viscosity, C: plastic viscosity, D: yield point, E: gel strength, and F: pH).

% CGWP, decreased the yield point of RBM by 50% (6 Ib/100 ft^2). Both WRP and CGWP reduced the yield point of referenced WBDF, to a substantial degree at the selected concentrations (1–3%). Although adding WRP additive shows a linear trend in modifying the yield point of RBM additives, however, a clear trend has not been observed for CGWP.

3.3.4. *Gel strength*

The ability of the mud to hold solids in the fluid is determined by its gel strength (Novrianti et al., 2021). It determines less gelation characteristics of the mud, which is essential for pumping cutting slurries during drilling (Abdul-Wahab et al., 2020). As shown in Fig. 4E At 1 wt%, 2 wt%, and 3 wt%, the difference between the initial and final gel strength for CGWP was 3 lb/100 ft^2, 2.5 lb/100 ft^2, and 2 lb/100 ft^2, respectively. These values represent significantly lower gel strength compared to both the reference drilling fluid and WRP. While the WRP had a negligible effect on the gel strength, the CGWP notably reduced the gel strength. Although a reduction in gel strength means that less energy is required to pump the fluid after a stoppage, it makes the mud less effective for suspending cutting at pump-off conditions. As the results in Fig. 4E illustrate, the CGWP exhibits excellent gel strength properties but may not be as efficient as WRP in suspending cutting during pump-off conditions.

3.3.5. Effect of adding additives on the pH

The pH level determines a drilling mud's relative acidity or alkalinity. A mud with pH below 7 is considered acidic and above 7 is alkaline. An acidic drilling mud is potentially hazardous to the environment and corrosive to the piping and drilling equipment (Amanullah and Yu, 2005). Maintaining the pH of a drilling fluid is crucial for preventing equipment corrosion and ensuring optimal rheology. Water-based drilling fluids generally perform best at pH values ranging from 8.0 to 10.5 (Peretomode, 2018). The pH of the drilling mud can be adjusted depending on the specific drilling conditions. When examining the effects of CGWP and WRP at different concentrations, it was observed that both additives reduced the pH of the drilling fluid. The measurement of the pH is presented in Fig. 4F. From the results, it can be observed that reference WBDF has a pH of 11.33. Adding a 1 wt% of WRP and CGWP to the referenced mud reduced the pH of the mud to 10.5 and 11.2, respectively. Increasing the concentration of the biodegradable WRP and CGWP to 2 wt% and 3 wt% would further decrease the pH of the based mud to 9.6, 8.9, 10.1 and 9.7, respectively. These findings suggest that both CGWP and WRP can serve as effective pH modifiers, particularly at higher concentrations. This ability to adjust the pH makes them valuable additives for achieving the desired drilling conditions. It should be noted that the acidity of the WBDM is still above 7, which classed the new drilling fluid muds as alkaline.

3.3.6. Effect on filtration properties

The filtration properties of mud play an important role on its performance. Filtration properties of drilling mud are generally evaluated and controlled by API filter loss test (API SPEC 13A, 1993). Filtration is the separation of suspended solids particles from a fluid by passing the fluid through a porous media known as a filter (Cheremisinoff, 1998). The filtration properties of drilling mud helps in controlling fluid loss, well bore stability, prevention of formation damage, enhancing drilling operation efficiency and well control (Saboori et al., 2018).

Fig. 5 shows a remarkable improvement in fluid loss with the new additives compared to the reference drilling fluid. Adding 1, 2, and 3wt.% of WRP to the reference mud reduced fluid loss by 23%, 27%, and 40%, respectively after 7.5 min. After 10 min of filtration, the reduction was 23, 28, and 41%, respectively. For 15 min and 30 min filtration, the reductions in fluid loss were 25, 37, and 42%; and 27, 32, and 41%, respectively. In contrast, adding CGWP additives at the weight concentrations of 1, 2, and 3wt.% to referenced mud decreased fluid loss for filtration by 41, 44, and 48%, respectively after 7.5 min. For 10 min filtration, the reduction was slightly increased to 48, 44, and 48%. For 15 min and 30 min filtration of the mud containing CGWP, the reductions were 44, 46, and 50, and 41, 49, and 53%, respectively. Both additives were very effective in fluid loss reduction, however, CGWP performed slightly better than WRP when compared to the reference drilling fluid. These results indicate the potential of both additives in improving fluid loss control during drilling operations.

3.3.7. Effect on filter cake thickness and its formation mechanism

When the drilling mud is circulating in the formation, the pressure forces the liquid part of the bentonite mud slurry into pore spaces in the formation. This phenomenon leaves behind the solid particles of the mud slurry in the formation, which leads to the formation of the mud cake or filter cake. The filter cake helps to control fluid loss into formation and enhances wellbore stability. Filter cake thickness is a critical factor of the WBDF to seal the wellbore effectively and prevent fluid loss. However, excessive filter cake thickness is undesirable as it increases the risk of wellbore instability (Yousefirad et al., 2020). The filtration loss of the RBM was high, resulting in the formation of a thick filter cake on the borehole wall, which will reduce the annular gas and reduce the drilling safety (Rabbani and Salehi, 2017). Moreover, filter cake thickness affects the differential sticking and wellbore clean-up (Gamal et al., 2020). Fig. 6 represents the results of filter cake thickness. As can be seen from the results, the CGWP produced the thinnest and impermeable filter cake at 3 wt%, showing a reduction of 41% in comparison to RBM. This finding highlights the excellent potential of CGWP in controlling and regulating filter cake formation during drilling operations. As shown in Table 5, adding 1, 2 and 3 wt% WRP to the referenced-based mud reduced the filter cake by 11, 19 and 23%, respectively. While adding the same concentration of CGWP reduced the filter cake by 18, 27, and 41%. The result indicates that the CGWP is a better choice for reducing the filter cake and controlling drilling mud loss at an optimum concentration of 3%.

The mechanism of formation of the filter cake is illustrated in Fig. 7. It is clear that when CGWP and WRP are mixed with the bentonitebased WBDM, it is precipitated onto the borehole wall within the porous intervals. Consequently, a thin layer of less permeable mud cake is formed within the intervals that prevent excessive fluid loss into the permeable formation. However, the circulation of the referenced-based mud over time leads to higher filter cake thickness. Furthermore, increased filtration rates and extended penetration into porous and permeable

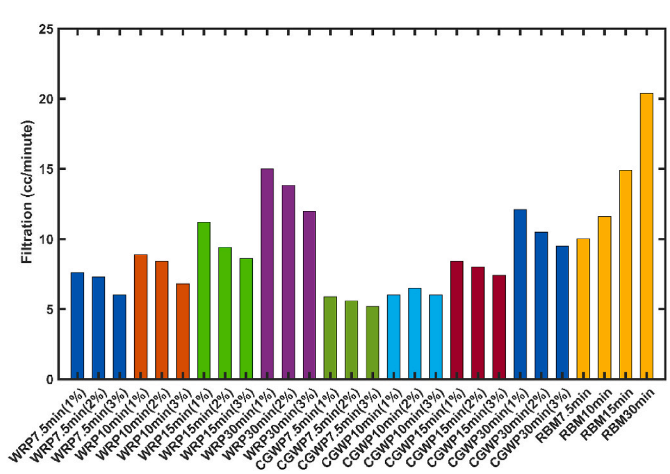

Fig. 5. The results of filtration loss of referenced-based mud and proposed drilling muds containing eco-friendly additives in a time of 7.5min, 10min, 15min, and 30min.

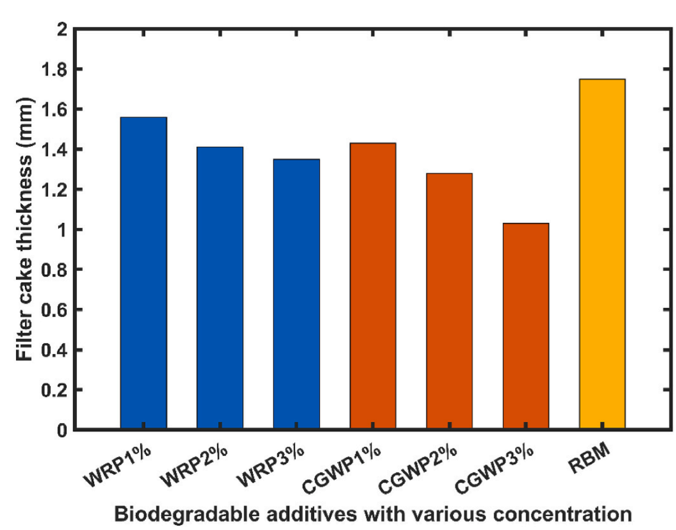

Fig. 6. The results of filter cake thickness of reference-based mud and proposed muds containing eco-friendly WRP and CGWP additives.

Table 5
Filter cake thickness reduction percentage of the drilling muds.

wc %.	Filter cake (mm), WRP	Filter cake (mm), CGWP	Filter cake RBM (mm)	WRP (percentage reduction %)	CGWP (percentage reduction %)
1%	1.56	1.43	1.75	11	18
2%	1.41	1.28		19	27
3%	1.35	1.03		23	41

formations may lead to intensified formation damage. Nevertheless, biodegradable additives of WRP and CGWP can mitigate this damage in the formation. In support of our findings Al-Hameedi et al. (2019a) explained the mechanism of the starch and grass powder additive in WBDM. The fine grass powder particles at room temperature and atmospheric pressure create a thin filter cake that helps to reduce fluid loss.

3.3.8. *Effect of shear stress on the drilling fluid*

The shear stress and shear rate of a drilling fluid can have a significant impact on the performance of the drilling fluid such that when a drilling fluid is subjected to shear stress, it's viscosity can be reduced (Bair, 2013). This effect can influence the ability of the drilling fluid to suspend drill cuttings and provide adequate lubrication to the drilling bits. If the viscosity of the fluid is too low, it may not be able to carry drill cuttings up to the surface of the wellbore, hence, resulting in blockages in the form of cuttings buildup. This can adversely affect the drilling operation (Piroozian et al., 2012). Wear and damage of the drill bit may occur due to the inability of the low viscosity drilling fluids to provide adequate lubrication. Hence it is important to understand the effect of adding additives on shear stress and shear rate of the drilling muds. To convert the experimental data to shear stress and shear rate, the instruction of Fann 35, recommended by API SPEC 13A (1993) was used. According to the API guidance and Fann viscometer, shear stress can be calculated as follow.

$$Shear\ stress = K_1 K_2 \Theta \tag{5}$$

where K_1 is the torsion constant of 386 dyne-cm/degree deflection, K_2 is the shear stress constant equal to 0.01323 cm^{-2}, and Θ is the viscometer reading. Subsequently, the shear rate is calculated as follows.

$$Shear\ rate = K_3 N \tag{6}$$

where K_3 is the shear rate constant of 1.7023 S^{-1}, and N is the viscometer speed in rpm. For the reference mud, the apparent viscosity was used to determine the shear stress, since it is the effective viscosity of the mud.

$$Apparent\ viscosity = \frac{shear\ stress}{shear\ rate} \times 100 = \frac{\tau}{\gamma} \times 100 \tag{7}$$

The result of the above calculation is presented in Fig. 8A and B for shear stress and shear rate, respectively. From the results, the shear stress of referenced based mud is increasing adding biodegradable WRP and CGWP additives at both shear rates of 510.9 S^{-1} and 1021.8 S^{-1}. This increasing trend in shear stress causes a decrease in the viscosity of the drilling mud containing additives due to the behaviour of non-Newtonian fluids. This behaviour of the fluid is known as shear thinning,which is advantageous to maintain the flow with minimum pressure loss to carry cutting to the surface (Ali et al., 2019; Awl et al., 2023). In addition, non-Newtonian fluids exhibit a nonlinear relationship between shear stress and shear rate. Their relationship depends on the viscosity component which is the apparent viscosity of the fluid (Uwaezuoke, 2022). To improve this thinning effect, more concentrations of the different biodegradable fluids can be used, as observed in Fig. 8.

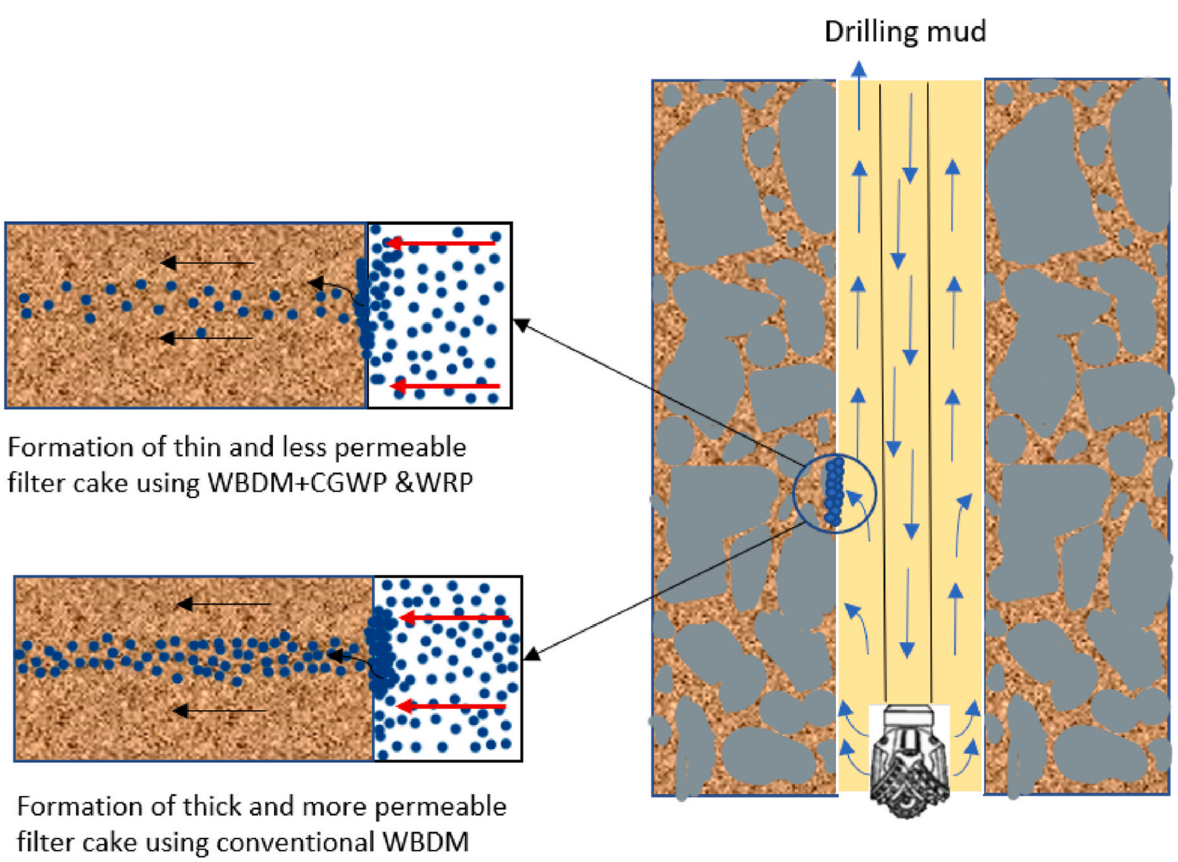

Fig. 7. The mechanism action of filter cake formation on the wall of the borehole with conventional WBDM and WBDM + CGWP & WRP.

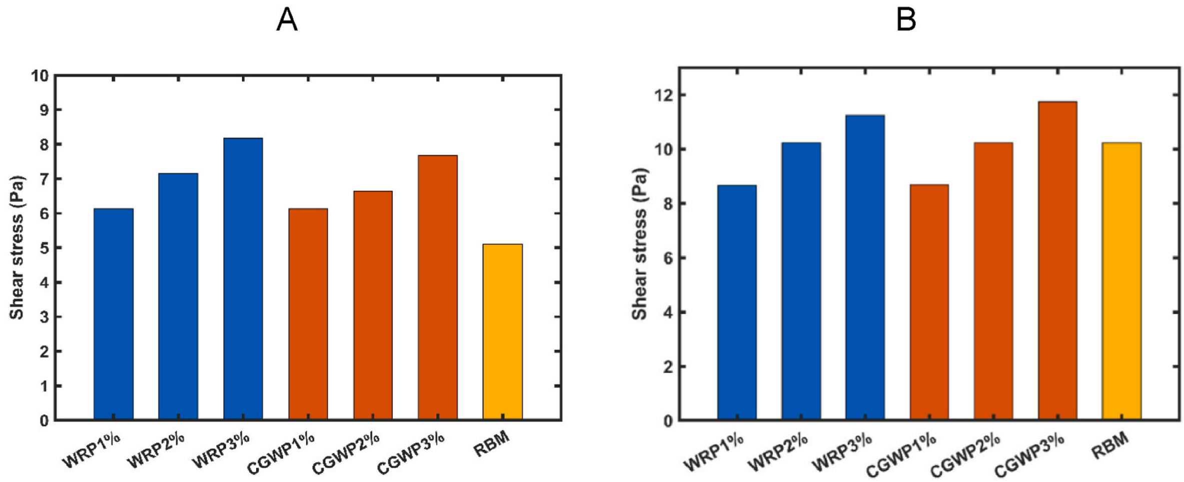

Fig. 8. Shear stress of the proposed drilling fluids and referenced-based mud (RBM) at a shear rate of 510.9 S^{-1} (A) and 1021.8 S^{-1} (B).

The comparative analysis of the fluid loss and filter cake reduction between this study and optimum results of previous research revealed a promising result of this research as shown in Table 2 and Fig. 9. Our investigation showed that using CGWP3%, CGWP2%, and WRP3% as WBDF additives were associated with a noticeable reduction in fluid loss and filter cake. In particular, using 3wt% of CGWP resulted in a 53% reduction of fluid loss combined with a 41% reduction in filter cake thickness. In addition, using 2wt% and 1wt% of CGWP led to 49% and 41% of fluid loss reduction, followed by 27% and 18% of reduction in filter cake, respectively. In contrast, using WRP as WBDFs additive has a smaller effect on fluid loss and filter cake thickness reduction in comparison to CGWP. Comparing the results of the literature showed distinctive results for biodegradable food and green waste materials, nanoparticles, and biopolymers. Pistachio shell powder achieved 38.57% reduction in fluid loss and 20.54% reduction in filter cake thickness, while potato peel powder achieved 30% and 40% reduction in fluid loss and filter cake thickness, respectively. Furthermore, using grass powder, palm tree leaves powder and broad beans powder exhibited 42%, 28% and 31.86% reduction of fluid loss, respectively coupled with 33.33%, 36.67% and 28.57% reduction in filter cake thickness, respectively. Additionally, using wheat husk powder, wild jujube pit powder and rice husk ash would reduce the fluid loss by 77.14%, 42.5% and 10%respectively. Nevertheless, the former two materials have no effect on the filter cake reduction while the later material resulted in increasing filter cake thickness. Moreover Dejtaradon et al., (2019), showed using Copper oxide (CuO) nanoparticle as WBDFs additive reduce the fluid loss by 30.20% and minimizes the filter cake thickness by 27.6%. Muhayyidin et al., (2019) also demonstrated that biopolymer reduced the fluid loss and filter cake thickness of WBDF by 33.33%. The above comparative examination highlights the efficacy of different materials in the reduction of drilling fluid loss and minimizing the filter cake thickness. Notably, it shows the significant potential of using CGWP and WRP as water-based drilling fluid additives in the reduction of both fluid loss and filter cake thickness. The results of the comparison in Table 6 and Fig. 9 reveal better or similar outcome for utilizing CGWP and WRP as fluid loss and filter cake

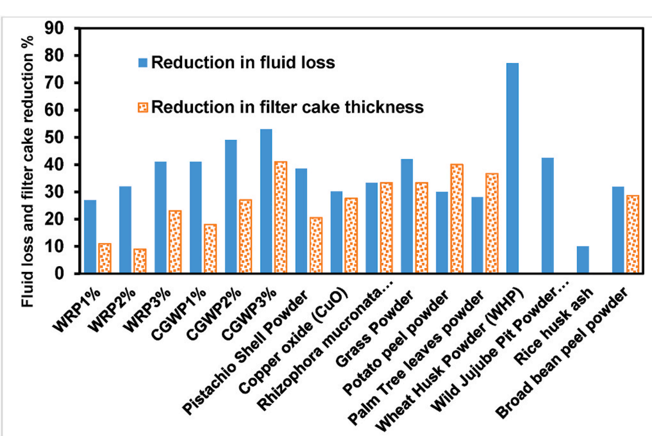

Fig. 9. Comparison of the CGWP, WRP, biodegradable, nanoparticle, and biopolymer in reduction of water-based drilling fluid loss and filter cake thickness.

Table 6
Effect of various drilling fluid additives including biodegradable, biopolymer nanoparticles, CGWP and WRP on reduction of drilling fluid loss and filter cake thickness of water-based drilling fluid.

Types of materials	Materials	Reduction in fluid loss (%)	Reduction in filter cake thickness (%)	Reference
Current study	WRP1%	27	11	
	WRP2%	32	9	
	WRP3%	41	23	
	CGWP1%	41	18	
	CGWP2%	49	27	
	CGWP3%	53	41	
Biodegradable food waste	Pistachio Shell Powder	38.57	20.54	Davoodi et al. (2018)
Nanoparticle	Copper oxide (CuO)	30.20	27.6	Dejtaradon et al. (2019)
Biopolymer	Rhizophora mucronata Tannin	33.33	33.33	Muhayyidin et al. (2019)
Biodegradable Green waste	Grass Powder	42	33.33	Al-Hameedi et al. (2019a)
Biodegradable food waste	Potato peel powder	30	40	(Al-Hameedi et al., 2019b)
Biodegradable Green waste	Palm Tree leaves powder	28	36.67	(Al-Hameedi et al., 2020)
Biodegradable Green waste	Wheat Husk Powder (WHP)	77.14	No effect	Yaseer et al. (2020)
Biodegradable Green waste	Wild Jujube Pit Powder (WJPP)	42.5	Not provided	Zhou et al. (2021)
Green waste	Rice husk ash	10	Increased	Yalman et al. (2021)
Biodegradable food waste	Broad bean peel powder	31.86	28.57	Awl et al. (2023)

reducer of WBDFs in comparison to the reviewed literature materials.

4. Conclusion

The research was to enhance the rheological properties of water-based drilling fluid (WBDF) to reduce fluid loss by introducing biodegradable additives of coffee ground waste powder (CGWP) and watermelon rind powder (WRP). It was determined that the optimal weight concentration is 3%, resulting in favorable properties including.

- The addition of CGWP and WRP additives led to a 53% and 41% reduction in fluid loss, respectively.
- Adding biodegradable CGWP and WRP exhibited a 41% and 23% reduction in filter cake thickness in comparison to formulated WBDF.
- CGWP additive effectively kept the pH level slightly above 10, preventing the formation of corrosive substances in the drilling equipment.
- The addition of WRP increased plastic viscosity by 75%, while CGWP exhibited a remarkable 100% increase.

The research shows the advantages of introducing WRP and CGWP to enhance the rheological properties of WBDF, making it more economically viable and more eco-friendly for industrial applications. The performance of formulated drilling muds using WRP and CGWP against other well-known WBDM additives at various temperatures can be an interesting future research avenue.

CRediT authorship contribution statement

Chukwuemeka Madu: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Foad Faraji:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mardin Abdalqadir:** Project administration, Methodology, Investigation, Data curation, Conceptualization. **Sina Rezaei Gomari:** Writing – review & editing, Supervision. **Perk Lin Chong:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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