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Review

Nanoparticles in Drilling Fluids: A Review of Types, Mechanisms, Applications, and Future Prospects

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Abstract: Nanofluids have gained significant attention as a promising solution to several challenges in drilling operations. Nanoparticles, due to their exclusive properties such as high specific surface area, strong adsorption potential, and excellent thermal conductivity, offer significant potential to improve the efficiency and performance of drilling processes. Regardless of the advancements in drilling fluids and techniques that have improved borehole stability, hole cleaning, and extreme operational condition (HTHP) management, limitations still persist. This review discusses a detailed summary of existing research on the application of nanofluids in drilling, exploring their types, properties, and specific uses in areas such as fluid loss control, wellbore stability, and thermal management. It also reports the challenges and future potential of nanotechnology in drilling, including nanoparticle stability, environmental considerations, and cost concerns. By synthesizing current research and highlighting gaps for further study, this review intends to guide researchers and industry professionals in effectively integrating nanofluid usage to optimize drilling practices and support a more sustainable energy future.

Keywords: drilling engineering; nano fluids; improved drilling operations; rheology; drilling fluids; oil and gas; geothermal

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1. Introduction

Drilling fluids, also known as drilling muds, play a fundamental part in oil and gas drilling operations. They serve numerous key functions for the success and safety of drilling activities. Principally, drilling fluids preserve wellbore stability by giving hydrostatic pressure to prevent blowouts and fluid influx from surrounding formations. They also assist in the removal of cuttings from the borehole, in cooling and lubricating the rotating drill string and drill bit, and in boosting overall drilling efficiency [1]. Furthermore, the properties of drilling fluids can be altered to fit diverse geological conditions, permitting improved control over the drilling process. Also, the effective administration of drilling fluids is essential for optimizing performance, warranting safety, and reducing environmental impact during drilling operations [2].

The basic types of drilling fluid are water-based drilling fluid, oil-based drilling fluid, and synthetic-based drilling fluid. Figure 1 explains the classification of drilling fluids. Water-based drilling fluids are the most frequently used, with water as the base fluid. Their additives include polymers, clays, and chemical additives for controlling properties such as viscosity, pH, fluid loss, etc. Oil-based drilling fluids use oil (usually diesel or mineral oil) as the base fluid. These offer greater lubrication and wellbore stability in comparison to water-based drilling fluids and are best suited for difficult formations like shale and reactive clays. However, they are also expensive and are of environmental concern due to their oil content. Synthetic-based drilling fluids are an amalgam of water-based and oil-based drilling fluids. Synthetic oils or esters make up their base fluid. These advanced fluids provide superior lubricity, wellbore stability, and temperature resistance, particularly in high-pressure, high-temperature (HPHT) wells [3,4]. The general composition of drilling fluids and types are shown in Table 1.

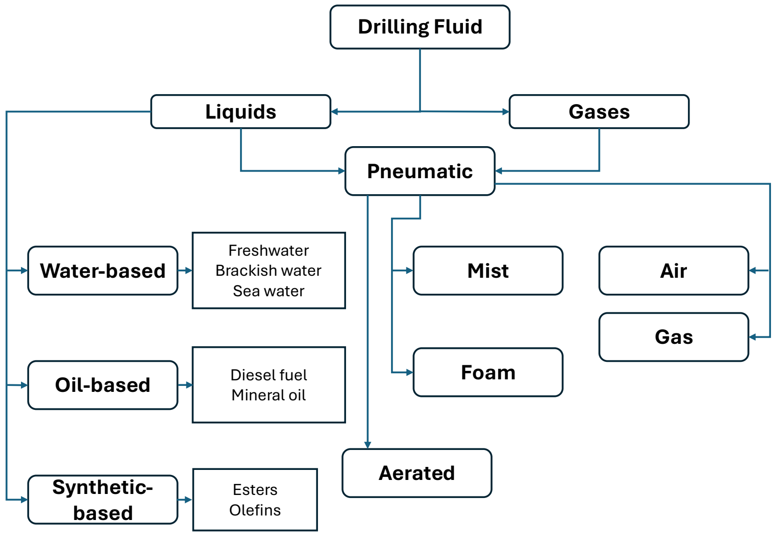

Figure 1. Classification of drilling fluids and types.

Table 1. Composition of various types of drilling fluids along with their preparation processes, advantages, and disadvantages.

Type of Drilling Fluid	Composition	Preparation Process	Advantages	Disadvantages	References
Water-based Drilling Fluid	Seawater (as needed); Freshwater (as needed); Bentonite (0–50) (lbs/bbl); Barite (0–500) (lbs/bbl); NaOH (0–5) (lbs/bbl); Soda Ash (0–3) (lbs/bbl); $NaHCO_3$ (0–3) (lbs/bbl); Drill solids (0–100) (lbs/bbl).	1. Mix water with bentonite and hydrate by stirring. 2. Add barite gradually whilst mixing. 3. Add in polymer and other additives consistently. 4. Add dispersants. 5. Modify pH as required.	Ecofriendly; Low cost; Easy handling and disposal.	Unstable at high temperatures compared to oil-based muds. Possible shale instability in particular formations.	[1,5]
Oil-based Drilling fluid	Base oil (diesel oil/mineral oil) (70–90% vol); Weighting agents (barite/$CaCO_3$/hematite); Emulsifiers (lignosulfonates/fatty acids/tall oil); Filtrate control/wetting agent; Alkalinity control agents (NaOH/Ca $(OH)_2$); Viscosifiers (Xantham gum/starches/organophilic clays).	1. Mix base oil with emulsifier and keep stirring. 2. Add barite progressively. 3. Add surfactants and other additives. 4. Fluid loss control additives can be added as needed.	Exceptional lubrication; High thermal stability; Enhanced cuttings transportation.	High price; Environmental concerns; Hard to clean up.	[1,6]
Synthetic-based drilling fluid	Synthetic organic compounds/esters/lubricants (30–90% vol); Salt (NaCl/KCl) brine; Emulsifiers; Wetting agents; Weighting material (barite, $BaSO_4$, or ilmenite, $FeTiO_3$) Clays; Lignite; Lime.	1. Blend the synthetic base fluid with emulsifiers. 2. Stir and keep hydrated. 3. Gradually add in weighting materials. 4. Add in fluid loss control agents. 5. Include the surfactants.	Eco-friendly options are available; Elevated performance in extreme conditions; Improved fluid loss control characteristics.	Costs more than water-based drilling fluids; Possible toxicity of certain synthetic elements.	[4,7]

After the introduction of OBMs and SBMs, specialized additives for drilling fluid technology were developed. Additives such as emulsifiers and viscosities, weighting agents, and fluid loss control agents resulted in the drilling fluids being more customized and optimized for the geological formations [8]. Nanotechnology in drilling fluids is an important step forward, as nanoparticles may improve rheological properties, thermal conductivity, and performance. This leads to an increased rate of penetration, less wear on equipment, and better wellbore stability [9,10]. Research into biodegradable nanoparticles and "smart" nanofluids that respond to downhole conditions underscores the potential of drilling fluids to optimize drilling operations with minimum environmental impact [11].

Background

The idea of nanofluids (fluids improved with nanoparticles) first emerged during the early 1990s as a possible solution to improving heat transfer in manufacturing applications [12]. After its success, researchers soon recognized the potential benefits of nanoparticles and tried their application in various fields, including the oil and gas industry, especially in drilling fluid technology [10]. By the early 2000s, research focused on tailoring NP properties to deal with particular drilling challenges such as high-pressure high-temperature (HPHT) environments [11]. NPs, usually less than a hundred nanometers in size, provide special properties that could substantially improve drilling fluid performance. Their increased surface area-to-volume ratio enables enhanced interaction with the drilling fluid and the drilling environment, resulting in enhanced rheological properties, reduced friction, and also much better heat transfer [13].

Additionally, the ability of NPs to seal micro-fractures in rock formations plays a role in wellbore stability, stopping potential wellbore collapse and fluid loss [14]. By the 2010s, a wide selection of NPs was being examined for drilling fluid applications, each one with unique benefits. For example, graphene oxide (GO) and carbon nanotubes (CNTs) are known for their exceptional mechanical strength and thermal conductivity [15]. Metal oxides, such as titanium dioxide (TiO_2), alumina (Al_2O_3), and silica (SiO_2), were analyzed for their ability to improve viscosity, filtration control, and lubricity [16]. The latest developments have focused on improving the environmental sustainability of nanofluids. Scientists are exploring non-toxic and biodegradable NPs to reduce the environmental impact of drilling operations [17]. Additionally, ongoing research in "smart" nanofluids, which can react to changes in temperature, pH, or magnetic fields, offers additional advantages in drilling operations. These responsive nanofluids might provide real-time control over fluid properties, optimize drilling efficiency, and reduce risks [11].

Figure 2 shows a clear uptrend in research papers on nanoparticles in drilling; two papers were published in 2007, then there was a gradual growth in papers until 2014 followed by rapid growth. This surge in interest likely reflects the growing recognition of the potential advantages that nanoparticles offer in drilling applications. These include enhanced lubrication, improved drilling fluid properties, increased efficiency, and reduced environmental impact. The continued growth in publications suggests that research in this area is gaining momentum and that the integration of nanotechnology into drilling practices is becoming an increasingly important area of exploration.

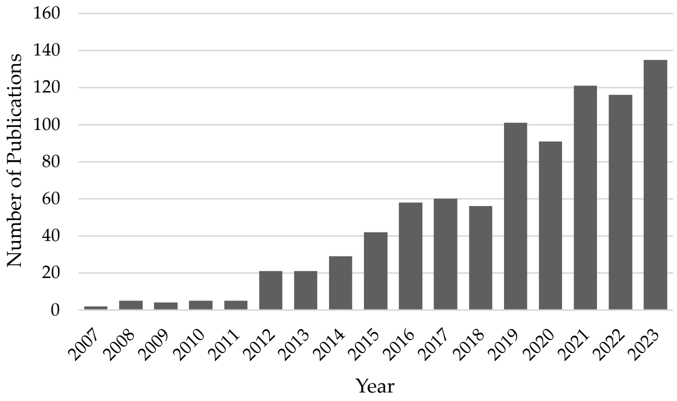

Figure 2. Evolution of research on nanoparticles in drilling: a bibliometric analysis (2007–2023). Data sourced from Dimensions.ai, focusing on publications with the keyword "nanoparticles in drilling" in their titles and abstracts.

Nanoparticle-enhanced drilling fluids hold great promise for improving drilling efficiency and wellbore stability. However, significant challenges remain in achieving widespread adoption. These challenges include maintaining nanoparticle stability in harsh drilling conditions, compatibility, addressing environmental concerns, optimizing heat transfer efficiency, and ensuring economic viability. Additionally, safety considerations, high production costs, scalability issues, and the lack of standardized characterization techniques need to be tackled. Further research and development in these areas are crucial to realizing the full potential of nanofluids in the oil and gas industry.

Given the rapid advancements and potential benefits of nanotechnology in drilling, this comprehensive review is of significant importance. It meticulously synthesizes existing research to address critical knowledge gaps, such as the efficacy of nanoparticles (NPs) across diverse drilling fluids (water-based, oil-based, and synthetic) and their impact on rheological properties, thermal stability, and filtration control. This paper thoroughly examines the applications of NPs in drilling, with a particular emphasis on their role in enhancing wellbore stability, fluid loss control, and thermal stability. Additionally, it examines the often-overlooked environmental and health implications associated with nanoparticle utilization. This synthesis serves as an invaluable resource to guide future research and development, ultimately fostering the responsible and effective integration of nanotechnology to optimize drilling efficiency, wellbore integrity, and the sustainability of drilling operations.

The rest of the paper is ordered as follows: Section 2 establishes the theory of nanofluids, explaining their unique properties and diverse classifications. Section 3 explores the property-based applications of nanofluids, highlighting their roles in lubrication, fluid stability, heat transfer, and sealing microfractures. Section 4 examines the specific drilling applications of nanofluids, examining their contributions to fluid loss control, wellbore stability, thermal stability, and borehole cleaning, while also addressing practical precautions. Section 5 critically evaluates the challenges and future scope of nanofluid implementation, including nanoparticle stability, environmental concerns, economic viability, and safety considerations. Finally, Section 6 summarizes the key findings and underscores the promising future of nanofluids in drilling practices.

2. Nano Fluids

Nanofluids are a subset of engineered fluids that contain nanoparticles (NPs) suspended within a base fluid. They typically measure from 1 to 100 nanometers and are composed of metallic, non-metallic, or composite materials [18]. These fluids employ water, oil, ethylene glycol, or other common fluids as a base in which nanoparticles, including metal oxides (alumina, silica, titania), carbon-based materials (graphene, carbon nanotubes), and metallic nanoparticles (gold, silver), are mixed to form a nanofluid [15]. The characteristics of nanofluids are enhanced thermal conductivity, improved rheological properties, good stability, increased heat capacity, and enhanced surface properties. In drilling fluids, they work through the mechanisms of forming a nano-filter cake that is thin and impermeable, bridging microfractures, and improving the fluid properties such as viscosity and gel strength that assure the reliable suspension and cutting transportation abilities of the fluid [18].

The preparation of drilling fluids with nanoparticles requires following sequential process steps.

i. Selection of nanoparticles: Identify the exact properties, such as improved viscosity, increased thermal conductivity, and enhanced stability, to be addressed in a drilling fluid. Choose the appropriate nanoparticle, for example silica for viscosity, copper for thermal management, zinc oxide for antimicrobial characteristics, and titanium dioxide for stability.

ii. Synthesis of nanoparticles: Based on the chosen nanoparticles, employ respective synthesis methods such as the sol–gel process (suitable for generating metal oxides at controlled sizes), hydrothermal synthesis (includes elevated operational conditions of temperature and pressure for nanoparticle generation), and chemical vapor deposition (appropriate for generating pure/high-quality nanoparticles. Characterize the generated nanoparticles through their size, morphology, and surface properties using transmission electron microscopy (TEM) or scanning electron microscopy (SEM) [12].

iii. Preparation of base fluid: Select water or oil for the base of the drilling fluid, depending on the drilling environment. Choose the necessary additives, such as weighing agents or polymers, based on the drilling environment and based on which could complement the functions of selected nanoparticles.

iv. Dispersion of nanoparticles: Add dispersing agents such as surfactants or stabilizers to prevent the agglomeration of nanoparticles in the base fluid. Use high-shear mixers or ultrasonic dispersers to confirm the even distribution of nanoparticles throughout the drilling fluid.

v. Mixing process: Add the nanoparticles slowly while maintaining continuous stirring to ensure good dispersion. Mechanical mixing or ultrasonication can guarantee a homogeneous mixture [19].

vi. Testing and optimization: Assess the rheological properties such as viscosity, yield point, and flow performance of the drilling fluid with the help of rheometers. Perform thermal stability tests on the fluid at different temperatures to warrant good performance in high-temperature environments. Analyze the test results and fine-tune the nanoparticle concentrations in the drilling fluid for the desired performance [20]. Figure 3 represents one of the basic processes of preparing a nanofluid.

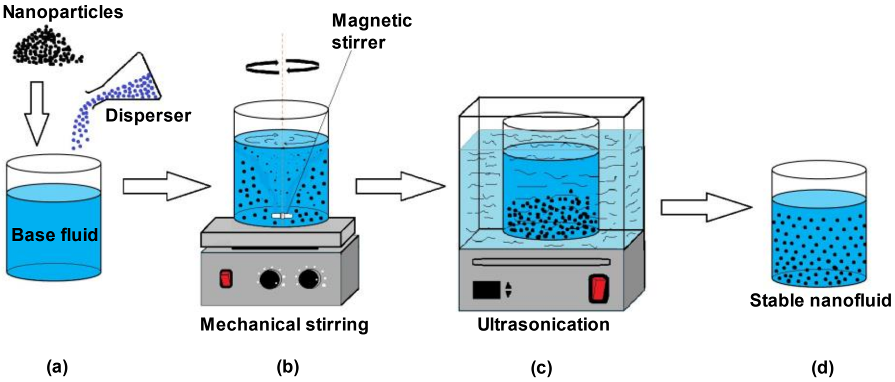

Figure 3. Nanofluid preparation process: (**a**) initial mixing of nanoparticles, dispersant, and base fluid; (**b**) mechanical stirring for preliminary dispersion; (**c**) ultrasonication for particle size reduction and stability enhancement; (**d**) final stable nanofluid with well-dispersed nanoparticles.

Nanofluids of various types are presented in this section, including metal-based, oxide-based, carbide-based, nitride-based, carbon-based, and composite nitride nanofluids. The composition, characteristics, and uses of each type are described, highlighting their benefits, such as enhanced thermal conductivity, improved lubrication, and increased stability under high-pressure and high-temperature conditions. Figure 4 lists the various and most popular nanoparticles used in drilling operations, which are further elaborated on in the following section. While nanomaterials present significant technical advantages in drilling fluids, their challenges cannot be overlooked. High costs related to synthesis and production are significant, mainly because of the required large volumes [21]. Compatibility with the exclusive conditions of individual oil fields, such as temperature and salinity, can also impact performance. Moreover, nanomaterial-related safety hazards and health risks remain vague [11].

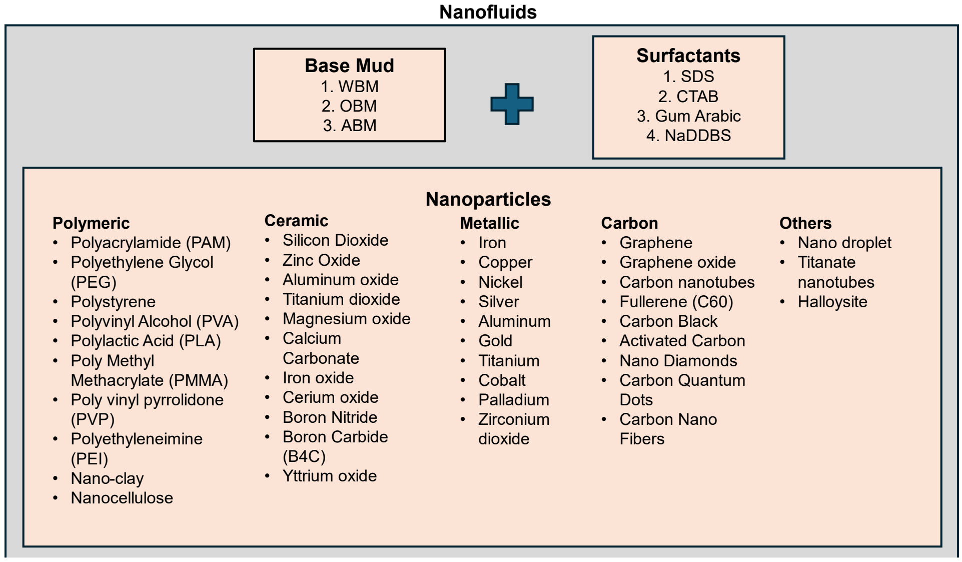

Figure 4. Classification of nanoparticles employed in the formulation of drilling nanofluids.

2.1. Types of Nanofluids

2.1.1. Metal-Based Nanofluids

Metal nanoparticles, such as gold, silver, and copper, are mixed with base fluids (water, ethylene glycol, or oil) to form metal-based nanofluids. Due to its superior corrosion resistance, copper is highly preferred in nanofluids, offering higher suspension stability. Surface-modified copper nanoparticles used with oil-based mud (OBM) have demonstrated enhanced thermal conductivity [18]. Silver nanoparticles, with a diameter of 5 nm, mixed in kerosene-based mud exhibited improved thermal conductivity at 50 °C compared to 25 °C, attributed to enhanced Brownian motion. The increase in the thermal conductivity of the drilling mud by the addition of nanoparticles made the mud cool faster as it moved up the surface [22]. Gold nanoparticles, recognized for their enhanced optical characteristics, are extensively used as coatings for SEM sampling to improve image quality [23].

2.1.2. Oxide-Based Nanofluids

The metal oxide-based nanoparticles, such as copper oxide (CuO), titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3), are mixed with the base fluid to form oxide-based nanofluids. Copper oxide nanoparticles in OBM improved the yield point, gel strength, and apparent viscosity of the drilling fluid. Additionally, at elevated concentrations, copper oxide nanoparticles enhance filtration results under high-temperature, high-pressure (HTHP) conditions [24]. As titanium oxide nanoparticles are highly thermally conductive, they are mostly suited for heat exchange applications. This increased thermal control is crucial in deep and ultra-deep drilling, where high temperatures can compromise wellbore stability and the efficacy of drilling tools [25]. Moreover, TiO_2 nanofluids offer enhanced lubrication, reducing the friction and wear of drilling equipment, thus extending tool lifespan and lowering operational costs [26]. In comparison (see Table 2), aluminum oxide nanoparticle dispersions, even at lower concentrations, improve the thermal stability of water-based drilling fluids more effectively than silica nanoparticles [27].

2.1.3. Carbide-Based Nanofluids

Incorporating carbide nanoparticles, such as boron carbide (B4C) and silicon carbide (SiC), in the base fluid creates carbide-based nanofluid. Despite dealing with price and dispersion stability issues, carbide nanofluids have significant benefits such as enhanced thermal control, improved lubrication, abrasion resistance, enhanced hardness, and improved stability of the wellbore. Boron carbide nanofluids have the capability of improving rheological and filtration properties and also improving the inhibition of shales for unconventional drilling [28].

2.1.4. Nitride-Based Nanofluids

Nitride nanoparticles, such as boron nitride (BN), aluminum nitride (AlN), and silicon nitride (Si_3N_4), are dispersed in the base fluid to make nitride-based nanofluids. These nanofluids are known for their high thermal conductivity. Specifically, as the concentration of hexagonal boron nitride (h-BN) in the fluid increases, the thermal conductivity correspondingly improves. Rheological studies suggest that with an increase in h-BN concentration, the viscosity of the fluid also increases [29]. Additionally, Si_3N_4 NPs can increase the optical absorption capacity of ethylene glycol-based nanofluids. Thermal conductivity also has a linear dependency on the NP concentration [30].

2.1.5. Carbon-Based Nanofluids

These nanofluids are a result of blending carbon nanoparticles, such as Carbon nanotubes, Graphene, and Fullerenes, with base fluid. They offer exceptional thermal and electrical properties. Carbon nanotubes are cylindrically rolled-up sheets of graphene (carbon atoms) and are of two types: single-walled (SWCNT) and multi-walled (MWCNT) carbon nanotubes. They possess superior strength compared to steel and possess high thermal conductivity. Fullerenes, globular and hollow carbon allotropes, are noted for their remarkable strength and high electrical conductivity [31,32]. Additionally, fullerenes are economical materials that can be used to prevent the growth of microorganisms and natural fouling [33].

2.1.6. Composite Nanofluids

When two or more different nanoparticle types are mixed with the base fluid, a composite nanofluid is formed. These composite nanofluids combine the properties of individual nanoparticles to create a fluid with enhanced thermal, chemical, and mechanical characteristics. The benefits of composite nanofluids include improved heat transfer, enhanced lubrication and resistance to wear, superior wellbore stability, and applicability to high-pressure and high-temperature conditions. Examples include metal/metal oxide composite nanofluids such as Fe-Cr/Al_2O_3, Co/Cr, Ni/Al_2O_3, Fe/MgO, Mg/CNT, and Al/CNT. Ceramic composites examples are SiO_2/Ni, Al_2O_3/SiC, Al_2O_3/TiO_2, Al_2O_3/SiO_2, and Al_2O_3/CNT. Polymeric composites are polymer/layered silicates, polymer /CNT, and polyester/TiO_2 [34].

Table 2. Comparison of various types of nanofluids based on cost, base fluid, reusability, and applicable conditions.

Type of Nanofluid	Cost	Base Fluid to be Used with	Reusability	Applicable under Conditions	References
Metal	High	Water, Oil	Moderate	High temperatures and pressures	[22,35]
Metal Oxide	Moderate	Water, Oil, Glycol	High	Moderate to high temperatures	[36–38]
Carbon-Based	High	Water, Organic Solvents	Moderate	High temperatures and pressures	[39]
Composite/Hybrid	Variable	Water, Oil	Moderate	Depends on components and usually high performance	[40–42]
Polymeric	Low	Water, Oil	High	Low to moderate temperatures, variable usage	[43,44]

2.2. Nanofluids in the Drilling Industry

This section explores various nanofluids popularly used in drilling operations and their impact on improved drilling efficiency.

2.2.1. Silica Nanofluids

Silica nanofluids are formed by dispersing silica nanoparticles into a base fluid. These are most useful for improving fluid stability and thermal conductivity. The effects of SiO_2 nanoparticles on the rheology of WBM show that at lower concentrations of NPs, there is no significant change. However, as the concentration of NPs increases, the rheology of WBM is better observed, and the best rheology was obtained at an NP concentration of 1.5 wt% [45]. A combination of SiO_2–xanthan gum (biopolymer/rheology controller) WBM was tested and proved to reduce the volume of filtrate loss. It also improved the swelling inhibition and rheology of the fluid [46]. Silica NPs paired with Gemini surfactants helped to improve thermal stability and reduce filtrate losses, while viscosity was mainly increased by the surfactant [47]. The dispersion of SiO_2 nanoparticles in the WBM allowed for improved viscosity that made the lifting and transporting of cuttings easy, ensuring a thorough cleaning of the wellbore [48].

2.2.2. Alumina Nanofluids

Aluminum oxide nanoparticles are mixed with the base fluid to form the alumina nanofluids. These nanofluids offer chemical stability (as alumina nanoparticles are inert), mechanical strength, lubrication, improved cuttings carrying capacity, better viscosity control, and enhanced thermal transfer abilities. Alumina nanoparticles helped increase the gel strength and shale integrity while reducing the fluid loss by 60% [49]. The dispersion of aluminum oxide NPs helps improve the thermal stability even at lower NP concentrations. Under high-pressure, high-temperature (HPHT) conditions, the degradation effect decreases with an increase in nanoparticle concentration. Filtration tests indicated an increase in filtrate loss with alumina nanoparticles, but this was reduced when silica NPs were added [27]. Aluminum oxide nanorods were used as a stabilizer for Pickering emulsion along with ethyl octanoate ester in creating an ester-based drilling fluid (EBDF). This combination reduced filtration losses by 45% at a 1 wt% nanoparticle concentration and exhibited stable gel rheology even at increased temperatures [49].

2.2.3. Copper Oxide Nanofluids

The blend of base fluid with copper oxide nanoparticles is known as copper oxide nanofluid. Due to the presence of copper oxide nanoparticles, they exhibit excellent heat transfer and antibacterial properties. When used in polyamine-based non-damaging drilling fluid, copper oxide nanoparticles showed thinning behavior, and this effect was amplified when combined with bentonite, leading to depleted fluid loss control and reduced viscosity [50]. CuO is paired with polyacrylamide PAM to form a nanocomposite, resulting in a significant reduction in fluid loss and the thickness of the filter cake of water-based bentonite drilling fluid. It also helped form a smooth and low-permeable filter cake. The CuO nanocomposite improved thermal conductivity significantly [51]. When used along with ZnO CuO in WBM with xanthan gum, the CuO NPs are stronger even at the demonstrated improved rheology, even under HPHT conditions [52].

2.2.4. Carbon Nanotube (CNT) Nanofluids

CNT nanofluids are a mixture of carbon nanotubes and base fluid. They possess great mechanical strength, high thermal conductivity, and high electrical conductivity, putting them in high demand for critical applications. CNT's thermal conductivity enhancement is higher at elevated temperatures and also showed significant filtrate reduction [53]. MWCNTs enhanced the rheological properties by increasing the gel strength (10 s) and reduced the volume of filtrate losses even at high temperatures of 250 °F and 350 °F [54]. When tested against TiO_2 CNTs showed a better ratio of convective-to-conductive heat transfer, about 30% greater than that of the drilling fluid, which consisted of TiO_2 nanoparticles [55].

2.2.5. Graphene Nanofluids

Graphene nanoparticles are introduced into the base fluid and form a mixture known as graphene nanofluids. These are in demand due to their excellent thermal properties and are employed to design nanofluids that significantly boost heat transfer rates. Graphene is a single sheet of carbon atoms that are orderly set in a hexagonal lattice [31]. Graphene is helpful as a pore-plugging filter in oil-based drilling muds. Due to its dispersion issue in water-based muds, it is not employed. Meanwhile, graphene oxide can be used in WBM as it has the proper stability [11]. Graphene oxide nanocomposites are very promising additives that can improve WBDF rheology. They yielded significant changes in plastic viscosity, gel strength, loss of filtrate, and yield point at both LPLT and HPHT conditions [56].

2.2.6. Titanium Dioxide Nanofluids

These nanofluids are formed when TiO_2 nanoparticles are combined with the base fluid. These nanofluids are known for their photocatalytic properties and also their capability to increase the thermal properties of the base fluid. They offer high thermal conductivity, chemical stability (as TiO_2 is chemically inert), tremendous mechanical strength, and excellent resistance to UV rays. TiO_2 nanoparticles are preferred in some applications because they provide a consistent heat transfer performance, even though they have lower thermal conductivity than CNT nanofluids. Also, the conductive heat transfer coefficient increases by 22%, which is on par with the decrease in NP size [55]. TiO_2 nanofluids can be employed in water flooding scenarios as the recovery flow is maximum with TiO_2 nanoparticles [25]. TiO_2 has proved its potential in producing low permeability filter cakes, eventually leading to a reduction in fluid loss [57].

2.2.7. Iron Oxide Nanofluids

These nanofluids are formed by blending iron oxide nanoparticles with a base fluid and are mostly preferred for their biocompatibility and magnetic properties that can be useful in selected drilling scenarios such as magnetic partition and better drilling path detection. Pure crystallites of magnetite (Fe_3O_4) are used in water bentonite drilling fluid. Under LPLT conditions, fluid loss is reduced compared to the base fluid, but the resulting filter cake is thicker. Increasing the nanoparticle concentration improves fluid loss control by thinning the filter cake and decreasing permeability, performing even better under high-pressure, high-temperature (HPHT) conditions compared to LPLT [58]. Smart magnetically controllable custom-made Fe_3O_4 nanoparticles were employed for in situ control of the fluid rheology. The fluid exhibited immense performance in withstanding rapid changes in viscosity and yield stress [59]. Hydrophobic iron oxide NPs are dispersed in hexane (OBM), and after examination, it was discovered that at an NP concentration of 0.5 wt%, the NPs were able to reduce the filtrate losses by 70%, friction coefficient by 39%, and thickness of the filter cake by 55% [37]. Adding Fe_3O_4 NPs improved the plastic viscosity, yield point, and gel strength of KCL-WBM and also reduced the friction coefficient [60].

3. Property-Based Applications

The use of nanoparticles in targeted drilling enhances several key properties, which improves efficiency and effectiveness in drilling operations. This section discusses in detail the key physical and chemical properties that are improved by using nanoparticles, with a focus on the underlying mechanisms.

3.1. Lubrication

Drilling fluids need lubrication in order to reduce friction, avoid stuck pipe situations, enhance drilling efficiency, dissipate heat, shield the drill bit, sustain wellbore stability, and promote safer and greener operations. Drilling operations can be made more efficient and economical by using efficient lubricants in drilling fluids. This has been proven by test results carried out in the TPAO research center using an OFITE lubricity tester on the water-based lignosulfonate mud to which a mixture of light oil and three different lubricants were added and tests were performed under laboratory conditions (room temperature and atmospheric pressure) [61].

The fundamental mechanism of lubrication involves decreasing the friction and wear between the moving components of the drilling setup such as drill bit and drill string to that of the wellbore. This was achieved by developing a lubricating film that can function in boundary, hydrodynamic, and mixed lubrication systems. Nano-titanium borate is an example of one such lubricant that has peak performance under extreme pressure conditions with a lubricity tester (Fann-212) [62,63]. Nanoparticles have an excellent tendency to develop such stable lubrication films on the surfaces and also fill in microscopic asymmetries that can significantly reduce friction between the drilling apparatus and the wellbore. This not only reduces wear and tear on drilling equipment but also enhances the rate of penetration by reducing resistance. Examples include metal oxide-based, diamond-based, and boron-based nanoparticles (withstanding high temperature and high pressure) [10,11,64].

3.2. Fluid Stability

A drilling fluid's stability refers to its ability to maintain its anticipated physical and chemical properties even at various operating settings such as temperature, pressure, and shear rate [65]. As the rheological behavior of the fluid mostly influences its physical properties, viscosity control is very crucial for maintaining fluid stability. Preserving proper viscosity is essential as it plays a crucial role in functions like cuttings transportation, particle suspension, wellbore stability, pressure control, lubrication, cooling, fluid loss control, the erosion and wear of the wellbore, and maintaining efficient circulation throughout the drilling operation [66].

Chemical stability in a drilling fluid is vital to ensure a proper balance of various chemical interactions between the components of a drilling fluid. It helps prevent fluid degradation and avoids undesirable reactions that could compromise the performance of drilling fluid [67]. Chemical compatibility, pH, ionic concentration, corrosion inhibition tendency, hydration, and swelling tendencies (towards reactive clay) of fluid additives are the responsible mechanisms of chemical stability [68–70]. The addition of proper thickeners/thinners, pH adjusters, emulsifiers and surfactants, chemical inhibitors, and rheology modifiers and maintaining proper solids and clay dispersion, hydration, shear rates, and temperatures, as well as real-time monitoring and feedback loop adjustments, collectively make up effective viscosity control and chemical stability, ensuring proper overall fluid stability [66,71]. Nanoparticles help control the viscosity of drilling fluids by preventing phase separation under high-pressure and high-temperature conditions typical of drilling environments, therefore increasing the stability of the fluid. Nanoparticles act as effective rheological modifiers, fluid loss reduction agents, thermal stabilizers, and particle suspension and lubrication enhancers. The experimental analysis of nanoparticles of carbon nanotubes (CNTs), SiO_2, and ferric oxide (Fe_2O_3) proved to be effective under both low and high temperature and pressure conditions when dealing with filtration losses. On the other hand, the NPs of graphene, graphene oxide, multi-walled carbon nanotubes (MWCNTs), and gold are successful under low-pressure and low-temperature conditions [72].

3.3. Heat Transfer

The crucial roles of heat transfer in drilling fluid are to maintain the rheological properties, prevent thermal degradation, provide wellbore stability, prevent gas hydrate formation, and enhance lubrication [65]. Heat transfer occurs through conduction (the movement of heat through the material without the material in motion) and convection (the circulation of the fluid down through the drill string and back up through the annulus), which helps remove heat from the wellbore surface and the drill bit [73,74]. Thus, some factors such as the rate of mud circulation, properties of the fluid (thermal conductivity and specific heat capacity), and well design parameters (borehole diameter and annular space) influence the effectiveness of heat transfer in drilling fluids [8]. Due to their high surface area, nanoparticles improve the thermal conductivity of fluids, aiding in more efficient heat transfer during drilling. This is particularly useful in high-temperature drilling environments. One such example is a novel improved drill-in fluid that is high in density, thermally stable, and consists of synthetic polymer, which is stable and effective at high temperatures of 355 °F. Multi-walled carbon nanotubes have been proven to improve the thermal conductivity of the drilling fluid by exhibiting linear trends with temperature and becoming stable at high temperatures [15,75–77].

3.4. Sealing Microfractures

Microfractures in the formation have to be sealed for various reasons, such as preventing fluid losses, maintaining control over pressure inside the wellbore, protecting the integrity of the formation, protecting the nearby environment (groundwater channels), and collectively assuring the stability of the wellbore [78]. To seal a microfracture, drilling fluids should contain lost circulation materials (LCMs), which aid in sealing. Due to their type (fibrous, granular, and flaked) and size, LCMs can bridge and plug the micro-cracks during mud circulation. As various shaped and sized particles pile up at the entrance of the fracture and form a seal, the additional particles aid in filling the remaining voids eventually strengthening the seal and making it impermeable [79]. The use of chemical additives (polymers and resins) helps in the formation of a gel-like substance that reinforces the seals [80,81]. Nanoparticles can plug microfractures in the rock formation, preventing the loss of drilling fluids and maintaining pressure within the well. Due to their size characteristics (nano-sized), NPs can infiltrate into the tiniest of spaces and cracks. They can form a nano-filter cake that ensures a stable wellbore and targets rheological properties like viscosity [82]. Laboratory experiment results suggest that silica nanoparticles made from rice husks (RH-SNPs) are capable of acting as a lost circulation material by optimizing the filtrate loss at an elevated temperature range (80 °F to 250 °F) [83]. When cellulose nanofibers (CNFs) and polyanionic cellulose (PAC) hybrids are mixed with bentonite water-based drilling fluids under laboratory conditions, they can achieve superior rheological and filtration properties [84].

4. Drilling Applications

In the previous section, the various physical properties and underlying mechanisms of nanofluids were elaborated on. This section focuses on the application of nanoparticles to enhance drilling operations. Specifically, we examine three key areas: fluid loss control, wellbore stability, and thermal stability. For each application, the importance is discussed, followed by an explanation of the mechanisms through which nanoparticles achieve these improvements and a detailed presentation of the specific nanoparticles used in the industry.

4.1. Fluid Loss Control

Drilling fluid loss should be controlled to limit the seepage of drilling fluids into surrounding formations. A suitable fluid loss control is needed to prevent formation damage from blocking natural hydrocarbon pathways and reducing well productivity. It is also essential to maintain wellbore stability because wellbore collapse or other structural problems could result from excessive fluid loss [85,86]. Also, fluid loss management reduces operational expenses by avoiding the need for additional drilling fluids and delays. This also addresses environmental concerns as it prevents the contamination of adjacent formations with drilling fluids. Drilling fluid into these formations may introduce environmental pollution that may persist in ecosystems [87]. The result is that the industry is always looking for better ways of controlling fluid loss and ensuring efficient drilling procedures.

Nanoparticle Solutions for Fluid Loss in Drilling

Nanoparticles are unique in limiting fluid loss during drilling operations. Figure 5 is a pictorial interpretation of how the nanoparticles aid in fluid loss control mechanisms. Their small size allows them to enter and seal tiny fractures and nanopores in the rock formation to reduce permeability and fluid loss. For example, silica nanoparticles are known to be stability and sealing agents that reduce fluid loss through the quality of filter cake formed on the wellbore wall [88]. Also, graphene oxide nanoparticles are very strong mechanically and create a superior barrier, thus reducing fluid loss [89]. Clay nanoparticles further enhance the rheology of drilling fluids by maintaining cutting suspension and regulating fluid movement, increasing drilling efficiency, and reducing fluid loss [90]. Carbon nanotubes and other carbon nanoparticles improve the thermal stability and general efficacy of drilling fluids [91]. Adding these nanoparticles to drilling fluids may improve fluid loss control and thus increase the efficiency, cost-effectiveness, and environmental sustainability of drilling operations.

Numerous research studies have emphasized the efficacy of different nanoparticles in managing fluid loss. In a study by Jung, Y. [92], the utilization of iron oxide nanoparticles in bentonite fluids was examined, revealing that elevating the concentration of these nanoparticles enhanced yield stress, viscosity, and particle interaction strength, particularly in high-temperature and high-pressure environments. The developed fluid suspensions exhibited viscosity variations at different temperatures due to the presence of larger particles linked to increased salinity in the colloidal system and heightened iron oxide content. Barry, M. [93], demonstrated that iron–oxide clay hybrids (ICHs) formed filter cakes with reduced permeability, leading to a substantial decrease in fluid filtrate volumes under both low-temperature, low-pressure (LTLP) and high-temperature, high-pressure (HTHP) conditions. In 2016, Mahmoud, O. [9], investigated the simultaneous use of ferric oxide and silica nanoparticles. They found that while ferric oxide nanoparticles improved the flow properties and controlled fluid loss, silica nanoparticles had a negative impact on flow behavior by increasing repulsion forces between clay platelets. A novel polymer-based micro-nanocomposite (nano-silica and hydrophobics-associated polymers) with a core–shell structure was created. As per Figure 6, the particle had a spreading limit from 280 nm to 320 nm with micro-crosslinked properties in aqueous solutions. WBM made of this novel micro-nanocomposite demonstrates its outstanding thermal stability and rheology at lower concentrations of composite. The brilliant sealing ability of this composite can hinder pressure transmission, enhance the pressure-bearing capability of formation, and isolate the fluid interaction (drilling and formation), helping to stabilize the borehole [94].

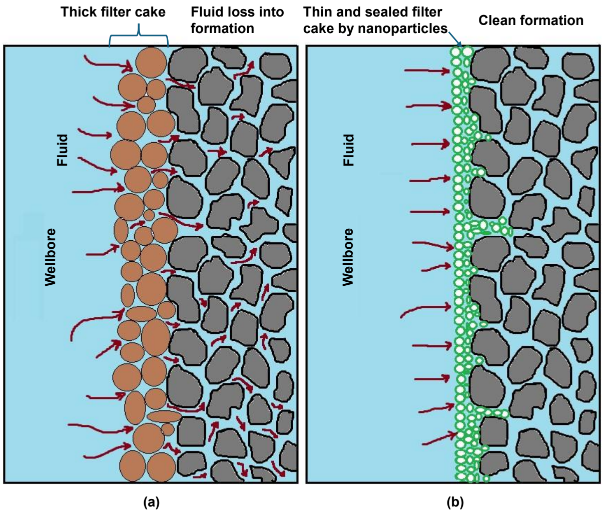

Figure 5. Fluid loss mechanisms: (**a**) conventional drilling fluid—thick, porous filter cake allows filtrate to escape into the formation; (**b**) nanoparticle-laden drilling fluid—nanoparticles bridge pore spaces in the filter cake, forming a thin, impermeable barrier that minimizes fluid loss.

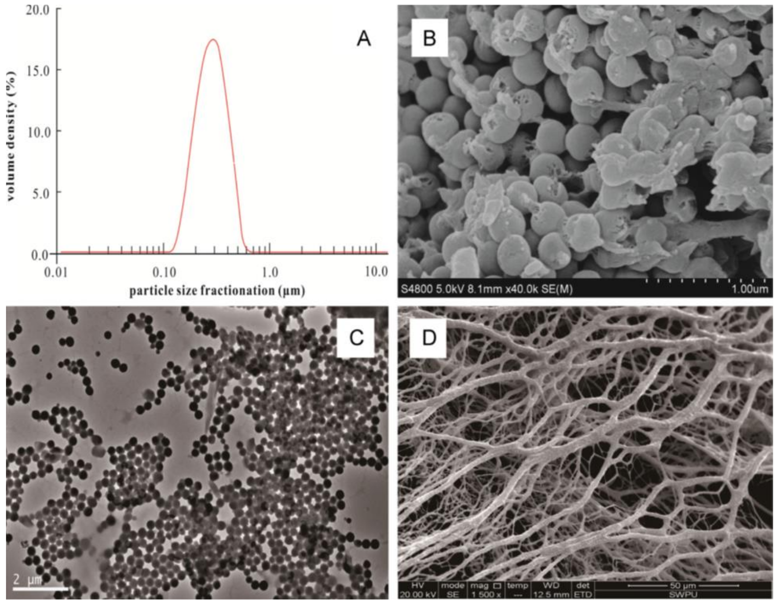

Figure 6. (**A**) Particle size distribution curve demonstrates the high surface area of the material. (**B**) SEM image of SDFL (a polymer-based nano-silica composite with a core–shell structure) reveals the morphology of the composite particles. The polymer matrix appears to form connections between the particles. (**C**) TEM image of SDFL confirms good dispersion in aqueous media, likely due to the hydrophobic polymer coating on the nano-silica particles, which supports the formation of a core–shell structured composite. (**D**) ESEM image of SDFL shows the strong crosslinking within the composite when nano-silica is mixed with the polymer, resulting in a tightly knit grid-like structure. (figure sourced from [94]).

Additionally, Vryzas, Z. [15] showed that specially made magnetite nanoparticles notably decreased fluid loss and enhanced filter cake properties, particularly at a 0.5 wt% concentration. Ismail, A.R. [95], and Sadeghalvaad, M. [96], discovered that carbon nanotubes and TiO_2 nanocomposites improved the flow properties and fluid loss characteristics of drilling fluids. Cao, Y. [97], demonstrated that cellulose nanocrystals boosted the flexural strength of cement pastes, suggesting potential advantages for drilling fluid formulations. The combined results emphasize the important function of nanoparticles in accomplishing effective, economical, and environmentally conscious drilling activities. Table 3 provides a summary of research studies that explored the use of nanoparticles to address fluid loss. The table includes details on the specific types of nanoparticles used in each study and the main findings.

Table 3. Summary of research papers investigating the application of nanoparticles to target fluid loss, including the specific nanoparticles used and key outcomes.

References	Nanoparticle	Outcomes
[95]	Carbon nanotubes and nano-silica	Adding multi-walled carbon nanotubes and nano-silica enhanced mud rheological properties, such as plastic viscosity and yield point, compared to the base fluid.
[98,99]	Nano-silica	Reduced fluid losses by 56% compared to the normal drilling fluid.
[100]	Mesoporous nano-silica	Remarkable fluid loss reduction up to 41.81%, even under HTHP conditions.
[15]	Fe_3O_4	Reduced fluid losses by 40%, even under HTHP conditions of 250°F and 300 psi.
[101]	Poly(sodium p-styrene sulfonate)-modified Fe_3O_4	Enhanced thermal, rheological, and filtration properties.

Table 3. *Cont.*

References	Nanoparticle	Outcomes
[93]	Fe_2O_3	Better rheology and controlled fluid losses.
[94]	Fe_2O_3—clay hybrid nanoparticles	Improved rheological properties of the drilling fluid.
[102]	Iron-based nanoparticles	Better fluid loss control.
[96]	TiO_2 nanocomposites	Less thickness of mud cake and a 64% decrease in fluid losses compared to conventional drilling fluids.
[15]	Calcium nanoparticles	Considerable fluid loss reduction and production of thinner filter cake which reduces permeability.
[103,104]	CuO and ZnO	Reduced thickness of mud cake while upholding filtration properties.
[105–108]	Graphene nanoparticles	Improved rheology and fluid loss control.
[109]	Polymer graphene oxide	Stable filtration properties using polymer graphene oxide composites.
[110]	Graphite–alumina	Reduction in fluid losses.
[111]	Sepiolite nanoparticles	Enhanced rheological and filtration properties of the drilling mud.
[112]	MgO	Decrease in fluid loss by 52% under HTHP conditions.
[27]	Al_2O_3	Enhanced filtration and rheological properties of water-based mud even under HTHP conditions.
[113]	$CaCO_3$	Effective plugging of pores and reducing filter losses.
[114]	$BiFeO_3$	Enhanced the force of attraction among clay particles due to NPs being highly ferroelectric and carrying permanent polarization, resulting in improved rheological properties, such as apparent viscosity and yield point.
[115]	Carbon black	Significant reduction in fluid loss.
[116]	Cellulose nanoparticles	Reduction in fluid loss at lower NP concentrations and improved rheology of the fluid.

4.2. Wellbore Stability

The ability of the wellbore to maintain its structural integrity and stability throughout the drilling process is called wellbore stability. Warranting wellbore stability is vital to avoid wellbore collapse, blocked and stuck pipe situations, the loss of drilling fluids, and other operational problems (in the completion and production phases), which can increase costs and cause delays [117]. The key factors that affect the wellbore stability include the mechanical properties of the rock, in situ stresses, drilling fluid properties, and drilling practices [117,118]. The mechanical properties of the formation, such as rock strength, porosity, and permeability, are linked to the reaction of the formation while drilling [119]. In situ stresses are prevailing stresses in the subsurface that can lead to wellbore collapse or fracture if not maintained appropriately. The properties of drilling fluid, such as chemical composition, density, and viscosity, play a critical part in maintaining wellbore stability by supporting the wellbore walls. Drilling procedures, such as the rate of penetration, the direction of drilling, and the design of the bottom hole assembly, also affect wellbore stability [117,120].

Mechanisms like improving the filter cake strength, clogging the pores and microfractures, enhancing the rheology of fluid, improving thermal stability, decreasing drag and friction, and ensuring thorough borehole cleaning are contributions of nanoparticles in maintaining wellbore stability [121].

4.2.1. Reinforcement of the Filter Cake

Nanoparticles improve the quality and integrity of the filter cake formed on the wellbore walls. This is achieved when nanosized particles deposit themselves between the larger particles and physically form a bridge across the pores, resulting in a thin, impermeable filter cake that reduces fluid incursion into the formation and offers a physical barrier that strengthens the wellbore walls. Their ability to form a densely packed matrix results in low permeability. Therefore, the overall stability is improved and the risk of collapse due to fluid loss is reduced [122]. Hydrophobic nano-silica is used in water-based drilling fluid to enhance wellbore strength. Figure 7 shows scanning electron microscopic (SEM) images of shale surfaces before and after treatment with HNS. Inhibiting osmotic hydration, inhibiting surface hydration, decreasing the capillary action, and increasing the effectiveness of pore-plugging shale contributed to wellbore stability [123]. A new nanofluid using various concentrations of nano-ZnO (0.25%, 0.50%, and 0.75%) resulted in increased shale stability due to the positive charge, size, and hydrophilic behavior of NPs [124]. Modified ZnO nanoparticle additives succeeded in blocking pore spaces in shale samples. Because of zinc oxide, the nano-fluid is positively charged and also hydrophilic, the negative charge of the shale clay adsorbs the nanofluid and succeeds in blocking the pore throats. It can be adsorbed by shale (clay) particles that are negatively charged and block the pore throats. ZnO NPs are widely dispersed in cores and are capable of bridging the pore throats [124]. Using ferric oxide NPs enhanced the filter cake and filtration characteristics of Ca–bentonite-based drilling fluids with polymer additives. The NP concentration of 0.3–0.5 wt% helped in generating a very good quality filter cake characteristics [125]. Calcium carbonate ($CaCO_3$) nanoparticles can also be a great additive that offers superior filtration properties and smooth filter cake surfaces. At an optimum NP concentration of 0.07 wt%, there is a 64% reduction in filter cake thickness [126].

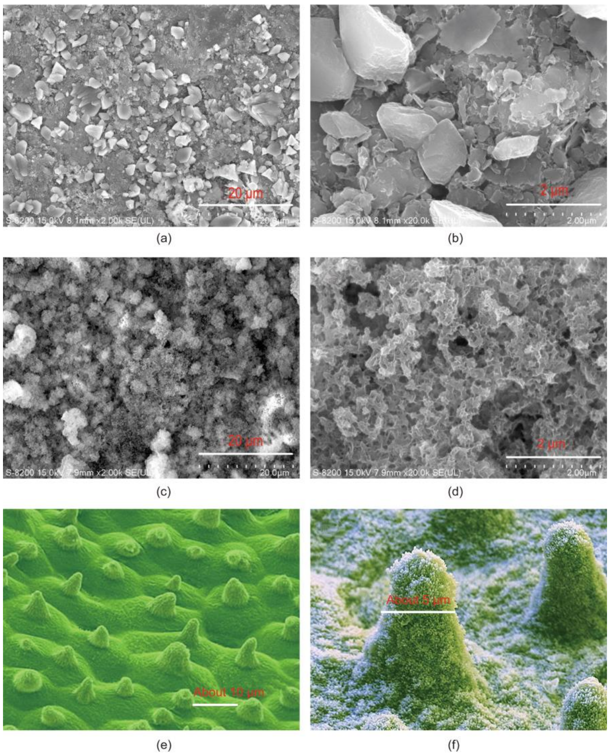

Figure 7. Scanning electron microscopy (SEM) images of (**a**,**b**) an untreated shale surface; (**c**,**d**) a shale surface treated with 1.0 wt% hydrophobic nano-silica (HNS) at 120 °C for 16 h; and (**e**,**f**) a lotus leaf surface (for comparison). HNS adsorption modifies the shale's microstructure, significantly increasing the contact angle and thus reducing surface free energy. This change in wettability hinders hydration and enhances wellbore stability by efficiently closing shale pores and forming a smooth, water-resistant film (figure adapted from [123]).

4.2.2. Closing Microfractures and Pores

One of its advantageous characteristics of being very small in size (nanometers) enables the nanoparticles to efficiently penetrate and close microfractures and pores inside the formation. They build a more consistent particle size distribution helping in clogging the pore spaces. This helps to stop the invasion of formation fluids into the wellbore, reducing the chances of weakening the wellbore; this results in wellbore integrity. Figure 8 is a schematic representation of how nanoparticles close the microfractures. In unstable formations, an appropriate shale stabilizer for the WBDF is the combination of polyethylene glycol and nano-silica. Additionally, the combination was used as an efficient agent to plug shale cracks and pores. Graphene derivatives are used as a filter or pore-plug in oil-based drilling fluids as they enable stability in the aqueous medium [127]. However, the poor dispersion is the reason for the poor performance of graphene derivatives in water-based drilling fluids [128]. Nanofluids made with a combination of hydrophobic CaCO3 nanoparticles and cetyl trimethyl ammonium chloride (CTAC) as a dispersion agent help to reduce filtrate losses with increasing nanoparticle concentrations, demonstrating that nanoparticles can efficiently plug the pores and thus decreasing the size of fluid loss channels [113]. Silica nanoparticles in a Pickering emulsion with low mass concentrations will settle on the fracture surfaces, evenly stabilizing the shale and preventing the hydration of clay [127,129].

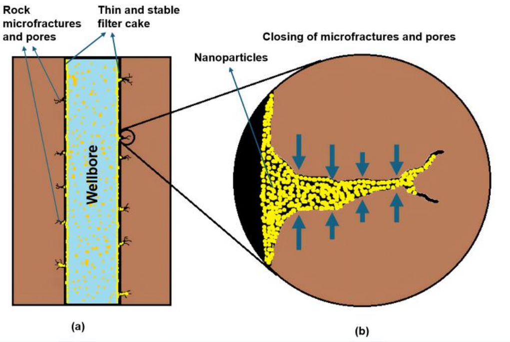

Figure 8. Wellbore stability mechanisms. (**a**) A stable wellbore is characterized by the presence of tiny microfractures and pores, which are effectively sealed by a thin layer of filter cake. (**b**) An enlarged view of a microfracture illustrates how nanoparticles can penetrate and fill the void spaces within the fracture, further enhancing wellbore stability and preventing fluid loss.

4.2.3. Improving Fluid Rheology

Rheology is the representation of a fluid's viscosity behavior under the variable conditions of temperature and pressure. Viscosity is the ratio of shear stress to shear rate and describes the behavior of the fluid flow. It is a constant number for Newtonian fluids like water and oil [130]. Conversely, once polymers are mixed into a Newtonian fluid, the polymer chains develop resistance to flow which is not directly proportional to the shear rate. Increasing shear rates cause expansion and alignment in polymer chains. Due to this, the viscosity becomes low at high shear rates and vice versa. This behavior is known as shear thinning, non-Newtonian or power law behavior. In simpler terminology, the effective viscosity becomes less compared to water while the shear rate increases. Shear stress is associated with the pressure required to initiate the flow. So, even a small pressure can start the flow in both Newtonian and non-Newtonian fluids [1]. Therefore, the rheological properties of drilling fluid are of utmost importance and are explained as follows.

i. Drilling fluid Density/Mud Weight: Density is the mass per unit volume of drilling fluid and is mostly measured in PPG (parts per gallon) or g/cm$_3$ (gram per cubic centimeter). Mud weight is mainly responsible for maintaining hydrostatic pressure inside the wellbore to counteract formation pressures and prevent blowouts. Lower densities of the drilling fluid would lead to borehole breakout (shear failure of rocks) and wellbore collapse, while higher densities would result in problems such as decreased rate of penetration, probable loss of circulation, and formation damage. Nanoparticles can help in maintaining the fluid density through weight addition by using heavier nanoparticles like barite, which would improve its overall density [123,131].

ii. Plastic Viscosity (PV): The resistance of the fluid to flow due to the friction between the solid particles and the fluid layers of the drilling fluid. As PV depends on the viscosity of the base fluid (water, oil, and solids concentrations), higher mud weights and solids concentrations in drilling fluid would lead to higher PV values, resulting in reduced drilling speeds that are unfavorable [72]. Nanoparticles can improve plastic viscosity by increasing the contact area among the particles in the fluid, enhancing interparticle interactions, and leading to a thicker fluid structure. Silica nanoparticles are well known for improving viscosity by developing a network that stabilizes the fluid [99].

iii. Yield Point (YP): The point (stress level) at which the fluid yields its ability to resist the initial flow (shear thinning behavior) in non-Newtonian drilling fluids. The YP facilitates the capability of carrying drill cuttings through suspension during mud circulation (dynamic condition) in the wellbore, thereby avoiding differential sticking. Smaller particle sizes (of solids/additives) could lead to higher YP values due to the enhancement of the attractive forces between the solid particles and result in the better carrying of drill cuttings and in better hole cleaning [1]. Nanoparticles can yield thixotropic properties, resulting in fluid thickening when at rest and thinning under shear stresses, resulting in a better yield point when the fluid is still. Bentonite nanoparticles are one of the examples that exhibit thixotropic behavior. They increase the yield point by preserving a gel structure that refuses to flow until enough stress is employed [132].

iv. Gel Strength (GS): This is the force required to break the gel structure (attraction force between particles) of a fluid after resting for some time. GS is the measurement of drill cuttings suspension capability while the fluid is at rest (static condition), in contrast to YP. GS is time-dependent; if the fluid is static for longer, then the GS increases and more pressure is required to break the gel to restart circulation [72]. Nanoparticles such as palygorskite (Pal), a natural hydrous clay mineral with a fibrous rod-like needle microstructure, provide exclusive colloidal properties that help to improve gelation and the better suspension of drill cuttings in drilling fluids [90].

v. v. Filtrate Loss and Mud Cake Thickness: Filtrate loss is the volume of liquid that escapes through a solid mud cake formation and infiltrates the surrounding formations due to the hydrostatic pressure being higher than the pore pressure. Suspended solids in the drilling fluid will fill the pores and form a mud cake. Higher solids concentrations in fluids tend to decrease the filtrate loss. Higher filtrate loss and mud cake thickness lead to differential pipe sticking. A good mud cake should be thin, strong, compressible, and have very low permeability [1,72]. The careful monitoring of factors such as drilling fluids composition, the amount of fluid loss control additives, the characteristics of suspended solids, and the thermal stability of the system helps us to achieve control over filtrate loss and mud cake thickness. Nanoparticles such as multi-walled carbon nanotubes (MWCNT) help us to achieve low filtrate volumes and thin impermeable filter cakes through high surface areas and nanotube structures [123,133].

Nanoparticles can alter the rheological properties of drilling fluids under variable temperature and pressure conditions to help make them more stable during the drilling process. Keeping the viscosity of the drilling fluid in check helps to improve cuttings suspension and transportation efficiency and the wall support of the wellbore. Metal oxide nanoparticles, such as copper oxide, aluminum oxide, and magnesium oxide, can reduce plastic viscosity by 50% and improve yield point and gel strength under low-temperature and low-pressure conditions [134]. Using nano-clay along with bentonite in commercial calcium carbonate drilling fluid will result in increased and stable gel strength and yield point and an overall enhanced fluid rheology [135]. Drilling fluids need to have low stress for easy pumping during the bit penetration, yet they must be strong enough to suspend the cuttings during operation pauses. Both ZnO and CuO nanoparticles improve the rheological properties of drilling fluid, even at elevated temperatures. At various higher concentrations of NPs, up to 1 wt%, ZnO surpassed CuO in performance [104]. Usually, salts damage the rheological and filtration properties of the WBDF, as it is salt-free. Fe_3O_4 NPs support and enhance the rheological properties of both salty and salt-free drilling fluids to a remarkable extent. Nano-sized Fe_3O_4 nanoparticles might reduce the filtration properties of the salt-free WBDF, yet it is an appropriate filtration control agent for drilling fluids contaminated with salt [136]. Table 4 outlines research on using nanoparticles to improve the stability of wellbores in drilling operations. It lists the types of nanoparticles studied and the main results observed in each study.

4.2.4. Improving Thermal Stability by Reducing Friction and Drag

Nanoparticles can enhance the thermal stability of drilling fluids by averting the degradation of fluid properties when exposed to high temperatures, which commonly occurs and is explicitly essential in deep and high-temperature wells. This helps preserve drilling fluid integrity and guarantees constant support for the walls of the wellbore. Nano-silica was able to stop the thermal degradation of polymer additives in the drilling fluid due to its increased apparent viscosity and yield point compared to the base mud [137]. Graphene oxide nanoparticles in drilling fluid showed good thermal conductivity.

The friction between the drill string and the wellbore walls is reduced with the help of specific nanoparticles like graphene and (CNT) carbon nanotubes. This decreases mechanical stresses and benefits from sustaining the wellbore stability by reducing the risk of pipes becoming stuck and collapsing because of mechanical forces.

4.2.5. Improving Borehole Cleaning

Nanoparticles help improve the suspension and transportation capabilities of cuttings in the drilling fluid, ensuring that the cuttings stay suspended even under static or low flow conditions. Such suspension capabilities help to avoid the settlement and packing of cuttings that can result in stuck pipe scenarios and thus destabilized the wellbore. Figure 9 illustrates a stuck pipe situation and how the filter cake thickness contributes to the scenario. Ensuring a stable and clean wellbore also helps to reduce operational difficulties.

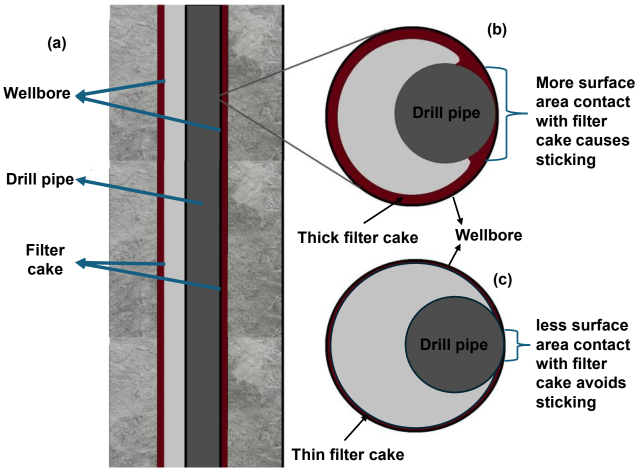

Figure 9. Schematic illustrating the stuck pipe mitigation with nanofluids. (**a**) A wellbore scenario where a drill pipe becomes stuck due to thick filter cake buildup on the wellbore wall. (**b**) Enlarged cross-section illustrating how the increased contact surface area of thick filter cake contributes to the pipe sticking. (**c**) Nanofluids offer a solution by forming a thin filter cake, reducing contact area, maintaining good particle suspension, and enhancing cuttings transport to prevent stuck pipe incidents.

Table 4. Summary of research papers investigating the application of nanoparticles to address wellbore stability issues, including the specific nanoparticles used and the key outcomes.

References	Nanoparticle	Outcomes
[99]	Silica (SiO_2)	Due to high surface area and chemical stability, it enhanced mud rheology and reduced fluid loss.
[138]	Amino nano-silica	Improved plugging performance compared to nano-silica.
[139]	Alumina (Al_2O_3)	High hardness and thermal stability of the nanoparticles aided in improving lubrication and increasing cutting transportation.
[140]	Titanium dioxide (TiO_2)-bentonite nanocomposite	Improved lubricity and mud cake development, layering on shale and bentonite plugs, easing of clay and shale swelling, and a decrease in friction coefficient.
[141]	Iron oxide (Fe_2O_3)	Improved coefficient of friction and fluid loss (filtrate loss).
[105]	Graphene oxide (GO)	The linear swelling, filtration, uniaxial compressive strength, and imbibition of shale help prevent wellbore instability.
[142]	Carbon nanotubes (CNTs)	Carbon nanotubes improve the performance of water-based drilling fluids in high-salinity and high-temperature conditions.
[143]	Zinc oxide (ZnO)	Zinc oxide nanoparticles enhance the rheological properties of water-based drilling fluids even at high temperatures.
[112]	Copper oxide (CuO)	Copper oxide nanoparticles are efficient in decreasing fluid loss and increasing wellbore stability in drilling fluids.
[41]	Magnesium oxide (MgO)	Magnesium oxide nanoparticles in water-based drilling fluids can improve rheological, filtration, and viscoelastic properties and enhance wellbore stability.
[144]	Bentonite nanoparticles	Decreases filtration loss by a mean of 34%, leading to better filtration; the nano-bentonite particles are layered onto the wellbore wall and close off the pores in the mud cake, thus helping with the “tight spot problem” in wellbores.

4.2.6. Practical Precautions

While choosing the nanoparticles, the selection should be made depending on the well conditions, alongside temperature, pressure, and formation characteristics. The compatibility of nanoparticles with drilling fluids should be checked by confirming that respective nanoparticles are cooperative and fit with the base drilling fluid and its other additives as it is important to avert hostile reactions and sustain fluid performance. The nanoparticle usage should be in compliance with environmental regulations and have safety standards so as to avoid any possible health risks and adverse environmental impacts (see Table 5).

Table 5. Environmental impacts and best application details of respective nanofluids.

Type of Nanofluid	Best Application for	Environmental Impact	Reference
Copper	Improved thermal conductivity and lubrication properties.	Moderate, yet toxic in higher concentrations.	[145]
Alumina (Al_2O_3)	Enhanced stability and viscosity.	Low, deemed safe in general but needs supervision.	[15]
Zinc oxide (ZnO)	Better lubrication and antimicrobial properties.	Moderate, toxic to aquatic life if released.	[146]
Titanium dioxide (TiO_2)	Enhancement of fluid stability at high temperatures.	Low, safe yet concerning for inhalation risks.	[147]
Iron oxide (Fe_2O_3)	Effective removal of cuttings.	Low and non-toxic, yet accountable disposal is required.	[148]

Table 5. *Cont.*

Type of Nanofluid	Best Application for	Environmental Impact	Reference
Silver	Fluid quality maintenance and antimicrobial nature.	High, toxic for aquatic life in higher concentrations	[149]
Silica	Improved fluid stability and transportation of cuttings.	Low and relatively non-toxic but carries risk of dust exposure.	[15]
Graphene oxide	Enhanced mechanical properties and sealing of micropores.	Moderate, caution required due to environmental persistence and potential toxicity.	[150]

4.3. Thermal Stability

Drilling projects require thermal stability, which refers to how well drilling fluids can withstand the heat underground [76]. This heat comes from several places: the friction from the actual drilling itself, the temperature increase with depth (geothermal gradient), and the proximity to the hot drill bit [151]. Such high temperatures destroy the properties of drilling fluid. For instance, high temperatures make the fluid thinner (less viscous). This may result in the poor removal of rock cuttings, unstable wellbores, and fluid loss into the rock. High temperatures also impede the fluid's ability to lubricate and reduce friction, and equipment failure is more likely [152]. Other problems include heat accelerating undesirable chemical reactions in the drilling fluid [28]. Such reactions give off noxious byproducts, change the chemistry of the fluid (pH and salinity), and damage equipment or stop drilling operations altogether. In conclusion, drilling fluid stability at high temperatures is very important. It impacts the viscosity, lubrication, and overall performance of the drilling fluid—which in turn affects the safety and success of the drilling operation. Nanoparticles have proven their ability to maintain the thermal stability of the drilling fluid by preventing the degradation of fluid by proficiently managing thermal conductivity (effective heat distribution due to smaller size and more surface area to accept heat), viscosity control (maintenance of viscosity at elevated temperatures), shear thinning behavior (being less viscous at high shear and more viscous at rest), and fluid loss reduction (stable filter cake) [90,98,153,154]. The following subsections will elaborate on how nanoparticles aid in achieving thermal stability in a drilling fluid.

4.3.1. Nanoscale Heat Management Mechanisms

Heat transfer at the nanoscale is controlled by nanoparticles for thermal stability improvement. Nanoparticles are generally good thermal conductors that can effectively radiate heat away from critical areas [15,77]. Two key mechanisms (static and dynamic) are responsible for heat movement in nanofluids. Figure 10 illustrates static (structural) mechanisms forming a liquid layer at the solid–liquid interface which acts as the heat-transporting bridge and a chainlike transportation path for heat due to particle aggregation. Figure 11 shows the dynamic mechanism comprising the particle's Brownian motion and its induced convection in the base fluid [155]. Nanoparticles form a physical barrier to protect the components of the drilling fluid from heat and damage [156]. Some nanoparticles also possess optical properties that reflect or absorb infrared radiation, reducing heat buildup [75]. Nanoparticles may stabilize emulsions and colloidal suspensions within the drilling fluid by foiling phase separation and maintaining homogeneity even under thermal stress. Higher concentrations of multi-walled carbon nanotubes in ester-based drilling fluids achieve better emulsion stability and other rheological properties [157]. This multifaceted thermal management makes nanoparticles an effective tool to maintain the stability and performance of materials at high temperatures [103]. The following paragraphs describe the influence of nanoparticles on the thermal stability, viscosity control, chemical stability, and lubrication control of drilling fluids at high temperatures.

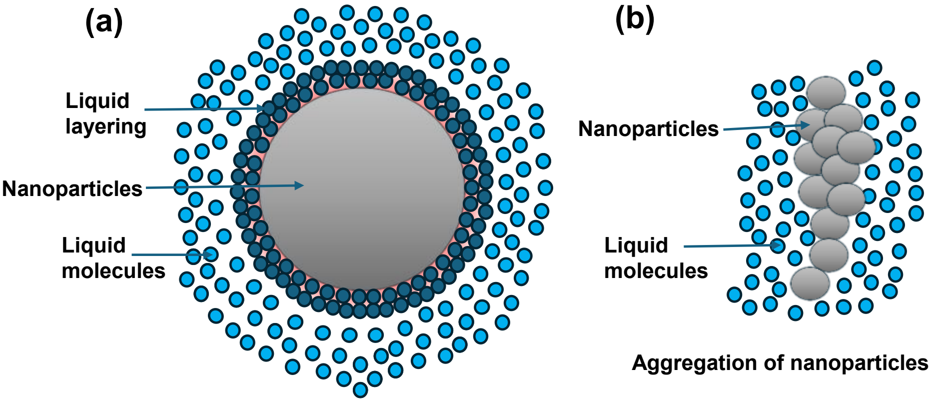

Figure 10. The static mechanism of heat transfer in nanofluids: (**a**) representation of how the liquid layering occurs at the solid–liquid interface of the nanoparticles; (**b**) aggregation of nanoparticles that act as a pathway for heat transfer.

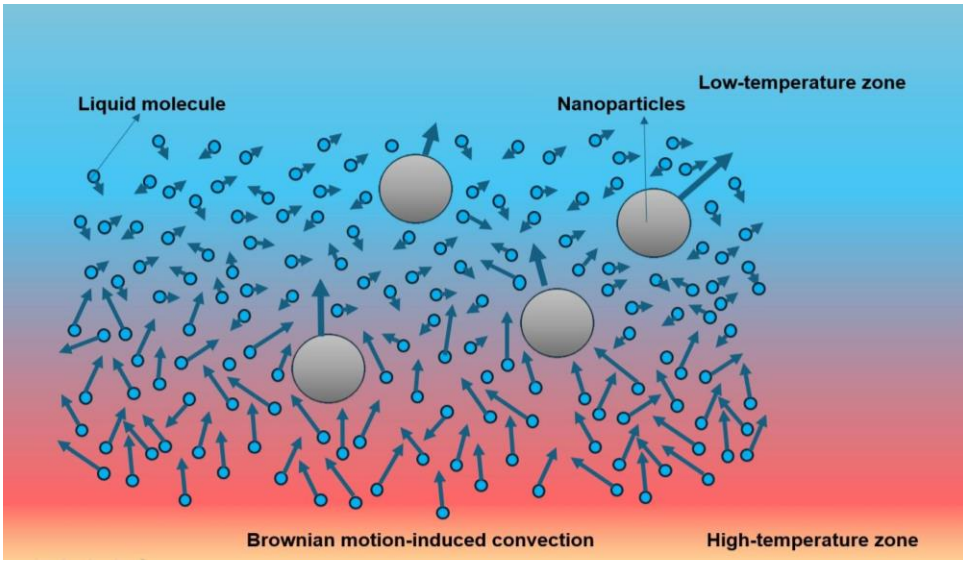

Figure 11. Dynamic mechanism of heat transfer: as the particles move in a Brownian motion (irregular movement), they collide with each other and also induce convection for the nearby liquid molecules of the base fluid, thus increasing the thermal conductivity.

4.3.2. Temperature Resistance:

The nanoparticles of metals (iron oxide, silica, titanium dioxide) and carbon-based materials (graphene oxide, carbon nanotubes) themselves are very thermally stable. If they are dispersed in the drilling fluid, these nanoparticles can act as heat sinks that absorb and dissipate heat efficiently. For example, iron oxide (Fe_3O_4) nanoparticles possess high thermal conductivity that helps maintain the thermal stability of drilling fluids. These nanoparticles can maintain shear stresses at predefined shear rates at elevated temperatures [141]. Modified Fe_3O_4 nanoparticles combined with poly-sodium p-styrene sulfonate enhanced the shear thinning of drilling fluids at different temperatures, particularly at 0.1% [101]. Nanoparticles help prevent the degradation of the base fluid by stopping the breakdown of polymers employed in the fluid through temperature resistance, extending its effective lifetime at higher temperatures. Improving the concentration of TiO_2 nanoparticles led to a decrease in the flow behavior index and an increase in yield stress. This leads to increased viscosity and the enhanced shear thinning behavior of drilling fluids. Also, adding the TiO_2 nanoparticles noticeably increased the low shear rate viscosity of the drilling fluid, confirming the enhancement of the fluid's rheology and affirming the better performance with higher viscosities at elevated temperatures [43]. Al_2O_3 nanoparticles also exhibit thermal stability by sustaining shear stresses at different temperatures and rates. Also, Al_2O_3 nanoparticles added to bentonite-based water-based mud (WBM) improved the gel strength, yield point, and plastic viscosity of the drilling mud [158]. Copper oxide (CuO) and zinc oxide (ZnO) nanoparticles also demonstrated their ability to improve the thermal and electrical properties of water-based drilling muds. With just 1% volume addition, these nanoparticles can improve these properties by 35% [53]. Yttrium oxide nanoparticles have shown good thermal stability at 300 degrees Fahrenheit and 10,000 psi. The optimum concentration for this purpose is 2.5 g of yttrium oxide nanoparticles [159]. Triton-X100 and coconut shell-based graphene (GN-CS) were added together, obtaining better dispersed modified graphene (GN-TX) particles. When used in WBM, results confirmed that GN-TX had excellent thermal resistance up to 300 °C. The graphene sheets become aggregated and form a crumpled topology due to microscopic buckling and crumpling that ensures enhanced thermal stability. Figure 12 gives a well-explained pictorial representation of this process [160]. A review of studies exploring the use of nanoparticles to address fluid loss, detailing the types of nanoparticles employed and any notable findings, is presented in Table 6.

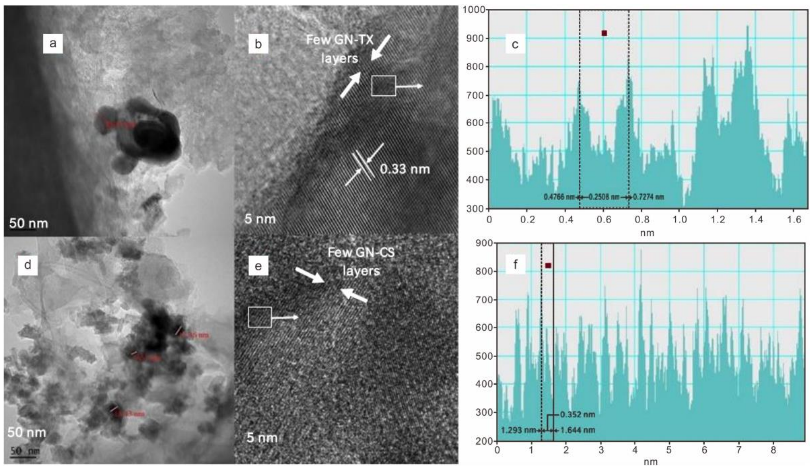

Figure 12. High-resolution transmission electron microscopy (HR-TEM) analysis of graphene nanoplatelet composites (GN). (**a**) HR-TEM image of modified GN-CS (GN-TX) surface post-modification, revealing significant alterations in surface morphology. (**b**) Magnified image of GN-TX highlighting the firm attachment and dispersion of the modified materials after ultrasonic treatment. Visible wrinkles (represented by arrows) indicate the presence of multiple (squares with dotted lines) graphene layers. (**c**) Intensity pattern of GN-TX, confirming the strong attachment of Triton to the GN-CS surface. (**d**) HR-TEM image of GN-CS, emphasizing the wrinkly regions with entangled graphene sheets. (**e**) Magnified image of GN-CS showing the multiple (squares with dotted lines), wrinkly (indicated by arrows) graphene layers that contribute to the composite's thermal stability. (**f**) Intensity patterns of GN-CS further reveal the structural details (figure adapted from [160]).

4.3.3. Viscosity Control

High temperatures weaken drilling fluids and reduce their ability to carry rock cuttings out of the wellbore [161]. Nanoparticle additives can ameliorate this by controlling the rheological properties—viscosity and flow behavior—of the drilling fluid, even at high temperatures. By combining nano-clay with nano-silica, for example, the stability and flow properties of oil-based inverted emulsion drilling fluids under extreme temperature and pressure were improved [154]. Also, nanoparticles of palygorskite (Pal), a naturally occurring hydrous clay mineral, can help drilling fluids keep their basic properties, even at elevated temperatures and pressures [90]. These include density, viscosity, gel strength, fluid loss, and filtration control. The maintenance of such properties is essential for drilling operations in diverse geological formations and under various conditions.

4.3.4. Chemical Stability

Elevated temperatures alter the chemical properties of drilling fluids or cause undesirable byproducts. Nanoparticles can make the drilling fluid chemically stable and less susceptible to thermal degradation or chemical reactions that change its properties. Particularly, titanium, iron, aluminum, zinc, copper, silver, and graphene metal oxide nanoparticles (NPs) improve the mechanical and thermal resistance of the drilling fluid [11]. Furthermore, silver, copper, and zinc oxide NPs have antimicrobial activity and may prevent the microbial degradation of fluid [36]. Other nanoparticles include carbon nanotubes/nano-clays and silicon dioxide, which provide better rheological and filtration properties and the better suspension of drilled cuttings which prevents their settling in the wellbore [162]. The diverse functionalities of different nanoparticles contribute to the chemical stabilization of the drilling fluid. Addressing individual property parameters can help reduce the risk of nanoparticle degradation and ensure compatibility with other chemical additives in the drilling fluid [13,163].

4.3.5. Lubrication Control

Elevated temperatures encountered during deep drilling operations pose a significant challenge to the lubrication properties of drilling fluids. This is primarily due to several interconnected mechanisms. Firstly, high temperatures can induce the thermal degradation of polymeric viscosifiers and lubricant additives, reducing the fluid's viscosity and its ability to form a lubricating film [164]. Secondly, elevated temperatures accelerate fluid loss into permeable formations, hindering the formation of an effective filter cake and increasing frictional forces [152]. Additionally, the precipitation of solids at high temperatures can further impede fluid flow and exacerbate wear [165]. Consequently, the degradation of lubrication under elevated temperatures can lead to increased friction, the premature wear of drilling equipment, and potential wellbore instability.

Nanoparticles have emerged as encouraging additives to enhance drilling fluid lubrication, particularly in high-temperature environments where traditional lubricants falter. Silica nanoparticles, for instance, contribute to the formation of robust lubrication films [54], while carbon nanotubes act as nano-bearings, reducing friction and wear [55]. Graphene and graphene oxide, renowned for their low friction coefficients, offer additional lubrication benefits. Molybdenum disulfide [56], nanodiamonds, and various metal oxide nanoparticles also exhibit lubricating properties, collectively minimizing friction and wear between the drill string and wellbore surfaces. These nanomaterials thus offer a viable solution for maintaining drilling efficiency and mitigating equipment damage in challenging drilling conditions.

Table 6. Summary of research papers investigating the application of nanoparticles in maintaining thermal stability, including the specific nanoparticles used and key outcomes.

References	Nanoparticle	Outcomes
[104]	CuO and ZnO	Proved to have better thermal and filtration properties.
[101]	Fe_3O_4	Increase in rheological and filtration properties along with improved thermal properties.
[96]	TiO_2	Improved thermal properties.
[160]	Y_2O_3	Improved rheology and thermal properties.
[52]	CuO and ZnO	Enhanced thermal characteristics.
[166]	Carbon nanoparticles	Enhanced thermal conductivity.
[167]	Al_2O_3	Intensified thermal properties.
[168]	Al_2O_3	Improved thermal and rheological properties.
[22]	Silver nanoparticles	Enhanced thermal properties.

Table 6. *Cont.*

References	Nanoparticle	Outcomes
[51]	CuO	Enhanced the thermal and rheological properties.
[77]	Multi-walled carbon nanotubes	Non-linear enhancement of thermal conductivity.
[108,169]	Graphene nanosheets	Enhanced thermal conductivity of the nanofluid.
[123,170]	Multi-walled carbon nanotubes	Modified MCNT enables the drilling fluid to have increased thermal conductivity and viscosity.
[110]	Graphite–alumina	Improved zeta potential, electrical conductivity, thermal conductivity, and degree of structural recovery.
[171]	Nano-silica	Improved thermal conductivity at high temperatures.
[172]	Molybdenum disulphide	Improved lubricity and thermal stability.
[90]	Palygorskite (Pal)	Good rheology modifier and improved thermal stability.

5. Challenges and Future Scope

5.1. Challenges

5.1.1. Challenges in Nanoparticle Stability

Maintaining the stability of nanoparticle (NP) dispersions in the harsh drilling environment is challenging. However, high temperatures, pressures, and the chemical composition of drilling fluids may lead to NP agglomeration and sedimentation, mainly due to van der Waals forces and high surface energy. All these phenomena can severely compromise the desired properties of drilling fluids like viscosity, rheology, and thermal conductivity.

To alleviate these problems, researchers have coated NPs with silanes, phosphonates, and polymeric surfactants. Such coatings provide steric or electrostatic stabilization to prevent NPs from aggregating and settling [173]. The stability and rheological properties of WBDFs were demonstrated by surface-modified silica NPs [174]. Also, polyvinylpyrrolidone (PVP) and polyethylene glycol (PEG) dispersants have shown promise for improving NP dispersion stability [90].

5.1.2. Interactions with Drilling Fluid Components

The polymers, surfactants, salt, and other additive complexes present in drilling fluids may affect the behavior of NPs. For instance, copper NPs increased the viscosity and yield point of water-based drilling fluids [50]. Additionally, NP interactions with drilling fluid components may affect fluid loss properties, filter cake formation, and wellbore stability [14]. As such, a complete understanding of these interactions is necessary for the formulation of tailored drilling fluid formulations, which can extract maximum benefit from NP addition and minimize undesirable side effects.

5.1.3. Environmental Concerns

Drilling operations release NPs into the environment, which has raised concerns about their consequence, transport, and possibly toxic effects. Recent studies of NPs' behavior in aquatic environments suggest that thorough assessments of their environmental impacts are required [175,176]. Such studies highlight the need for biodegradable or environmentally benign NPs and the development of robust mitigation strategies to limit ecological risks [177].

5.1.4. Heat Transfer Efficiency

NPs have promising potential applications in drilling fluids to improve heat transfer efficiency. Yet optimal thermal performance requires the precise control of particle properties such as material, shape, and size distribution [178]. These parameters have shown that they affect the heat transfer properties of nanofluid-based drilling fluids [179]. NPs have to be adapted to the drilling conditions to maximize heat transfer properties.

5.1.5. Economic Viability

The economic feasibility of nanotechnology incorporation in drilling fluids is a critical consideration. Producing specialized NPs requires expensive techniques such as chemical vapor deposition and laser ablation. The scalability and cost-effectiveness of these methods prevent their widespread adoption [14]. Therefore, alternative synthetic routes such as wet chemistry methods [180] and long-term cost–benefit analyses are necessary for economically viable NP-enhanced drilling fluids.

5.1.6. Safety Considerations

The potential toxicity and environmental impact of nanomaterials require detailed risk assessments and strict regulatory frameworks. The health and environmental hazards of NPs have been questioned [181,182]. Such studies show that strict safety evaluations, including toxicity testing and exposure assessment, are necessary before deploying nanotechnology in field applications.

5.1.7. Other Technical Challenges

Other technical hurdles, besides those mentioned above, that must be overcome include the following:

High Cost of NP Synthesis and Functionalization—High-quality NPs with tailored surface properties are expensive to produce and are thus limited in their large-scale implementation in drilling fluids [15].

Scalability Issues—It is still challenging to scale up NP production to meet oil and gas industry demands through developing economically viable manufacturing processes [183].

Standardization of Characterization Techniques—A lack of standard methods for characterizing NP properties such as size, shape, and surface chemistry can lead to discrepancies in research results and prevent the development of reliable performance metrics [184].

5.2. Future Scope and Technical Innovations

5.2.1. Strategies for Nanoparticle Stability and Compatibility Improvement

Robust surface modification strategies for nanoparticle stability under extreme drilling conditions should be targeted in future research. This could involve the investigation of new charge-neutral coating materials, such as zwitterionic polymers, which are resistant to pollution in harsh environments [185]. The mechanical and chemical inert oxide coatings of silica or alumina also impart enhanced stability [186]. Optimizing coating thicknesses and investigating multi-layered coatings combining electrostatic and steric stabilization mechanisms may further enhance nanoparticle dispersion and prevent agglomeration, as shown in studies with silica nanoparticles coated with polymer coatings [187].

Understanding the interactions of nanoparticles with drilling fluid components is needed. Systematic studies with advanced characterization techniques like dynamic light scattering (DLS) and zeta potential measurements can elucidate the influences of different polymer types (xanthan gum, polyacrylamide), surfactants, and salts on nanoparticle behavior. In one study, salts were shown to be able affect the stability of nanoparticles in drilling fluids and divalent cations were able to increase aggregation [188]. This knowledge might help to modify drilling fluid formulations to maximize nanoparticle benefits and minimize adverse effects.

5.2.2. Environmental Stewardship and Sustainability

Sustainable nanotechnology applications in drilling require environmentally friendly nanoparticles and strict mitigation strategies. Research should focus on biodegradable nanoparticles synthesized following green chemistry principles, such as using plant-based surfactants from cellulose or starch and avoiding hazardous chemical usage [189]. Nanoparticles' destination and transport can be monitored during drilling operations using real-time monitoring systems like nanoparticle tracking analysis (NTA) or inductively coupled plasma mass spectrometry (ICP-MS) with minimum environmental compliance and ecological risks. Studies show that such techniques can detect and quantify nanoparticles in environmental matrices [190,191].

5.2.3. Nanomaterial Tuning for Heat Transfer Optimization

An adequate understanding of the relationship between nanoparticle properties and thermal performance is required for the optimal heat transfer efficiency of nanofluid-based drilling fluids. Studies should investigate the effects of nano-particle material (e.g.: graphene, carbon nanotubes), shape (spherical, rod-like), size, and concentration on thermal conductivity and viscosity. Some studies report enhanced thermal conductivity when nanoparticles like graphene and carbon nanotubes are added to base fluids. Simulations of heat transfer in drilling scenarios can be used to predict optimal nanoparticle configurations for given well conditions [178,179].

5.2.4. Economic Feasibility and Scalability

To become a standard part of drilling operations, nanotechnology has to be cost-effective. Developed scalable and economic nanoparticle synthesis methods deserve further research and attention. This may include investigating innovative synthesis methods like continuous flow reactors or microwave-assisted synthesis that offer improved yield with reduced expenses instead of batch processes. These techniques have shown that they can produce nanoparticles with precisely regulated dimensions at a larger scale [192,193]. LCAs can evaluate the financial and ecological effects of nanoparticle-enhanced drilling fluids and provide insight into feasibility and long-term sustainability [194].

5.2.5. Safety First: Rigorous Risk Assessment and Regulation

Nanomaterial safety is of prime concern in drilling applications. Future studies should focus on the detailed risk assessments of nanoparticle toxicity and the long-term environmental impact in drilling fluids. This involves performing detailed toxicity studies with relevant model organisms like zebrafish or Daphnia, which are commonly used in ecotoxicological research [195,196]. Exposure limits must be established considering realistic scenarios such as nanoparticle release rates and environmental persistence [197]. Normative protocols for the handling, storage, and disposal of nanomaterials in accordance with international guidelines and regulations are needed for safe and responsible nanotechnology use in the oil and gas [198].

6. Summary

Nanofluids, enriched fluids containing nanoparticles, are an emerging technology in the drilling industry that may improve efficiency, cost, and environmental impact. Nanoparticles less than 100 nanometers in size possess unique properties that enhance drilling fluid performance. Their large area-to-volume ratio facilitates interactions with the drilling fluid and forms, improving rheological properties, reducing friction, and increasing heat transfer. This provides certain benefits, including the better lubrication, improved fluid stability, enhanced heat transfer, and improved sealing of microfractures in the rock formation for better wellbore stability.

Nanoparticles have been used in various drilling applications, including fluid loss control, wellbore stability, and thermal stability. Still, there are challenges to be overcome before wide adoption. These include maintaining nanoparticle stability in harsh drilling conditions, avoiding interactions with other drilling fluid components, addressing environmental issues, improving heat transfer efficiency, and ensuring economic viability. High production costs, safety issues, scalability, and nonstandard characterization techniques also create difficulties.

Developing robust surface modification strategies to improve nanoparticle stability, understanding the interactions of nanoparticles with drilling fluid constituents, designing environmentally benign nanoparticles, and implementing mitigation strategies are future research directions. The safe and responsible use of nanotechnology in the oil and gas sector is crucial, and future studies should concentrate on standardizing protocols for the handling, storage, and disposal of nanomaterials in accordance with international guidelines and regulations.

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