Synthesis, Characterization and Performance Evaluation of Bio-Derived Surfactant for Emulsification, Carbon Entrapment and Thermal Energy Storage

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The escalating challenges posed by climate change, environmental pollution and the unsustainable consumption of natural resources demand urgent and innovative responses from the scientific community. In this context, sustainable development goals (SDGs) set by the United Nations, particularly SDG 7 aiming to ensure access to affordable, reliable, sustainable and modern energy solutions. This thesis explores bio-derived natural surfactants as sustainable, multifunctional materials for mechanical, thermal and environmental applications. By integrating nanotechnology and green chemistry, it aims to replace synthetic chemicals, enhance energy efficiency, support carbon capture and enable waste valorization, advancing clean energy systems and circular economy goals in line with global sustainability targets. In this context, thesis investigates bio-based natural surfactants extracted from fenugreek seeds, exploring their physicochemical properties and applications in sustainable mechanical and thermal systems. Key findings include enhanced emulsion stability with silica nanofluids, effective paraffin emulsification in saline environments, improved nano-phase change material (n-PCM) emulsion for thermal storage and innovative carbon dioxide (CO_2) entrapment using surfactant–fly ash composites. Overall, the work demonstrates the potential of these eco-friendly materials to advance energy efficiency, environmental remediation and sustainable industrial processes. The basic layout of the work is as under:

Chapter 1 outlines the global need for sustainable technological transformation, emphasizing the integration of green chemistry with traditional knowledge to develop bio-inspired, eco-friendly materials. It highlights the thesis's focus on harnessing natural surfactants for multifunctional performance in complex mechanical and energy systems. The chapter also explores hybrid innovations combining surfactants with nanotechnology for enhanced functionality, addresses environmental remediation through CO_2 entrapment and aligns the research with SGD 7 for sustainable and reliable energy solutions.

In Chapter 2, natural surfactant was extracted from fenugreek seeds via Soxhlet extraction technique and characterized for mechanical and thermal fluid applications. FTIR, UV-Vis, MBAS, FESEM and surface tension analyses confirmed anionic saponins with strong surface activity, low adsorption, foamability and thermal stability, indicating suitability for fluid transport systems.

In Chapter 3, the physicochemical performance of a natural surfactant derived from fenugreek seeds was evaluated for its potential in mechanical and industrial systems. Surfactant exhibited strong surface activity, reducing interfacial tension effectively at low concentrations near its CMC (0.2 wt.%). Rheological analysis showed shear-thinning behavior, suitable for flow-based applications. Contact angle measurements indicated enhanced wettability, while stable foam formation under different conditions highlighted its applicability in foam-assisted transport. Its biodegradable, low-toxicity nature supports sustainable use in thermal, fluid and cleaning processes.

In Chapter 4, the emulsification behavior of paraffinic compounds was examined using a bio-derived surfactant synthesized from fenugreek seeds, targeting mechanical applications involving multiphase flow. The surfactant effectively reduced interfacial tension and stabilized paraffin–water emulsions, even under saline conditions. Optical microscopy revealed uniform droplet distribution, while rheological analysis indicated shear-thinning behavior suitable for dynamic flow environments. Micromodel experiments demonstrated improved phase displacement and reduced trapping in porous structures. These results highlight the surfactant's potential for use in sustainable, salt-tolerant fluid systems relevant to thermal management and flow control technologies.

In Chapter 5, stability and performance of emulsions were enhanced by combining a natural surfactant with single-step synthesized silica nanofluids. Two formulations: surfactant-polymer (SP) and nanoparticle-surfactant-polymer (NSP) were compared. NSP formulations outperformed SP, showing better interfacial tension reduction, thermal stability and droplet uniformity. Rheology, zeta potential and wettability results confirmed improved structure and stability, making NSP emulsions ideal for heat transfer and multiphase mechanical systems.

In Chapter 6, the use of natural surfactants in stabilizing n-PCM emulsions was explored for thermal energy storage (TES) applications in mechanical systems. Silica nanofluid–surfactant combination was developed to enhance emulsion stability and thermal efficiency of PCM. Techniques like DSC, interfacial tension, microscopy, and rheology confirmed improved performance. Lower nanoparticle concentrations offered optimal thermal efficiency and long-term stability, making the system suitable for TES applications in energy management and mechanical heat exchange operations.

In Chapter 7, a sustainable approach for CO_2 entrapment was developed using a natural surfactant derived from fenugreek seeds in combination with industrial fly ash. The combination enabled efficient CO_2 capture, as confirmed by pressure decay tests and microscopic analysis showing stabilized gas bubbles. FTIR revealed carbonate formation, indicating chemical interaction. This eco-friendly system offers a dual benefit of effective gas entrapment and industrial waste utilization in mechanical applications.

In Chapter 8, the thesis concludes by presenting an integrated view of bio-derived surfactants as multifunctional materials for mechanical and energy systems. Extracted from fenugreek seeds, the surfactants showed strong surface activity, thermal stability and compatibility with nanomaterials. Their use in stabilizing emulsions, managing multiphase flow, enhancing thermal energy storage and entrapping CO_2 through fly ash composites was validated. This work underscores the potential of green surfactants in fluid control, heat management and environmental remediation within mechanical applications, aligning with sustainability and circular economy frameworks.