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Effect of TiO_2 and BN Nanoparticles on the Lubricity of Jatropha-Based Bio-Lubricant

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Abstract

This study investigates the enhancement of Jatropha oil lubricity through the incorporation of titanium dioxide (TiO_2) and hexagonal boron nitride (BN) nanoparticles. Nanolubricants were prepared at varying nanoparticle concentrations (0.05%, 0.1%, and 0.2% by weight), surfactant (oleic acid) volumes (1X, 5X, and 10X relative to nanoparticle volume), and sonication times (30, 60, and 90 minutes). Lubricity was evaluated using a ball-on-disk tribometer at a speed of 1500 RPM under controlled test conditions. Results showed that TiO_2 at 0.05 wt% with 60 minutes of sonication and without surfactant achieved the highest lubricity improvement, while BN also enhanced performance but to a lesser extent. Moderate use of surfactant and sonication proved beneficial for nanoparticle dispersion, although excessive amounts led to diminished gains. These findings suggest that tailored nanoformulations can significantly enhance the friction-reducing capabilities of bio-based oils, offering a sustainable alternative to conventional lubricants.

Keywords: Jatropha oil, nanolubricants, titanium dioxide, hexagonal boron nitride, lubricity enhancement, bio-based lubricants

1.Introduction

Vegetable oils such as Jatropha oil are increasingly investigated as sustainable alternatives to petroleum-based lubricants due to their renewability, biodegradability, and favorable viscosity indices (Fox & Stachowiak, 2007; Ibrahim et al., 2022). However, their relatively poor oxidative stability, lower extreme pressure performance, and inferior frictional behavior have limited their broader adoption in industrial tribological applications (Ponnekanti & Savita, 2012; Clarissa et al., 2021). To overcome these limitations, recent studies have explored the incorporation of nanoparticles into bio-lubricants to enhance their tribological properties (Elhaseeb et al., 2022; Uppar et al., 2024). Jatropha oil has emerged as a promising base for bio-lubricants due to its renewable nature, good oxidative stability, and favorable fatty acid profile. Studies have shown that its high viscosity index and biodegradability make it suitable for reducing friction and wear in mechanical systems, especially when chemically modified or enhanced with additives (Iis et al., 2021; Rajasozhaperumal & Kannan, 2023; Rajendra et al., 2024).

Nanoparticles can reduce friction and wear by mechanisms such as filling surface asperities, forming protective tribofilms, and rolling or sliding between contacting surfaces at the nanoscale (Sabar & Ghosh, 2023; Purva et al., 2024; Uppar et al., 2024). Among the various nanoparticles studied, titanium dioxide (TiO_2) and hexagonal boron nitride (h-BN) are two promising candidates. TiO_2, a ceramic metal-oxide nanoparticle, is known for its high load-carrying capacity, chemical inertness, and ability to form self-healing films that reduce direct metal-to-metal contact (Filip & Cristina, 2016; Ravikiran et al., 2025; Kai et al., 2025). h-BN, on the other hand, is a layered material with a structure analogous to graphite, known for its excellent thermal stability and low shear strength due to its lamellar morphology. Several studies have shown that even at low concentrations, h-BN can significantly reduce wear and friction in various base oils (Shariq & Charoo, 2021; Victoria et al., 2024; Himanshu et al., 2024).

A major challenge in utilizing nanoparticles effectively is achieving and maintaining a stable dispersion in the oil medium. Without stabilization, nanoparticles tend to agglomerate due to van der Waals attractions, leading to sedimentation and inconsistent tribological performance (Amir et al., 2022). Surfactants such as oleic acid are commonly used to enhance nanoparticle dispersion in oils. Oleic acid, with its polar carboxyl group and nonpolar hydrocarbon tail, adsorbs onto the nanoparticle surface while maintaining compatibility with the oil, thus preventing agglomeration (Xianjun et al., 2021; Fátima et al., 2022).

Ultrasonication is another widely adopted technique to break up nanoparticle clusters and ensure uniform mixing. Studies indicate that moderate sonication times (typically 60 to 90 minutes) are optimal for achieving stable suspensions, as excessive sonication may lead to thermal degradation of the dispersant or re-agglomeration due to overexposure to cavitation energy (Asif et al., 2019; Sandhya et al., 2021; Khairunnisa et al., 2021). The balance between surfactant volume, nanoparticle loading, and sonication time is critical for producing effective nanolubricants.

Despite the growing interest in nanolubricants, direct and systematic comparisons between TiO_2 and h-BN nanoparticles in a consistent base oil such as Jatropha remain scarce. Most existing studies focus on a single type of nanoparticle or adopt varying experimental protocols, which limits the ability to draw generalized conclusions. The present study addresses this gap by evaluating the friction-reducing performance of both TiO_2 and h-BN nanoparticles dispersed in Jatropha oil under identical conditions. It systematically investigates the combined influence of nanoparticle concentration, surfactant volume, and sonication time on lubricity over a wide range of operating speeds. The results provide practical insights for optimizing bio-based nanolubricant formulations suitable for sustainable and high-performance tribological applications.

2. Materials and Methods

Refined Jatropha curcas oil (food-grade) was selected as the base bio-lubricant for this study. Titanium dioxide (TiO_2) nanoparticles in anatase form (average particle size ~20 nm) and hexagonal boron nitride (h-BN) flakes (~50 nm) were used as nanoadditives (Figure 1). Oleic acid (technical grade) was employed as a dispersing agent to enhance the colloidal stability of the nanolubricant formulations.

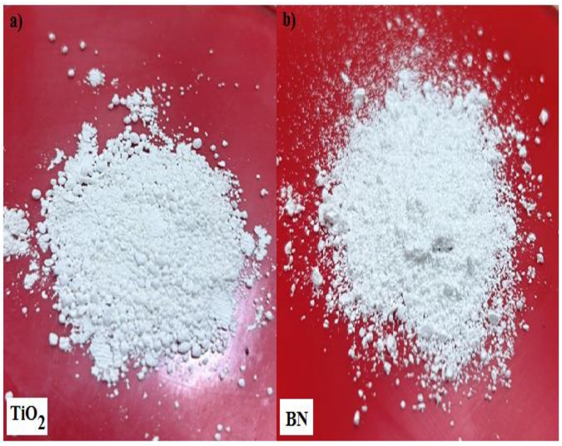

Figure 1. Digital image of nanoparticle powder (a) TiO_2 (b) BN

To prepare the samples, the required mass of each nanopowder was calculated to obtain concentrations of 0.05%, 0.10%, or 0.20% by weight relative to the oil. Separate batches were prepared for TiO_2 and h-BN. The oil, nanoparticles, and a small quantity of hexane (used as a low-volatility solvent) were combined in clean glass beakers. Oleic acid was then added in three ratios—1×, 5×, or 10× the volume of the nanopowder. For example, a nanopowder volume of 0.5 mL received 0.5, 2.5, or 5.0 mL of oleic acid, respectively. The mixtures were initially stirred magnetically for 15 minutes at room temperature to ensure proper wetting of the particles. Ultrasonication followed, using a probe-type sonicator operating at ~40 kHz while immersing the samples in an ice bath to avoid thermal degradation. Sonication durations of 30, 60, and 90 minutes were evaluated. The prepared nano-lubricants are shown in Figure 2.

Figure 2. Nano lubricant samples prepared

Samples are prepared considering four variables: nanoparticle type (TiO_2 or BN), concentration (0.05, 0.10, or 0.20 wt%), oleic acid volume (1×, 5×, or 10×), and sonication time (30, 60, or 90 minutes), resulting in 81 distinct formulations. A control sample consisting of pure Jatropha oil without nanoparticles or surfactant was also prepared for baseline comparison. All samples were allowed to cool and stand for 30 minutes before testing to ensure thermal equilibrium.

Figure 3. Lubricity tester (OFI Testing Equipment, Inc.)

Lubricity testing was conducted using a ball-on-disk tribometer (OFI Testing Equipment, Inc.), shown in Figure 3. The tribometer conformed to ASTM G99 standards and operated under boundary/mixed lubrication regimes. A hardened steel ball (6 mm diameter) was slid against a hardened steel disk under a constant normal load of 20 N at 25 °C ambient temperature. Fresh lubricant was applied before each test, and friction coefficients were recorded continuously at rotational speeds of 10, 100, 300, 500 and 1000RPM, corresponding to surface velocities from approximately 0.5 to 75 m/s. Each test condition was repeated in triplicate to ensure reproducibility. While the primary focus was on evaluating lubricity, qualitative wear assessments were also made by observing the wear scar on the steel ball after testing.

This methodology facilitated a systematic evaluation of how nanoparticle characteristics and processing conditions influence the frictional performance of Jatropha oil-based nanolubricants across a wide operating speed range.

3. Results and Discussion

The lubricity results across varying speeds (Figure 4) indicate a significant influence of both nanoparticle type and concentration on the tribological behavior of Jatropha-based nanolubricants. All formulations demonstrated a characteristic U-shaped trend with respect to speed: lubricity (i.e., reduced friction) was high at very low speeds (10–30 RPM), reached a minimum around 40–50 RPM, and gradually improved again at higher speeds up to 1500 RPM. This behavior reflects the transition from boundary to mixed lubrication regimes, where the effectiveness of nanoparticles in maintaining a stable lubricant film becomes more pronounced. Among the tested concentrations, the 0.1 wt% TiO_2 formulation exhibited superior lubricity throughout the speed range, with friction reduction improving by approximately 38% compared to the base oil. This optimal concentration likely ensures sufficient nanoparticle availability for surface interaction without leading to agglomeration, a phenomenon observed at higher concentrations like 0.2 wt%, which exhibited relatively poor lubricity performance. The 0.1 wt% BN formulation also showed strong performance, closely matching that of TiO_2, suggesting that the lamellar structure of BN contributes effectively to forming shear-resistant films at the contact interface. In contrast, both lower (0.05 wt%) and higher (0.2 wt%) concentrations of BN and TiO_2 resulted in suboptimal lubricity, highlighting the delicate balance required in nanoparticle dosing for tribological applications.

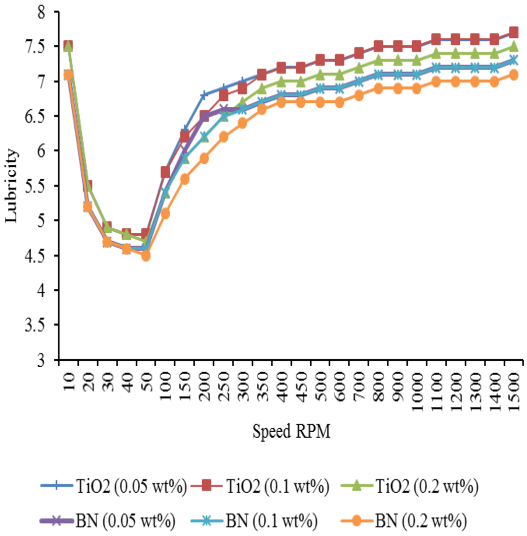

Figure 4. Lubricity vs. speed for Jatropha oil with varying TiO_2 and BN nanoparticle concentrations.

These observations align with previous findings in the literature. A similar trend has been reported, where the incorporation of TiO_2 nanoparticles led to a noticeable improvement in tribological performance, particularly at intermediate concentrations. This enhancement was primarily attributed to stable nanoparticle dispersion and effective interaction with surface asperities (Rajendra et al., 2024). Similarly, the addition of BN nanoplatelets was found to enhance lubrication performance by forming protective tribofilms and enabling easy sliding along their basal planes (Himanshu et al., 2024; Anthony et al., 2025). The trend of reduced effectiveness at higher concentrations, likely due to particle agglomeration and sedimentation, a critical concentration threshold beyond which friction and wear began to increase (Ibrahim et al., 2022; Amir et al., 2022). The lubricity improvement at higher RPMs in the present study may be attributed to the dynamic reorientation and redistribution of well-dispersed nanoparticles, as well as increased thermal energy promoting tribochemical interactions (Pownraj & Valan, 2021; Ibrahim et al., 2022). Thus, the current work corroborates and extends existing knowledge by directly comparing TiO_2 and BN under consistent conditions in a Jatropha oil matrix, underscoring the importance of optimized concentration, dispersion stability, and the unique tribological mechanisms of each nanomaterial.

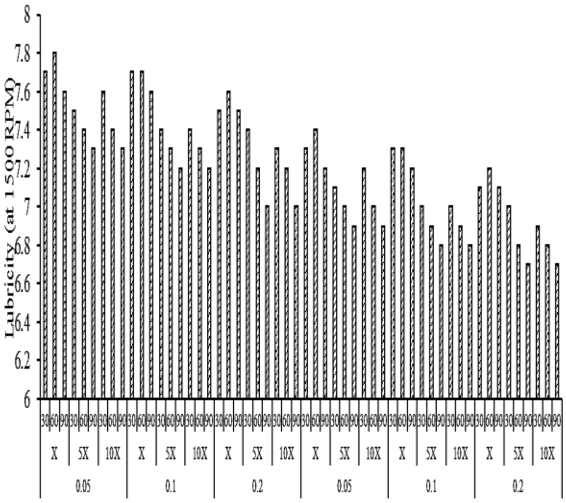

Figure 5. Lubricity at 1500 RPM for Jatropha oil with varying nanoparticle concentrations, surfactant volumes, and sonication times.

The experimental data presented in Figure 5 highlight the influence of nanoparticle type, concentration, oleic acid content, and sonication time on the tribological performance of Jatropha oil-based nanolubricants. Overall, both TiO_2 and BN nanoparticles improved lubricity compared to the base oil, although the extent of improvement depended strongly on the formulation parameters. For TiO_2-based lubricants, the highest lubricity values (7.8) were observed at a concentration of 0.05 wt% with 60 minutes of sonication and no additional oleic acid, suggesting that even minimal particle additions can significantly enhance performance if well dispersed. However, increasing the oleic acid content to 5X or 10X generally caused a slight reduction in lubricity (to around 7.3–7.4), especially with longer sonication. This indicates a possible saturation of surface-active molecules at the particle-oil interface, where excess surfactant may lead to steric hindrance or reduce nanoparticle interaction with the metal surface. Huang et al. (2021) similarly observed diminishing returns with excessive surfactant additions in TiO_2-based nanolubricants, attributing the effect to over-stabilization that limits tribofilm formation.

The 0.1 wt% TiO_2 concentration emerged as an optimal balance, with lubricity values remaining consistently high (7.6–7.7) across sonication durations and oleic acid levels. This suggests that moderate nanoparticle loading, aided by mild dispersion techniques, promotes a stable colloidal system capable of reducing friction. However, increasing the concentration to 0.2 wt% did not further improve performance and, in some cases, led to marginal declines in lubricity, especially when coupled with higher oleic acid volumes and extended sonication. This observation is consistent with earlier findings that an excess of TiO_2 nanoparticles can lead to agglomeration, reducing effective surface coverage and increasing abrasive interactions under load (Corina et al., 2022; Ravikiran et al., 2025).

In contrast, BN-based nanolubricants exhibited slightly lower lubricity values overall but showed a more pronounced sensitivity to formulation conditions. At 0.05 wt%, lubricity values peaked at 7.4 (with 60 min sonication and no surfactant) and declined with increased oleic acid, especially at higher sonication durations. This trend persisted across all BN concentrations, with lubricity dropping to 6.7 under the most extreme conditions (0.2 wt%, 10× oleic acid, 90 min sonication). The lamellar structure of hexagonal boron nitride (h-BN) is known to facilitate low-shear sliding between layers, which contributes to reduced friction. BN particles require careful control of dispersion energy and surfactant levels to maintain their structure and avoid stacking or curling that can diminish their lubricating effect (Dmitry et al., 2022; Wiesław et al., 2022).

Notably, longer sonication (up to 90 minutes) led to better performance for both TiO_2 and BN at lower concentrations, confirming the role of acoustic cavitation in breaking up agglomerates and enhancing dispersion. However, beyond a threshold, prolonged sonication combined with high surfactant concentration appeared to have a counterproductive effect, likely due to nanoparticle re-agglomeration or breakdown into ineffective sizes (Khairunnisa et al., 2021; Behzad et al., 2022). From the dataset, the best-performing formulation was TiO_2 at 0.05 wt% with 60 minutes sonication and no added oleic acid (lubricity = 7.8), followed closely by 0.1 wt% TiO_2 with similar treatment. For BN, the highest lubricity (7.4) was achieved at 0.05 wt%, 60 minutes' sonication, and no added surfactant, supporting the conclusion that minimal chemical modification and moderate sonication yield optimal tribological performance.

These results highlight the importance of a balanced formulation strategy in nanolubricant development. The interplay between nanoparticle properties, concentration, surfactant level, and energy input significantly influences dispersion stability and lubricity. Similar observations have been reported in other nanoparticle-based systems, where optimal additive levels were key to achieving reduced friction and improved performance (Corina et al., 2022; Surinder & Rajesh, 2023). The present findings add to this growing body of knowledge and offer practical guidance for tuning bio-based lubricant formulations.

Conclusion

This study demonstrated that the addition of TiO_2 and BN nanoparticles can significantly improve the lubricity of Jatropha oil when optimized for concentration, dispersant level, and sonication time. Among the tested formulations, TiO_2 at 0.05 wt% with 60 minutes of sonication and without surfactant exhibited the highest lubricity at 1500 RPM, indicating that lower concentrations of well-dispersed TiO_2 are sufficient to enhance friction-reducing characteristics. BN-based samples also improved lubricity but were comparatively less effective, particularly at higher surfactant dosages. The results suggest that while oleic acid aids in nanoparticle dispersion, excessive amounts may hinder tribological performance by interfering with boundary film formation. Similarly, moderate sonication times helped achieve uniform dispersion, but longer durations showed diminishing or adverse effects. Overall, the findings highlight the importance of carefully balancing nanoparticle loading, surfactant content, and dispersion energy to achieve optimal performance in bio-based lubricants. This work supports the potential of nanotechnology to transform vegetable oils like Jatropha into efficient, sustainable lubricants for tribological applications.

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