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# Synthesis and Characterization of Carboxymethyl Cellulose from Kepok Banana Peel Waste for Application as a Water-Based Drilling Mud Additive

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**Abstract**

The oil and gas drilling sector is increasingly exploring bio-based additives to reduce reliance on conventional materials and mitigate their environmental impacts. This study evaluates carboxymethyl cellulose synthesized from Kepok banana peel waste as a filtration-control and rheology-modifying additive for water-based drilling muds. CMC was synthesized through delignification, bleaching, alkalization, and carboxymethylation and characterized using Fourier-transform infrared spectroscopy, X-ray diffraction, and thermogravimetric analysis. Mud rheological properties, filtration loss, mud cake thickness, and density were evaluated following American Petroleum Institute procedures. FTIR confirmed successful carboxymethylation, XRD indicated a semi-crystalline structure with 50.6% crystallinity, and TGA indicated thermal stability up to 180°C. The base mud exhibited an apparent viscosity of 18 cP, a plastic viscosity of 10 cP, a yield point of 16 lb/100 ft², and a filtration loss of 15 mL/30 min. At CMC additions of 3, 6, and 9 g, apparent viscosity increased to 21, 22, and 23 cP; plastic viscosity increased to 13, 13, and 14 cP; and yield point reached 16, 18, and 18 lb/100 ft², respectively. Filtration loss decreased to 12, 11, and 10 mL/30 min, respectively, corresponding to reductions of 20.0%, 26.7%, and 33.3% relative to the base mud. These results demonstrate progressively improved filtration control and increased apparent and plastic viscosities with increasing CMC dosage, whereas the yield point remained unchanged at 3 g and plateaued between 6 and 9 g. Kepok banana peel-derived CMC therefore shows potential as a waste-derived additive for controlling filtration and modifying the rheological properties of water-based drilling muds.

**Keywords:** Carboxymethyl Cellulose; Kepok Banana Peels; Drilling Mud Additive, Rheological Properties, Filtration Loss.

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## Introduction

The oil and gas industry is increasingly developing sustainable technologies to reduce the environmental impacts and operational costs of drilling. One approach uses natural materials and agricultural waste as alternatives to, or complements for, conventional drilling-fluid additives. Various materials, including rice husk ash, mandarin orange peel, rambutan seeds, watermelon peel, Ambon banana peels and corn cobs, have been investigated for improving rheological properties and controlling fluid loss (Al-Hameedi et al., 2020; Le et al., 2025; Suhascaryo & Dhaffa, 2024; Wastu et al., 2026; G. Zhou et al.,

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2021). Studies on sawdust and cellulose nanomaterials have also demonstrated potential improvements in the viscosity, gel strength, and filtration performance of water-based mud (Shuvo et al., 2024; S. Zhou et al., 2023). However, the performance of unmodified residues still depends on particle size, concentration, and their ability to form a compact filter cake. A recent review further highlights cellulose derivatives as promising additives for water-based drilling fluids because of their renewable origin, biodegradability, and roles in rheological modification, fluid-loss control, and shale inhibition (Khan et al., 2024).

Converting cellulose into carboxymethyl cellulose (CMC) offers a way to produce functional polymeric additives from agricultural waste. CMC has been synthesized from various feedstocks, including asparagus stalk ends, oil-palm empty fruit bunches, broccoli stems, and sugarcane leaves (Ab Rasid et al., 2021; Hastuti et al., 2024; Klunklin et al., 2020; Sayanjali et al., 2024; Suchaiya et al., 2022). In Indonesia, Kepok banana peel is a promising feedstock because it is readily available as a waste material and has high cellulose content. (Bunga et al., 2020) reported Kepok banana production of 22,489.50 tons in 2017, while studies on banana-derived materials reported cellulose contents ranging from 35% to 51.05% (Abdullah et al., 2013; Bilba et al., 2007; Quintana et al., 2009). Nevertheless, researchers must demonstrate this feedstock's potential through successful CMC synthesis and evaluation of the resulting material properties. More directly relevant to drilling applications, (Mohammed & Elrayah, 2025) synthesized CMC from date-palm frond waste with a DS of 0.77 and evaluated its structural, thermal, rheological, and filtration characteristics. Their findings demonstrate that waste-derived CMC can be assessed through an integrated synthesis characterization performance approach, while also emphasizing the need for feedstock-specific evaluation.

CMC synthesis generally involves alkalization and etherification, with the degree of substitution (DS) serving as a key parameter. DS represents the average number of carboxymethyl groups per anhydroglucose unit and affects product solubility and viscosity. Previous studies show that the cellulose source and synthesis conditions influence CMC DS, yield, morphology, and functional properties (Ab Rasid et al., 2021; Chen et al., 2020; Sayanjali et al., 2024; Suchaiya et al., 2022; Susi et al., 2024). Therefore, the suitability of CMC as a drilling-fluid additive cannot be determined solely from its feedstock's cellulose content. Beyond chemical and structural characteristics, thermal behavior must be examined to support its evaluation for high-temperature applications. Studies on cellulose-based additives have combined thermal analysis with rheological and filtration testing; however, their findings cannot be directly generalized to Kepok banana peel-derived CMC because of differences in feedstocks and synthesis processes (Li et al., 2022; S. Zhou et al., 2023).

Although CMC has been used as a fluid-loss-control agent in drilling operations (Shakib et al., 2016), the literature reviewed does not directly establish the effectiveness of CMC synthesized from Kepok banana peel for this application. Previous research has generally examined agricultural residues as drilling-fluid additives or has studied waste-derived CMC synthesis separately. The research gap, therefore, lies in integrating cellulose extraction from Kepok banana peel, CMC synthesis, physicochemical characterization, and drilling-fluid performance testing into a single study. This integration is necessary to link the synthesized material's properties to its effectiveness as an additive, rather than assuming that successful synthesis necessarily yields adequate drilling-fluid performance.

To address this gap, this study evaluates CMC derived from Kepok banana peel as a bio-based additive for water-based drilling fluids. The material is characterized using Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and thermogravimetric analysis (TGA), while drilling-fluid testing follows relevant American Petroleum Institute (API) procedures. The evaluation covers rheological properties, fluid loss, filter-cake characteristics, and density, including performance under high-temperature conditions, with a standard water-based mud formulation used as a reference. By linking the synthesized CMC's characteristics to its drilling-fluid performance, this study aims to support converting Kepok banana peel waste into a value-added product.

## Material and Methods

The primary materials used in this study consisted of fresh water, bentonite, and Kepok banana peels. Additionally, several reagent-grade chemicals were used to synthesize carboxymethyl cellulose from Kepok banana peels, including sodium hydroxide, sodium chloride, sodium acetate, sodium hypochlorite, isopropanol, sodium monochloroacetate, and glacial acetic acid.

### Collection and Physical Pretreatment of Kepok Banana Peel Powder

This study used Kepok banana peels obtained as waste from the Unggul Barakah chip factory in Bojonggede, Bogor. In the initial preparation stage, the banana peels were oven-dried at 60–70 °C for 48 hours to remove moisture and sap. After drying, the sample was ground in a food processor into a powder. To ensure particle homogeneity and reduce particle size, the resulting Kepok banana peel powder was sieved using a sieve shaker to achieve a mesh size of 100 microns.

**Synthesis of CMC from Kepok Banana Peels**

The synthesis of carboxymethyl cellulose from Kepok banana peel powder involved three sequential stages: delignification, bleaching, and chemical modification via alkalization and carboxymethylation. During delignification, 100 g of dried Kepok banana peel powder was reacted with 500 mL of a 17.5% NaOH solution at 100 °C for 3 hours to remove non-cellulosic impurities. The resulting solid residue was washed with distilled water until free of residual NaOH, then 10 g NaCl and 35 mL of 10% $CH_3COOH$ solution were added. The bleaching stage was carried out using 500 mL of 6% NaOCl at 60 °C for 3 hours. The residue was then washed with boiling distilled water to remove the odor of sodium hypochlorite. The wet cellulose obtained was dried in an oven at 60 °C, yielding 50 g of dry cellulose. The alpha-cellulose purity test showed 89%.

The alkalization stage began by dispersing 50 g of the extracted cellulose in 1000 mL of isopropanol in a 1-L beaker, then slowly adding 200 mL of 15% NaOH. The solution was heated on a hot plate magnetic stirrer at 60 °C for 1 hour at 100 rpm. During carboxymethylation, 50 g of sodium monochloroacetate was added, and the mixture was stirred continuously at 45 °C and 100 rpm for 4 hours using a hot plate magnetic stirrer. The mixture was filtered, and the residue was neutralized with glacial acetic acid until a neutral pH was reached. Finally, the product was filtered, washed with 96% ethanol, dried at 60 °C, and ground using a mortar and pestle to obtain 30 g of purified CMC powder.

**Characterization of CMC Kepok Banana Peels**

The obtained Kepok banana peel CMC will be analyzed using several characterization techniques. The characterization analyses conducted in this study include FTIR, XRD, and TGA testing. FTIR spectroscopy is used to identify the functional groups formed in the material sample and to assess the success of the carboxymethylation reaction. XRD is used to evaluate changes in crystallinity after modification. TGA measures the material's thermal stability by continuously monitoring its weight during heating. Following characterization, the sample is incorporated into a base drilling mud formulation to investigate its impact on rheological and filtration properties. FTIR analysis was conducted using a Shimadzu FT/IR-6X1 Type A spectrometer to identify functional groups; spectra were recorded in the 4000–500 $cm^{-1}$ range at 2 $cm^{-1}$ resolution. XRD patterns were obtained using a Bruker D8 Advance diffractometer with Cu Kα radiation (λ = 1.5418 Å) under standard conditions.

$$\% \text{ Cristalinity} = \frac{\text{Reduced Area}}{\text{Global Area}} \text{ x } 100\% \quad (1)$$

Thermal stability testing was also performed using a Hitachi STA7300 TG/DTA instrument.

**Drilling Mud Formulation**

The base mud was prepared by gradually adding 19 g of bentonite to 350 mL of distilled water under continuous stirring to minimize clumping and promote uniform dispersion. The suspension was then homogenized for 10 minutes using a Hamilton Beach high-speed mixer (model MHD200) operated at its high-speed setting.

Kepok banana peel-derived carboxymethyl cellulose was subsequently incorporated into separate base-mud samples at dosages of 3, 6, or 9 g. These dosages were in addition to 19 g of bentonite and did not replace or reduce the bentonite content. Accordingly, the three formulations contained 19 g bentonite and 3, 6, or 9 g CMC, respectively, in an initial distilled-water volume of 350 mL. All additive dosages reported here refer to this initial water volume rather than the final suspension volume. The CMC powder was added slowly under continuous stirring to minimize agglomeration, followed by an additional 10 minutes of mixing using the same Hamilton Beach MHD200 mixer operated at its high-speed setting.

After mixing, each sample was transferred to a sealed container and allowed to hydrate under static conditions at room temperature, approximately 25–27 °C, for 1 hour. This hydration period was intended to promote bentonite swelling and CMC hydration and dispersion. After hydration, each sample was transferred to a stainless steel aging cell and subjected to dynamic aging in a rolling oven at 25 rpm and 93.3 °C (200 °F) for 16 hours. This procedure was used to assess the thermal resistance and rheological stability of the CMC-modified drilling fluids under elevated-temperature rolling conditions. After aging,

the samples were cooled to room temperature and homogenized by manual agitation or brief remixing for 1–2 minutes before rheological and filtration measurements.

**Rheological Measurement**

Mud rheological properties are measured in accordance with API Recommended Practice 13B-1 standards using a Fann VG Meter. Plastic viscosity and yield point values are determined based on instrument scale readings at rotational speeds of 600 and 300 rpm for rheological modeling purposes. Based on these dial readings, calculations are performed using the following formulas:

$$\text{Apparent Viscosity} = \frac{\theta 600}{2} \quad (2)$$

$$\text{Plastic viscosity} = \theta 600 - \theta 300 \quad (3)$$

$$\text{Yield point} = \theta 300 - PV \quad (4)$$

where the numbers 600 and 300 represent the viscometer readings at 600 and 300 rpm, respectively

Gel strength measurements were performed using a Fann VG Meter following the procedure below. After the initial stress measurement was completed, the slurry was stirred with the Fann viscometer at 600 rpm for 15 seconds. The viscometer is then turned off, and the slurry is allowed to stand for 10 seconds. After a 10-second interval, the viscometer is turned back on at 3 rpm, and the maximum deflection on the indicator scale is read and recorded as the 10-second gel strength value, expressed in units of lbs/100 ft². Next, the Fann viscometer rotor is rotated at 600 rpm for 60 seconds, then the viscometer is turned off, and the slurry is allowed to stand for 10 minutes. After 10 minutes, the viscometer is turned back on at 3 rpm, and the maximum deflection on the indicator scale is read and recorded as the 10-minute gel strength value.

**Filtration Loss and Mud Cake Measurement**

Filtration loss in drilling mud is determined using an API Filter Press. Filtration performance is evaluated using an OFITE Series 300 LPLT filter press in accordance with the American Petroleum Institute (API) standard procedures. A measured volume of drilling mud is introduced into the filter press chamber, and a constant pressure of 100 psi is applied via a $CO_2$ cartridge. The resulting filtrate is collected in a measuring cylinder for 30 minutes at room temperature. Subsequently, the thickness of the filter cake on the filter paper is measured with a vernier caliper and reported in millimeters (mm).

**Density Measurement**

Drilling fluid density was measured using a Fann mud balance calibrated with fresh water at 8.33 lb/gal (ppg) on a level surface. After recording the sample temperature, the clean, dry cup was filled with drilling fluid and capped with a slight twist to expel trapped air through the vent. The cup and arm were wiped dry, and the rider was adjusted until the bubble was centered. Density was read from the rider's left edge and recorded in ppg to an accuracy of 0.1 lb/gal, or as specific gravity (SG).

## Result and Discussions

**Characterization Analysis: CMC of Kepok Banana Peels**

The FTIR spectrum of the Kepok banana peel CMC sample in Figure 1 indicates successful carboxymethylation of cellulose, as confirmed by the characteristic functional groups of carboxymethyl cellulose. The FTIR spectra of the Untreated Kepok Banana Peel (black line) and CMC Kepok Banana Peel Powder (red line) samples exhibit several significant absorption differences at specific wavenumbers. At the wavenumber region of 3405.12 $cm^{-1}$, both samples show a broad absorption band corresponding to the stretching vibration of (–OH) groups and hydrogen bonding interactions. Absorption bands at 2921.23 $cm^{-1}$ and 2850.55 $cm^{-1}$ indicate the symmetric and asymmetric stretching vibrations of alkyl C-H ($sp^3$) bonds within the cellulose backbone.

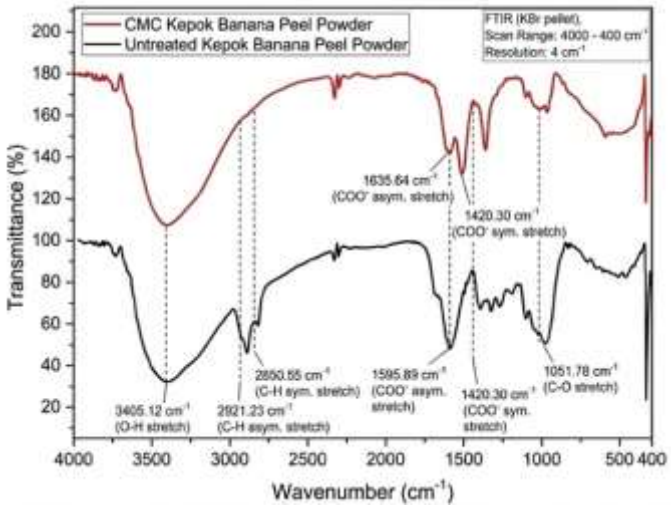



**Figure 1. FTIR spectra of CMC kepok banana peel and untreated kepok banana peel.**

The most important functional change confirming the success of the carboxymethylation reaction is the carboxylate ($–COO^-$) absorption region. For the Untreated Kepok Banana Peel Powder sample, the asymmetric carboxylate absorption peak appears at 1595.89 $cm^{-1}$. Following etherification into CMC, this peak shifts (hypsochromic/blue shift) to a higher wavenumber at 1635.64 $cm^{-1}$, accompanied by a sharper increase in absorption intensity. This intensity enhancement confirms substitution and the formation of carboxymethyl ($–CH2COO^-$) groups on the cellulose backbone (Adinugraha & Marseno, 2005; Lin et al., 2021; Syahira Zaini et al., 2022; Teng et al., 2022). Furthermore, the appearance and shift of the peak at 1420.30 $cm^{-1}$ indicate the symmetric stretching vibration of the carboxylate ($–COO^-$) group. The sharp absorption peak at 1051.78 $cm^{-1}$ observed in both spectra corresponds to the stretching vibration of ether bonds (C–O–C) and pyranose rings inherent to the primary cellulose structure. Overall, the characteristic shifts in carboxylate peaks and the structural variations in the CMC spectrum confirm that the hydroxyl groups in Kepok banana peel cellulose were successfully substituted by carboxymethyl groups.

X-ray Diffraction (XRD) reveals significant differences in diffraction patterns between untreated Kepok banana peel powder and CMC Kepok banana peel powder (Figure 2). The untreated Kepok banana peel powder pattern is dominated by a broad amorphous halo in the 2θ range of 15°−25°, with primary peaks at 18.2° and 22.1°, reflecting the biomass's non-crystalline components, such as pectin, hemicellulose, and lignin. Conversely, the diffraction pattern of CMC Kepok Banana Peel Powder shows increased structural ordering, characterized by sharp crystalline diffraction peaks at 2θ values of 11.5°, 16.8°, 19.1°, 22.5°, 29.8°, and 31.8°. This change in the diffraction profile confirms that alkalinization and carboxymethylation effectively degrade the amorphous fraction and disrupt the native cellulose matrix, forming a more organized carboxymethyl cellulose (CMC) derivative. Furthermore, the distinct high-intensity diffraction peaks observed at 2θ angles around 29.8° and 31.8° are attributed to the crystalline phase of inorganic salt by-products, such as sodium chloride (NaCl) and sodium glycolate ($C_2H_3NaO_3$), which were formed during the neutralization reaction between sodium monochloroacetate (NaMCA) and sodium hydroxide (NaOH) in the CMC synthesis.

The CMC sample's 50.6% degree of crystallinity was calculated quantitatively using the area integration method, comparing the reduced area (crystalline region) of 151.24 to the global area (total area) of 299.12. For comparison, the Untreated Kepok Banana Peel sample yielded a reduced area of 39.512 and a global area of 180.38, resulting in a significantly lower degree of crystallinity at 21.9%. The substantial increase in crystallinity from 21.9% to 50.6% confirms that chemical treatments effectively removed amorphous matrix components and enhanced polymer-chain ordering.

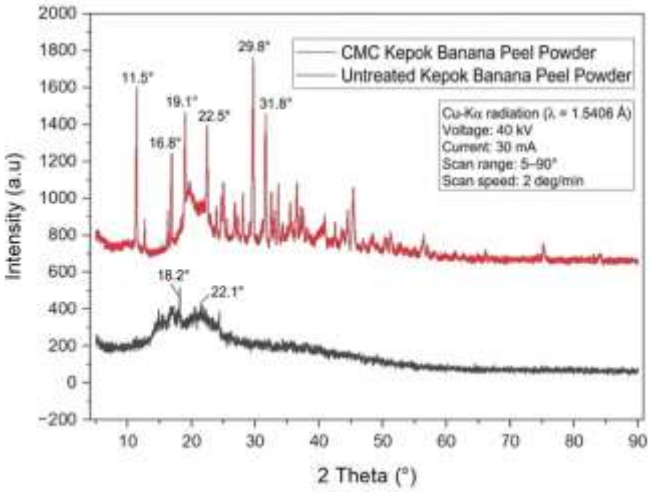
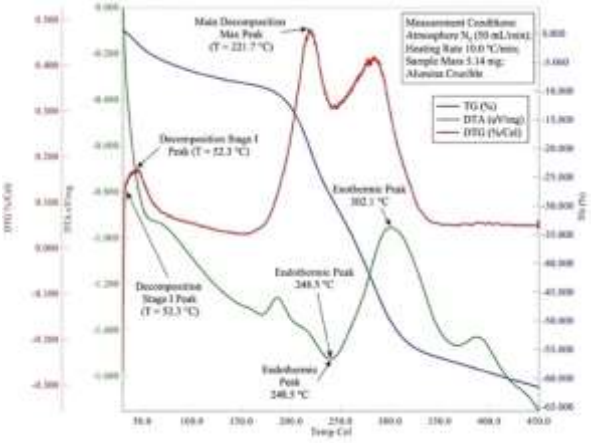



**Figure 2. XRD diffractograms of CMC Kepok banana peel and untreated Kepok banana peel.**

Based on the Simultaneous Thermal Analysis (STA) profiles comparing Kepok banana peel Carboxymethyl Cellulose (CMC) (Figure 3a) and untreated Kepok banana peel powder (Figure 3b), the thermal analysis shows significant differences in degradation behavior resulting from the chemical modification process. In the initial heating stage up to approximately 100–150 °C, both samples showed an initial mass loss on the TG (Thermogravimetry) curve, supported by an early DTG (Derivative Thermogravimetry) peak around 52.3 °C for CMC. The mass loss in this early temperature range does not represent the onset of thermal degradation of the polymer backbone; rather, it is attributed to the evaporation of absorbed moisture and light volatile compounds. The sample's thermal stability is preserved up to approximately 180 °C before the main stage of polymer degradation begins.

The main thermal decomposition stage (main decomposition) for the Kepok banana peel CMC occurred at a peak DTG temperature of 221.7 °C, marked by a sharp mass reduction and an endothermic peak on the DTA curve at 248.5 °C. Conversely, untreated Kepok banana peel powder showed greater thermal resistance during its main decomposition phase, with a main DTG peak at approximately 295 °C, an endothermic DTA peak at around 265 °C, and an exothermic peak at approximately 302 °C. The shift of the main decomposition peak to a lower temperature in CMC (221.7 °C) relative to the untreated raw material (295 °C) indicates that substituting carboxymethyl groups onto the cellulose backbone reduces structural crystallinity.

**(a)**



**(b)**

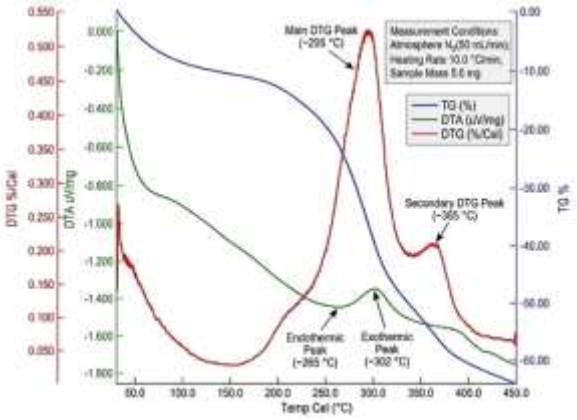



**Figure 3 (a) Simultaneous thermal analysis results for kepok banana peel CMC, (b) Simultaneous thermal analysis results for untreated kepok banana peel.**

**Rheology Result**

Apparent Viscosity (AV) is a rheological parameter that reflects a fluid's resistance to flow under dynamic shear conditions; it is influenced by fluid composition, solids content, and additive concentration (Le et al., 2025). As shown in Figure 4, the base mud sample has an AV value of 18 cP. Adding Kepok banana peel CMC at concentrations from 3 g to 9 g per 350 mL gradually increased AV, reaching a maximum of 23 cP at 9 g/350 mL. The increase from 18 to 23 cP corresponds to approximately 27,8%, demonstrating a measurable thickening effect under the tested conditions.

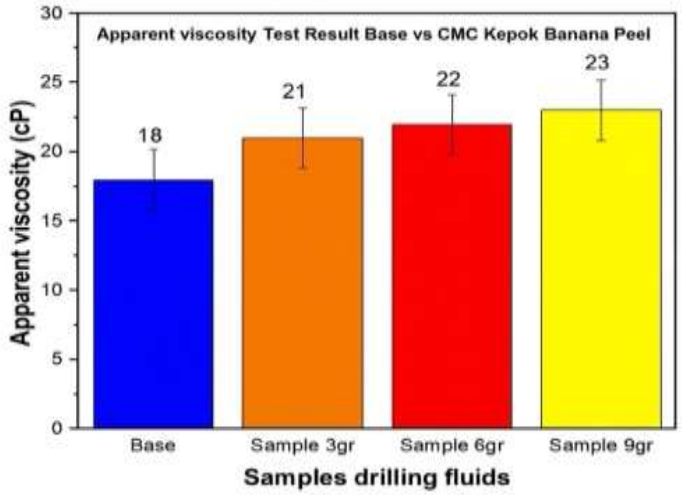



**Figure 4. Variation of apparent viscosity of bentonite based mud with the addition of kepok banana peel CMC concentration.**

Plastic viscosity primarily reflects the drilling fluid's viscous resistance to flow. Therefore, an increase in PV should not be interpreted as direct evidence of improved solids suspension, since higher PV may also increase pumping requirements and circulating pressure losses (Le et al., 2025; Murtaza, Alarifi, et al., 2021). As shown in Figure 5, the base mud exhibited a PV of 10 cP, which increased to 14 cP following the addition of Kepok banana peel-derived carboxymethyl cellulose (CMC) at a concentration of 9 g/350 mL. This increase indicates greater viscous resistance and may be associated with polymer hydration and increased liquid-phase viscosity. Water uptake and swelling of cellulose-based materials, together with potential polymer–particle interactions, provide a conceptual basis for interpreting this rheological response (Hubbe et al., 2017; Kaur et al., 2018; Klemm et al., 2005).

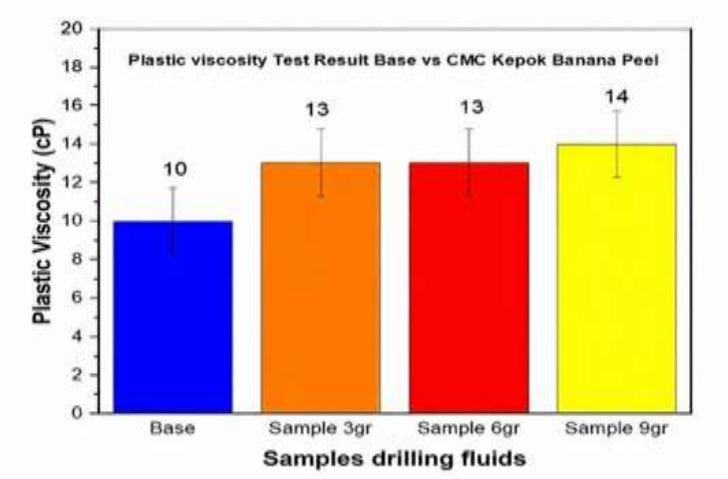



**Figure 5. Variation of plastic viscosity of bentonite based mud with the addition of kepok banana peel CMC concentration.**

Additionally, the physicochemical characteristics of Carboxymethyl Cellulose (CMC) derived from Kepok banana peels are characterized by its degree of substitution and purity. A degree of substitution value of 1 indicates the number of carboxymethyl groups successfully bound to the cellulose chain. This increases the polymer's hydrophilicity and its ability to interact with water molecules, promoting the formation of a stable polymer network. Meanwhile, a CMC purity level of 88.64% indicates that the cellulose fraction was effectively converted with low impurity content, allowing the additive to disperse perfectly in the system with a solution viscosity of 1.39 cP. This high purity and complete dispersibility ensure optimal polymer hydration and efficient rheological structure formation, which directly contributes to the measured increase in plastic viscosity.

This distinction between the measured response and its proposed explanation is important when comparing the present results with previous studies. (Kelessidis et al., 2011) reported that CMC addition could initially decrease yield stress and the flow consistency index, while the contribution of liquid-phase thickening became increasingly important at higher concentrations. Their findings suggest that increased flow resistance does not necessarily reflect stronger interparticle interactions. Accordingly, the increase in PV observed in the present study is consistent with a possible contribution from liquid-phase thickening.

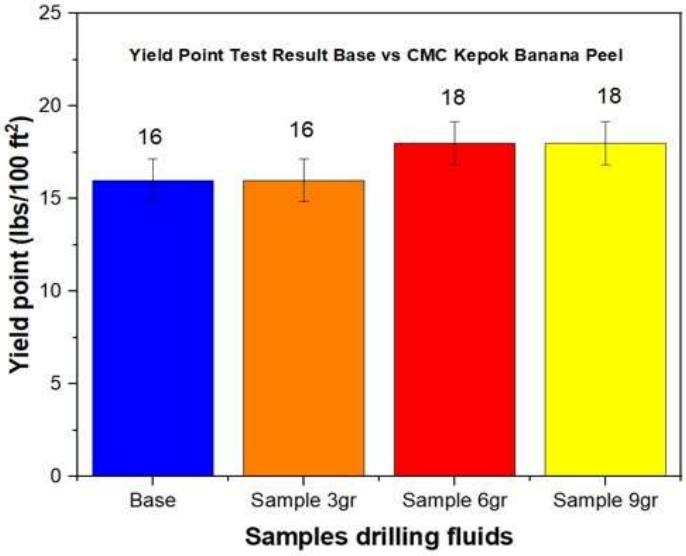
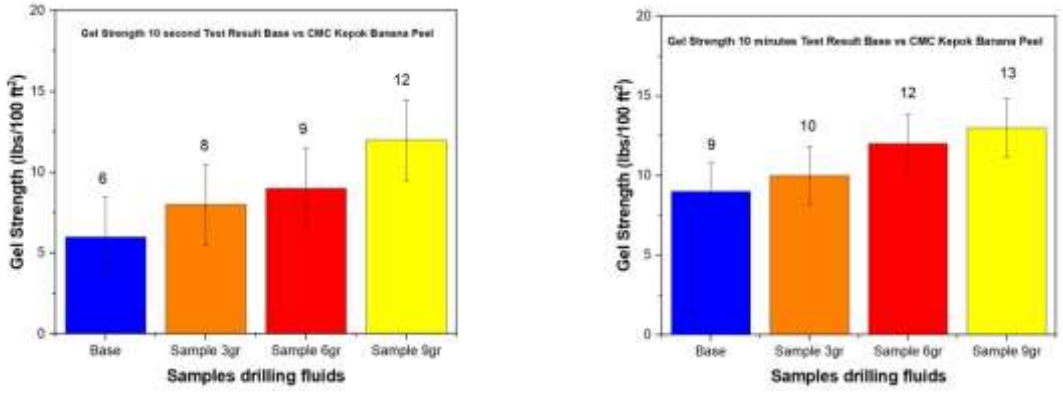



**Figure 6. Variation of yield point of bentonite based mud with the addition of kepok banana peel CMC concentration.**

Yield Point (YP) measures the initial stress required to initiate flow and indicates the fluid's ability to transport drill cuttings under low-shear conditions (Le et al., 2025). As shown in Figure 6, adding Kepok banana peel CMC increases the YP value compared to the base fluid sample, which has a value of 16

lb/100 ft². Adding Kepok banana peel CMC increased YP, reaching a maximum of 18 lb/100 ft². The enhancement of the Yield Point (YP) and drilling fluid performance is driven by the crucial role of hydrophilic and charged functional groups in Kepok banana peel CMC, such as hydroxyl (–OH) groups at 3,448.72 $cm^{-1}$ and carboxylate ($–COO^-$) groups at 1,635.64 $cm^{-1}$, which impart high hydrophilicity, allowing them to function optimally as viscosifiers and rheology modifiers (Kusrini et al., 2018; Menezes et al., 2010). These negatively charged carboxymethyl groups induce inter-chain electrostatic repulsion that forces the molecules to expand fully, while the cellulose fiber content and hydrophilic biopolymers strengthen solid-solid and solid-liquid interactions within the fluid matrix (Mohamed et al., 2020). These molecular interactions may contribute to the observed increase in YP and suggest improved potential for cuttings suspension and transport. However, the study did not directly measure transport efficiency, which must be evaluated alongside annular velocity and the hydraulic consequences of increased viscosity.

Gel Strength (GS) reflects the drilling fluid's ability to suspend cuttings under static conditions without circulation (Le et al., 2025). The fluid's network structure typically develops at 10-second and 10-minute intervals; a controlled difference in GS values is crucial to prevent excessive gel formation, which could otherwise trigger pressure spikes or stuck-pipe incidents. As shown in Figures 7a and 7b, the base-case sample yielded 6 lb/100ft² at 10 seconds and 9 lb/100ft² at 10 minutes. Adding Kepok banana peel CMC increased GS values to 8–12 lb/100ft² at 10 seconds and 10–13 lb/100ft² at 10 minutes at concentrations of 3, 6, and 9 g. These findings support the general observation that increasing bio-based additive concentration can enhance static gel strength. At the molecular level, this phenomenon occurs because long, branched CMC polymer chains adsorb onto bentonite particle surfaces via a polymer-bridging mechanism. The water-soluble Kepok banana peel CMC, rich in carboxymethyl groups, acts primarily as a viscosifier and gelling agent (Adinugraha & Marseno, 2005). Electrostatic interactions between the charged CMC chains and bentonite surfaces create a stronger, more stable gel network (Assi & Haiawi, 2021; Kaur et al., 2018).




**(a)** **(b)**

**Figure 7 (a) Variation of GS 10 Second of bentonite based mud with the addition of kepok banana peel CMC concentration, (b) Variation of GS 10** minutes of bentonite based mud with the addition of kepok banana peel CMC concentration.

**Operational Implications of the Rheological Changes**

Cuttings in suspension and increased flow resistance. Based on the reported data, at 9 g/350 mL, apparent viscosity (AV) increased from 18 to 23 cP, plastic viscosity (PV) from 10 to 14 cP, and yield point (YP) from 16 to 18 lb/100 ft². These changes represent increases of approximately 28%, 40%, and 13%, respectively. Thus, the proportional increases in viscosity exceeded the increase in YP, and these changes do not necessarily indicate improved drilling-fluid performance.

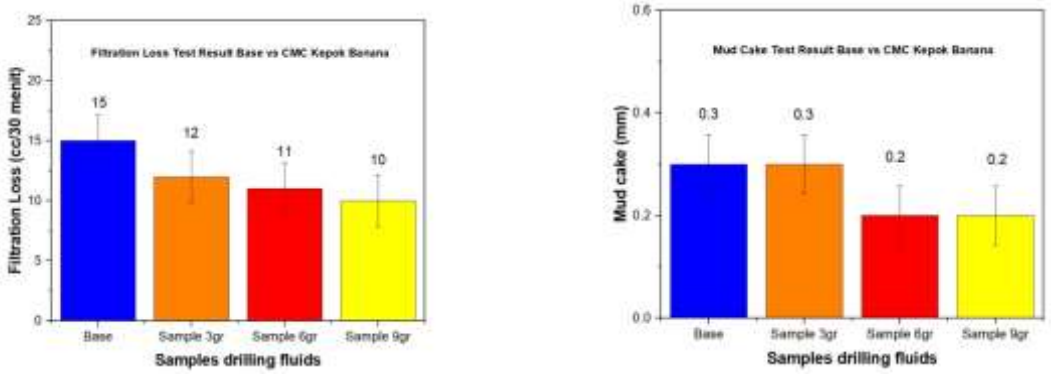
Higher AV and PV can increase frictional pressure losses and pumping-pressure requirements. Increased annular pressure losses can also raise the equivalent circulating density. Conversely, a higher YP may support cuttings transport; however, hole-cleaning efficiency also depends on annular velocity, well geometry, and operating conditions. Therefore, increased viscosity does not necessarily improve cuttings transport (Murtaza, Tariq, et al., 2021; Xu et al., 2025).

Higher gel strength may help maintain cuttings in suspension when circulation stops, but it can also increase the pressure required to restart circulation. Accordingly, the paired 10-second and 10-minute gel-strength values should be evaluated for each formulation, rather than assuming that the highest values represent the best performance (Wei et al., 2022).

The optimal concentration should therefore balance adequate cuttings suspension and transport against acceptable circulation-pressure requirements. Because the reported data do not include direct measurements of pumpability, pressure losses, or cuttings transport, the operational benefits of Kepok banana peel CMC remain inferred rather than experimentally verified. Hydraulic calculations and circulation tests are required before selecting a concentration for field application.

**Filtration Loss and Mud Cake Analysis**

Based on the filtration loss test results in Figure 8a, the base sample showed a filtration loss of 15 cc over 30 minutes at 100 psi and 25 °C. Adding banana peel-derived carboxymethyl cellulose (CMC) at concentrations of 3 g/350 mL, 6 g/350 mL, and 9 g/350 mL reduced filtration loss to 12 cc/30 min, 11 cc/30 min, and 10 cc/30 min, respectively. Compared to the base sample, these reductions correspond to decreases of 20.0%, 26.7%, and 33.3%, respectively. These results show that adding CMC improves fluid loss control under the specified testing conditions.




**(a)** **(b)**

**Figure 8 (a) Variation of filtration loss of bentonite based mud with the addition of kepok banana peel CMC concentration, (b) Variation of mud cake of bentonite based mud with the addition of kepok banana peel CMC concentration.**

As a cellulose derivative obtained through carboxymethylation, CMC yields an anionic polymer with high water-binding capacity. Functional group analysis supports this characteristic, showing hydroxyl groups (–OH) at 3,448.72 $cm^{-1}$ and carboxylate groups ($–COO^-$) at 1,635.64 $cm^{-1}$ and 1,564.27 $cm^{-1}$, confirming the polymer's high hydrophilicity. The fluid-loss control mechanism of Kepok banana peel CMC involves forming an adsorbed polymer layer on bentonite particle surfaces, along with a denser gel structure. The negative charge on the anionic carboxymethyl groups interacts electrostatically with the positively charged edges of bentonite particles, resulting in a more stable and cohesive matrix structure. Hydrogen bonding between CMC hydroxyl groups and the bentonite surface reinforces this interaction, forming an effective network that restricts filtrate flow. The compatibility between bentonite and Kepok banana peel CMC shows that bentonite remains an optimal base-mud matrix. At the same time, Kepok banana peel CMC effectively controls fluid loss by suppressing the filtration rate without adversely affecting the primary rheological properties of the drilling mud.

The mud cake thickness test results shown in Figure 8b indicate that the base sample produced a cake thickness of 0.3 mm. Adding banana peel-derived carboxymethyl cellulose (CMC) at 3 g/350 mL, 6 g/350 mL, and 9 g/350 mL resulted in mud cake thicknesses of 0.3 mm, 0.3 mm, and 0.2 mm, respectively. Mud-cake thickness was measured using a digital vernier caliper at three locations within the central region of each cake.

This reduction in filtration rate shows that adding Kepok banana peel-derived CMC effectively controls drilling fluid filtration through its physicochemical properties. A degree of substitution (DS) of 1.00 indicates an abundance of carboxymethyl groups, which increases hydrophilicity and enhances the ability of CMC to form polymer-particle bridges, thereby strengthening surface coagulation and particle adhesion within the filter cake (Asl et al., 2017). Supported by a high purity of 88.64%, which minimizes contaminants that could disrupt structural regularity, a crystallinity of 50.6% (based on XRD analysis) may contribute to the mechanical strength of the cake matrix. The synergy among a high degree of substitution, high purity, and significant crystallinity results in a thinner, denser filter cake, indicating that the drilling fluid better limits filtrate infiltration into the rock formation, a crucial factor for minimizing the risk of formation damage and maintaining wellbore stability.

**Density Analysis**

Based on Figure 9, the base case was recorded at 8.5 ppg. The addition of CMC Kepok banana peel increased the drilling mud density to approximately 8.8 ppg across the test concentrations (3 g, 6 g, and 9 g). In the CMC sample, the density increase was slightly higher. This occurred because carboxymethylation changed not only solubility and viscosity-forming ability but also the mass distribution in the fluid volume (Lima et al., 2022). Chemically, at a degree of substitution of around 1, approximately 0.8 $–CH_2COONa$ groups are bound per glucose unit, increasing the effective mass per monomer (Toğrul & Arslan, 2003). In addition, the substituted carboxymethyl groups strengthen hydration interactions through hydrogen bonding and electrostatic interactions with sodium ions, thereby increasing the amount of bound water around the polymer chains. Increasing the polymer concentration from 3 g to 9 g further enhances the three-dimensional network formation. This increases the effective solid fraction in the fluid volume, resulting in a more homogeneous, denser mass distribution. Thus, the slightly higher density in this sample compared to the base case is attributed to chemical modification by CMC. This modification effectively increases the mass per monomer and the extent of hydration interactions, thereby contributing to a denser mass distribution within the fluid volume.

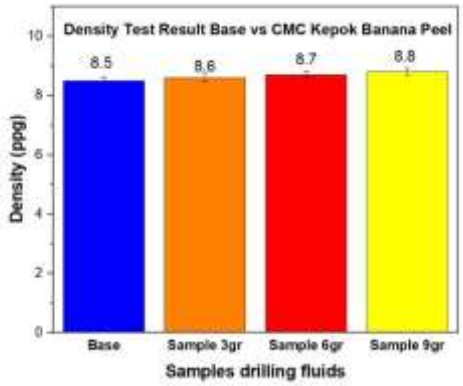



**Figure 9. Variation of density of bentonite based mud with the addition of kepok banana peel CMC concentration.**

## Conclusions

This study demonstrates the feasibility of converting Kepok banana peel waste into carboxymethyl cellulose (CMC), extending its utilization beyond the simple biomass powders employed in previous studies. Physicochemical characterization supports the successful chemical modification of cellulose. At the same time, drilling-fluid evaluations indicate that the resulting CMC can function as both a rheology modifier and a fluid-loss control additive in water-based drilling muds under the conditions investigated. These findings highlight its potential for further development as a waste-derived drilling-fluid additive.

The measured rheological and filtration responses may involve polymer hydration and CMC–bentonite interactions. Hydrogen bonding, electrostatic effects, adsorption, and polymer bridging are proposed explanations, not mechanisms directly demonstrated in these experiments. Their occurrence and relative contributions require further investigation.

Several limitations should be acknowledged. The absence of direct benchmarking against commercial CMC prevents definitive conclusions regarding comparative performance and commercial competitiveness. Moreover, the limited temperature range investigated does not establish performance across broader downhole conditions, and thermal characterization alone should not be interpreted as confirmation of sustained drilling-fluid functionality at elevated temperatures. The study also did not conduct long-term stability and environmental assessments; therefore, the additive's durability and environmental advantages remain to be verified.

Overall, Kepok banana peel-derived CMC represents a promising approach to agricultural waste valorization with potential applications in water-based drilling fluids. Future research should prioritize benchmarking against commercial CMC, testing over a broader temperature range, evaluating long-term formulation stability, and assessing environmental impacts and production costs before concluding field applicability, sustainability, or economic benefits.

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**Author Contributions**
All authors contributed equally.

**Conflict of Interest**
The authors declare no competing interests.

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