



# Insights into application of acorn shell powder in drilling fluid as environmentally friendly additive: filtration and rheology

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## Abstract

Conventional additives used in drilling fluid may have detrimental short- and long-term impacts on the surrounding environment. The employment of biodegradable green material in drilling fluid as alternative additives will eliminate these harmful impacts. In this study, acorn shell powder is proposed as a novel biodegradable additive for application in drilling fluid. First, the acorn shell powder was prepared and then characterized in terms of chemical structure, particle size, and morphology. The acorn shell powder, with four different concentrations, was then introduced into a water-based fluid; its functionality in the fluid system was evaluated with respect to rheological and filtration characteristics at high-pressure, high-temperature and low-pressure, low-temperature conditions. The observed results indicated that the incorporation of acorn shell powder into the fluid significantly improves filtration behavior; the introduction of 9 lb per barrel of the powder into the fluid system led to a dramatic reduction in volume filtrates by 80.1 and 63.3%, respectively, at high-pressure, high-temperature and low-pressure, low-temperature conditions. The rheological test outcomes displayed a considerable enhancement in the fluid system's rheology in the presence of the powder. Furthermore, the efficiency of the proposed powder in reducing the filtration was compared with those of four traditional additives, in which the powdered acorn shell demonstrated a comparable efficiency in filtration controlling with those of the traditional additives. The promising efficiency with which the proposed powder controls filtration and enhances rheology justifies its applicability and employment in drilling fluid as a low-cost and eco-friendly additive.

**Keywords** Acorn shell characterization · Eco-friendly drilling mud · Fluid loss reducer · Green additive · Rheological models · Rheology modifier

## List of symbols

API	American Petroleum Institute	HB	Herschel–Bulkley
ASP	Acorn shell powder	HCl	Hydrochloric acid
BF	Base fluid	HPHT	High-pressure high-temperature
BP	Bingham plastic	ICP	Inductively coupled plasma
CMC	Carboxymethyl cellulose	K	Consistency index
CMS	Carboxymethyl starch	KCl	Potassium chloride
EDAX	Energy-dispersive X-ray spectroscopy	LPLT	Low-pressure low-temperature
FESEM	Field emission scanning electron microscopy	<i>n</i>	Flow index
FTIR	Fourier transform infrared spectroscopy	NaCl	Sodium chloride
		Na <sub>2</sub> CO <sub>3</sub>	Sodium carbonate
		OBF	Oil-based fluid
		PAC	Polyanionic cellulose
		PAC-LV	Low-viscosity polyanionic cellulose
		PHPA	Partially hydrolyzed polyacrylamide
		PAM	Polyacrylamide
		ppb	Pounds per barrel
		ppg	Pounds per gallon
		PV	Plastic viscosity
		PPP	Potato peel powder

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SBF	Synthetic-based fluid
WBF	Water-based fluid
$\tau$	Shear stress
$\tau_y$	Yield stress
$\gamma$	Shear rate
$\mu_p$	Plastic viscosity

## Introduction

During the well constructing process, drilling fluid (mud) is circulated into the well to perform several crucial functions: transporting drill cuttings to the surface for removal, stabilizing the wellbore wall, controlling formation pressure, and cooling and lubricating the drill string (Al-Hameedi et al. 2020; Bageri et al. 2020). Generally, drilling fluids are categorized into three main groups: water-based fluid (WBF), synthetic-based fluid (SBF), and oil-based fluid (OBF). Of these, WBF is the most applicable due to being environmentally friendly (Akkouche et al. 2020; Kiani et al. 2019; Ozyurek and Bilkay 2018; Rana et al. 2020; Sun et al. 2020), cost-effective, and easy to prepare and maintain (Dejtaradon et al. 2019; Moslemizadeh et al. 2017; Rana et al. 2020; Razali et al. 2018). There are three crucial factors that must be considered in fluid selection: environmental effects, technical performance, and cost.

The operational conditions (pressure and temperature) of the well in which drilling fluids are circulated directly affect their technical performance. Due to the depletion of conventional reservoirs today, there is an increasing demand to drill deeper formations under elevated temperature and pressure conditions to access and produce from unconventional reserves (Amani et al. 2012; Bageri et al. 2020). Hence, designing and preparing an appropriate drilling fluid with stable properties under such operational conditions is one of the remarkable tasks of mud engineers (Ekeinde et al. 2019; Ibrahim et al. 2017). In this regard, the two main properties of drilling fluids, steady shear flow (rheological) behavior and filtration (fluid loss), are meticulously engineered to ensure the success of the drilling operation (Li et al. 2015; Mohamadian et al. 2019).

During drilling and tripping operations, due to differential pressure existing between the wellbore fluid and fluid occupying formation, the liquid phase of the drilling fluid can become separated and invade the formation. This process of water invading permeable and porous formations is known as water or fluid loss (Caenn et al. 2011). Failure to design a fluid with minimum loss of fluid into the surrounding formation might lead to severe issues, including the formation of a highly thick filter (mud) cake, superfluous drag and torque, increased likelihood of differential pressure sticking, high surge and swab pressure, significant increase in equivalent circulating density, formation damage, and well productivity

reduction (Amanullah and Yu 2005; Yuxiu et al. 2016). Consequently, designing a drilling fluid with desirable fluid loss behavior is critical for the drilling operation. To do so, formulating a drilling fluid with the capability of depositing a thin impermeable mud cake on the wellbore wall is suggested (Davoodi et al. 2019). The rheological characteristics of drilling fluid, such as viscosity and yield point, are hugely important, and determine the capability of drilling fluid to carry drill cuttings and clean the well (Davoodi et al. 2019; Sadeghalvaad and Sabbaghi 2015).

Thus far, various chemicals and polymers have been employed in the drilling industry, providing fluids with relatively suitable rheological and filtration behaviors (Amanullah et al. 1997; Davoodi et al. 2018). Polyacrylamide (PAM), carboxymethyl cellulose (CMC), carboxymethyl starch (CMS), partially hydrolyzed polyacrylamide (PHPA), polyacrylates, and polyanionic cellulose (PAC) are some examples of polymeric additives widely recommended and used in the drilling industry (Agin et al. 2019; Ghaderi et al. 2019; Li et al. 2015; Mohamadian et al. 2018; Nunes et al. 2014); however, the low performance, instability, and degradation of polymeric additives under extreme temperatures limit their use in deep drilling (Ahmadi et al. 2015; Weaver et al. 2003). In addition to this operational drawback, the application of these additives leads to a dramatic increase in the preparation cost of drilling fluid that will in turn impose a high cost on oil and gas well drilling operations (Ahmadi et al. 2015; Amanullah et al. 2016; Davoodi et al. 2018, 2019; Hossain and Wajjheuddin 2016). Furthermore, it has been highlighted in several studies that commercial additives and chemicals may have harmful short- and long-term effects on the surrounding environmental ecosystems (Amanullah et al. 2016; Ghaderi et al. 2020; Rae and Di Lullo 2001; Tehrani et al. 2009). Due to these risks, drilling fluid additives selection has become much more complex regarding both technical and environmental aspects, considering that protecting environmental ecosystems is more urgent than the exploration and extraction of hydrocarbon (Hossain and Wajjheuddin 2016). Consequently, local, biodegradable, green, non-toxic, and natural additives have appeared to be a proper solution for reducing and minimizing the negative impacts of drilling fluids on the environment. These materials have been primarily employed in drilling fluids to prevent lost circulation. Cocoa bean shells (Green 1984), rice fractions (Burts Jr 1997), and date tree trunk fibers (Ramasamy and Amanullah 2017) are three instances of these indigenous, eco-friendly, green waste lost circulation materials, having been used in or proposed for drilling fluid. The successful application of natural lost circulation materials in drilling fluids has raised the attention given to applying these materials as indigenous environmentally friendly materials in drilling fluid for mitigating filtration and modifying rheological behavior (Davoodi et al. 2018; Ghaderi et al. 2020).



Over the past few years, a handful of studies have examined the application of micronized natural green materials and their efficiency in drilling fluid as a low-cost, environmentally friendly filtration control agent. For instance, Amanullah et al. (2016) have studied the impact of powdered date seed on the filtration property of a WBF system under high-pressure, high-temperature (HPHT) and low-pressure, low-temperature (LPLT) conditions. The results of their study revealed that powdered date seed improves the filtration properties of the WBF. Movahedi et al. (2017) have researched the effect of hydrated basil seeds on the hole cleaning capacity of WBFs. Their results revealed that the hydrated basil seeds were able to modify rheology and improve the fluid's cutting carrying capacity. Davoodi et al. (2018) have carried out a study on the potential use of pistachio shell powder as an additive to control fluid loss behavior in a field-applicable WBF. They observed that the new fluid loss controller dramatically decreased the LPLT and HPHT filtration volumes and enhanced the fluid's rheology. Al-Hameedi et al. (2020) examined the impact of powdered grass on the fluid loss and rheological properties of WBFs and compared its efficiency with starch. Their results showed that the grass powder was much more efficient at controlling fluid loss than starch. The 5% grass powder fluid displayed a 42% and 26% filtration reduction under LPLT and HPHT conditions, respectively; however, the starch was found to be relatively more efficient in improving rheology than the powder. Recently, Al-Hameedi et al. (2020) have proposed another biodegradable green additive, potato peel powder (PPP), for application in water-based drilling fluid. They performed comprehensive laboratory testing on water-based drilling fluids connoting four different amounts of PPP application. The outcome of their studies demonstrated that PPP was able to effectively decrease filtration properties and act as a thinner. However, in the study the applicability of PPP was not justified in terms of technical performance, as the ability of PPP with which it controls filtration was not compared with traditional additives used in drilling fluids.

There are approximately 600 different species of oak tree growing in various parts of the world including Asia, America, South Africa, and Europe. This tree is one of the most abundant plant species in Iran, where oak forests cover the main part of the Zagros Mountains and produce thousands of tons of acorn annually. Although acorn has been used globally in folk medicine, tanneries, human nutrition, and animal feed in throughout history (Cantos et al. 2003; Claudia 2013; Lopes and Bernardo-Gil 2005; Nieto et al. 2002; Papoti et al. 2018), its shell is a very low-cost forest waste material (Celebi and Gök 2017).

Considering the aforementioned drawbacks of traditional polymeric additives as well as the increasing demand for green, eco-friendly, and cost-effective drilling fluid additives, the present study is aimed at the introduction of

a novel green additive, acorn shell powder (ASP), into a WBF system as both a fluid loss (filtration) controller and rheology modifier. The ASP with four different concentrations was introduced into a WBF; the efficiency of ASP in enhancing the drilling fluid characteristics was then evaluated with respect to the filtration property under HPHT and LPLT conditions as well as rheological characteristics. The efficiency and applicability of ASP as a fluid loss additive was confirmed by comparing its ability to mitigate filtration and modify rheology with those of four traditional additives, including starch, low-viscosity polyanionic cellulose (PAC-LV), CMC, and CMS. Finally, as cost is a key factor playing an important role in decision-making regarding drilling fluid selection, a financial impact assessment was conducted on the studied drilling fluid systems to demonstrate how the employment of ASP could assist in cost reduction. This study was conducted in laboratories at Tomsk Polytechnic University and Sharif University of Technology between 2019 and 2020.

## Materials and methods

In this section, a description of the materials and methods used for making and testing the drilling fluid systems is provided. The drilling fluid testing conducted in this study was performed in accordance with the field testing practice 13B-1 recommended by the American Petroleum Institute (API) in 2009 for water-based fluids.

### Materials

The components used to prepare the drilling fluids are as follows: acorn shells, freshwater, limestone (lime, AO «Вектон», purity  $\geq 99\%$ ), sodium chloride (NaCl, AO «Вектон», purity  $\geq 98\%$ ), sodium carbonate ( $\text{Na}_2\text{CO}_3$ , ООО «Реахим», purity  $\geq 98\%$ ), sodium hydroxide or (NaOH, AO «Вектон», purity  $\geq 99\%$ ), potassium chloride (KCl, AO «Вектон», purity  $\geq 98\%$ ), xanthan gum (Yanxing, purity  $\geq 95\text{--}98\%$ ), CMS (MI SWACO, purity  $\geq 78\%$ ), CMC (THC, purity  $\geq 99\%$ ), starch (Распак, purity  $\geq 97\%$ ), and PAC-LV (MI SWACO, purity  $\geq 72\%$ ).

### Testing equipment

The equipments used for preparing the ASP and fluid samples and investigating the properties of drilling fluids include the following: a laboratory miller (Vilitek, model VLM-8), HPHT filter press (Ofite, model 171-00-C), LPLT (API) filter press (Fann, Series 300), rotational viscometer (Ofite, model 900), a mixer (Hamilton Beach, model HMD 400), weighing balance (Ohaus, model PA214C), wire mesh, digital pH meter (Измерительная техника, pH-150MI), and



digital caliper (Autocraft, model AC507). The equipments used for characterizing the ASP sample include: a Fourier transform infrared (FTIR) spectroscopy (Bruker, model Tensor 27), energy-dispersive X-ray (EDAX) spectrometer (Oxford Instruments), field emission scanning electron microscope (FE-SEM, TESCAN, model MIRA3), and an inductively coupled plasma–optical emission spectrometer (ICP–OES, Varian, model 730-ES).

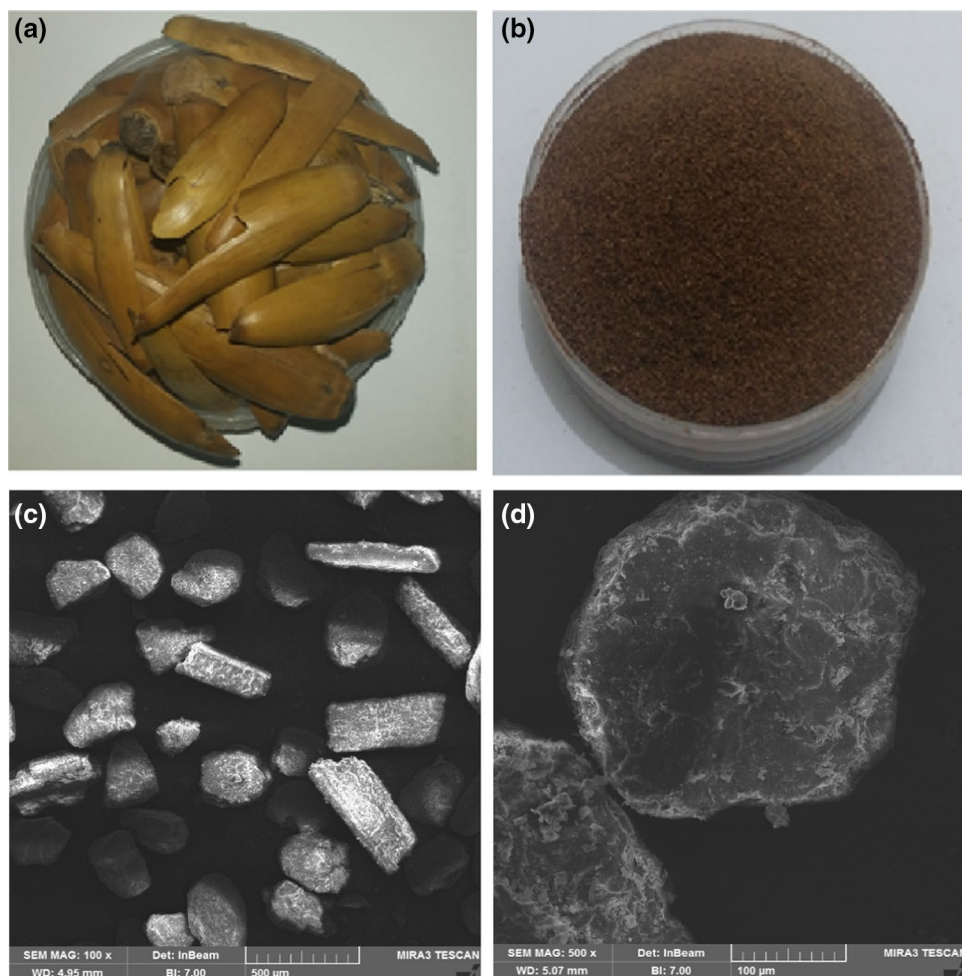
### Preparation and characterization of ASP

The acorns were obtained from the Iranian Oak tree, a species of oaks growing in the southwestern part of the Zagros Mountains in Iran. A thermo-physical method was used to prepare the ASP sample. First, the acorns were washed to remove dirt from their external shells and dried at room temperature. The dry acorns were then broken, and the shells and seeds were separated. Next, the shells were milled by the laboratory grinder and a sieve analysis was conducted to isolate the ASP particles ranging in size between 100 and 350  $\mu\text{m}$ . Finally, to remove moisture, the prepared powder was placed in an oven and dried at 85  $^{\circ}\text{C}$  for 12 h. The

prepared ASP sample was brown in color with a density of 0.75–0.85 g/cc. As for solubility, the ASP was insoluble in water and partially and highly soluble in the concentrated hydrochloric acids, HCl 15% and HCl 28%, respectively. The chemical and morphological properties of the prepared ASP sample were then assessed using the FTIR, 70-element ICP, EDX, FESEM tests. The FTIR, EDX, and FESEM tests were carried out according to procedures used by Ghaderi et al. (2019), and the ICP test was performed following the Test Method 6010D, as recommended by the Environmental Protection Agency (EPA) in 2018.

Figure 1 illustrates the acorn shells before and after milling and presents FE-SEM micrographs of the ASP taken at different magnifications. The micrographs show that the ASP sample is composed of irregularly shaped particles of varying sizes ranging approximately between 100 and 350  $\mu\text{m}$ . Figure 1c shows that ASP may have a porous structure on a mesoscale, which can affect its colloidal behavior in drilling fluid.

**Fig. 1** Acorn shells and FESEM micrographs of ASP: **a** before milling, **b** after milling (ASP sample), **c** ASP micrograph at 100 $\times$ , and **d** ASP micrograph at 500 $\times$





### Drilling fluid system preparation

In this study, a WBF formula was designed to achieve a fluid density ranging from 10.30 to 10.50 lb per gallon (ppg) and a pH value of 9.50. To prepare the base fluid (BF), first Na<sub>2</sub>CO<sub>3</sub> and NaOH were added to a cup containing 350 mL of freshwater; the solution was stirred for 10 min. Next, NaCl and KCl were added to the fluid and stirred for 10 min. Once the salts were thoroughly dissolved, the xanthan polymer was added to the solution and stirred for 15 min. To reach the target density, the BF density was then increased by adding 60 g of lime to the solution and mixing for 15 min. Afterward, two groups of fluids were prepared by adding the proposed green additive (ASP) and the traditional additives (CMC, CMS, starch, and PAC-LV). The first group (Batch A) included four drilling fluid systems, A1, A2, A3, and A4, with different amounts of ASP and was designed to appraise the impact of ASP concentration on the fluid filtration and rheology properties. The second group (Batch R) was designed to compare ASP’s efficiency in improving fluid properties with the efficiency of traditional additives. This group included four reference fluids, R1, R2, R3, and R4, containing 9 lb per barrel (ppb) of CMC, CMS, starch, and PAC-LV, respectively. Table 1 shows the formulated drilling fluid systems and their components with the corresponding concentration.

### Filtration testing

The filtration behaviors of the fluid systems were studied under two different conditions: API (LPLT) and HPHT. To evaluate the filtration behavior of the fluids under low-pressure, low-temperature conditions (100 psi and ambient temperature), an Ofite LPLT filter press was utilized. HPHT fluid loss testing was conducted at 250 °F and 500 psi using an Ofite HPHT filter press.

**Table 1** Components of drilling fluid systems and their corresponding concentration

Fluid component	Unit	BF	Batch A				Batch R			
			A1	A2	A3	A4	R1	R2	R3	R4
Freshwater	bbbl	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Lime	ppb	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
NaCl	ppb	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
NaOH	ppb	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
KCl	ppb	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
Xanthan gum	ppb	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Na <sub>2</sub> CO <sub>3</sub>	ppb	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
ASP	ppb	–	3.0	5.0	7.0	9.0	–	–	–	–
CMC	ppb	–	–	–	–	–	9.0	–	–	–
CMS	ppb	–	–	–	–	–	–	9.0	–	–
Starch	ppb	–	–	–	–	–	–	–	9.0	–
PAC-LV	ppb	–	–	–	–	–	–	–	–	9.0

### Rheological testing and modeling

The rheology of fluids is measured by the relation between the shear stress and shear rate of the fluids. Drilling fluids mostly display a non-Newtonian behavior, in which shear stress is not directly proportional to the shear rate. Thus far, several rheological models have been mathematically established to characterize the flow behavior of drilling fluids, including the Herschel–Bulkley (HB), power-law, and Bingham plastic (BP) models, which have been used widely throughout the drilling industry (Becker et al. 2003; Nasiri and Ashrafizadeh 2010).

In this study, the HB and BP models were chosen for describing the drilling fluid systems’ rheology, since the studied fluid systems demonstrated a non-Newtonian behavior. The BP model can be described as a two-parameter model established to describe the non-Newtonian fluids’ characteristics (Lauzon and Reid 1979). Fluids with a behavior matching the BP model require a certain minimum stress to be inserted to start flowing, known as “yield stress,” with the assumption that shear stress is directly proportional to shear rate (Bourgoyne Jr et al. 1991; Caenn et al. 2011; Hamad et al. 2019). This model has been commonly used because of its simplicity in visualizing and accommodating yield stress, which is found in most drilling fluids and cement pastes (Viloria Ochoa 2006). The BP model is expressed by the mathematical expression displayed in Eq. 1:

$$\tau = \mu_p(\dot{\gamma}) + \tau_y \tag{1}$$

where  $\dot{\gamma}$  stands for the shear rate (measured in sec<sup>-1</sup>),  $\tau$  and  $\tau_y$  represent shear and yield stresses (measured in lb/100 ft<sup>2</sup>), respectively, and  $\mu_p$  stands for the plastic viscosity (PV) and is measured in centipoise (cP).

The HB model is another mathematical model established to define non-Newtonian fluids’ behavior in a nonlinear way. The HB model, which considers both the shear-thinning

behavior and yield stress of fluid, uses three parameters for determining the rheology of fluids. These parameters are yield stress ( $\tau_y$ ), consistency index ( $K$ ), and flow index ( $n$ ) (Bourgoyne Jr et al. 1991; Hamad et al. 2019; Herschel 1924; Vilorio Ochoa 2006). The HB model is expressed by the mathematical expression displayed in Eq. 2:

$$\tau = \tau_y + K(\dot{\gamma})^n \quad (2)$$

The shear stress value for the HB model can be obtained by Eq. 3

$$\tau_y = 2\theta_3 - \theta_6 \quad (3)$$

where  $\theta_6$  and  $\theta_3$  denote the dial reading values at 6 and 3 rpm rotor speeds. These speeds indeed represent shear stresses at the 5.11 and 10.22  $s^{-1}$  shear rates, respectively. The procedure of testing and modeling the rheology of fluid systems is briefly described in the following section.

The values of shear stress for the prepared fluid systems at different shear rates range from 5.11 to 1021.8  $s^{-1}$  by means of the rotational viscometer. Next, the rheological parameters for each of the studied models were computed using Eqs. 1–3. To investigate the steady shear flow behavior, the rheograms of the fluid systems were fitted by the BP and HB models, in which the suitability of the model was investigated by the coefficient of determination (R-squared value). Finally, the parameters of the model which was best fit to the experimental data were chosen for analyzing the rheological behavior of the investigated fluids. To ensure the accuracy of the measurements and validate the experimental data, the experiments were repeated three times and the relative uncertainty of the measurements was computed and reported for the studied fluid systems.

## Results and discussion

### ASP characterization

#### FTIR analyses of ASP

The FTIR spectrum for the ASP is presented in Fig. 2. ASP displayed the absorption peaks of components mainly corresponding to cellulose, lignin, and hemicellulose. The broad absorption band at 3412  $cm^{-1}$  corresponded to the hydroxyl groups (O–H) (Doshi et al. 2014; Prieto-García et al. 2019; Reddy et al. 2012). The presence of carboxylic acids and alkenes was confirmed by the absorption band observed at 2928  $cm^{-1}$  attributing to the O and  $CH_2$  and  $CH_3$  asymmetrical and symmetrical stretching vibrations. It should be noted that the peaks observed at 3412 and 2928  $cm^{-1}$  are a strong indication that cellulose and hemicellulose are present in the acorn shell (Naik et al. 2010; Thipkhunthod et al. 2007). The peak at 1736  $cm^{-1}$  originated from the carbonyl group, which is another indication that hemicellulose is present (Pandey 1999; Reddy et al. 2012). Furthermore, the peaks at 1618 and 1516  $cm^{-1}$  are attributed, respectively, to the aldehyde and aromatic skeleton vibration, showing the unique characteristic of lignin. In addition, the absorption peaks at 1405 and 1329  $cm^{-1}$  corresponded to the asymmetrical stretching mode of the  $CH_2$  present in lignin and the O–H in-plane bending (Doshi et al. 2014; Mwaikambo and Ansell 2002; Prieto-García et al. 2019). The C–O–C asymmetrical stretch corresponding to the ester groups existing in hemicellulose was noticed at 1180  $cm^{-1}$  (Lei et al. 2008; Liu et al. 2009; Reddy et al. 2012), while the peak observed at 1045  $cm^{-1}$  was produced by C–O stretching vibrations,

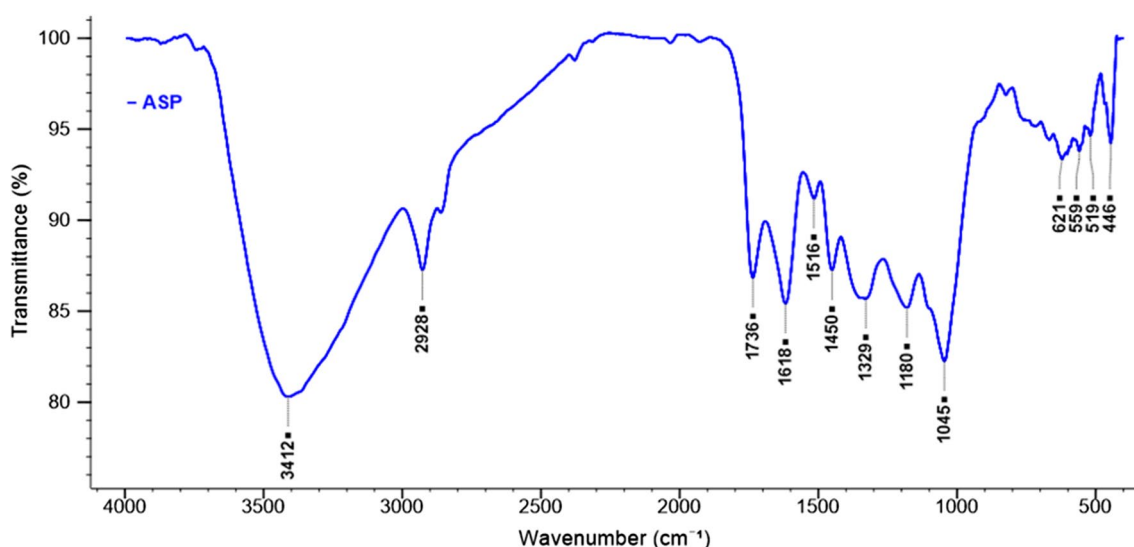


Fig. 2 FTIR spectrum of the ASP sample



reflecting the presence of polysaccharides or cellulose (Lei et al. 2008; Pandey and Pitman 2003). Finally, the vibrations observed in the region of 500–850  $\text{cm}^{-1}$  could be partially attributed to the C–X vibration of alkyl halide functional groups, where X could be Cl or Br.

### Elemental analysis of ASP

The characterization test results demonstrated that the major chemical elements present in ASP detected by the ICP test are sodium (0.13 wt%), magnesium (0.47 wt%), phosphorus (0.47 wt%), potassium (0.36 wt%) and calcium (0.22 wt%), zinc (0.07 wt%), and sulfur (0.06 wt%), which collectively comprise about 1.73% of the sample’s total weight. The remaining weight percentage is related to C, H, O, N, and halogens which cannot be measured by the ICP method.

Figure 3 shows the EDAX spectrum of the ASP sample and the identified chemical elements with their corresponding mass fractions. According to the results of EDAX analysis, the ASP sample was mainly composed of ten chemical elements, among which oxygen, carbon, and nitrogen with a weight percent of 41.3, 48.53, and 9.22%, respectively, were the major chemical elements existing in the ASP compound.

### Assessment of rheological properties

#### Impact of ASP concentration on fluid rheology

In this study, to monitor the effect of ASP concentration on the rheological characteristics of water-based fluids, the steady rheological flow behavior was investigated for fluids containing 3–9 ppb of ASP. The rheograms for the BF and

the fluid systems with 3, 5, 7, and 9 ppb of ASP (A1 to A4) are plotted in Fig. 4.

The trend observed for the curves of the shear stress–shear rate (Fig. 4) demonstrates that the BF and fluid systems with ASP all exhibited shear-thinning behavior. It can be noticed that an incremental increase in the concentration of ASP results in an increase in the shear stress value. For instance, at a shear rate of 1021.8  $\text{s}^{-1}$ , the fluid systems with 3, 5, 7, and 9 ppb of ASP displayed shear stress values of 30.41, 34.46, 42.25, and 49.93  $\text{lb}/100 \text{ft}^2$ , whereas that of the BF was 25.39  $\text{lb}/100 \text{ft}^2$ . The increased shear stress value for the fluid systems with ASP is an indication of increased viscosity, which improves the capability of a fluid to carry drilled rock fragments from the wellbore (Ghaderi et al. 2020; Li et al. 2015).

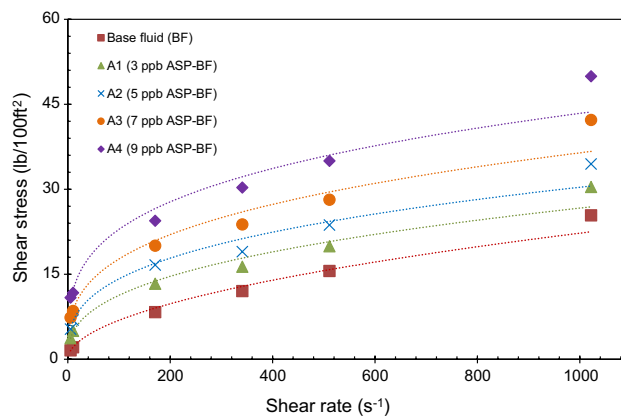
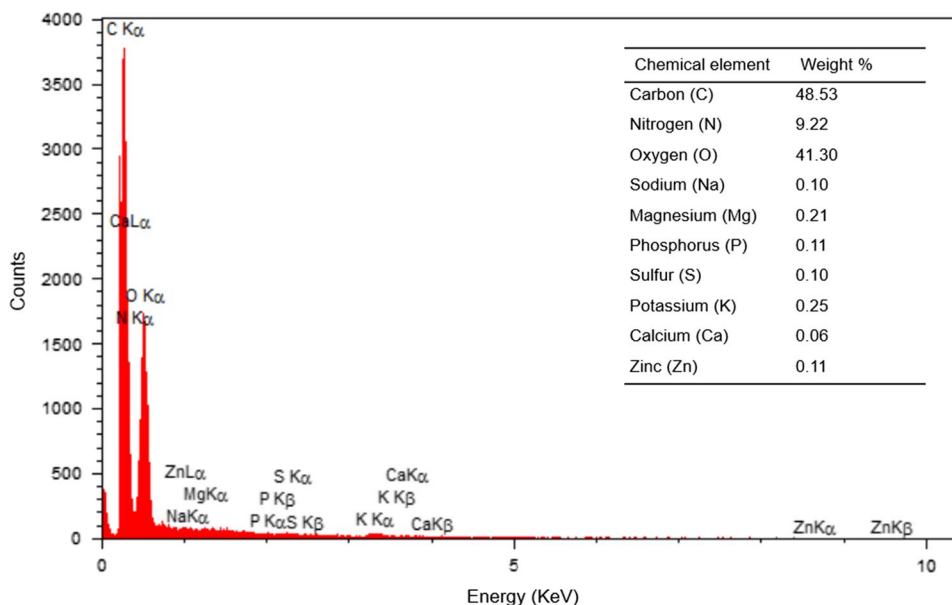


Fig. 4 Rheograms for BF and fluids with 3 to 9 ppb of ASP

Fig. 3 EDAX spectrum of ASP and identified chemical elements with their corresponding weight percentage



The rheological parameters calculated by the BP and HB models and the *R*-squared values for each model fitted to the experimental data are presented in Table 2.

The HB model, which considers both the yield stress and shear-thinning behavior of mud, displayed a more desirable fit for the rheograms in comparison with the BP model, as indicated by the higher *R*-squared values (closer to 1). Therefore, the rheology performance of the drilling fluid systems was examined based on the HB model and its rheological parameters. As previously mentioned, the HB model determines fluid rheology using three parameters: yield stress, *K*, and *n*. A comparison of the yield stress values of the BF with those of ASP-contained fluids (A1–A4) revealed that the introduction of ASP into the fluid system considerably enhanced the yield stress. The BF had a yield stress value of 1.08 lb/100 ft<sup>2</sup>, whereas the fluids with 3, 5, 7, and 9 ppb of ASP (A1–A4) had yield stress values of 2.45, 3.73, 4.91, and 6.72 lb/100 ft<sup>2</sup>, respectively. Similarly, the increasing ASP concentration enhanced the consistency index, which increased from 0.28 to 0.61, 0.80, 1.40, and 1.65 with the addition of 3, 5, 7, and 9 ppb of ASP into the BF, respectively. Drilling engineers use fluid yield stress and *K* to predict the fluidizing ability of drilling fluids in addition to cutting transport capacity and hole cleaning efficiency. Generally, high *K* leads to high fluid viscosity and high cutting transport capacity, resulting in superior hole cleaning (Bageri et al. 2020; Li et al. 2015) and a higher rate of penetration (ROP). *n* is another rheological parameter of the HB model that provides insight into fluid behavior, where *n* > 1 represents shear-thickening fluid (dilatant fluid) and *n* < 1 denotes shear-thinning fluid (pseudoplastic fluid) (Hamad et al. 2020). Based on the values of *n* shown in Table 2, all prepared fluid systems displayed shear-thinning behavior. As for the effect of ASP on *n*, the addition of ASP into the BF led to a slight reduction in the value of *n* of the fluid. According to the results observed from rheological testing and modeling, it can be concluded that the incorporation of ASP into the BF enhanced its rheological properties, indicating an improved wellbore cleaning performance.

### Comparison of ASP efficiency with traditional drilling fluid additives

To compare the ASP efficiency in enhancing rheology with fluid loss reducers and rheology enhancers commonly used in the drilling industry, CMS, CMC, starch, and PAC-LV were selected as the reference additives. Since the most effective rheological properties for ASP-contained fluids were observed at a 9 ppb of ASP (A4), this concentration was selected as the reference concentration. Four reference fluids (R1, R2, R3, and R4) were prepared by adding 9 ppb of CMS, CMC, starch, and PAC-LV to the BF, respectively (see the formulation of the fluid systems in Table 1). The rheological parameters calculated using the HB model for fluid A4 and the reference fluids are summarized in Table 3.

The reference fluids (R1–R4) also presented shear-thinning behavior as their flow indices were less than 1. The value of *K* for the fluid with 9 ppb of ASP was 1.65, whereas those of the fluids with 9 ppb CMC and PAC-LV (fluids R1 and R4) were 1.85 and 2.36, respectively. As previously mentioned, a high value of *K* leads to high viscosity; therefore, the higher values of *K* observed for fluids R3 and R4 demonstrated that CMC and PAC-LV were both more influential than ASP in modifying the fluid rheology. It is worth noting that the cost of ASP can be a fraction of those associated with CMC and PAC-LV. The fluids with 9 ppb of CMS (R2) and 9 ppb of starch (R3) had a *K* value of 1.37 and 1.22, respectively, which were slightly lower than that of A4, suggesting that the ASP had a better and comparable capacity in modifying rheology than CMS and starch. Regarding the accuracy of the rheological measurements, the maximum

**Table 2** Calculated rheological parameters for BF and fluid systems with ASP

Fluid systems	BP model			HB model			
	$\tau_y$ (lb/100ft <sup>2</sup> )	$\mu_p$ (cP)	<i>R</i> <sup>2</sup>	$\tau_y$ (lb/100ft <sup>2</sup> )	<i>K</i>	<i>n</i>	<i>R</i> <sup>2</sup>
BF	3.99	11.20	0.9676	1.08	0.28	0.65	0.9849
A1 (3 ppb ASP-BF)	6.17	12.07	0.9545	2.45	0.61	0.54	0.9913
A2 (5 ppb ASP-BF)	8.29	13.07	0.9439	3.73	0.80	0.52	0.9885
A3 (7 ppb ASP-BF)	10.37	15.80	0.9525	4.91	1.40	0.47	0.9898
A4 (9 ppb ASP-BF)	14.12	17.71	0.9454	6.72	1.65	0.45	0.9853

**Table 3** Calculated rheological parameters for the reference fluids and fluid with 9 ppb concentration of ASP

Fluid systems	<i>K</i>	<i>n</i>	$\tau_y$ (lb/100ft <sup>2</sup> )	<i>R</i> <sup>2</sup>
A4 (9 ppb ASP-BF)	1.65	0.45	6.72	0.9853
R1 (9 ppb CMC-BF)	1.85	0.47	9.98	0.9827
R2 (9 ppb CMS-BF)	1.37	0.48	6.22	0.9825
R3 (9 ppb starch-BF)	1.22	0.53	5.73	0.9903
R4 (9 ppb PAC-LV-BF)	2.36	0.46	9.63	0.9831



relative uncertainty observed for the rheological measurements was about 4.8%.

### Assessment of filtration properties

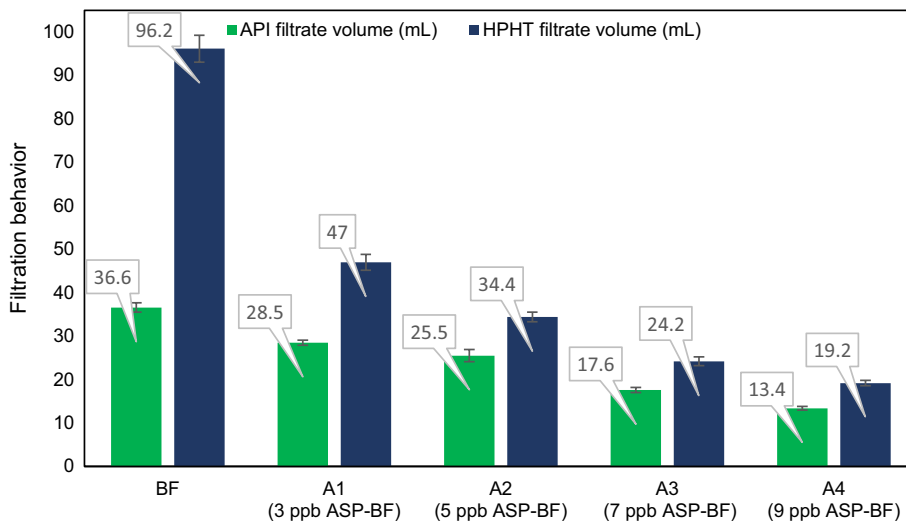
#### Impact of ASP concentration on the API and HPHT filtrations

Figure 5 shows the total volume of API filtrate for the BF and fluid systems containing 3, 5, 7, and 9 ppb of ASP (A1 to A4). It can be clearly observed that the addition of ASP into the fluid system led to a reduction in both the API and HPHT filtration properties, where the volume of API and HPHT filtrates gradually decreased as the ASP concentration increased from 3 ppb to 9 ppb. The volume of API filtrate

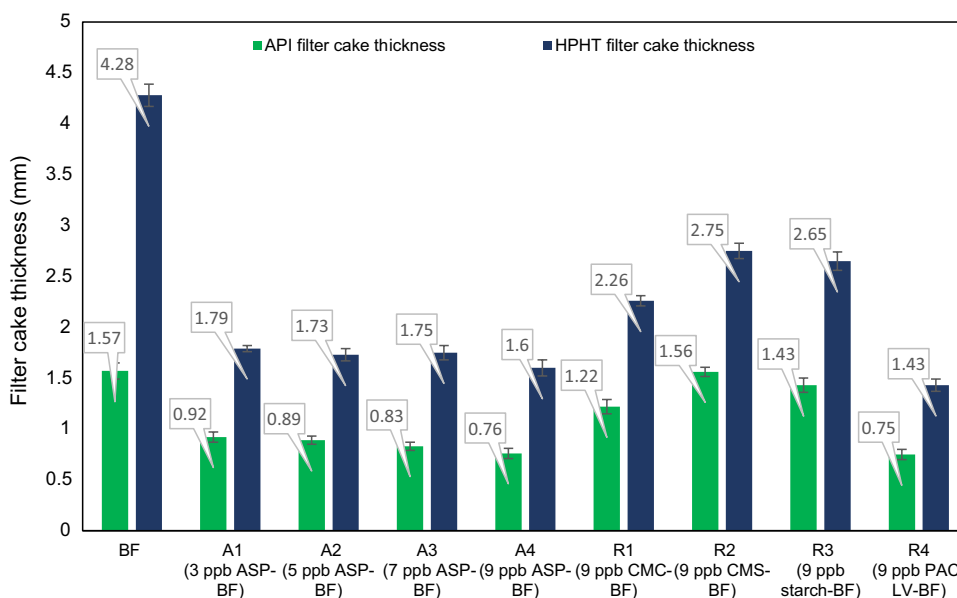
collected for the BF was 36.6 mL, whereas those of the fluids with 3, 5, 7, and 9 ppb had volumes of 28.5, 25.5, 17.6, and 13.4 mL, displaying a decrease of 22.1, 30.3, 51.9, and 63.3%, respectively, when compared to the BF. Regarding HPHT filtration behavior, the incorporation of 3, 5, 7, and 9 ppb of ASP into the BF decreased the volume of HPHT filtrate by 51.1, 64.2, 74.8, and 80.1%, respectively, in comparison with the BF.

Figure 6 displays the thickness of the mud cake developed by the investigated fluid systems. It can be noticed that the thickness of the filter cake deposited by the BF was 1.57 and 4.28 mm for the HPHT and API filtration tests, respectively. Highly similar to the filtration results, the incorporation of ASP into the fluid system reduced mud cake thickness, whereas the fluid systems with ASP (A1 to A4) developed

**Fig. 5** Comparison of API and HPHT filtration behavior for BF and fluids with different ASP concentrations



**Fig. 6** API and HPHT filter cake thickness comparison for investigated fluid systems



filter cakes with a thickness of less than 1 mm under API conditions and less than 2 mm under HPHT conditions.

Overall, the HPHT and API filtration measurements indicated that the addition of ASP into the fluid system resulted in a significant reduction in both filtration behaviors (HPHT and API) as well as a thin, compact, low-permeability filter cake. The notable decrease in API and HPHT filtrate volume observed for the fluids with ASP (A1–A4) verifies the low permeability and high quality of the filter cake. The improvement observed in the filtration properties could be due to: (1) enhancement of fluid viscosity in the presence of ASP, resulting in a decreased fluid loss rate, and (2) the deposited ASP particles in the filter cakes acted as a coat, thus closing the gaps and flowing paths of fluid filtrate, thereby decreasing the filter cakes' permeability as well as the filtration rate (Davoodi et al. 2018; Li et al. 2015). Oseh et al. (2019) have stated that deep filtrate invasion into a formation resulting from the deposition of low-quality filter cakes on the wellbore wall may lead to serious damage to the reservoir, which can reduce the production rate of oil and gas wells. Therefore, it can be speculated that the ability of ASP to mitigate filtration and develop high-quality filter cakes could help reduce formation damage, thereby enhancing production rate.

#### Comparison of ASP efficiency in filtration controlling with traditional additives

Figure 7 presents the total volume of API and HPHT filtrates for the fluid with 9 ppb of ASP (A4) and reference fluids (R1, R2, R3 and R4), which contained similar concentrations of CMC, CMS, starch, and PAC-LV, respectively.

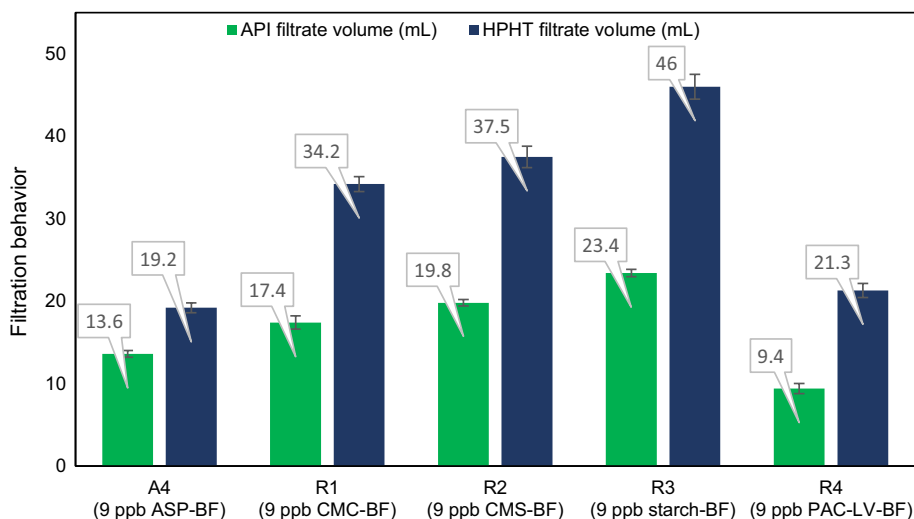
Comparing the volume of API filtrate collected for the reference fluids with that of fluid A4 demonstrates that the ASP displayed a slightly better efficiency in mitigating the filtration when compared with the CMC, CMS, and starch;

however, the PAC-LV was more efficient than the ASP in controlling filtration, considering it had an API filtrate volume of 9.4 mL, which is less than that of the fluid with 9 ppb of ASP. Interestingly, when the fluid systems were exposed to the HPHT conditions (500 psi and 250 °F), the volume of filtrate collected from the fluids with CMC, CMS, and starch (R1, R2, and R3) was much higher than that of the fluid with ASP (A4), which could be attributed to the low tolerance of the biopolymers and their degradation under HPHT conditions. The HPHT filtrate volume collected was 34.2, 37.5, and 46.0 mL for fluid R1, R2, and R3, respectively, while fluid A4 had a volume of 19.2 mL, suggesting that ASP was much more efficient than the traditional polymers in controlling filtration under HPHT conditions. Contrary to the API condition under which PAC-LV displayed a relatively better capability in mitigating filtration, the fluid with PAC-LV (R4) presented 21.3 mL of HPHT filtrate, which was slightly higher than the ASP-contained fluid (A4). Regarding filter cake thickness, laboratory data (see Fig. 6) show that the ASP was better than CMC, CMS, and starch in terms of developing a thin low-permeability filter cake; however, as expected, PAC-LV was more efficient than ASP in depositing a thin low-permeability filter cake. The comparison of ASP's efficiency with the traditional polymers commonly applied in drilling fluid to control filtration also justified the applicability of employing ASP in drilling fluids as a low-cost, eco-friendly filtration controller agent. Finally, it should be noted that the highest relative uncertainty observed for the filtration measurements was 6.4%.

#### Financial impact assessment

Importing drilling fluid additives imposes a large financial burden on the drilling industry of developing countries. For instance, the financial assessment of drilling fluid additives imported from overseas by the Kingdom of Saudi Arabia

**Fig. 7** Comparison of API and HPHT filtration behavior for reference fluids and fluid with 9 ppb ASP concentration



demonstrated that the cost spent solely on importing fluid loss reducer additives was approximately 50 million dollars in 2012 (Amanullah et al. 2016). As a result, employing potential natural, low-cost, green waste material in drilling fluid has come into consideration.

Analysis of the results obtained from the drilling fluid systems testing conducted in this study highlights the promising capability of the proposed green additive in reducing fluid loss under both conditions (HPHT and LPLT) as well as enhancing rheological and mud cake characteristics, indicating that employing ASP as a filtration reducer in drilling fluid is technically acceptable. Because cost is another crucial parameter in making the decision to employ an additive in drilling fluid, the preparation cost for all the studied fluids

was assessed, and that of ASP-contained fluids was compared with those of fluids containing traditional additives. The actual cost of the components used in the studied fluid systems in two scales (cost/metric ton and cost/lb) and their corresponding concentration are presented in Table 4. The actual costs required for preparing one barrel of each fluid system is displayed in Fig. 8.

The actual cost of the BF was \$13.13/bbl. Comparing the cost spent on preparing the BF with the ASP-contained fluids (A1–A4) demonstrates that the addition of ASP into the BF led to a slight change in the fluid cost. For instance, the specific cost for fluid A4, which contained the highest amount of ASP (9 lb), was only \$13.54/bbl. The actual cost, however, increased dramatically when the traditional fluid loss reducers were added to the fluid, where at the same concentration of 9 ppb, the actual cost for fluids with CMC, CMS, starch, and PAC-LV (R1–R4) were \$25.38, \$18.03, \$16.81, and \$20.07 per barrel, respectively. The conducted cost analysis revealed that the incorporation of ASP into drilling fluid systems could effectively decrease fluid preparation costs, where the actual cost of the fluid A4 (9 ppb of ASP) was 46.65, 24.90, 19.45, and 32.53% lower than those of fluids with CMC, CMS, starch, and PAC-LV, respectively.

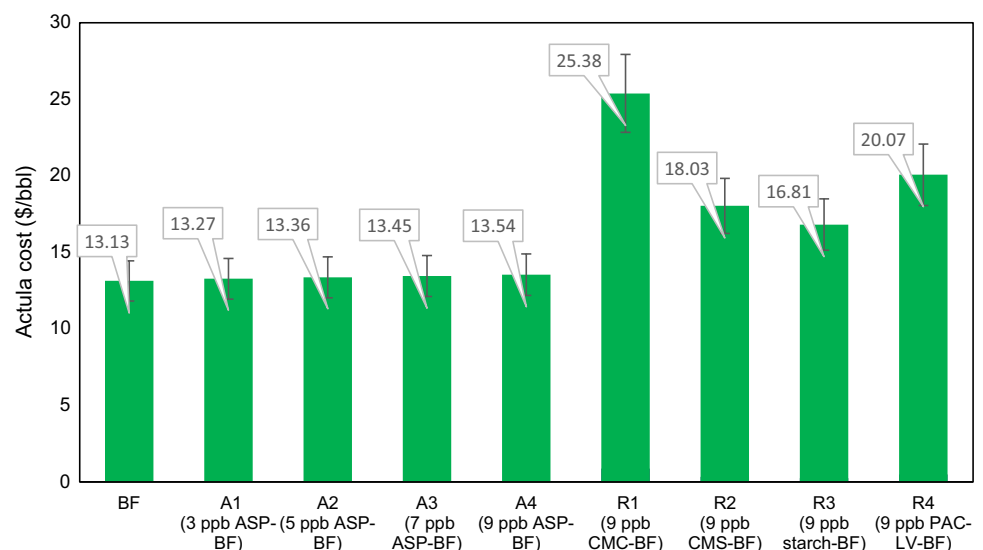
**Table 4** Actual cost of commercial additives and ASP used in drilling fluid systems and their corresponding concentration

Additives	Concentration (ppb)	Actual cost (\$/ton)	Actual cost (\$/lb)
Na <sub>2</sub> CO <sub>3</sub>	0.50	300	0.136
NaOH	0.50	900	0.408
KCl	20.0	75	0.034
NaCl	90.0	55	0.025
XC polymer	0.60	1500	0.680
Limestone	60.0	350	0.159
CMC	9.0	3000	1.361
CMS	9.0	1200	0.544
PAC-LV	9.0	1700	0.771
Starch	9.0	900	0.408
ASP	3.0	100	0.045
	5.0		
	7.0		
	9.0		

### Conclusion

Experimental studies were performed on the introduction of a newly considered green additive, ASP, into a WBF for enhancing its functionality. The findings of the study demonstrated that the incorporation of ASP in the fluid system resulted in considerable improvement in both filtration behavior and rheological characteristics. Regarding the impact of ASP on steady shear flow behavior, all of the investigated fluids exhibited shear-thinning behavior,

**Fig. 8** Comparison of actual cost for studied drilling fluid systems (left to right): BF, fluids with ASP (A1–A4), fluids with traditional additives (R1–R4)



which was described accurately using the HB model. The yield stress and the value of  $K$  for the studied fluids was significantly enhanced with incremental increases in the ASP concentration of the fluid, where the fluid with the highest content of ASP (9 lb) had a yield stress value of 6.72 lb/100 ft<sup>2</sup>, while that of the BF was 1.08 lb/100 ft<sup>2</sup>. The volume of HPHT and API filtrates for the fluid containing 9 ppb ASP were reduced by 63.3% and 80.1% when compared to those of the BF. Moreover, the comparison of ASP efficiency in improving the filtration behavior with four traditional drilling fluid additives exhibited that ASP displayed a comparable efficiency in filtration controlling under LPLT conditions with traditional additives. However, under HPHT conditions, the efficiency of ASP in mitigating filtration was much higher, where the HPHT filtrate volume for the fluid with 9 ppb was 43.8, 48.8, 58.3, and 9.8% lower than those of the reference fluids containing the same amount of CMC, CMS, starch, and PAC-LV. Furthermore, from an economic standpoint, the assessment performed on the actual costs of the studied fluid systems showed that, at the same concentration, the employment of the ASP in the fluid system could result in a reduction in the fluid's actual cost about 19.45–46.65% when compared to those of the fluids containing traditional additives. It is also worth noting that due to its organic nature and using a thermo-physical method to prepare the ASP, the application of this material in drilling fluid would leave no harmful or damaging effects on environmental ecosystems.

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