Development of Sustainable Microwave-Assisted Nanomaterials for Upstream Hydrocarbon Industry Applications

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Abstract

Global energy security has become a major concern in the twenty-first century due to the rapid increase in energy demand driven by industrialization, technological advancement, and population growth. Energy is essential for economic development, supporting industries, transportation, communication systems, and daily life. Among the available energy resources, fossil fuels, particularly crude oil and natural gas, remain the dominant sources because of their high energy density, established infrastructure, and economic viability. However, the continuous rise in energy consumption has placed significant pressure on finite hydrocarbon reserves. As easily accessible oil and gas resources become depleted, the petroleum industry is increasingly forced to exploit geologically complex and challenging reservoirs, resulting in higher production costs and greater sustainability concerns. Therefore, improving drilling efficiency and maximizing hydrocarbon recovery have become critical for ensuring long-term energy security and sustainable resource utilization. Nanotechnology has emerged as a promising approach to address these challenges due to the unique physicochemical properties of nanomaterials, including their high surface area, enhanced reactivity, tunable surface characteristics, and multifunctional behavior. These properties enable nanomaterials to improve drilling fluid performance, enhance wellbore stability, and increase oil recovery efficiency. At the same time, environmental concerns associated with conventional chemical synthesis methods have stimulated interest in green nanotechnology. Among the various green synthesis approaches, plant-mediated microwave-assisted synthesis of nanoparticles has gained considerable attention because it is rapid, energy-efficient, cost-effective, and environmentally friendly. The phytochemicals present in plant extracts act as natural

reducing, capping, and stabilizing agents, eliminating the need for hazardous chemicals while facilitating the controlled synthesis of nanoparticles with desirable properties.

In this study, ZnO-SnO_2 nanocomposites, ZnO-CaO nanocomposites, and SnO_2 nanoparticles were synthesized through a green microwave-assisted route using *Colocasia esculenta* leaves extracted as a natural reducing and stabilizing agent. The synthesized nanomaterials were further subjected for characterization using FTIR, XRD, XPS, FESEM, TEM, HRTEM, SAED, UV–Visible spectroscopy, DLS and Zeta potential analyses. The performance of biosynthesized ZnO-SnO_2 and ZnO-CaO nanocomposites in water-based drilling fluids was evaluated under high-pressure high-temperature (HPHT) conditions as prevailing in Indian hydrocarbons' reservoirs. The nanocomposites significantly enhanced rheological properties, gel strength, and filtration control while reducing fluid loss and improving filter-cake quality of the fluids. Furthermore, the nanoparticles acted as effective nano-bridging agents, sealing nanopores and microfractures and thereby improving wellbore stability.

The role of biosynthesized SnO_2 nanoparticles in improving the oil recovery factor was evaluated using wettability alteration, interfacial tension, and flooding experiments. The enhanced recovery performance was attributed to wettability modification, interfacial tension reduction, improved mobility control, and increased sweep efficiency. Overall, the findings demonstrate that microwave-assisted greenly synthesized nanomaterials possess significant potential for next-generation oilfield applications due to their eco-friendly nature, excellent thermal stability, multifunctionality, and superior performance under harsh drilling and reservoir conditions.

Chapter 1 provides an overview of the global energy demand, drilling (drilling fluid systems) and petroleum production technologies along with enhanced oil recovery (EOR) methods, and the emerging role of nanotechnology in Petroleum engineering. It discusses the challenges associated with declining conventional hydrocarbon reserves and harsh reservoir conditions, emphasizing the importance of efficient drilling and recovery techniques. This chapter highlights the functions and classifications of different drilling fluids such as water-based, oil-based and pneumatic and the role of various drilling fluid additives in improving drilling performance while working on drilling operations. The limitations of conventional drilling fluids under high-pressure high-temperature (HPHT) conditions, such as filtration loss, rheological instability, and thermal degradation, are also discussed. Furthermore, the chapter presents an overview of major EOR techniques including thermal, chemical, and gas injection methods and their operational challenges. It also identifies major research gaps and outlines the research objectives of the present work.

Chapter 2 presents a comprehensive review of nanomaterials, including their classification, synthesis approaches, and applications in petroleum engineering. The chapter discusses the classification of nanomaterials based on dimensionality, origin, composition, and morphology, providing a fundamental understanding of their structural diversity and functional properties. Various nanomaterial synthesis approaches, including top-down and bottom-up methodologies, are reviewed. Particular emphasis is placed on the role of phytochemical-mediated synthesis as an environmentally benign route for nanoparticle production. Furthermore, the chapter examines the applications of nanomaterials in drilling fluids and enhanced oil recovery (EOR), highlighting their influence on rheological behaviour, filtration control, wettability alteration, interfacial tension reduction, and hydrocarbon recovery.

Chapter 3 describes the materials, microwave-assisted green synthesis of ZnO-SnO_2 nanocomposites, ZnO-CaO nanocomposites, and SnO_2 nanoparticles using *Colocasia esculenta* leaves extract as a natural reducing, capping and stabilizing agent, experimental methodologies, and characterization techniques. The chapter presents the detailed synthesis procedures, preparation of nanofluids, and formulation of water-based drilling fluids containing the synthesized nanomaterials. Comprehensive characterization techniques, including FTIR, UPLC-PDA, XRD, XPS, FESEM, HRTEM, SAED, DLS, zeta potential, and BET analysis. Furthermore, the chapter outlines the experimental procedures adopted for rheological measurements, filtration performance evaluation, thermal stability analysis, contact angle measurements, interfacial tension studies, and sand-pack flooding experiments used to assess the effectiveness of the synthesized nanomaterials in drilling fluid and enhanced oil recovery applications.

Chapter 4 begins with the phytochemical characterization of *Colocasia esculenta* leaves extract using Ultra-performance liquid chromatography coupled with photodiode array detection (UPLC–PDA) and Gas chromatography mass spectrometry (GC–MS) analyses to identify the bioactive compounds responsible for nanoparticles formation and stabilization. The synthesized ZnO-SnO_2 nanocomposites were subsequently characterized using FTIR, XRD, XPS, FESEM, TEM, SAED, DLS, and zeta potential analyses to evaluate their structural, morphological and surface properties. XRD analysis revealed crystallite sizes ranging from 4.86 to 18.72 nm, while SEM and TEM analyses confirmed the formation of spherical and rod-shaped nanocomposites. The performance of the nanocomposites in drilling fluids was assessed through thermal stability, rheological, and filtration studies under both low-pressure low-temperature (LPLT) and high pressure high temperature (HPHT) conditions. The incorporation of ZnO-SnO_2 nanocomposites significantly improved apparent viscosity, plastic viscosity (40−60% increment from 15 cP of base mud), yield point and gel strength, indicating enhanced rheological stability. The nanocomposite-containing drilling fluids also exhibited superior filtration-control performance, achieving a 56.52% reduction in fluid loss under LPLT conditions (from 23 mL to 10 mL) and a 62.5% reduction under HPHT conditions (from 64 mL to 24 mL). The chapter concludes by highlighting the potential of ZnO-SnO_2 nanocomposites as environmentally benign and cost-effective additives for improving drilling-fluid performance and operational efficiency under challenging drilling environments.

Chapter 5 focuses on the application of ZnO-CaO nanocomposites in water-based drilling fluids, where green nanotechnology and waste valorization principles are employed to develop high-performance and sustainable drilling-fluid additives. The synthesized ZnO-CaO nanocomposites were further characterized using various analytical tools such as FTIR, XRD, BET, XPS, FESEM, TEM, and SAED analyses, which confirmed the formation of highly crystalline nanostructures with spherical morphology and particle sizes ranging from 10 to 45 nm. BET analysis revealed a high specific surface area (99.445 m^2/g), indicating the presence of abundant active sites capable of interacting effectively with drilling-fluid constituents. The performance of the nanocomposites in WBFs was evaluated through hydrodynamic stability, rheological, gel strength and filtration studies under both LPLT and HPHT conditions. The incorporation of ZnO-CaO nanocomposites significantly improved the rheological properties of the drilling fluids, resulting in an approximately 54% increase in apparent viscosity and upto a 2.6-fold increase in plastic viscosity compared with the base mud. Enhanced yield point and gel strength values further demonstrated improved suspension and carrying capacity. In addition, the nanocomposites containing drilling fluids exhibited excellent filtration-control performance, achieving approximately 47.5% reduction in fluid loss under LPLT conditions and 54% reduction under HPHT conditions. These findings demonstrate that ZnO-CaO nanocomposites effectively improve rheological stability, and filtration performance, highlighting their potential as environmentally benign and cost-effective additives for advanced drilling-fluid applications.

Chapter 6 investigates the application of microwave-biosynthesized SnO_2 nanoparticles for enhanced oil recovery. Structural and morphological characterization was conducted using FTIR, XRD, FESEM, TEM, SAED, XPS and DLS analyses, confirming the formation of stable nanoscale particles with favorable physicochemical properties. The influence of nanoparticles concentration, salinity, and surfactant interactions on wettability and interfacial properties was systematically evaluated. Contact angle measurements demonstrated significant wettability alteration towards more water-wet conditions with increasing nanoparticles concentration. Interfacial tension studies demonstrated substantial reductions in oil-water interfacial tension, particularly when SnO_2 nanoparticles were combined with sodium dodecyl sulfate (SDS) surfactant. The effects of monovalent and divalent salts on nanoparticles performance were also examined, revealing the critical influence of ionic strength and ion valency on nanoparticles stability and interfacial behavior. Sand-pack flooding experiments demonstrated notable improvements in oil recovery efficiency. While SDS flooding alone achieved cumulative oil recovery of approximately 65% of the original oil in place, the addition of low concentrations of SnO_2 nanoparticles increased recovery efficiencies to approximately 86–88%. These improvements were attributed to wettability alteration, interfacial tension reduction, enhanced mobility control and improved sweep efficiency.

Chapter 7 consolidates the outcomes of the research and highlights the scientific contributions of the study towards the development of sustainable nanomaterials for upstream hydrocarbon applications. The findings demonstrate that green nanotechnology based on *Colocasia esculenta* extract can successfully produce multifunctional metal oxide nanomaterials with excellent physicochemical properties and industrial applicability. The incorporation of ZnO-SnO_2 and ZnO-CaO nanocomposites in water-based drilling fluids significantly improved rheological behavior, filtration control and stability under highpressure high temperature conditions. Furthermore, SnO_2 nanoparticles showed considerable potential for enhanced oil recovery by promoting wettability alteration, reducing interfacial tension, and improving oil displacement efficiency. The collective results validate the applicability of bio-mediated nanomaterials as effective alternatives to conventional additives in drilling and recovery operations. The chapter also outlines future research directions, including field-scale validation, development of hybrid nanomaterials, long-term performance assessment under reservoir conditions, optimization of nanofluid formulations, and strategies for large-scale industrial implementation.

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