

Biodegradable Materials for Lubricity Enhancement of Drilling Fluids: A Review

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ABSTRACT

Biodegradable lubricants are essential to meet the demand for sustainable and environment-friendly drilling activities in the oil and gas industry. Lubricants play a major role in decreasing frictional, drag, and torque values that result from the interaction of drill bit, drill string, wellbore, or any other metal surfaces in contact, particularly in directional and extended-reach wells. Oil-based muds (OBMs) pose environmental challenges despite being the ideal lubricating mud. Alternate to this, water-based muds (WBMs) with biodegradable lubricants have promising benefits of lubricity, reduced pour point, increased flash point, and high thermal as well as oxidative stabilities. The potential of biodegradable additives like nano-sized lubricants and lubricants derived and modified from mineral oil and vegetable oil have been explored in this paper. It also highlights recent developments in enhancing drilling fluid using materials such as Henna extract, Wild Jujube Pit Powder (WJPP), and Okra powder. The performance of lubricity of mud is determined through the evaluation of the coefficient of friction directly, whereas the coefficient of adhesion and other mud properties also help to assess lubricity performances. The knowledge of the mechanisms of lubricants – like particle rolling, adsorption mechanism, and layered structure sliding – is essential to find other materials that can possess the same mechanisms and enhance the lubricating property. Therefore, this paper focuses on reviewing the already existing and utilized biodegradable lubricants along with their results and future development ideas. By utilizing biodegradable materials having the properties of enhancing lubricity, the drilling operations can successfully result in less pollution to the environment, and switch to cost-effective and superior lubricating properties without compromising performance.

Keywords: Drilling mud, mud additives, lubricity, biodegradable materials, biodegradable lubricants.



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1. Introduction

The petroleum sector, a vital part of the worldwide energy supply, has historically depended on drilling fluids to aid in oil and gas extraction, providing the efficiency of drilling operations. Drilling fluid, also known as drilling mud, serves multiple tasks. The most important task is maintaining adequate formation pressure by its density. The ability to hold up and transport rock cuttings to the surface, uphold wellbore stability by creating a filter cake on borehole walls, and support the casings are among some other reasons that make drilling fluid vital [1][1]. However, in extended-reach and directional wells, problems like increased friction due to dog-legs, bit balling, and instability of holes cause increased torque and drag values. Furthermore, these increased values result from drill string and casing or wellbore interaction causing over-pulls in trip-outs, differential sticking of pipes, and even losing the well [2]. Inside the casing, the metal-to-metal surface in contact between the casing and drill string results in an increase of energy that causes casing wear [3]. Additionally, the drilling bit gets worn out and heated. These together necessitate the addition of lubricants to the drilling fluid [4].

Drilling fluids are complex systems that contain solids, liquids, and chemical additives to perform various tasks during the circulation period of drilling operations [4]. Fundamentally, depending on the type of base fluid, drilling muds are of three types: water-based, oil-based, or foam-based [5]. Kania et al. highlighted that lubricants that possess high strength lubricating film, relatively higher viscosity, high solubility, significant thermal stability, high oxidative stability, low flammability, low corrosivity, low pour point, and non-toxic are considered good. Only a minimal amount such as 1%

of lubricant is sufficient to reduce torque by 20% to significantly enhance the drilling mud lubricity [6]. The optimal concentration of lubricant is often considered to be below 3% [7].

Common lubricants include oils (diesel, mineral, animal, or vegetable oils), graphite, powders, surfactants, graphite, asphalt, gilsonite, polymer, glass beads, and soaps [1]. Oil-based muds (OBMs) have long been used for their excellent thermal stability, lubricity resulting from reduced torque and friction values, and ability to prevent swelling of shale [1, 2]. Despite the superior lubricity characteristics of OBMs, their toxic characteristics and disposal problems pose a serious issue that requires expensive waste management protocols and strict compliance with environmental laws [1, 2, 7]. Water-based muds (WBMs) are an environmentally friendly choice due to their reduced toxicity and simplified waste handling [1]. However, WBMs are often inadequate to provide lubrication [4, 7]. The emergence of Synthetic-based muds (SBMs) in the late 20th century, well known for their natural lubricating properties by lowering the coefficient of friction, was an attempt to minimize environmental effects while combining the benefits of both OBMs and WBMs. SBMs enhanced biodegradability and decreased toxicity [1, 7].

The need for the development of drilling muds that are environmentally friendly has seen an upsurge in recent years. The shift towards biodegradable materials as additives is a significant concept to enhance the effectiveness of drilling mud and is in accordance with the industry's goal of limiting the negative effects on the environment by drilling activities [5]. A wide number of biodegradable materials have been used for the enhancement of drilling fluid properties. For instance,

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natural materials such as palm tree leaves [8], mandarin peel powder [9, 10], potato peel powder [11], acorn shell powder [12], various pinecones [13], and coffee ground waste and watermelon rind [14] were used to investigate their effects on pH, filtration, and viscosity, but these studies did not focus on lubricity. Conversely, lubricity enhancement using biodegradable materials has been the target of some research. For instance, materials like henna extract [15], wild jujube pit powder (WJPP) [16], and okra [17] were examined for their ability to enhance lubricity, reduce friction and optimize the drilling mud performance. However, biodegradable lubricants can vary in their performance depending on their formulation and their compatibility with other drilling mud components. Recent studies emphasize the necessity for more thorough research to enhance the formulation and application of these materials in drilling muds [5].

This review focuses on presenting a comprehensive study of the recent advances in using natural biodegradable materials for the enhancement of drilling mud lubricity. It also intends to provide potential future research directions.

2. Biodegradable Lubricants in Drilling Operations

Initially, OBMs were the best lubricants in the drilling industry as mentioned previously. Owing to the renewable and biodegradable nature of plant-derived natural oil, it has been encouraged to find uses in drilling muds [7]. Solid lubricants that were used traditionally were characterized as inactive, the process of degradation was difficult, and could easily be removed by solid control systems. Solid lubricants do not bond particularly to any type of mud and hence their performance does not depend on the mud type [2]. In response to the issues posed by traditional solid lubricants, new solid powder lubricants have been developed. These powders spread out uniformly in the drilling mud, can be transported easily, and can adsorb well on the surface of contact [18]. Solid, liquid, and natural lubricants that are utilized in the drilling industry are discussed in the upcoming sections.

2.1 Solid Lubricants

2.1.1 Starch-based

A popular and widely used drilling fluid additive is starch, which is cost-effective, environment-friendly, and non-hazardous. During drilling operations, modified starch versions have been found to play an important role in regulating rheological properties and fluid loss [18]. Additionally, the starch lubricant along with the ability to control fluid loss effectively, lowers the coefficient of friction of the drilling mud to a similar level where it is comparable with OBMs [19]. The interaction of solid lubricants with other components of the drilling fluid is possible due to its surface modifications [18]. This was observed in the starch lubricant powder prepared by Sifferman et al. through the process of jet cooking where starch and several lubricants of olefin were combined. His experiment also showed improved results in controlling fluid loss and increased values of yield point, plastic viscosity, and gel strength. Therefore, the management of the drilling mud rheology requires the addition of treatment agents during its application [19].

2.1.2 Nano-sized Lubricants

Nanotechnology has taken over almost all spheres of life with its development in the past few years. It has been successful in improving wellbore stability when used as an additive in drilling mud [18].

The reason behind their success is attributed to their size which provides a larger surface area for interaction with frictional points of contact [20]. Nano-lubricants such as nanoparticles and nano-graphene are examples of biodegradable nano-lubricants that have remarkable abilities to reduce friction [18]. A very common nano-additive, SiO₂ nanoparticle, was found to enhance the lubricity of filter cake with just a concentration of 1 weight % SiO₂ [21]. Whereas a combination of SiO₂ and TiO₂ nanoparticles in the presence of lubricants can reduce the coefficient of lubrication of drilling mud [22].

Nano-borate particles like aluminum, magnesium, titanium, and zinc can increase resistance to wear and decrease surface roughness by forming protective layers on friction surfaces, particularly in high-temperature and high-saline environments. These spherical-shaped nano-borates convert sliding friction to rolling-sliding friction thus improving tribological performance and make them a viable biodegradable choice for WBMs [18, 20].

Graphene, although intrinsically hydrophobic, surface changes have made it suitable for use in WBMs. Nanographene is biodegradable, demonstrates resilience at elevated temperatures (up to 300°C), and can considerably decrease torque in drilling fluids. It forms a lubricating coating on friction surfaces, reducing oxidation and wear, hence improving its suitability for environmentally sensitive areas [18].

2.2 Liquid Lubricants

2.2.1 Mineral and Vegetable oils

Another traditional liquid lubricant is mineral oil which comprises mixtures of petroleum-refined liquid hydrocarbons. Mineral oil containing aromatic hydrocarbons when used as base oil results in elevated fluorescence and causes environmental damage by not degrading easily [18]. A few types of vegetable oils such as palm, coconut, castor, jojoba, tallow, rapeseed, linseed, olive, sunflower, and soybean have been utilized as the base fluid for drilling mud owing to their natural characteristics and superior biodegradability [6, 18]. Triglycerides that are found in these oils create a lubricating coating on interaction with metal surfaces via hydroxyl bond thereby reducing friction and wear [18, 23, 24]. However, vegetable oil is rendered unsuitable when applied directly to drilling mud formulation [7]. This is because the utilization of raw vegetable oil in drilling mud of invert emulsion has shown high chances of hydrolysis leading to an increase in viscosity [25]. In addition, due to their poor oxidative stability, poor behavior of cold flow, and low thermal stability, their application in drilling operations of the petroleum industry is likewise limited as highlighted in Table 1 [26]. Therefore, vegetable oil requires modification before its application [18].

2.2.2 Modified Castor oil

Castor oil has a high concentration of ricinoleic acid (95%) that provides high-temperature lubricity and low-temperature viscosity [18]. Castor oil was modified using a sulfonation process by Livescu et al. that resulted in sulfonated castor oil with enhanced and long-lasting lubricity along with better resistance to temperature and higher stability. Interestingly, the sulfonated castor oil showed the lowest value of the coefficient of friction in a base fluid in comparison to other samples containing no lubricant [27]. Sulfated castor oil in combination with glycerol monolaurate in WBMs and OBMs has been successful in reducing friction [7].

2.2.3 Modified Vegetable Oils

Vegetable oils modified by the process of hydrogenation and transesterification improve their inherent qualities by increasing thermal stability and resistance to oxidation [7]. Such modifications ensure that the oils enhance their performance in harsh drilling conditions by maintaining their biodegradability [18]. Large amounts of available vegetable oil pose a threat of disposal in industries such as food and catering [28]. These can be used as cost-effective lubricants after making them environmentally friendly with enhanced properties such as low-temperature fluidity and increased lubricity by altering them using the esterification process [18, 28]. An example is ARC Eco-Lube, a green water-based drilling mud made by this process of esterification of waste vegetable oil by methanol. After esterification, it is segregated and then processed to produce pure vegetable esters by washing and heating. This enhances the lubricity, where only 3% of ARC Eco-Lube is sufficient to minimize the coefficient of friction significantly. Additionally, it can decrease viscosity and ensure safety due to its high thermal stability both in terms of operation and transportation [28].

2.2.4 Biodiesel and Modified Biodiesel

Non-fluorescent, non-toxic, and promising lubricant known as biodiesel or monoalkyl esters extracted from vegetable oil or animal fats is biodegradable [7, 29]. The ability of biodiesel to decrease friction better than petroleum hydrocarbons arises from the presence of oxygen components in biodiesel that can form polar bonds with metal surfaces [30]. However, owing to its foaming nature with age, the rheological characteristics of drilling muds are influenced and hence require modification for optimal performance [18]. Modified biodiesel-based lubricants like BL which is formed by the integration of biodiesel with polyhydroxy polymers and sulfur-containing compounds are very effective for seawater and freshwater drilling muds as they enhance the lubricity by decreasing about 80% friction in different fluid systems [18, 31].

2.2.5 Ester-based

Diesters and polyol esters are ideal biodegradable lubricant substitutes for mineral oil. Dibasic acids react with monohydric alcohols and form diesters. While diesters may have restricted hydrolytic stability, it is to be noted that they offer high thermal stability, low pour points, and a high Viscosity Index (VI) [7]. Similarly, monobasic acids react with polyhydric alcohols and form polyol esters which have a wide range of viscosity, significant hydrolytic and oxidative stability, and superior performance at low temperatures [7, 32].

2.3 Natural Lubricants

Limited studies have been conducted particularly focusing on the lubricity of drilling mud using natural biodegradable materials. However, some notable results have been exhibited in few studies as summarized in Table 1.

A study conducted by Moslemizadeh et al. used Henna extract to improve the lubricity of water-based drilling mud. Lubricity experiments were performed utilizing an EP/Lubricity tester, measuring the torque reading parameter (TRP) before and after the addition of Henna extract at concentrations of 10 g/L and 30 g/L. The results indicated that the 30 g/L of Henna extract markedly enhanced the lubricity of the drilling fluids, decreasing TRP by significant amounts across various test fluids which is advantageous for minimizing friction in directional drilling applications as

summarized in Table 1. Other results indicated were reduction in swelling properties and wettability alteration [15].

The effects of wild jujube pit powder (WJPP) at various particle sizes and concentrations on the lubricity of drilling fluid were examined by Zhou et al. The coefficient of friction decreased with the reduction of particle sizes and increase of concentrations. The values of the coefficient of friction for different particle sizes are summarized in Table 1. The optimal lubricity was attained at a 3% concentration with reduced particle sizes. The lowest value of coefficient of friction due to changes in concentration as depicted in Fig. 1 is attained at 5% concentration [16].

In research by Murtaza et al., the performance of drilling mud utilizing varying quantities of okra powder was investigated. Fluid loss studies were performed revealing that fluid loss diminished with increasing okra content. Specifically, 3 grams of okra decreased fluid loss by 42% from the baseline fluid. The filtration test indicated that the thickness of the filter cake reduced as okra concentration increased, measuring 1.0 mm at 3 grams. Okra was compared with starch and Xanthan gum polymer, demonstrating competitive performance. The findings indicated that okra-based fluids effectively manage fluid loss and hence can be considered to enhance lubricity thereby mitigating potential drilling complications such as pipe sticking although direct lubricity tests were not performed.

Table 1 Lubricity performance summary of natural lubricants.

Author (Year) Material [Reference]	Concentration and/or size of materials used	Performance data
Moslemizadeh et al. (2017) Henna Extract [15]	10 g/L and 30 g/L	Torque readings decreased by 11.4%, 16.66%, and 2.32% on addition of Henna extract.
Zhou et al. (2021) Wild Jujube Pit Powder [16]	0.5%, 1%, 3%, and 5% concentration. Particle sizes of (+100), (+75), and (+54 μ m) at 150° F and 300 psia.	The coefficient of friction readings at different concentrations is depicted in Fig. 1. The coefficient of friction readings were 0.3321, 0.3102, and 0.2963 at the mentioned particle sizes.

There are many other unexplored natural biodegradable materials such as edible portions of banana, taro, arum lobe, Malabar spinach, etc. that exist in nature and have some specific properties. Attention must be paid to investigating the effect of these materials on the lubricity of the drilling mud.

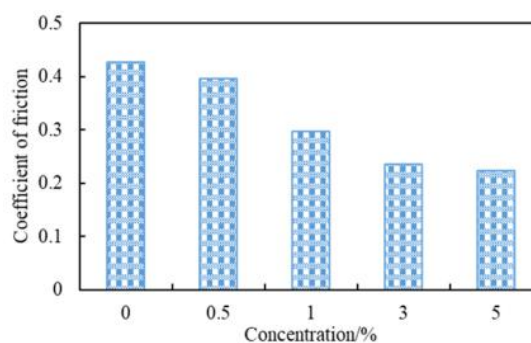


Fig. 1 Coefficient of friction of Wild Jujube Pit Powder at various concentrations (copyright@2021 Zhou et al.) [16].

3. Comparison between Conventional Lubricants and Biodegradable Lubricants

The performance of one type of lubricant in a particular condition is favored over other types of lubricant available as illustrated in Table 2.

Table 2 Performance comparison of conventional and biodegradable lubricants.

Property	Conventional	Biodegradable	Ref.
Lubricity	High	Moderate to high	[1, 2]
Thermal stability	High	Moderate	[5, 6]
Oxidative stability	Low	High	[6, 8]
Toxicity	High	Low	[3, 9]
Time for degradation	Very slow	Fast	[4]
Environmental impact	High	Low	[6, 9]
Solubility in water	Mostly insoluble	Few are soluble	[10]
Compatibility with WBMs	Low	High	[9]
Modifications	Minimal need	Needed	[6]
Cost	Low	Initially high	[4]
Favorable applications	SBMs, OBMs	WBMs	[18]

Conventional lubricants have long been used for their high lubricity. Mineral oil is an example. Fatty acids, modified castor oil, and triglycerides reduce the coefficient of friction indicating enhanced lubricity when used under various conditions making them a better alternative to conventional ones. Biodegradable esters provide significant lubricity particularly in extreme conditions because of their polar structure of molecules which enables them to adhere well to surfaces of metal.

Additionally, polyol esters have a thermal stability that is lower than that of conventional lubricants making them more suitable for conditions of elevated temperatures [7]. Modifications to vegetable oil using depressants, diluents, and defoamers enhance their thermal stability yet are not comparable to that of conventional mineral oils [4]. Moreover, an effective way for pertaining the lubricating properties of biodiesel and vegetable oils under complex environments is their structural modification [18].

Biodegradable lubricants like biodiesels are a potential lubricant in WBMs because of their excellent dispersion in water, though they require modification to prevent the loss of their performance under conditions of foaming and high viscosities [18]. Additionally, esters also owe to their polar structure to solubilize in WBMs well making them more compatible than conventional lubricants. Conventional lubricants may take up to years to degrade causing toxicity

and pollution to the environment. Mineral oils show poor biodegradability. On the other hand, biodegradable lubricants like polyol ester and diesters degrade rapidly [7].

Processes and methods for using conventional lubricants are already developed which makes them overall less expensive as compared to the cost of individual lubricants used in the case. On the other hand, biodegradable materials are initially expensive due to their sourcing, processing, and modifications [4, 7]. A possible intermediate solution to this is the use of natural biodegradable materials that are cost-effective particularly because they are readily available such as okra [17] and require very little processing compared to that of biodegradable lubricants.

Biodegradable lubricants are critical to enhancing the performance of drilling muds and reducing environmental challenges because of their low degradation time, less toxicity, and compatibility particularly with WBMs.

4. Mechanism of Biodegradable Lubricants

It is important to understand how biodegradable materials enhance the lubricity of drilling fluids and contribute to the efficiency of drilling operations.

Zhao et al. overview three mechanisms of lubricity as illustrated in Fig. 2, for water-based drilling muds: 1. Particles rolling, 2. Adsorption mechanism, and 3. Layered structure sliding. Biodegradable materials create a protective layer on surfaces that come into touch, which decreases both friction and wear [33].

For instance, WJPP enhances the lubricity of drilling fluid by introducing spherical particles that reduce sliding friction and promote rolling friction owing to the rolling of particles mechanism. On the other hand, the polymer in WJPP forms a hydration film, further reducing friction and optimizing the fluid's lubrication performance owing to the mechanism of adsorption [16].

Similarly, Henna extract also forms a hydration film on the surface of shale through hydrogen bonding between its hydroxyl groups and the oxygen atoms on the shale surface. This coating makes the shale hydrophobic, reducing water adsorption and stabilizing the formation, which in turn improves the lubricity of the drilling fluid [15]. Most mud lubricants tend to adsorb onto almost any surface, including exposed surfaces. A thin film or coating of mud lubricant can thus protect exposed surfaces from corrosion and prevent the adhesion of sticky solids [33].

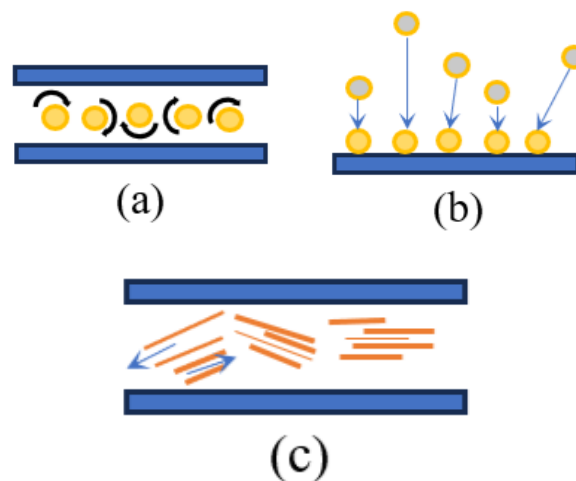


Fig 2. Lubricity mechanisms: (a) particle rolling, (b) adsorption, and (c) sliding of layered structure.

5. Challenges and Future Prospects

Lubricity is best improved by minimizing the torque and friction between the borehole filter cake and the surface of the tools used in drilling. Biodegradable lubricants are a promising alternative to traditional lubricants in terms of cost and environmental considerations, yet some challenges remain. For instance, castor oil and soybean oil are modified by expensive processes to attain thermal and oxidative stability.

The expensive modification process is a significant challenge specifically when the operations are carried out on a large scale where cost-effectiveness is important to ensure the operation is economically viable. Furthermore, a technical challenge occurs when consistent performance under varying downhole conditions is necessary, since these lubricating materials can demonstrate varied results depending on the pressure, temperature, and chemistry of the drilling mud.

Therefore, the compatibility of lubricants with other drilling mud components is necessary for stable performance. It is technically difficult to maintain the integrity of filter cake and differential sticking using biodegradable lubricants. In addition, to comply with the environmental laws, biodegradable lubricants need to be tested extensively and require certification. This could hinder their acceptance in regions where high compliance standards are necessary. Another challenge is scaling up output while preserving consistency and reducing ecological impacts.

The prospects are strong for biodegradable lubricants despite these challenges. For example, oxidative and thermal stability is attained through the esterification of oils derived from plants. Moreover, nano-sized particles such as SiO₂ and TiO₂ show growing potential in lubricity enhancement, which could further be enhanced if integrated with biodegradable material as a hybrid system in drilling muds.

Bio-additives, including surfactants and polymers demonstrate improved rheological properties of drilling mud making them promising for the future. Additionally, green chemistry and developments in catalysis could allow the production of biodegradable materials with improved performance measures. Furthermore, biodegradable materials having properties showing similar mechanisms could increase the variance in the availability of these materials. Thus, coordinated research between industry and academia is important to overcome the existing restrictions and to optimize the formulation of these lubricants. Their worldwide acceptance will increase with the establishment of uniform performance measurement rules.

6. Conclusions

Biodegradable lubricants are a key solution to the future of enhancement of drilling mud performance cost-effectively against strict environmental regulations. Biodegradable lubricants are more reliable than conventional lubricants as summarized by their comparison in properties. Modified lubricants through processes of esterification ensure the thermal and oxidative stability of traditional lubricants as in the case of modified vegetable oils.

Solid lubricants contribute to the reduction of friction by forming layers that reduce contact between metals under high pressure and high-temperature conditions. Moreover, powdered forms of lubricants are easy to transport and mix better than any other form. Advances in technology ensure the great potential of nano-sized particles in the drilling industry. Nano-sized particles ensure the reduction of drag,

torque, and wear due to their homogeneous dispersion in extreme environments. Polymeric lubricants derived from renewable materials contribute to enhancing performance by improved shear stability and optimized viscosity under dynamic conditions downhole.

Exploration of natural biodegradable materials possessing specific properties is essential for a green drilling future. A remarkable observation from the use of Wild Jujube Pit Powder as a lubricant is the enhancement of lubricity performance with a reduction in particle size. Various other natural materials exist in nature that can be tested for enhancement of lubricity. Drilling technology for an efficient and sustainable future is aligned with the integration of biodegradable and modified lubricants and mechanism-based similar biodegradable materials into drilling muds for a twofold advantage of improved drilling efficiency and decreased ecological footprint.

References

- [1] Hossain, M. E., Al-Majed, A. A., Fundamentals of Sustainable Drilling Engineering, 1st ed., Hoboken, NJ: Wiley, 2015.
- [2] Sönmez, A., Kök, M. V., Özel, R., Performance analysis of drilling fluid liquid lubricants, *Journal of Petroleum Science and Engineering*, vol. 108, pp. 64–73, 2013.
- [3] Foxenberg, W. E., Ali, S. A., Long, T. P., Vian, J., Field experience shows that new lubricant reduces friction and improves formation compatibility and environmental impact, in *SPE/IADC Drilling Conference*, 2008.
- [4] Ma, C., et al., Preparation and application of an environmentally friendly compound lubricant based on biological oil for drilling fluids, *Arabian Journal of Chemistry*, vol. 15, no. 3, p. 103610, 2021.
- [5] Bourgoynne, A. T. Jr., Millheim, K. K., Chenevert, M. E., Young, F. S. Jr., Applied Drilling Engineering, 1st ed., Richardson, TX: Society of Petroleum Engineers, 1991.
- [6] Lescure, J., Teng, J., Degouy, D., Espagne, B., Development and field trial of a non-aqueous-based mud lubricant, in *SPE/IADC Middle East Drilling Technology Conference*, 2013.
- [7] Kania, D., Yunus, R., Omar, R., Rashid, S. A., Jan, B. M., A review of biolubricants in drilling fluids: Recent research, performance, and applications, *Journal of Petroleum Science and Engineering*, vol. 135, pp. 177–184, 2015.
- [8] Al-Hameedi, A. T. T., et al., Experimental investigation of bio-enhancer drilling fluid additive: Can palm tree leaves be utilized as a supportive eco-friendly additive in water-based drilling fluid system?, *Journal of Petroleum Exploration and Production Technology*, vol. 10, no. 2, pp. 595–603, 2019.
- [9] Al-Hameedi, A. T. T., et al., Experimental investigation of environmentally friendly drilling fluid additives (mandarin peels powder) to substitute the conventional chemicals used in water-based drilling fluid, *Journal of Petroleum Exploration and Production Technology*, vol. 10, no. 2, pp. 407–417, 2019.
- [10] Medved, I., Gaurina-Medimurec, N., Mavar, K. N., Mijić, P., Waste mandarin peel as an eco-friendly water-based drilling fluid additive, *Energies*, vol. 15, no. 7, p. 2591, 2022.

- [11] Al-Hameedi, A. T. T., et al., Proposing a new biodegradable thinner and fluid loss control agent for water-based drilling fluid applications, *International Journal of Environmental Science and Technology*, vol. 17, no. 8, pp. 3621–3632, 2020.
- [12] Davoodi, S., Al, A. R. S., Rukavishnikov, V., Minaev, K., Insights into the application of acorn shell powder in drilling fluid as an environmentally friendly additive: Filtration and rheology, *International Journal of Environmental Science and Technology*, vol. 18, no. 4, pp. 835–848, 2020.
- [13] Khalaf, H. A., Alhaj, M. N., Kovacsne, G. F., Evaluation of using waste pinecones as an eco-friendly additive to water-based mud, *Rudarsko-geološko-naftni Zbornik*, vol. 37, no. 2, pp. 1–11, 2022.
- [14] Madu, C., Faraji, F., Abdalqadir, M., Gomari, S. R., Chong, P. L., Feasibility study of biodegradable coffee ground waste and watermelon rind as water-based drilling fluid additives, *Gas Science and Engineering*, vol. 125, p. 205322, 2024.
- [15] Moslemizadeh, A., Shadizadeh, S. R., A natural dye in water-based drilling fluids: Swelling inhibitive characteristic and side effects, *Petroleum*, vol. 3, no. 3, pp. 355–366, 2017.
- [16] Zhou, G., Qiu, Z., Zhong, H., Zhao, X., Kong, X., Study of environmentally friendly wild jujube pit powder as a water-based drilling fluid additive, *ACS Omega*, vol. 6, no. 2, pp. 1436–1444, 2021.
- [17] Murtaza, M., et al., Okra as an environment-friendly fluid loss control additive for drilling fluids: Experimental & modeling studies, *Journal of Petroleum Science and Engineering*, vol. 204, p. 108743, 2021.
- [18] Zhao, X., Li, D., Zhu, H., Ma, J., & An, Y., Advanced developments in environmentally friendly lubricants for water-based drilling fluid: a review, *RSC Advances*, 12(35), pp. 22853–22868, 2022.
- [19] Sifferman, T. R., Muijs, H. M., Fanta, G. F., Felker, F. C., & Erhan, S. M., Starch-Lubricant compositions for improved lubricity and fluid loss in Water-Based drilling muds, *All Days*, 2003.
- [20] Saffari, H. R. M., Soltani, R., Alaei, M., Soleymani, M., *Journal of Petroleum Science and Engineering*, vol. 171, pp. 253–259, 2018.
- [21] Taraghikhah, S., Kalhor, M., Tahmasbi, K., presented in part at the *International Petroleum Technology Conference*, 2015.
- [22] Mijić, P., Gaurina-Medimurec, N., Pasic, B., Medved, I., The influence of SiO₂ and TiO₂ nanoparticles on the properties of water-based mud, in *Proceedings of the ASME 36th International Conference on Ocean Offshore and Arctic Engineering*, vol. 8, 2017.
- [23] Rudnick, L. R., Synthetics, Mineral Oils, and Bio-Based Lubricants: Chemistry and Technology, *CRC Press*, 2005.
- [24] Amorim, L. V., Nascimento, R. C., Lira, M., Magalhães, D. S., Evaluation of the behavior of biodegradable lubricants in the differential sticking coefficient of water-based drilling fluids, *Braz. J. Pet. Gas*, vol. 5, no. 4, pp. 197–207, 2011.
- [25] Fink, J., Petroleum Engineer's Guide to Oil Field Chemicals and Fluids, *Elsevier Science*, 2011.
- [26] Borugadda, V. B., Goud, V. V., Improved thermo-oxidative stability of structurally modified waste cooking oil methyl esters for bio-lubricant application, *J. Clean. Prod.*, 2015.
- [27] Livescu, S., Delorey, J., Misselbrook, J., Lubricating compositions for use with downhole fluids, 2014.
- [28] Amanullah, M., Ramasamy, J., Alouhali, R., presented in part at the *International Petroleum Technology Conference*, 2020.
- [29] Moser, B. R., In Vitro Cell. Dev. Biol.: *Plant*, vol. 45, no. 3, pp. 229–266, 2009.
- [30] Knothe, G., Steidley, K. R., *Energy Fuels*, vol. 19, no. 3, pp. 1192–1200, 2005.
- [31] Li, W., Zhao, X., Peng, H., Guo, J., Ji, T., Chen, B., You, Z., Liu, L., presented in part at the *IADC/SPE Asia Pacific Drilling Technology Conference*, 2016.
- [32] Bart, J. C. J., Cavallaro, S., Gucciardi, E., Biolubricants: Science and Technology, *Elsevier Science*, Cambridge, UK, 2012.
- [33] Manosroi, A., Pattamapun, K., Chankhampan, C., Kietthanakorn, B., Kitdamrongtham, W., Zhang, J., & Manosroi, J., A biological active artificial saliva formulation containing flower mucilage from Ceylon Spinach (*Basella alba* Linn.), *Saudi Journal of Biological Sciences*, 27(3), pp. 769–776, 2020.