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Thermal conductivity and viscosity of surfactant-stabilised biolubricants containing TiO_2 and BN nanoparticles

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Abstract
This study examines how adding titanium dioxide (TiO_2) and boron nitride (BN) nanoparticles to Jatropha-based biolubricant improves its viscosity and thermal conductivity. The impact of sonication time, concentration of surfactant (oleic acid), nanoparticle type and nanoparticle content on the thermal and rheological behaviour of the biolubricants was assessed. To guarantee homogeneous dispersion, biolubricants containing 0.05 – 0.20 wt. % TiO_2 or BN were made using ultrasonic agitation. To determine the importance of the parameters and their interactions, a statistical analysis of thermal conductivity and viscosity was conducted. Because of its higher heat transfer properties and dispersion stability, BN consistently produced significant improvements in the biolubricant's thermal performance when nanoparticles were added. The highest thermal conductivity of 0.262 W/mK was obtained at 0.20 wt. % BN nanoparticle content and a 10X surfactant concentration, while viscosity remained within acceptable limits for lubrication applications. Type of nanoparticle emerged as the most significant factor, followed by nanoparticle content, for both thermal conductivity and viscosity. Overall, the results indicate that optimising formulation parameters can significantly improve heat transfer performance without compromising flow behaviour. Biolubricants filled with BN and TiO_2, therefore, show strong potential as environmentally sustainable lubricants for thermal management and industrial applications.

1. Introduction

In recent years, biolubricants have been increasingly used in hydrodynamic journal bearings as sustainable alternatives to conventional mineral oils, driven by the necessity for environmentally friendly alternatives that offer lower toxicity, biodegradability and renewability [1,2]. Traditional mineral oils, derived from non-renewable fossil fuels, contribute considerably to environmental degradation and carbon emissions. By lessening the environmental impact of lubrication procedures in industrial applications, the switch to biolubricants advances the global sustainability goals [2]. A higher viscosity index is one of the important benefits of biolubricants over conventional mineral-based lubricants, which provides consistent lubrication over a wide range of operating temperatures [2,3]. This property is particularly advantageous in hydrodynamic journal bearings, where varying load conditions and thermal fluctuations demand stable lubrication. Recent studies have revealed that the integration of nanoparticles into biolubricants considerably improves their tribological and thermal properties, making them competitive with, or even superior to, conventional mineral oils [2,4].

Issues such as poor oxidation stability, thermal degradation and high friction hindered the adoption of biolubricants [2]. Adding nanoparticles to biolubricants has proven effective in improving their performance, wear resistance and reducing friction under extreme conditions [5]. Biolubricants offer an eco-friendly alternative to traditional lubricants [6]. The properties of bio-based nanolubricants are influenced by nanoparticle attributes such as size, shape and content [7]. Several studies have explored the impact of titanium oxide (TiO_2) [7,8] and boron nitride (BN) [9,10] nanoparticles on bio-based lubricant properties.

The incorporation of TiO_2 nanoparticles into chemically modified rapeseed oil has been shown to reduce the coefficient of friction by 15.2 %, likely due to the spherical shape of the nanoparticles, which act as nanoball bearings that minimise surface contact between frictional components [7]. The synergistic addition of TiO_2 and graphene nanoparticles to rice bran oil significantly improved its rheological and tribological properties during minimum quantity lubrication turning of steel, reducing tool wear and surface roughness while enhancing viscosity and thermal stability [11]. The BN nanoparticles have gained significant attention for their tribological performance when incorporated into biolubricants. Studies have shown that the inclusion of BN nanoparticles into biolubricants significantly improves tribological properties, such as reducing friction coefficients and increasing wear resistance [10,12]. Studies have demonstrated that the addition of non-toxic nanostructures (h-BN, silver and MgO) to environmentally friendly vegetable oils like soybean and sunflower oil significantly improves their tribological properties, with h-BN nanosheets notably reducing friction and wear, and enhancing thermal conductivity by 24 % at a 0.25 wt. % content [12]. The incorporation of h-BN nanoparticles as eco-friendly additives in Mahua oil and linseed oil significantly improves rheological and tribological properties, with 0.25 wt. % h-BN resulting in a 25.3 % reduction in wear scar diameter and a 96.27 % reduction in the coefficient of friction for Mahua oil [10].

Nanoparticles improve the lubricating properties of biolubricants by forming a protective tribofilm on bearing surfaces, reducing friction and minimising wear [13]. The load-carrying capacity of hydrodynamic journal bearings is also significantly enhanced with the addition of nanoparticles, preventing lubricant film breakdown under high-load conditions [14]. The heat dissipation of nanofluid-based biolubricants enhances thermal management in the bearing system. Enhancing the thermal conductivity of the base oil with nanoparticles enables efficient heat evacuation and maintains ideal operating conditions [15]. This characteristic is crucial in high-speed and heavy-load applications because excessive heat production can cause lubricant deterioration and premature bearing failure.

A thorough statistical technique called full factorial analysis systematically alters every input variable at the same time in order to evaluate both the independent and combined effects of each variable on response variables [16]. Finding the percentage contributions of various control parameters and their interactions are made easier with the use of the analysis of variance (ANOVA) [17]. This study systematically evaluates the influence of nanoparticle type (TiO_2 or BN), nanoparticle content, concentration of surfactant, and sonication time on the thermophysical properties of biolubricants. Experimental and statistical analyses were conducted to optimise the thermophysical behaviour of TiO_2 and BN nanoparticle-filled biolubricant.

2. Materials and methods

The non-edible and widely accessible Jatropha seed oil was chosen as the base fluid because of its cost-effectiveness, sustainability and advantageous tribological properties [18]. *Jatropha curcas* seeds were mechanically cold-pressed to extract the oil. The extracted oil was then filtered through filter paper with a pore size of approximately 10 µm to remove suspended impurities and residual solid particles before being used in the preparation of the biolubricant. *Jatropha curcas* oil mainly consists of oleic and linoleic acids, along with smaller amounts of palmitic and stearic acids, which are commonly reported as the major fatty acids in this oil. At room temperature, the oil exhibits a density of about 910 – 930 kg/m^3, a specific heat capacity of approximately 1.8 – 2.1 kJ/kgK and a thermal conductivity of around 0.17 – 0.18 W/mK. Since the goal of the study was to assess its direct application as a base oil for biolubricants, no additional chemical refinement or transesterification was done.

Jatropha oil is a wise choice for sustainable applications because of its accessibility and low cost of production, which further enhances its environmental advantages. To enhance its performance, TiO_2 and BN nanoparticles were incorporated. TiO_2 improves lubrication by reducing friction, enhancing thermal conductivity and filling surface asperities [19]. BN offers superior thermal stability, oxidation resistance and wear reduction [10,20]. The TiO_2 and BN nanoparticles used in the present work were procured from Sigma-Aldrich, India. The TiO_2 nanoparticles had an average particle size of about 21 nm, a reported purity of 99.5 %, a density of approximately 4.23 g/cm^3 and a thermal conductivity of 8.4 W/mK. The BN nanoparticles had an average particle size of around 50 nm, a purity of 99 %, a density close to 2.1 g/cm^3 and a thermal conductivity of 30 W/mK. Oleic acid with a purity higher than or equal to 99 % was used as the surfactant to facilitate stable dispersion of the nanoparticles in the base oil. All materials were used in the as-received condition without any further treatment.

To examine the influence of nanoparticles on the thermophysical behaviour of Jatropha oil, a series of biolubricants was prepared by dispersing TiO_2 or BN nanoparticles into the base oil at 0.05, 0.1 and 0.2 wt. % content. Oleic acid was added as a surfactant at 1X, 5X and 10X concentrations to improve dispersion stability, and the corresponding volumes and masses for different nanoparticle contents are listed in Table 1.

The mixtures were ultrasonicated using a probe-type ultrasonic processor VCX 750 (Sonics & Materials Inc.) operating at a frequency of 20 kHz with a maximum power output of 750 W. A Ti-6Al-4V titanium alloy probe with a 0.5-inch tip diameter was used for sonication. The ultrasonication process was carried out for controlled durations to ensure effective dispersion and uniform distribution of the nanoparticles in the base fluid. In order to achieve uniform nanoparticle distribution in the base oil, the biolubricants were created utilising a two-step dispersion approach that involved mechanical stirring followed by ultrasonication. In the current work, dispersion stability was guaranteed for short-term experimental settings, which aligned with the goals of evaluating rheological properties and thermal conductivity. Immediately following sonication, all measurements were made while there was no discernible sedimentation or agglomeration. As a qualitative stability check, visual examination was used to verify consistent dispersion throughout the test.

Since the focus of this investigation was on property measurements under newly manufactured and steady dispersion settings, advanced characterisation techniques like zeta

Table 1. Composition of TiO_2 and BN biolubricant formulations with Jatropha oil and oleic acid surfactant

Nanoparticle				Surfactant			Jatropha oil	
type	content, wt. %	mass, g	volume, ml	concentration	mass, g	volume, ml	mass, g	volume, ml
TiO_2	0.05	0.46	0.109	1X	0.098	0.109	919.43	999.38
				5X	0.488	0.545	918.99	998.90
				10X	0.975	1.090	918.44	998.31
	0.10	0.92	0.218	1X	0.195	0.218	918.86	998.76
				5X	0.975	1.090	917.98	997.81
				10X	1.951	2.180	916.90	996.63
	0.20	1.84	0.435	1X	0.389	0.435	917.77	997.58
				5X	1.946	2.175	916.03	995.68
				10X	3.893	4.350	913.85	993.32
BN	0.05	0.46	0.219	1X	0.196	0.219	919.31	999.25
				5X	0.980	1.095	918.43	998.29
				10X	1.960	2.190	917.33	997.10
	0.10	0.92	0.438	1X	0.392	0.438	918.67	998.56
				5X	1.960	2.190	916.91	996.65
				10X	3.920	4.380	914.73	994.28
	0.20	1.84	0.876	1X	0.784	0.876	917.23	996.99
				5X	3.920	4.380	913.71	993.17
				10X	7.840	8.760	909.33	988.41

potential and dynamic light scattering, which offer quantitative assessment of long-term stability, were not used. The enhanced thermal performance and dependability of BN dispersions are supported by their greater stability. After thoroughly mixing the nanoparticles with the surfactant oleic acid, they were left undisturbed for a whole day. After this blend was added to Jatropha oil, it was sonicated for predetermined times (30, 60, and 90 minutes) to achieve uniform distribution and ensure that the nanoparticles were properly wet with the surfactant oleic acid. During sonication, care was taken to prevent excessive temperature rise. By varying the nanoparticle type and content, concentration of surfactant and sonication time, a total of fifty-four samples were prepared, enabling a systematic assessment of their impact on lubricant properties.

Using a rotational rheometer, viscosity measurements were carried out in a thermostatically controlled environment. In order to replicate normal lubricant operating conditions and ensure accurate sample comparison, the test temperature was set to 40 °C. The ASTM D445 standard for lubricant viscosity evaluation was followed when conducting the tests. An analyser based on transient hot wires was used to evaluate thermal conductivity. Each sample had three readings, and statistical analysis was performed using the mean value.

A full factorial design was employed to examine the effects of surfactant concentration, sonication time, nanoparticle type and nanoparticle content (Table 2). Heat transfer and dispersion stability are directly affected by these characteristics. While content influences the development of conductive channels within the base oil, nanoparticle type dictates intrinsic thermal properties. To ensure adequate dispersion and reduce agglomeration, the concentration of surfactant and sonication time were selected as influencing factors. ANOVA was used to determine the main and interaction effects of the variables, with thermal conductivity and viscosity being the principal response variables.

Table 2. Experimental variables and their levels

Factor	Levels	Values
Nanoparticle type	2	TiO_2 | BN
Nanoparticle content, wt. %	3	0.05 | 0.10 | 0.20
Concentration of surfactant	3	1X | 5X | 10X
Sonication time, min	3	30 | 60 | 90

3. Results and discussion

This study assessed the effects of TiO_2 and BN nanoparticles on the viscosity and thermal conductivity of biolubricants based on Jatropha oil. Using a 90-minute sonication, Figure 1a illustrates how the TiO_2 and BN nanoparticle content affects the thermal conductivity of Jatropha-based biolubricant stabilised with oleic acid surfactant (10X concentration). Because of better surface contact and heat transfer channels, thermal conductivity increased dramatically as the nanoparticle content increased from 0.05 to 0.20 wt. %. BN's improved thermal characteristics were demonstrated with the 0.2 wt. % TiO_2 and BN-filled biolubricant's thermal conductivities of 0.236 and 0.262 W/mK, respectively. By reducing agglomeration, surfactant concentration and sonication time affect the stable dispersion. These patterns are consistent with other research showing that surfactant and sonication settings significantly increased heat conductivity in biolubricants [21,22].

The effect of the concentration of surfactant (oleic acid) on the thermal conductivity of Jatropha-based biolubricant with 0.2 wt. % TiO_2 and BN, after 90 minutes of sonication, is shown in Figure 1b. At the minimal concentration of surfactant, the thermal conductivity of biolubricant with BN was 0.249 W/mK, while that with TiO_2 was 0.224 W/mK. Because of better nanoparticle dispersion and decreased agglomeration, values of 0.236 W/mK (TiO_2) and 0.262 W/mK (BN) were significantly improved by increasing the surfactant concentration to 10X. As expected, given its greater phonon transmission and stability, BN performed better than TiO_2. For stability and thermal performance, surfactant concentration optimisation is essential [23]. By avoiding aggregation and enhancing thermal conductivity, surfactants stabilise nanofluids [15].

The impact of sonication time on the thermal conductivity of biolubricants containing 0.2 wt. % nanoparticles and 10X surfactant is shown in Figure 1c. Longer sonication improves stability and heat transfer by breaking up nanoparticle agglomerates. When the sonication time was extended from 30 to 60 minutes, the thermal conductivity of BN-filled lubricant increased from 0.260 to 0.264 W/mK, whereas for TiO_2-filled lubricant it decreased from 0.234 to 0.231 W/mK. The superior dispersion and crystal structure of BN are responsible for its superior performance. By verifying uniform dispersion and lowering heat resistance, the ideal sonication time significantly improves nanofluid performance [23].

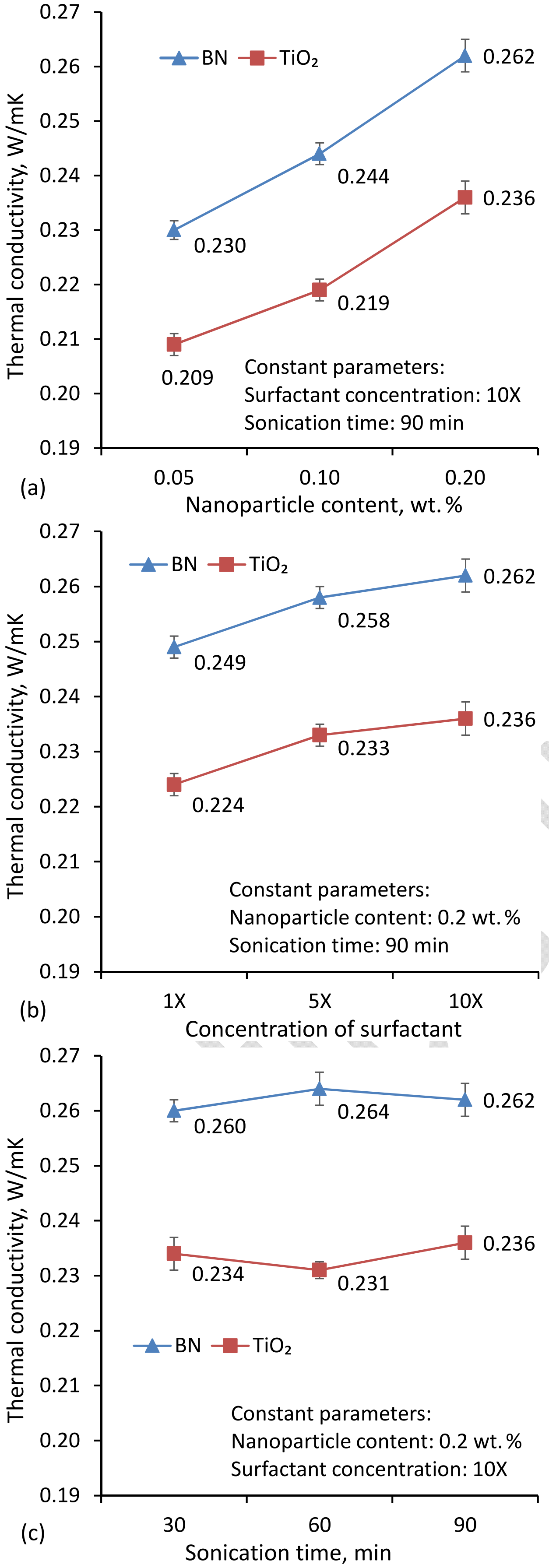

Figure 1. Effect on thermal conductivity of: (a) nanoparticle type, (b) concentration of surfactant and (c) sonication time

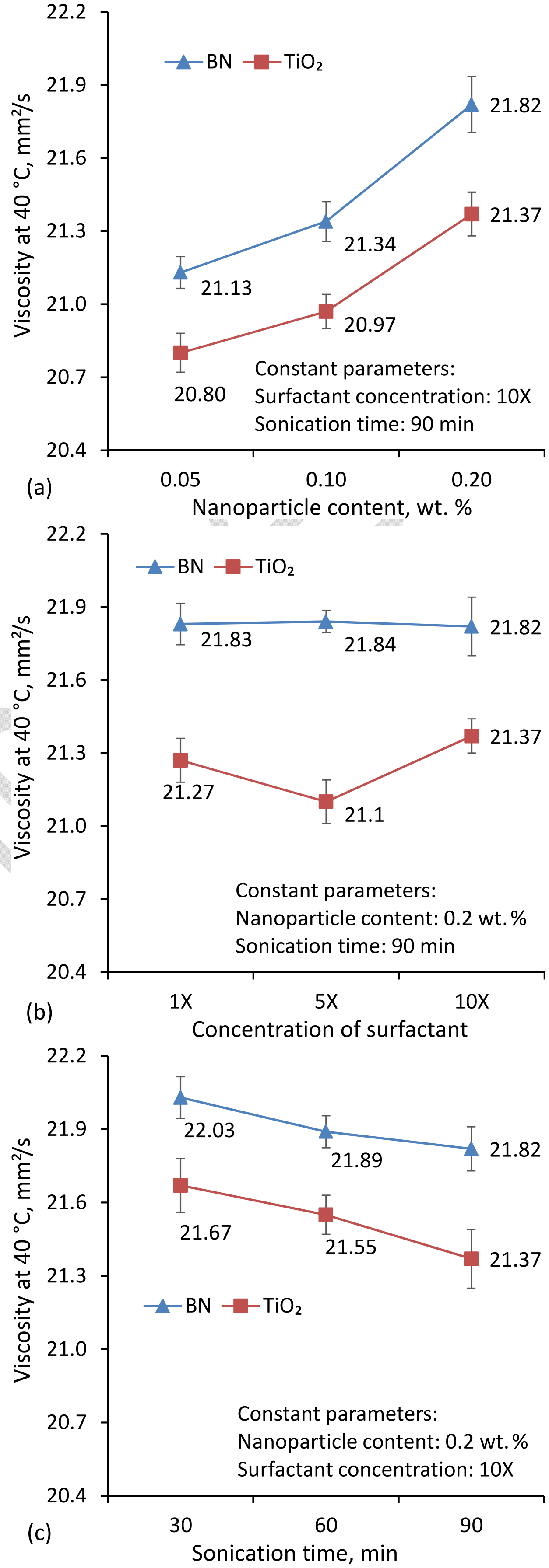

Figure 2. Effect on viscosity of: (a) nanoparticle type, (b) concentration of surfactant and (c) sonication time

Table 3. Experimental conditions as per a full factorial design and thermal conductivity and viscosity values

Test no.	Nanoparticle type	Nanoparticle content, wt. %	Concentration of surfactant	Sonication time, min	Thermal conductivity, W/mK	Viscosity at 40 °C, mm^2/s
1	BN	0.10	5X	30	0.236	21.73
2	BN	0.10	10X	30	0.238	21.63
3	TiO_2	0.20	10X	60	0.231	21.55
4	BN	0.05	1X	90	0.228	21.33
5	BN	0.20	5X	30	0.252	22.13
6	TiO_2	0.10	5X	30	0.214	21.37
7	BN	0.05	10X	90	0.230	21.13
8	TiO_2	0.10	1X	30	0.208	21.45
9	BN	0.05	10X	60	0.232	21.20
10	BN	0.10	1X	90	0.234	21.48
11	BN	0.10	5X	90	0.240	21.42
12	BN	0.05	5X	30	0.229	21.53
13	BN	0.05	1X	30	0.226	21.62
14	TiO_2	0.10	10X	90	0.219	20.97
15	TiO_2	0.20	10X	30	0.234	21.67
16	BN	0.10	10X	60	0.242	21.50
17	TiO_2	0.05	5X	30	0.205	21.17
18	BN	0.20	5X	60	0.256	21.98
19	TiO_2	0.20	5X	60	0.229	21.22
20	BN	0.20	1X	60	0.248	22.08
21	BN	0.10	1X	30	0.231	21.84
22	TiO_2	0.20	10X	90	0.236	21.37
23	BN	0.10	5X	60	0.238	21.59
24	TiO_2	0.05	5X	60	0.207	21.01
25	TiO_2	0.10	1X	60	0.212	21.32
26	TiO_2	0.10	1X	90	0.214	21.14
27	BN	0.20	10X	30	0.260	22.03
28	TiO_2	0.10	5X	60	0.216	21.16
29	TiO_2	0.20	5X	30	0.226	21.40
30	TiO_2	0.05	10X	90	0.209	20.80
31	TiO_2	0.10	10X	60	0.221	21.13
32	TiO_2	0.20	1X	30	0.222	21.47
33	BN	0.05	1X	60	0.227	21.49
34	TiO_2	0.05	5X	90	0.211	20.90
35	BN	0.20	10X	90	0.262	21.82
36	BN	0.20	1X	30	0.246	22.14
37	TiO_2	0.20	1X	90	0.224	21.27
38	BN	0.05	5X	90	0.233	21.22
39	TiO_2	0.05	1X	90	0.206	20.86
40	TiO_2	0.10	5X	90	0.218	21.01
41	BN	0.20	1X	90	0.249	21.83
42	BN	0.20	10X	60	0.264	21.89

Table 3. *Continued*

Test no.	Nanoparticle type	Nanoparticle content, wt. %	Concentration of surfactant	Sonication time, min	Thermal conductivity, W/mK	Viscosity at 40 °C, mm^2/s
43	BN	0.05	5X	60	0.230	21.36
44	TiO_2	0.05	10X	30	0.208	20.97
45	TiO_2	0.05	10X	60	0.210	20.86
46	BN	0.20	5X	90	0.258	21.84
47	TiO_2	0.05	1X	30	0.203	21.24
48	TiO_2	0.05	1X	60	0.205	21.11
49	TiO_2	0.20	1X	60	0.223	21.31
50	BN	0.10	10X	90	0.244	21.34
51	TiO_2	0.10	10X	30	0.220	21.21
52	BN	0.05	10X	30	0.231	21.33
53	TiO_2	0.20	5X	90	0.233	21.10
54	BN	0.10	1X	60	0.232	21.67

Figure 2 illustrates the influence of nanoparticle type, concentration of surfactant and sonication time on the viscosity at 40 °C of the prepared biolubricants. As shown in Figure 2a, an increase in the nanoparticle content from 0.05 to 0.20 wt. % results in a gradual increase in viscosity for both BN- and TiO_2-filled lubricants, indicating that higher particle content increases resistance to flow due to enhanced particle-fluid interactions. BN-filled lubricants exhibit slightly higher viscosity than TiO_2-filled lubricants at all wt. %. Figure 2b shows that variations in surfactant concentration produce only minor changes in viscosity, suggesting that the surfactant primarily aids nanoparticle dispersion without significantly affecting the flow behaviour. In contrast, Figure 2c shows a slight decrease in viscosity with increasing sonication time from 30 to 90 minutes for both biolubricants, which can be attributed to improved dispersion and reduced agglomeration of nanoparticles within the base oil. Overall, nanoparticle content has a more pronounced effect on viscosity compared with surfactant concentration and sonication time.

Table 3 presents the experimental conditions according to the full factorial design, together with the associated viscosity and thermal conductivity values. Figure 3a displays the primary influence plot on thermal conductivity for various process parameters. Because of its increased capacity for heat transfer, BN has a higher conductivity than TiO_2. The conductivity increases with the nanoparticle content increase from 0.05 to 0.20 wt. %. Oleic acid, as a surfactant, significantly affects stability. Conductivity peaks at 10X and decreases at lower concentrations. By increasing particle dispersion, longer sonication (up to 90 minutes) also improves conductivity. At 0.20 wt. % BN, 10X oleic acid and 90 minutes of sonication, the best results are obtained. Up to the stability limit, thermal transport is improved by an increase in nanoparticle concentration [24,25]. Earlier studies [26] emphasised the significance of sonication in achieving homogenous dispersion and the need for surfactants in achieving the full potential of nanofluid heat transfer.

The main effects plot for viscosity is shown in Figure 3b, which illustrates how influencing factors affect the biolubricant's viscosity. The type of nanoparticle has the biggest impact of all the criteria. Lubricants filled with BN have higher viscosity than the corresponding lubricants filled with TiO_2. Viscosity gradually increases when nanoparticle content increases from 0.05 to 0.20 wt. %, presumably as a result of changed particle interactions and suspension rearrangements at higher contents. Viscosity decreases as surfactant concentration increases, suggesting a more modest role for surfactant concentration. The influence of sonication time is more noticeable. As it increases, viscosity decreases, most likely due to improved nanoparticle dispersion, greater effective surface area, and stronger particle-fluid interactions that increase flow resistance. These consistent results demonstrate that the type and content of nanoparticles remain the principal parameters influencing the flow properties of biolubricants, even though surfactant concentration and sonication time have a minor impact on viscosity.

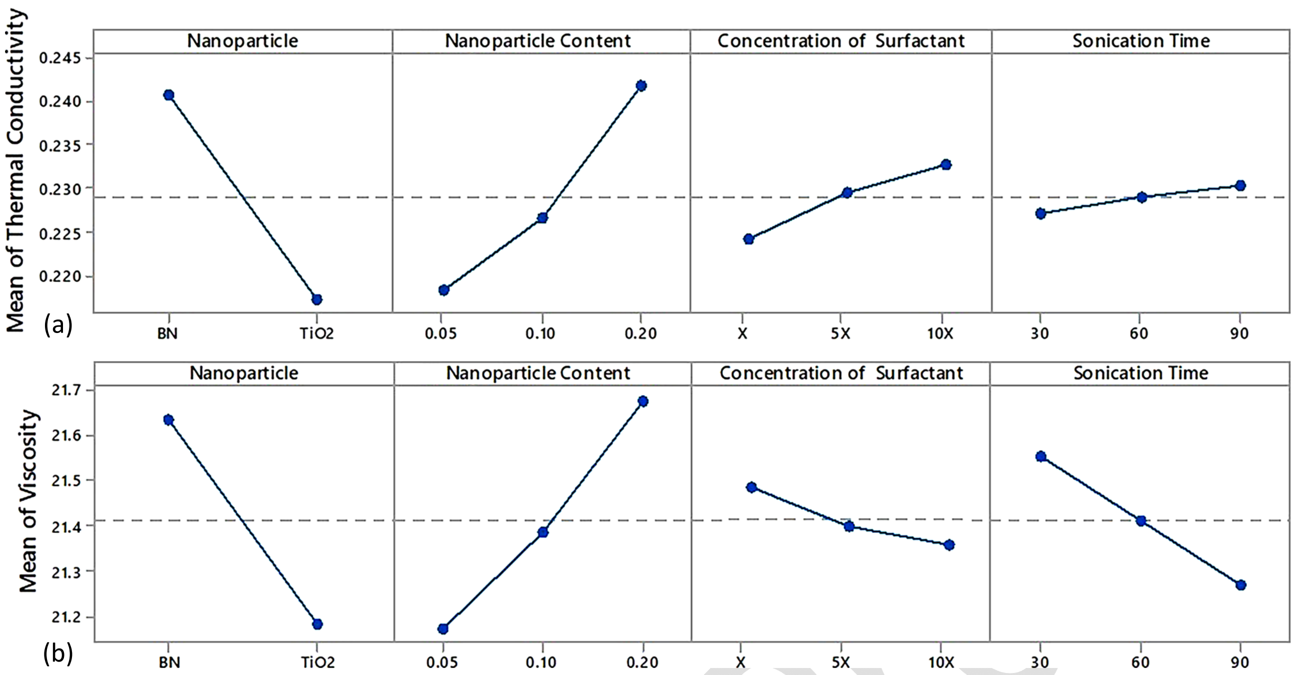

Figure 3. Main effects plots showing the influence of process parameters on the thermophysical properties of biolubricants: (a) thermal conductivity and (b) viscosity at 40 °C

The control factors (process parameters) interaction plots are shown in Figure 4. As shown in Figure 4a, thermal conductivity increases sharply with increasing nanoparticle content, especially with a 10X concentration of surfactant (oleic acid), indicating that a higher amount of surfactant improves dispersion. Longer sonication (up to 90 minutes) significantly improves conductivity for higher nanoparticle contents. BN outperforms TiO_2, particularly under ideal circumstances. Prolonged sonication partially compensates for the effect of low surfactant concentrations. However, both parameters need to be high for the best results. The lowest conductivity is achieved with short sonication times and minimal surfactant concentrations. Overall, the maximum conductivity is obtained with 0.20 wt. % BN, a 10X concentration of oleic acid, and 90 minutes of sonication. These findings are in line with other studies that demonstrated that proper stability and higher nanoparticle content greatly enhance the heat transmission potential of nanofluids [27].

Figure 4b illustrates how the same process parameters interact to affect the viscosity of the biolubricants that contain nanoparticles. BN-filled biolubricants are more viscous than TiO_2-filled lubricants, especially for lower nanoparticle contents. For both biolubricants, viscosity increases with increasing nanoparticle content. The correlation between the concentration of surfactant and nanoparticle type shows that for BN, viscosity increases with the decrease of surfactant concentration, whilst for TiO_2, viscosity varies relatively little. Sonication time also has a major impact on viscosity. Longer sonication (90 minutes) reduces viscosity, enhances particle dispersion and boosts interparticle interactions, all of which contribute to a more stable suspension. This impact is amplified at higher concentrations, suggesting that dispersive energy and surfactant availability combine to provide stable rheological behaviour.

Table 4 presents ANOVA results for thermal conductivity of biolubricants. The analysis was performed at a level of significance of 0.05, corresponding to a 95 % confidence level. The ANOVA results further reinforce the strength and predictive capability of the model in estimating the thermal conductivity of biolubricants enhanced with nanoparticles. The model exhibits a very high R^2 value of 99.616 %, with linear terms alone accounting for 98.167 % of the total variation. Among the individual linear factors, the concentration of surfactant (oleic acid) stands out as the most significant, accounting for 54.683 % of the variation. This confirms that surfactant plays a significant role, likely by improving the dispersion stability of the nanoparticles. Nanoparticle content is the second most influential factor, contributing 37.880 % to the overall variability, suggesting that increasing nanoparticle content significantly improves thermal conductivity. Although the concentration of surfactant and sonication time are statistically significant, their individual contributions are relatively modest at 4.879 % and

0.717 %, respectively. This indicates that while both factors affect thermal conductivity, their impact is considerably lower than that of nanoparticle type and nanoparticle content.

The two-way interaction accounts for 1.499 % of the total variation, with the most notable interaction occurring between nanoparticle content and concentration of surfactant, contributing 0.776 %. This indicates a strong synergistic relationship, where the thermal conductivity enhancement depends not just on the amount of particles or surfactant used individually, but on their combination. The interaction between the concentration of surfactant and sonication time also shows a moderate influence of 0.163 %. In contrast, interactions involving nanoparticle type, particularly with sonication time, contribute very little (as low as 0.015 %), indicating a minimal impact. Overall, the model confirms that the most effective enhancement in thermal conductivity results from optimising the nanoparticle type and content, followed by fine-tuning the surfactant (oleic acid) concentration and sonication time.

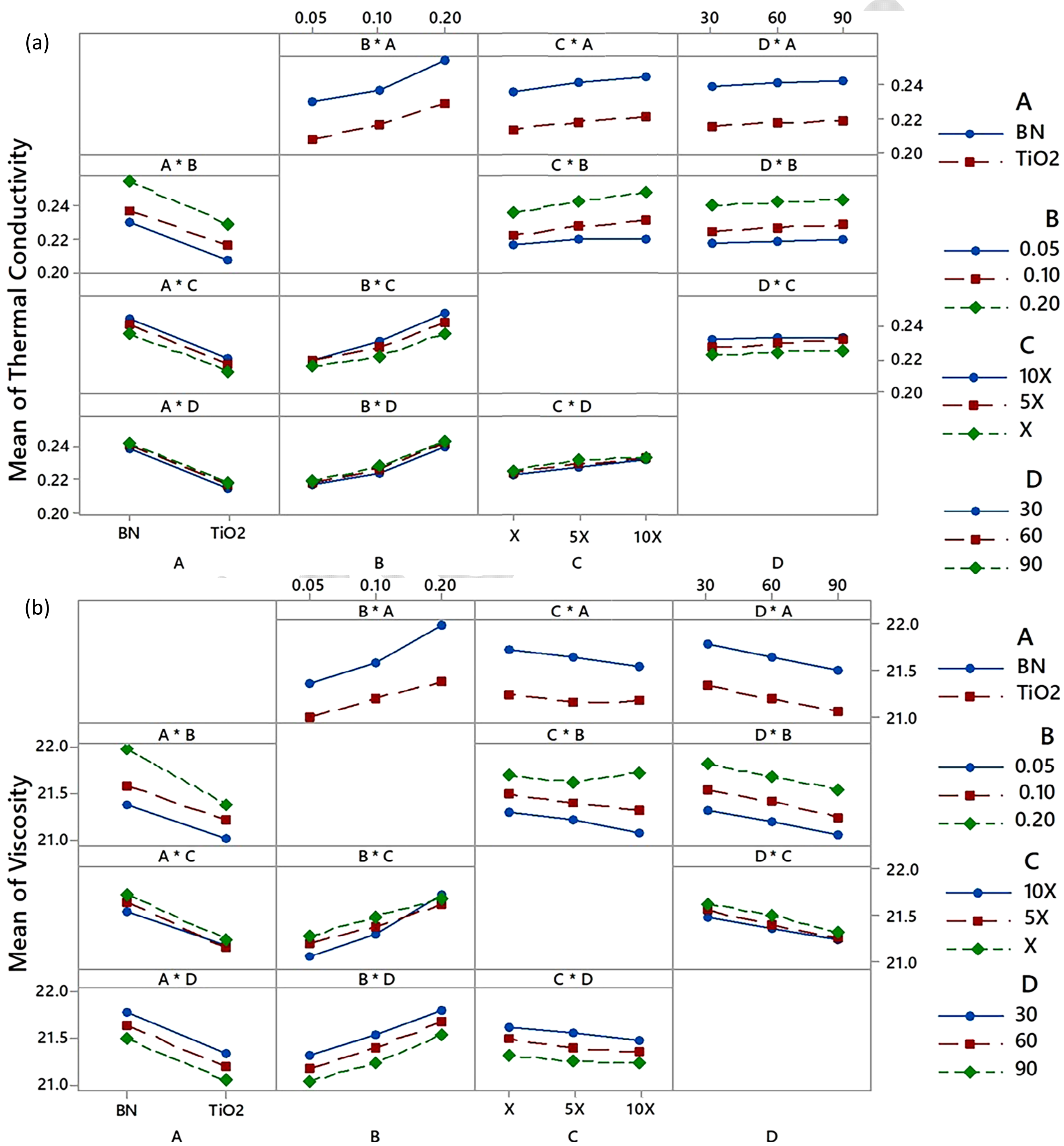

Figure 4. Interaction plots showing the combined effects of process parameters (A – nanoparticle type, B – nanoparticle content, C – concentration of surfactant and D – sonication time) on the thermophysical properties of biolubricants: (a) thermal conductivity and (b) viscosity at 40 °C

Table 4. ANOVA results for thermal conductivity of biolubricants

Source	Degree of freedom	Adjusted sums of square	Adjusted mean square	F-value	p-value	Percentage contribution
Model	25	0.013475	0.000539	288.79	0.000	99.616
Linear	7	0.013279	0.001897	1016.38	0.000	98.167
Nanoparticle type (A)	1	0.007397	0.007397	3963.10	0.000	54.683
Nanoparticle content (B)	2	0.005124	0.002562	1372.78	0.000	37.880
Concentration of surfactant (C)	2	0.000660	0.000330	176.90	0.000	4.879
Sonication time (D)	2	0.000097	0.000049	26.10	0.000	0.717
Two-way interactions	18	0.000196	0.000011	5.84	0.000	1.449
A × B	2	0.000060	0.000030	16.08	0.000	0.444
A × C	2	0.000004	0.000002	1.02	0.373	0.030
A × D	2	0.000002	0.000001	0.43	0.657	0.015
B × C	4	0.000105	0.000026	14.11	0.000	0.776
B × D	4	0.000003	0.000001	0.43	0.785	0.022
C × D	4	0.000022	0.000006	2.98	0.036	0.163
Residual error	28	0.000052	0.000002			0.384
Total	53	0.013527				100

Table 5 presents the ANOVA results for viscosity of biolubricants. The ANOVA results clearly demonstrate that the chosen factors have a significant impact on viscosity, with the model explaining more than 98 % of the variability (R^2 = 98.40 %). Among the linear terms, nanoparticle type is the most dominant factor, accounting for 43.094 % of the variation (F-value = 755.16, p-value < 0.05), with BN-filled biolubricants showing significantly higher viscosities than TiO_2-filled biolubricants. Although higher contents tend to reduce viscosity, probably due to particle interactions, nanoparticle content is the second most important factor, accounting for 35.717 %. Prolonged sonication greatly improves fluid resistance and nanoparticle dispersion, as evidenced by the significant effect of 11.466 % of the sonication time. Although statistically significant, the concentration of surfactant only explains 2.318 % of the variation, indicating that surfactant addition improves stability rather than causing major changes on its own.

Additional information is provided by the two-way interaction analysis, which shows that the interaction between nanoparticle content and nanoparticle type accounts for over 5.8 % of the variability (F-value = 20.99). The relationship between nanoparticle type and sonication time, as well as between nanoparticle content and sonication time, is low, and other interaction effects are comparatively inconsequential. Similar results have been reported by other researchers, who have emphasised that stable dispersions require both adequate mixing energy and an optimum concentration, as well as the substantial influence of nanoparticle type and sonication time on viscosity [24-26]. These findings collectively demonstrate that, although all variables affect viscosity, the type of nanoparticle and their interaction during sonication are the most important determinants of rheological behaviour of nanofluids.

The created biolubricants show significant potential for applications requiring reliable lubrication, as well as effective heat dissipation. By reducing wear and friction in engines and moving parts, nanoparticles can increase operational efficiency and prolong the life of industrial and automotive equipment. Prior research has demonstrated that the use of nanoparticles improves surface contacts and reduces frictional losses, thereby increasing the longevity and performance of lubricated systems [28]. Additionally, it has been found that biolubricants exhibit enhanced tribological performance and better thermal conductivity, suggesting that they are suitable for lubricating engines under high-temperature, highly loaded conditions [29,30]. These biolubricants' combination of cooling and lubrication benefits makes them ideal for applications where wear reduction and efficient heat management are crucial.

Table 5. ANOVA results for viscosity of biolubricants

Source	Degree of freedom	Adjusted sums of square	Adjusted mean square	F-value	p-value	Percentage contribution
Model	25	6.20136	0.24805	68.97	0.000	98.402
Linear	7	5.83540	0.83363	231.80	0.000	92.595
Nanoparticle type (A)	1	2.71578	2.71578	755.16	0.000	43.094
Nanoparticle content (B)	2	2.25091	1.12546	312.95	0.000	35.717
Concentration of surfactant (C)	2	0.14611	0.07306	20.31	0.000	2.318
Sonication time (D)	2	0.72259	0.36130	100.46	0.000	11.466
Two-way interactions	18	0.36596	0.02033	5.65	0.000	5.807
A × B	2	0.15100	0.07550	20.99	0.000	2.396
A × C	2	0.04107	0.02054	5.71	0.008	0.652
A × D	2	0.00028	0.00014	0.04	0.962	0.004
B × C	4	0.15574	0.03894	10.83	0.000	2.471
B × D	4	0.00420	0.00105	0.29	0.881	0.067
C × D	4	0.01366	0.00342	0.95	0.450	0.217
Residual error	28	0.10070	0.00360			1.598
Total	53	6.30205				100

4. Conclusion

Given that BN consistently outperforms TiO_2 across most test conditions, this work demonstrates the potential for Jatropha-based biolubricants to achieve higher thermal performance by adding nanoparticles. The type of nanoparticle was shown to be particularly significant among the criteria considered, with BN offering the best results. Additionally, adding nanoparticles had a noticeable impact, and the 0.20 wt. % showed the highest gain, especially when paired with sufficient surfactant and an extended 90-minute sonication time.

The significance of formulation strategy was highlighted by the interaction analysis, which showed that the greatest improvements are achieved only when these parameters are tuned together. The viscosity patterns of BN-filled biolubricants remained within realistic bounds for lubrication applications, while their peak thermal conductivity of 0.264 W/mK further demonstrated their benefits for heat transfer applications.

These findings were further corroborated by statistical analysis and interaction graphs, which demonstrated that performance is mostly determined by both individual elements and their combined effects. All things considered, the results show that BN-filled Jatropha-based lubricants are a viable, environmentally friendly choice for industrial lubrication and sustainable heat control, offering a green alternative without sacrificing functionality.

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