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Experimental Investigation of the Characteristics and Tribological Effectiveness of *Pongamia pinnata* Lubricant Oil Blended with Nanoadditives

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Abstract: The amalgamation of nanomaterials with bio-lubricants presents a promising approach to enhance the performance and efficiency of mechanical systems. To address the overuse of conventional lubricants, a viable strategy involves harnessing the potential of naturally available lubricants to operate effectively under extreme operating conditions, such as high loads and high-temperature and high-friction environments. The incorporation of nanomaterials, with their high surface area, extended thermal conductivity, and enhanced load-carrying capacity, offers an effective means of producing alternatives to traditional lubricants. This study aimed to investigate the impact of incorporating nanomaterials in small percentages of 2%, 4%, and 6% into bio-lubricants to reduce friction and improve their tribological performance. A systematic analysis of the effects of nanomaterials on lubrication parameters, such as shear rate, shear stress, torque, and viscosity, was performed. The experimental results indicate that the incorporation of nanomaterials into bio-lubricants aligns their parameters closely with those of commercial lubricants, suggesting their potential as a viable alternative in the lubricant industry.

Keywords: nanomaterials; *Pongamia pinnata* oil; rheometer; viscosity; shear stress

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1. Introduction

Nanotechnology is widely regarded as one of the most revolutionary technologies of the 21st century, significantly advancing materials science. In the field of tribology, numerous studies have investigated the effects of adding nanoparticles to lubricants, revealing their effectiveness in reducing wear and friction. The tribological performance of nanoparticles depends on factors such as size, shape, and concentration, with particle sizes typically ranging from 2 to 120 nm [1–3].

Direct mechanisms include the ball-bearing and tribofilm mechanisms, while indirect mechanisms include the mending and polishing mechanisms. Direct mechanisms are believed to be more effective than indirect mechanisms. Due to the fact that nanoparticles are often spherical, they behave as if they were little ball bearings. When they roll into the contact zone, they transform the sliding friction into a combination of the rolling and sliding types of friction. Tribofilm creation happens when additives and tribosurfaces interact with one another. This interaction can result in the formation of a protective tribofilm. It is recommended that the creation of tribofilm take precedence over wearing in order to provide superior protection for the surfaces. Tribosinterization is a process that eventually

leads to the repair of the surfaces by filling NPs in the grooves and scars. The mechanism of polishing involves the NPs, which are hard, causing abrasion of the rough surfaces, which ultimately results in polished surfaces [4,5].

The mechanisms behind friction reduction and anti-wear behaviors include the following:

1. Colloidal Effect: Nanoparticles penetrate electrohydrodynamic (EHD) contacts, forming a boundary film that reduces surface interactions.
2. Rolling Effect: Spherical nanoparticles, such as IF particles, enable rolling friction, reducing direct metal-to-metal contact.
3. Protective Film: Nanoparticles deposit tribo chemical reaction products, forming an anti-wear boundary film and reducing shear stress.
4. Third-Body Mechanism: Nanoparticles act as spacers or fillers, preventing asperity contact and improving load-carrying capacity, especially under high loads [6–8].

This work delves into a detailed analysis and comprehensive interpretation of experimental data acquired during the investigation of nano-bio-lubricants as advanced additives in natural lubricants. The overarching objective of this research was to explore the suitability of nano powders as additives, emphasizing their capability to enhance the performance characteristics of traditional lubricating oils. Nano-bio-lubricants, due to their unique properties derived from nanotechnology and biological origins, offer significant advantages in reducing friction and wear, which are critical in extending the lifespan of mechanical systems and improving overall efficiency.

The experimental work conducted in this study involved evaluating the physical and tribological properties of nano-bio-lubricants, ensuring their compatibility with natural base oils, and analyzing their dispersion stability. Nanopowders, with their nanoscale dimensions, provide a vastly increased surface area-to-volume ratio, enabling superior interaction with the lubricant matrix. This enhanced interaction facilitates improved lubrication properties, such as reduced friction coefficients and enhanced thermal stability, making them a viable solution for high-performance and eco-friendly applications. According to studies in the field, nanoparticles such as metal oxides, carbon-based materials, and bio-derived nanopowders have shown potential in minimizing wear and friction in tribological systems.

The experiments further included assessing blends of base oils and nanoparticles through various performance tests. This encompassed the measurement of critical attributes, such as viscosity and density, both prior to and after subjecting the blends to 20,000 cycles of mechanical operation under controlled conditions. The findings indicate that the addition of nanoparticles to natural lubricants significantly improves their ability to withstand oxidative degradation and maintain consistent performance, even under high-pressure and high-temperature conditions. Such properties are particularly valuable in automotive engines, industrial machinery, and other systems where prolonged operational reliability is paramount. Wear and friction characteristics were central to this study, with nano-bio-lubricants exhibiting marked improvements in reducing wear scar diameter and friction coefficients when compared to conventional lubricants. This was achieved through the inherent ability of nanoparticles to form a protective tribofilm on contact surfaces, reducing direct asperity contact and thereby minimizing wear. The reduction in wear rates not only extends the operational life of components but also decreases maintenance costs and downtime, a key consideration for industries focused on operational efficiency [9].

Moreover, the comparative analysis of bio-based nanomaterials and synthetic nanomaterials revealed an edge for the former in terms of environmental sustainability and biodegradability. The adoption of bio-derived nanoprecipitates aligns with worldwide efforts to reduce reliance on fossil fuels and mitigate environmental impacts. Furthermore,

bio-based materials have demonstrated enhanced dispersion stability in natural base oils, a factor critical for the uniformity and consistency of lubrication properties throughout the operational lifecycle [2,10,11].

Hence, efforts have been made to ensure the effective utilization of naturally available resources and to protect the environment from depletion. The important aspect of adding nano-lubricants such as zinc oxide and graphene is to enhance lubricant performance through diverse mechanisms, with their size, shape, and concentration playing critical roles in optimizing tribological properties. Given the transformative potential of nano-bio-lubricants in advancing lubrication technology due to their leveraging the unique attributes of nanomaterials, this research supports the development of greener, more efficient alternatives to traditional lubricants. Future implications include their potential for widespread industrial adoption, with further studies recommended to evaluate their long-term performance and scalability in real-world applications.

2. Materials and Methods

The work explored the optimization of various lubricant blends by balancing parameters such as nanoparticle concentration and blending techniques. Through experimental trials, the study determined that a 2% concentration of nanoparticles dispersed in natural lubricants achieved an optimal balance of performance and stability. Ultrasonication and magnetic stirring were identified as effective methods for achieving uniform dispersions, a prerequisite for maximizing the tribological benefits of nano additives. These results underscore the importance of both material selection and process optimization in developing high-performance nano-bio-lubricants.

2.1. Materials

Pongamia pinnata is the botanical name of a species of the pea family, Fabaceae, that belongs to eastern and tropical Asia. It is more commonly called the *Pongamia* oil tree and Karanja in India. This tree is largely found on the roads of Karnataka. The lubricant oil derived from this plant is biodegradable and non-toxic, unlike conventional mineral-based oils. The lubricant should be thoroughly examined for its effectiveness in reducing wear and minimizing abrasion during machine operations. Proper utilization ensures optimal performance, reduced maintenance, and improved efficiency of machines and their components. When vegetable oils are used as base stocks for lubricants, they exhibit good lubricity and high viscosity indices; hence, the base oil chosen was that of *Pongamia pinnata*. Although commercial oils are available in plenty, they cause environmental hazards in one way or another due to the residues they leave behind. The seeds of *Pongamia pinnata* trees are non-edible; hence, these seeds could be effectively utilized as a bio-lubricant source. The main intention of this research was to utilize these naturally available resources. The nanomaterials considered were nano-zinc oxide and -graphene. Zinc oxide (ZnO) can form neutral hexagonal minerals or a pale grimy precipitate. When heated, it takes on a lemon-yellow color, and it turns back to white when cooled. Zinc oxide has a density of 5.61 g/cm^3. Evaporation starts at 1300 °C and goes on to sublimation when the temperature reaches 1800 °C. Graphene's particle size ranges from D 50 < 1 to 2 µm, and its thickness ranges from 5 to 10 nm. Its surface area is limited to around 110 m^2/g. The nano-zinc and -graphene used in this study were obtained from Adnano technologies Pvt Limited, Shimoga, Karnataka, and had a purity of 99%; the graphene was black in color, and the zinc oxide was white in color. These materials are most commonly used as anti-corrosion agents and for coatings to protect from rust. The lubricants play a critical role in the performance and longevity of machinery [12–14]. Figure 1 shows images of the raw materials used.

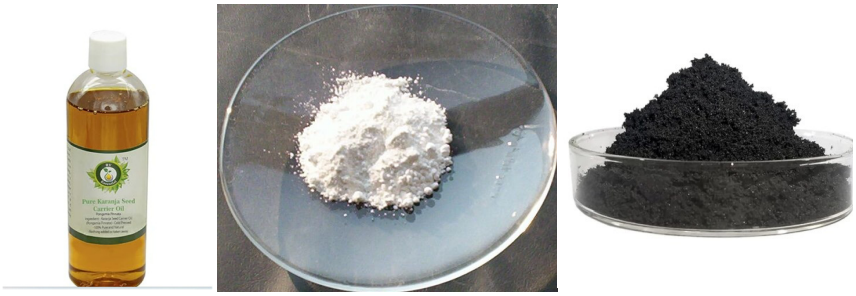


Figure 1. Pongammia pinnata, nano-zinc oxide, and nanographene.

2.2. Samples

The main aim of the experiment was to compare the viscosity of the samples. The detailed experimental approach provided a clear understanding of the nano-bio-lubricating oils' characteristics and rheological behavior [3,8,15]. Six samples of nano-bio-lubricating oils were examined. Sample 1 (S1) consisted of 248 mL *Pongamia* oil mixed with 2 g nano-zinc oxide, sample 2 (S2) comprised 246 mL *Pongamia* oil mixed with 4 g nano-zinc oxide, sample 3 (S3) consisted of 244 mL *Pongamia* oil mixed with 6 g nano-zinc oxide, sample 4 consisted of 248 mL of *Pongamia* oil and 2 g graphene, sample 5 consisted of 244 mL of *Pongamia* oil and 4 g graphene, and sample 6 consisted of 246 mL of *Pongamia* oil and 8 g graphene. The nano compounds were thoroughly blended with the bio-lubricant using a magnetic stirrer for approximately 20 min. The samples were prepared with different combinations are tabulated in Table 1.

Table 1. Samples and the quantities of their constituents.

Samples (Case 1)	***Pongamia pinnata* Oil in mL**	**Zinc Oxide in g**
Sample 1	248	2
Sample 2	246	4
Sample 3	244	6
Samples (Case 2)	***Pongamia pinnata* Oil in mL**	**Graphene in g**
Sample 4	248	2
Sample 5	246	4
Sample 6	244	6

2.3. Characteristics of Base Oil and Nanoparticles

Lubricants have several key characteristics that determine their performance and suitability for various applications. Here are some important ones:

1. Viscosity: This is the measure of a lubricant's resistance to flow. It is crucial because it affects the lubricant's ability to form a protective film between moving parts. A higher viscosity means a thicker lubricant, which can provide better protection but may also increase friction.
2. Density: The density of a lubricant affects its load-carrying capacity. Higher-density lubricants can support heavier loads, making them suitable for high-pressure applications.
3. Flash Point and Fire Point: The flash point is the lowest temperature at which a lubricant can vaporize to form an ignitable mixture in air. The fire point is the temperature at which the vapor continues to burn after being ignited. These properties are important for safety, especially in high-temperature environments.
4. Thermal Stability: This refers to a lubricant's ability to resist breaking down at high temperatures. Good thermal stability ensures that a lubricant maintains its properties and effectiveness over a wide temperature range.

5. Oxidation Stability: This is a lubricant's resistance to reacting with oxygen, which can cause it to degrade and form sludge or varnish. High oxidation stability is important for long-lasting performance.
6. Corrosion Protection: Lubricants often contain additives that protect metal surfaces from corrosion and rust. This is especially important in environments where moisture or corrosive substances are present.
7. Wear Protection: Lubricants reduce wear by forming a protective film between moving parts. Additives like anti-wear agents and extreme-pressure additives enhance this property.
8. Foam Resistance: Foam can reduce the effectiveness of a lubricant by causing it to overflow or fail to provide adequate lubrication. Lubricants with good foam resistance maintain their performance even under conditions that promote foaming.
9. Pour Point: This is the lowest temperature at which a lubricant remains fluid. It is important for applications in cold environments, ensuring that a lubricant can flow and provide protection even at low temperatures.
10. Additives: Lubricants often contain various additives to enhance their properties. These can include anti-wear agents, corrosion inhibitors, antioxidants, and detergents, among others.

These characteristics are essential for selecting the right lubricant for specific applications, ensuring optimal performance and longevity of machinery and equipment. In this work, the following characteristics were considered: flash point, fire point, kinetic viscosity, absolute viscosity/dynamic viscosity, and density.

Able–Pensky–Martens instrument was used to determine the flash and fire points. These tests are critical for evaluating the flammability and safety of various fuels and oils The flash points and fire points of the various samples were obtained and discussed.

A Say bolt viscometer was used to evaluate the density, absolute viscosity, and kinematic viscosity of the samples. The viscosity of fluids is measured by recording the time it takes for a specified volume to flow through a calibrated orifice as per the ASTM D445-19 [16]. Kinematic viscosity is the ratio of a fluid's absolute viscosity to its density. It is particularly useful for high-viscosity fluids, making it ideal for examining nano infused bio-lubricants. Density is an important property that affects a lubricant's capacity to form a protective film between moving parts. A higher density can improve the load-carrying capacity of a lubricant. Absolute viscosity (or dynamic viscosity) measures the internal resistance of a fluid to flow and is measured as per the ASTM D445-19 [16]. Both properties are essential for understanding flow characteristics and lubrication performance at different temperatures. Lubricants often exhibit different viscosities at varying temperatures. For instance, at higher temperatures, viscosity typically decreases, which can affect a lubricant's ability to maintain a protective film. The lubricants considered in this study incorporated nanoparticles to enhance their properties. Nanoparticles can improve thermal stability, reduce friction, and increase wear resistance, making nano-bio-lubricants highly effective in various applications. The samples' flash points, fire points, densities, kinetic viscosities, and absolute viscosities are tabulated in the following Table 2.

Table 2. Samples and their characteristic values.

Samples	Flash Point, °C	Fire Point, °C	Density, g/cm^3	Kinetic Viscosity, N-s/m^2·10^{-5}	Absolute Viscosity, N-s/m^2·10^{-5}
SAE	210	215	0.88	2.77	1.97
Pongamia oil	220	245	0.9	2.72	2.66
Sample 1	240	260	0.94	3.95	3.71
Sample 2	240	264	0.98	3.88	3.8
Sample 3	248	268	0.93	3.86	3.58
Sample 4	246	270	0.94	3.83	3.6
Sample 5	242	260	0.93	3.92	3.65
Sample 6	248	268	0.94	3.9	3.67

3. Tribological Testing

The samples were tested using a shear rheometer, also known as a rotational rheometer, as per the ASTM D2983-21 [17]. The temperature was consistently maintained at 23 °C, and parameters such as viscosity, shear stress, shear rate, and torque were measured using the Rheometer MCR302 (SN000000, ID 80963516, from Anton Paar at Reva University, Bengaluru, India) with the PP25/PE-SN25125 (d = 0.4 mm) measuring system and the TUI = P-PTD200-SN 81183777 accessory (from Anton Paar at Reva University, Bengaluru, India). Initially, the raw blended samples were considered and tested in a rheometer as case 1. Following this, each sample underwent another 40 h of testing in a two-stroke engine under varying speed,. This was case 2. The temperature was set between 20 °C and 30 °C. The blends were subjected to the Hero Honda splendor, a two-stroke engine, for about 40 h. Each sample were tested for 6-day 8 h schedule at varied speed rates, such as at 40 rpm, 60 rpm, and 80 rpm. Then, the samples were observed for any changes in viscosity, adhering to general sampling recommendations as per the guidelines on the lubrication of machinery. The viscosities of samples S1, S2, S4, S5, and S6 were compared before and after the operational period using the same rheometer parameters. The values obtained from the experiments for case 1 (C1) and for case 2 (C2) are tabulated below in Table 3.

Table 3. Rheometer values before and after running condition.

Samples	Shear Rate C1, 1/s	Shear Rate C2, 1/s	Shear Stress C1, Pa	Shear Stress C2, Pa	Viscosity C1, mPa·s	Viscosity C2, mPa·s	Torque C1, mN·m	Torque C2, mN·m
(SAE40w20)	45.4	45.4	13.4	15.2	220	226	0.03	0.03
Sample 1	49.68	49.68	15.52	21.41	329	471	0.03	0.05
Sample 2	49.68	49.68	17.4	33.99	309	698	0.04	0.07
Sample 3	49.68	49.68	19.96	26.11	411	531	0.04	0.06
Sample 4	49.68	49.68	11.34	39.39	235	799	0.02	0.09
Sample 5	49.68	49.68	8.7	39.87	200	818	0.02	0.1

4. Results and Discussion

The most important property of any lubricant is its viscosity, i.e., the resistance offered by the fluid against the rate of flow. It has been determined that if the viscosity of a lubricant is high, then there may exist a hinderance to carrying away the generated heat, which causes wear [12,18]. The results obtained from the experiment, shown in Tables 2 and 3 for case 1 (C1) and for case 2 (C2), are considered in this discussion.

The kinetic viscosity and absolute viscosity values are tabulated in Table 2, and the corresponding graph is plotted in Figure 2. When the kinematic viscosities and absolute viscosities were compared for various samples of *Pongamia* oil along with nanomaterials, they showed higher values, such that they consume less and contribute less wear. However, the samples shown possess good physical properties, the values of sample 2 being very close to those of the reference oil and SAE20 and while others showing minor differences [1,19].

A good lubricant must have a high fire point and a low flash point. Nano-bio-lubricants with high flash points are considered, as there could be a possibility of fire in the chamber. The flash points and fire points of the samples are shown in Table 2. The results and Figure 3, below, show that the fire and flash points of the samples are close to those of the reference oil, SAE20W40 [3,18,19].

Additionally, the samples' densities were calculated and contrasted with that of the optimal lubricant. The density of an effective lubricating oil is reported to range from 700 to 950 kilograms per cubic meter (kg/m^3). Table 2 demonstrates that, in comparison to the optimum lubricant, SAE20W40, the densities of samples 1, 2, 3, 4, 5, and 6 were rather similar. Figure 4 indicates that the samples closely matched SAE20W40 [3,18,19].

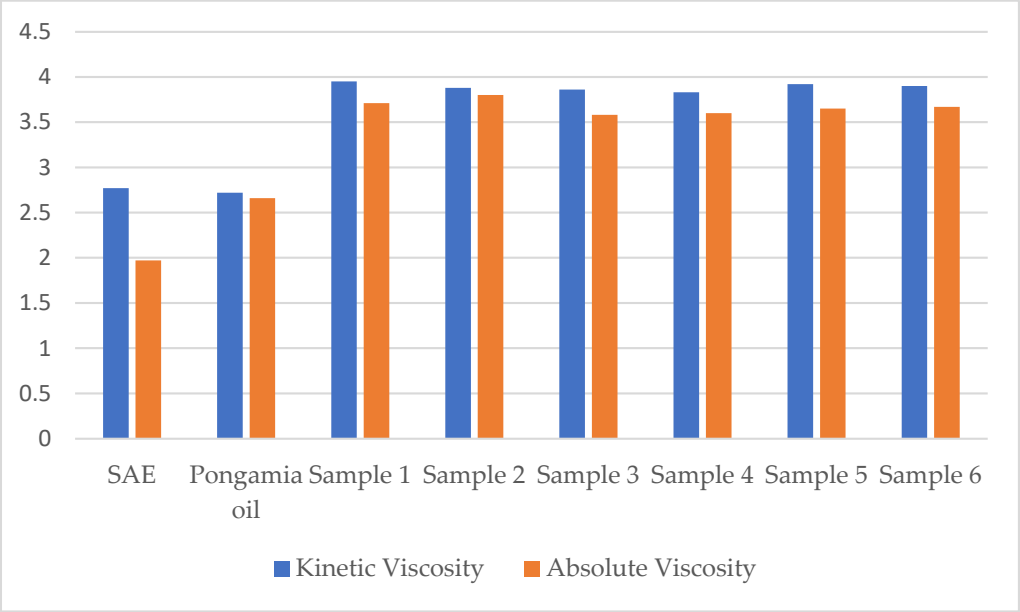


Figure 2. Kinetic viscosity and absolute viscosity values of the samples.

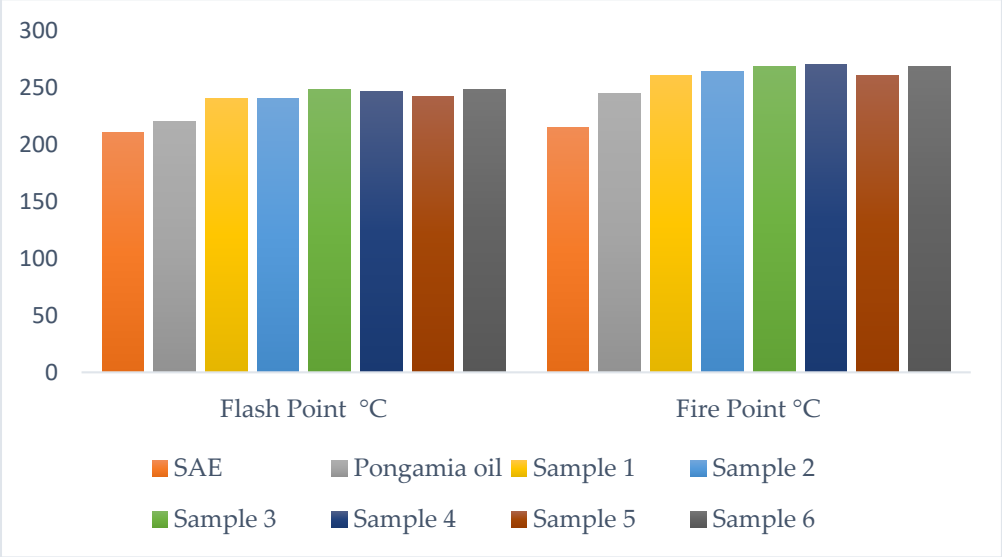


Figure 3. Flash and fire points of the samples.

The tribological analysis obtained via the rheometer depicted the shear rate, shear stress, viscosity, and torque of the samples. The performance and stability of lubrication systems can be determined by their shear rates. The shear rates of the samples before the run, that is, as in case 1, and after the run, that is, as in case 2, were considered for analysis, and a graph was plotted, as shown in Figure 5. The analysis shows that by optimizing the shear rate, it is possible to enhance the longevity of mechanical systems, improve energy efficiency, and minimize wear. Consequently, understanding and controlling the shear rate is essential for the design of effective lubrication strategies in a wide range of industrial applications. The rates of sample 1, sample 2, sample 3, sample 4, and sample 5 were in close accordance with those of SAE oil, as shown in Figure 5 [20,21].

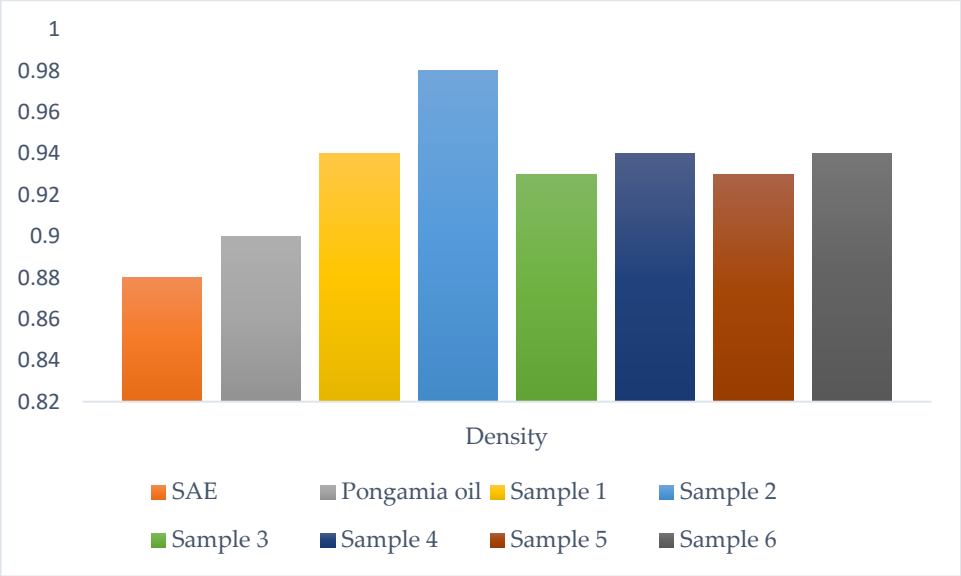


Figure 4. Density of samples in case 1 and case 2.

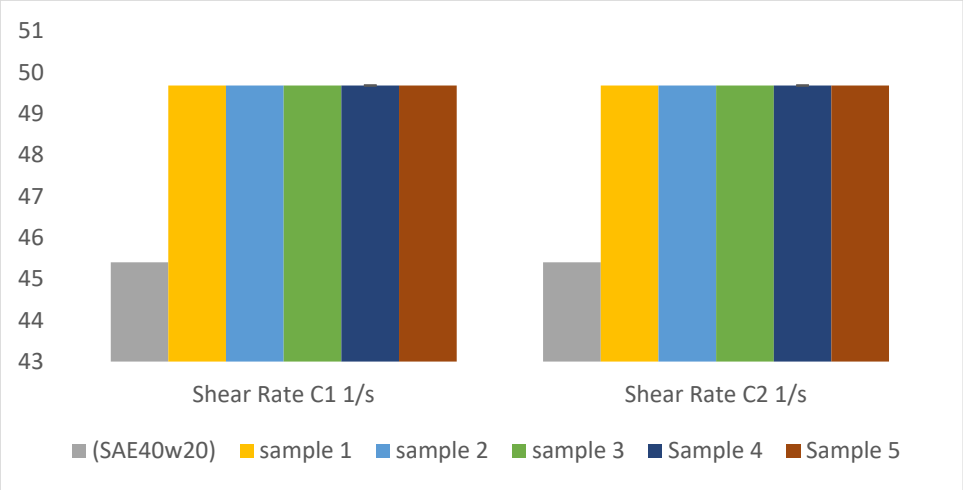


Figure 5. Shear rate values of the samples for case 1 and case 2.

Shear stress is said to vary according to the thickness of a fluid. The results show that the different percentage of nano-lubricant added contributed to drastic variation in the function, which suggests that sample 1 and sample 3 lubricant can be used as alternative lubricant with dual properties. Interval and data points were collected between 1 and 50. The temperature was maintained around 23 °C. The tabulated shear stress values for sample 1, sample 2, sample 3, sample 4, and sample 5 are plotted in Figure 6. From the graph shown in Figure 6, it can be clearly observed that the shear stress in case 1 was very much aligned with that of the reference oil but after the samples were exposed to the machine there was a drastic variation in the shear stress values, such that a secondary level of treatment, such as the addition of filters, may be suggested for better efficiency, since additives were added, according to studies on molecular structure and desiccant breathers [20,21].

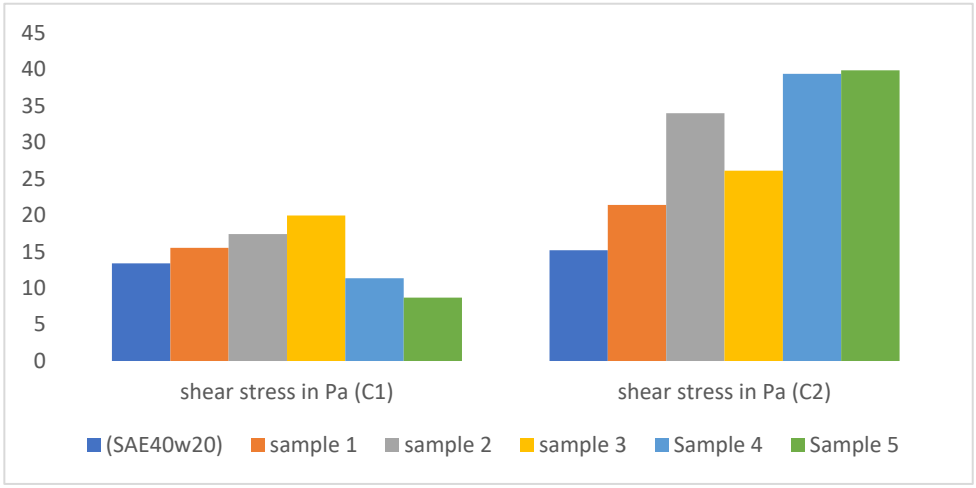


Figure 6. Shear stress values of the samples for case 1 and case 2.

Viscosity is an important aspect in any machine, as it determines the amount of energy required to pump the lubricant. The unit of viscosity is taken as mPa·s. There are two types of viscosity: dynamic viscosity and absolute viscosity. The standard viscosity for machine oil ranges between 250 and 310 at 30 °C. But as the samples have viscosity is high, this lubricant can be used as cylinder oil, where the standard values for viscosity range from 500 to 800 mPa·s [22,23]. The viscosities for sample 1, sample 2, sample 3, sample 4, and sample 5 were plotted on a graph, and the values shown for C1 are favorable to the shear stress when compared with SAE 40. Figure 7 clearly shows that there was a large difference between case 1 and case 2. The case 1 values are close to that of the reference oil and the samples are in a close range, but in case 2, sample 2 alone is in close proximity to the reference oil [20,21].

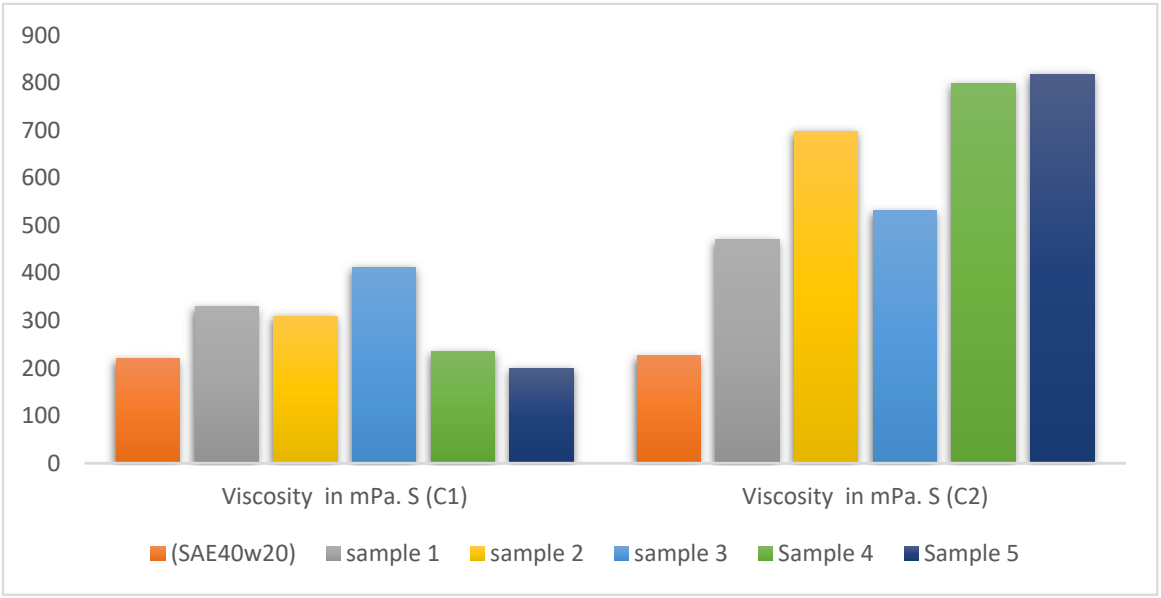


Figure 7. Viscosity values of the samples for case 1 and case 2.

The torque values observed for all six samples were in close proximity to that of the standard oil, SAE 40. Optimizing lubrication not only reduces mechanical strain but also contributes to energy savings, making it a key factor in the overall efficiency of a system. The samples values observed are crucial for reducing energy consumption, preventing overheating, and minimizing wear in mechanical systems. Figure 8 clearly shows that there

was a wide difference between case 1 and case 2. The values infer that in case 1 all the samples are in close to that of the reference oil and the samples are in a close range, while in case 2 the torque values are enhanced, since the viscosity and shear stess were also in the same range. But sample 2 in case 2 alone is satisfiable as it is almsot close to the reference oil [20,21].

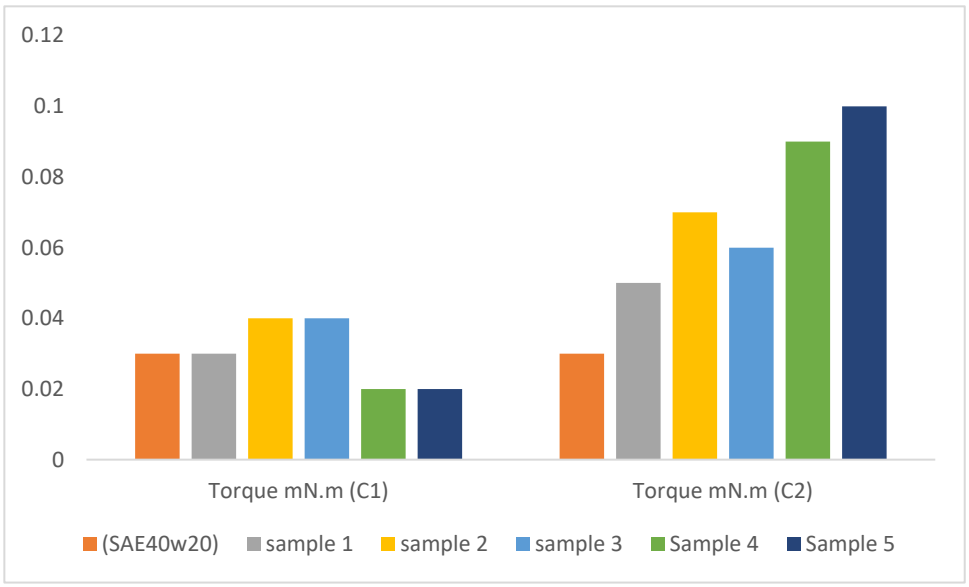


Figure 8. Torque values of the samples for case 1 and case 2.

C.M. Lai et al. showed that the inclusion of hybrid graphene in a base oil enriched the lubrication properties [1]. Zhou et al.'s and Singh et al.'s findings revealed that the inclusion of vegetable oil can enhance lubrication characteristics [15,22]. Milan Bukvić et al. proved that nanocomposite additives enriched lubrication properties [18], and Jyothi, P et al. showed the importance of using bio-lubricants as cutting fluids as an alternative to industrial oils [3]. W. Alghani et al.'s, Zhao Y et al.'s, and Gulshan Verma et al.'s findings proved that nano-zinc oxide and nanographene in engine oil enhanced its tribological performance [2,13,14]. Fu, et al. showed that the effects of neem oil and *Pongamia pinnata* oil in lubrication and recommend them as a cutting fluid oil [19]. Maurya et al. highlighted the importance of liquid-nanoparticle-based hybrid nano-lubricant additives due to their drastically improving the tribological properties of lubricants [11]. Sharma et al. found that the influence of nanoparticles in lubrication enhanced dynamic lubrication across a wide range of loads [24]. Nassef et al. highlighted the importance of zinc oxide and graphene in lubrication, which contributed to surface polishing, increased surface hardness, and reduced wear and friction [25].

The experimental results reflect that nano zinc oxide and nano graphene have a synergistic effect on the lubricant. The property of zinc oxide is to nurture the lubricant chamber, while the property of graphene is to reduce wear and the coefficient of friction and increase the load-carrying capacity. Although graphene induced in sample 6 has not given favorable results, it may be due to the utilization of nano compound in the range of 5–10 nm thickness. Therefore, it suggests that 0.3 nm thickness should be used and this should set the scope for future research to enhance tribological properties [26]. The findings of the present study suggest that a combination of *Pongamia pinnata* oil and nanomaterials, such as zinc oxide and graphene, can be an alternative lubricant with some saponification, its effects including the alteration of friction, such that nano biofluids can be used as an effective strategy for reducing friction.

5. Conclusions

The benefits of using nano infused bio-lubricants in a two-stroke engine were investigated experimentally. The main conclusions are as follows:

1. *Pongamia* oil, a bio-lubricant, along with nano compounds such as zinc oxide and graphene could be used as a natural alternative to SAE 20/30/40 crude lube oil, and it worked efficiently in a two-stroke engine.
2. The shear rate of the lubricant did not show much variation after it was subjected to several cycles. The shear rates of piston rings can be as high as 2×10^7 s^{-1}. Hence, the sample shear values in the range of 1 to 100 s^{-1} signify that it can be used as an alternative lubricant.
3. The shear stress values of the lubricant samples are in very close adherence with reference oil there by influencing the lubricant's ability to maintain a consistent film, which is vital for minimizing wear and tear on components.
4. The standard viscosity for machine oil ranges between 220 and 818 at 30 °C. The viscosity range of the samples considered here was high for machine oil, but the oil can be used as cylinder oil as its viscosity ranged from 500 to 800 mPa·s.
5. The percentages of the constituents of the nano-bio-lubricant can be modified to provide a significant influence on the viscosity, its potential use as a machine oil can be investigated in future studies.
6. Sample 6 was not considered for further analysis as the experiment showed that the high percentage of graphene chocked the machine and affected the scavenging process.

Thus, incorporating recycling as an important aspect of sustainability, this work examined the utilization of non-edible seeds that have previously been ignored. An effort was made to conduct an investigation on bio-oil derived from *Pongamia pinnata* seeds, enhanced by nano additives possessing specialized properties to emerge as an nano infused bio-lubricant alternative for commercial lubricants. The studies on its tribological performance suggest it holds promise as a sustainable and eco-friendly lubricant option.

Author Contributions: S.N.P. and V.S.—Conceptualization, Investigation, Methodology, Resources, Formal analysis, Writing—original draft and review and editing. All authors will be updated at each stage of manuscript processing, including submission, revision, and revision reminder, via emails from our system or the assigned Assistant Editor. All authors have read and agreed to the published version of the manuscript.

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References

1. Lai, C.M.; How, H.G.; Jason, Y.J.J.; Teoh, Y.H.; Yaqoob, H.; Zhang, S.; Sher, F. Tribological Characterisation of Graphene Hybrid Nano lubricants in Biofuel Engines. *Fuel* **2024**, *357*, 129654. [CrossRef]
2. Alghani, W.; Karim, M.S.A.; Bagheri, S.; Zaharinie, T.; Gulzar, M. Formulation, tribological performance, and characterization of base oil with ZnO, graphene, and ZnO/graphene nanoparticles additives. *Mater. Werkst.* **2020**, *51*, 1515–1532. [CrossRef]
3. Jyothi, P.N.; Susmitha, M.; Sharan, P. Performance evaluation of NEEM oil and *Pongamia* oil as cutting fluid in drilling operation of mild steel. *IOP Conf. Ser. Mater. Sci. Eng.* **2024**, *191*, 012026. [CrossRef]

4. Bhaumik, S.; Maggirwar, R.; Datta, S.; Pathak, S.D. Analyses of Anti-Wear and Extreme Pressure Properties of Castor Oil with Zinc Oxide Nano Friction Modifiers. *Appl. Surf. Sci.* **2018**, *449*, 277–286. [CrossRef]
5. Kolawole, S.K.; Odusote, J.K. Performance Evaluation of Vegetable Oil-based Cutting Fluids in Mild Steel Machining. *Chem. Mater. Res.* **2013**, *9*, 35–45.
6. Deepika. Nanotechnology implications for high performance lubricants. *SN Appl. Sci.* **2020**, *2*, 1128. [CrossRef]
7. Kumar, B.S.; Padmanabhan, G.; Krishna, P.V. Experimental Investigations of Vegetable Oil Based Cutting Fluids with Extreme Pressure Additive in Machining of AISI 1040 Steel. *Manuf. Sci. Technol.* **2015**, *3*, 030101. [CrossRef]
8. Chandrakar, J.K.; Suhane, A. The Prospects of Vegetable Based Oil as Metal Working Fluid in Manufacturing. Application—A Review. *Int. J. Eng. Res. Technol.* **2014**, *3*, 2197–2293.
9. Fairuz, M.A.; Nurul Adlina, M.J.; Azmi, A.I.; Hafiezal, M.R.M.; Leong, K.W. Investigation of Chip Formation and Tool Wear in Drilling Process Using Various Types of Vegetable-Oil Based Lubricants. *Appl. Mech. Mater.* **2015**, *799*, 247–250. [CrossRef]
10. Rajkumar, R.M.; Kiruthiga, K.; Induja, S.; Raghavan, P.S.; Shafee, M.; Pandiyan, P.; Kabeel, A.E. Studies on Tribological behaviour of ZnO Nanorods Suspended in SAE 20w 40 Engine Oil. *Solid State Commun.* **2021**, *328*, 114235. [CrossRef]
11. Maurya, U.; Vasu, V.; Kashinath, D. Ionic Liquid-Nanoparticle-Based Hybrid-Nano lubricant Additives for Potential Enhancement of Tribological Properties of Lubricants and Their Comparative Study with ZDDP. *Tribol. Lett.* **2022**, *70*, 11. [CrossRef]
12. Vardhaman, B.A.; Amarnath, M.; Ramkumar, J.; Mondal, K. Enhanced tribological performances of zinc oxide/MWCNTs hybrid nanomaterials as the effective lubricant additive in engine oil. *Mater. Chem. Phys.* **2020**, *253*, 123447. [CrossRef]
13. Zhao, Y.; Geng, Z.; Li, D.; Wang, L.; Lu, Z.; Zhang, G. An investigation on the tribological properties of graphene and ZDDP as additives in PAO4 oil. *Diam. Relat. Mater.* **2021**, *120*, 108635. [CrossRef]
14. Verma, G.; Harsha, A.P.; Goshwami, R.N.; Khatri, O.P. Khatri Performance Study of Graphene-Zinc Oxide Hybrid Nano lubricants under Various Test Conditions. *J. Mater. Eng. Perform.* **2024**, *34*, 2600–2616. [CrossRef]
15. Zhou, L.; Wang, J.; Luo, J. Environmental impact of bio-based lubricants: A systematic analysis. *Green Chem.* **2020**, *22*, 1425–1434.
16. *ASTM D445-19*; Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids. ASTM: West Conshohocken, PA, USA, 2019.
17. *ASTM D2983-21*; Standard Test Method for Low-Temperature Viscosity of Lubricants Using a Rotational Viscometer. ASTM: West Conshohocken, PA, USA, 2021.
18. Bukvić, M.; Gajević, S.; Skulić, A.; Savić, S.; Ašonja, A.; Stojanović, B. Tribological Application of Nanocomposite Additives in Industrial Oils. *Lubricants* **2024**, *12*, 6. [CrossRef]
19. Fu, J.; Summers, S.; Morgan, T.J.; Turn, S.Q.; Kusch, W. Fuel properties of pongamia (*Milletia pinnata*) seeds and pods grown in Hawaii. *ACS Omega* **2021**, *6*, 9222–9233. [CrossRef]
20. Loo, D.L.; Teoh, Y.H.; How, H.G.; Le, T.D.; Nguyen, H.T.; Rashid, T.; Sher, F. Effect of Nanoparticles Additives on Tribological Behaviour of Advanced Biofuels. *Fuel* **2023**, *334*, 126798. [CrossRef]
21. Zhang, S. Nanoparticle-enhanced lubrication: Current trends and future perspectives. *J. Tribol.* **2021**, *143*, 010201.
22. Singh, A.; Patel, R.; Gupta, V. Advances in bio-lubricant technologies: Integration of nanotechnology. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110647.
23. Agrawal, S.M.; Patil, N.G. Experimental study of non-edible vegetable oil as a cutting fluid in machining of M2 Steel using MQL. *Procedia Manuf.* **2018**, *20*, 207–212. [CrossRef]
24. Sharma, D.K.; Mahant, D.; Upadhyay, G. Application of nanotechnology in lubricants: A review. *Mater. Today Proc.* **2020**, *28*, 145–153.
25. Nassef, B.G.; Pape, F.; Poll, G. Enhancing the Performance of Rapeseed Oil Lubricant for Machinery Component Applications through Hybrid Blends of Nano additives. *Lubricants* **2023**, *11*, 479. [CrossRef]
26. Liu, Y.; Ge, X.; Li, J. Graphene lubrication. *Appl. Mater. Today* **2020**, *20*, 100662. [CrossRef]

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