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RESEARCH

Friction and Wear Performance of Rice Bran–Castor Oil Biolubricant Using Hybrid Microcrystalline Cellulose and Hexagonal Boron Nitride Additives

M.N. Thejaswini[a], U. Bhavana[a]*, D. Shrinivasa[b], R. Hemanth[c], A. Anand[c], P.B. Bharath[d], B. Suresha[a]

[a]Department of Mechanical Engineering, JSS Science and Technology University, Mysuru – 570006, India,
[b]Department of Mechanical Engineering, Vidyavardhaka College of Engineering, Mysore-570002, India,
[c]Department of Mechanical Engineering, The National Institute of Engineering, South Campus, Mysore-570008, India,
[d]Department of Mechanical Engineering, S J M Institute of Technology, Chitradurga-577502, India.

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* Corresponding author:

U Bhavana
E-mail: bhavana.umanath@jssstuniv.in

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A B S T R A C T

High-performance bio-based lubricants with improved tribological properties are becoming more popular as substitutes for conventional lubricants. Microcrystalline cellulose (MCC) at concentrations of 0.1–0.5 wt% and a hybrid MCC/hexagonal boron nitride (h-BN) additive were added to a binary bio-lubricant developed in this study utilizing an 85:15 ratio of Rice Bran Oil (RBO) and Castor Oil (CO). A four-ball tribometer was used to assess tribological performance in terms of wear scar diameter (WSD) and coefficient of friction (CoF). The findings demonstrated that the addition of 0.5 wt% MCC reduced the WSD from 1159 to 922 µm (20.45%) and the CoF from 0.121 to 0.063 (47.93%) when compared to the neat bio-lubricant. Also, in comparison to 0.5 wt% MCC, the hybrid formulation MB3, which contained 0.25 wt% MCC and 0.25 wt% h-BN, showed the lowest CoF (0.061) and WSD (892 µm), equating to additional reductions of 3.2% and 3.3%, respectively. When comparing the additive-containing formulations to the neat bio-lubricant, SEM studies of the worn surfaces revealed relatively smoother and less damaged wear scars. These findings demonstrate that, under the tested conditions, adding MCC and MCC/h-BN can improve the RBCO-based lubricant's evaluated wear performance and friction.

1. INTRODUCTION

The development of renewable, biodegradable lubricants as substitutes for petroleum-based products has accelerated due to the increased focus on sustainable manufacturing, carbon neutrality, and environmental protection. Due to their renewable source, high viscosity index, low volatility, good lubricity, and biodegradability, vegetable oils have garnered a lot of attention [1]. However, their comparatively low thermo-oxidative stability and insufficient wear resistance under harsh operating conditions restrict their broader industrial utilization. As a result, adding eco-friendly micro/nano-additives has become a successful tactic for enhancing tribological performance while upholding the tenets of green tribology [2].

Rice bran oil (RBO) is a promising biolubricant due to its natural antioxidants, balanced fatty acids, biodegradability, and ability to lubricate boundaries [1,3]. High polarity, viscosity, film-forming ability, and load-carrying capacity are provided by castor oil (CO), which is high in ricinoleic acid [2]. Although better wear resistance and tribofilm stability are still required in extreme circumstances, their combination can increase rheological and tribological performance [4].

Eco-friendly solid additives that enhance lubrication through load sharing, asperity filling, surface mending, and protective tribofilm development are the subject of increased research. When compared to sulphur, phosphorus-, and zinc-based additions, renewable bio-derived and inorganic additives provide efficient tribological performance with less environmental problems [3,5,6]. Thus, hybrid systems offer a viable path toward long-lasting, low friction biolubricants.

Microcrystalline cellulose (MCC) is a promising bio-derived lubricating ingredient due to its hydroxyl-rich structure, renewability, biodegradability, and crystallinity. These features can enhance wear resistance, viscosity, load-carrying capacity, and tribofilm stability by encouraging boundary-film development, asperity filling, load sharing, and decreased metal-to-metal contact [7–9].

To improve lubrication through complimentary mechanisms, cellulose-based additives have recently been mixed with multilayer solid lubricants. Because of its graphite-like layered structure, high thermal stability, oxidation resistance, thermal conductivity, and low interlayer shear strength, hexagonal boron nitride (h-BN) is a promising environmentally benign solid lubricant. Smooth interlayer sliding and little friction under boundary lubrication are made possible by weak van der Waals forces between neighboring basal planes. Additionally, h-BN creates compact protective tribofilms that lessen adhesive wear, increases load-carrying capacity, and dissipates frictional heat. With optimized h-BN concentrations in vegetable-oil lubricants, four-ball experiments have shown notable decreases in coefficient of friction (CoF) and wear scar diameter (WSD) [10,11].

By measuring the CoF and WSD, the ASTM D4172 four-ball wear test is commonly used to assess lubricant performance under extreme boundary lubrication conditions. It is frequently used to compare lubricant compositions for hydraulic, bearing, gear, and automotive applications [12,13]. Lubricant additives improve lubricant longevity and wear resistance by reducing direct asperity contact through mechanisms like asperity filling, surface mending, load sharing, rolling action, and protective tribofilm development [14].

The efficacy of h-BN and cellulose-based additives separately in sustainable lubricating systems has been shown in recent investigations. While cellulose-based additives can strengthen boundary films and improve lubricant viscosity and load-carrying performance through their hydroxyl-rich surfaces [7,15], h-BN's layered structure and low interlayer shear strength enable low-friction sliding and decreased wear [16–18]. When compared to individual additives, hybrid systems that combine cellulose and layered solid lubricants have demonstrated enhanced tribofilm stability, load-carrying capacity, and wear resistance [19]. The current study is motivated by the lack of comprehensive research on MCC/h-BN hybrid additives in rice bran oil–castor oil (RBCO) binary biolubricants under ASTM D4172 boundary conditions.

Despite extensive research, performance and environmental issues still limit the technical applications of vegetable oil-based lubricants. The majority of research focuses on specific vegetable oils that have been altered using metal or metal-oxide nanoparticles. Concerns about toxicity, environmental persistence, expense, and disposal persist despite increased tribological performance. There is currently little research on binary vegetable-oil blends with biodegradable solid additions.

For sustainable biolubricants, castor oil and rice bran oil provide complementing qualities. Castor oil gives excellent viscosity, polarity, and film-forming ability, whereas rice bran oil offers superior lubrication, oxidative stability, and biodegradability. Nevertheless, RBCO binary blends with eco-friendly MCC/h-BN hybrid additives under ASTM D4172 boundary lubrication conditions have not received much attention.

This work is novel in that it develops a stable RBCO binary bio lubricant with ultra-low concentrations (0.1–0.5 wt%) of MCC and hybrid MCC/h-BN additives. In contrast to earlier research that looked at h-BN or cellulose-based additives separately, this work thoroughly analyzes MCC-only and hybrid formulations to assess additive hybridization effects. The ASTM D4172 four-ball test is used to evaluate tribological performance using WSD and CoF, and wear-scar shape is related to potential lubrication mechanisms using optical microscopy and SEM. The goal of the project is to create high-performing, sustainable hybrid biolubricants for use in engineering.

2. MATERIALS AND METHODS

2.1 Materials

Refined rice bran oil (RBO) and commercial grade castor oil (CO) were chosen as base oils for bio-lubricant formulation due to the complementary tribological and rheological properties of these oils. Refined RBO was obtained from A.P. Refineries Pvt Ltd, Chennai, Tamilnadu, India and it was used as received. RBO is a good lubricant, highly resistant to oxidation, biodegradable and has natural antioxidant properties. Commercial grade CO was obtained from Hubli Organic oils & Chemicals Pvt Ltd., Hubballi, Karnataka, India and the same was used as received. CO has high viscosity due to high ricinoleic acid content, strong polarity and good film forming capacity, which makes it highly suitable for use in boundary lubrication applications.

To alter the tribological performance of the bio-lubricant, solid additives such as hexagonal boron nitride (h-BN) and microcrystalline cellulose (MCC) were employed. The average particle size of the h-BN powder (Product No. 790532, Sigma-Aldrich, USA) was less than 150 nm, and its purity was claimed to be 99% (trace-metals basis). The cellulosic additive was MCC (Product No. 310697, CAS No. 9004-34-6, Sigma-Aldrich, USA), which has a nominal particle size of about 20 μm. They were chosen for friction and wear modification because of the layered structure of h-BN and the particulate properties of MCC.

2.2 Preparation of rice bran–castor oil binary base stock

Preparation of Rice Bran–Castor Oil Binary Base Stock (RBCO) was conducted. RBO and CO were dried for 60 min at 105 °C under continuous stirring, prior to blending, in order to remove moisture that can have negative effects on lubricant stability, viscosity and additive dispersion. The oils were then cooled down to room temperature.

A binary base stock comprising rice bran oil (RBO) and castor oil (CO) at an 85:15 ratio (RBCO 85:15) was selected for the present investigation. The needed amounts of RBO and CO were blended together in the same mechanical stirrer at 1000 rpm for 30 min and then were subjected to high-speed homogenization for 15 min to form a homogeneous and stable base stock for lubricant production. The prepared RBCO blend was kept at room temperature in airtight amber glass bottles until required.

2.3 Preparation of the lubricant formulation and fillers dispersion

The concentrations of additives MCC and hybrid MCC/h-BN in the base stock used were as shown in Table 1. The additives MCC and hybrid MCC/h-BN were added to the base stock RBCO (85:15) at the following concentrations as shown in Table 1. The amount of each additive needed was carefully weighed (with an analytical balance to within ±0.1 mg) and was added to the base oil, which was then subjected to the preliminary dispersion for 30 min under magnetic stirring at 800 rpm. The produced lubricant mixtures were subjected to 30 min of probe-ultrasonication at 20 kHz and 500 W using a Sonics Vibra-Cell VCX 500 fitted with a 13 mm titanium probe. In order to limit heat accumulation and encourage homogeneous particle dispersion, sonication was carried out in a pulse mode of 3 s ON/3 s OFF. To reduce thermal deterioration and oxidation of the vegetable-oil-based lubricant, the samples were stored in an ice-water bath, and their temperature was monitored during the process and kept below 40 °C. The creation of uniform lubricant compositions was made easier by the combination of magnetic stirring and ultrasonication. A 24-h visual sedimentation test was used to assess the produced lubricants' dispersion stability. During the 24-h test period, no discernible sedimentation or phase separation was seen, suggesting that the produced formulations had adequate short-term dispersion stability. A four-ball tribotester was then used to evaluate the stable lubricant samples tribologically.

Table 1. Formulation details of RBCO (85:15) base oil and additive-modified bio-lubricant formulations.

Lubricant formulation	Code	MCC (wt%)	h-BN (wt%)
RBCO (Rice Bran Oil: Castor Oil = 85:15)	RBCO	–	–
RBCO + 0.1 wt% MCC	M1	0.10	–
RBCO + 0.3 wt% MCC	M2	0.30	–
RBCO + 0.5 wt% MCC	M3	0.50	–
RBCO + 0.05 wt% MCC + 0.05 wt% h-BN	MB1	0.05	0.05
RBCO + 0.15 wt% MCC + 0.15 wt% h-BN	MB2	0.15	0.15
RBCO + 0.25 wt% MCC + 0.25 wt% h-BN	MB3	0.25	0.25

For the current investigation, the RBCO base lubricant was prepared using an 85:15 ratio of rice bran oil (RBO) to castor oil (CO). As indicated in Table 1, MCC-only and hybrid MCC/h-BN formulations were made at total additive amounts of 0.1, 0.3, and 0.5 weight percent. While the hybrid formulations had equal amounts of MCC and h-BN at total additive concentrations of 0.1, 0.3, and 0.5 wt% (MB1–MB3), the corresponding MCC concentrations for the MCC-only formulations were 0.1, 0.3, and 0.5 wt% (M1–M3). Therefore, at the same total additive concentration, MB3 (0.25 wt% MCC + 0.25 wt% h-BN) offers a direct comparison with M3 (0.5 wt% MCC). For assessing the wear and friction properties of the modified bio-lubricants, the chosen concentration range serves as a low-additive regime.

2.4 Four-ball wear test procedure

Using a four-ball tribometer in accordance with ASTM D4172-21, the anti-wear and friction-reducing properties of the produced binary Rice Bran–Castor Oil (RBCO) lubricants were evaluated [20]. For every lubricant formulation, two separate experiments (n = 2) were carried out under the same circumstances. Three stationary, 12.7 mm diameter, 64–66 HRC, mirror-polished AISI 52100 chromium steel balls that were completely submerged in the lubricant were used in each test, along with a fourth AISI 52100 steel ball of the same size and hardness that was fixed to the revolving spindle. Every ball was utilized exactly as given; no surface alteration or further treatment was applied to any of the balls. Before testing, the balls and test cup were cleaned with acetone and dried, and new sets of balls were utilized for each independent test.

To prevent impact loading, the recommended load and spindle speed were delivered gradually while the lubricant temperature was kept at 75 ± 2 °C. Each test lasted 60 min, and the operating conditions are listed in Table 2. The balls were meticulously cleaned after testing so as not to damage the wear scars. Using an optical microscope, the WSD of each stationary ball was measured in two mutually perpendicular directions (X and Y). The average of these measurements was used to determine the WSD for that ball. The WSD of a single four-ball test was represented by the mean WSD of the three stationary balls. The arithmetic mean of the two separate tests (n = 2) was used to determine the final WSD provided for each lubricant formulation; the experimental variation was represented by the standard deviation between these independent tests. As a result, the three stationary balls inside a single test were considered measures from the same test rather than independent experimental duplicates.

Table 2. Test conditions for the ASTM D4172 std.

Test condition	Temp. (°C)	Speed (rpm)	Load (Kgf)	Duration (min)
Values	75 ± 2	1200 ± 10	40 ± 0.1	60 ± 1

The coefficient of friction (CoF) was calculated using the frictional torque that was recorded continuously by the tribometer data-acquisition system in accordance with IP 239 [21]. The results of the CoF were obtained by applying Equation (1):

$$\mathrm{CoF} = \frac{0.22248\,\mathrm{T}}{\mathrm{W}} \tag{1}$$

T is the frictional torque (kgf·mm) and W is the applied load (kgf). The reported CoF for each formulation is the average CoF during the entire test period (60 mins) and not based on a steady-state period selected. Averaging the two independent tests' CoF values gave the final CoF value, and the standard deviation of the two tests' values was used as the error bar.

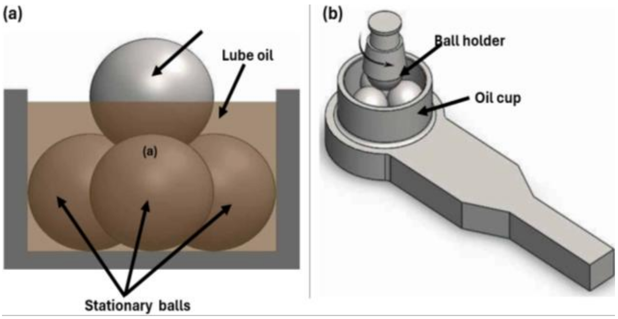

Fig. 1. Four-ball tribometer setup: (a) schematic and (b) ball cup assembly.

The picture of the experimental set-up is depicted in Figure 1a, b. Mean CoF and WSD from two separate four-ball tests were used to evaluate tribological performance, with standard deviations signifying experimental variation.

3. RESULTS AND DISCUSSION

3.1 Effect of MCC on wear scar diameter and coefficient of friction

Figure 2 and Table 3 depict the effect of MCC concentration on the WSD and CoF of the RBCO (85:15) biolubricant formulation. The RBCO (85:15) blend was selected as the base lubricant formulation for the present investigation. It contains 85% rice bran oil (RBO) and 15% castor oil (CO).

Table 3. Mean CoF and WSD of RBCO-based lubricant formulations. Error bars indicate standard deviation (n = 2).

Lubricant sample	CoF	WSD (μm)
RBCO	0.121 ± 0.001	1159 ± 2
M1	0.072 ± 0.002	1040 ± 1
M2	0.068 ± 0.002	950 ± 2
M3	0.063 ± 0.001	922 ± 2
MB1	0.070 ± 0.001	1012± 2
MB2	0.065 ± 0.002	938± 2
MB3	0.061 ± 0.001	892± 1

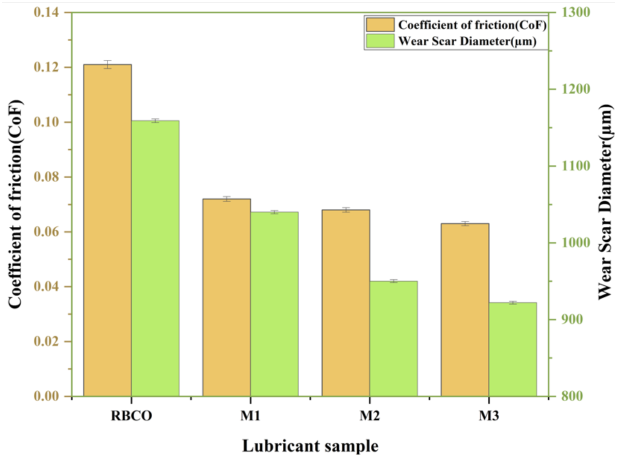

Fig. 2. Effect of MCC content on CoF and WSD of RBCO bio-lubricant. Error bars indicate standard deviation (n = 2).

Two separate four-ball tests were conducted on each formulation, under the same conditions as specified in ASTM D4172 (n = 2). The two tests are the reported WSD and CoF values and are taken as arithmetic means. For each test, the three WSD values of the stationary lower balls were averaged but these three were not considered independent repetitions. The standard deviation of the independent tests is shown as error bars.

The WSD decreased progressively with MCC addition, reaching 1040, 950 and 922 μm at 0.1, 0.3, and 0.5 wt% MCC, respectively. This decrease could be explained by MCC particles filling up surface micro-defects and creating a protective layer [3,22,23]. Similarly, the CoF decreased from 0.121 for neat RBCO to 0.072, 0.068 and 0.063 for M1, M2 and M3, corresponding to reductions of 40.50%, 43.80% and 47.93%, respectively. The lower friction relates to the formation of a low shear protective film, as well as the surface filling effect of the MCC particles [3,22,24]. The overall addition of MCC to RBCO gave improvement in anti-wear and friction reducing performance with M3 showing the lowest and minimum WSD and CoF respectively.

The CoF of the formulations used was compared against the MCC modified formulations and the results are presented in Figure 2. Compared with neat RBCO (0.121), the CoF decreased to 0.072, 0.068 and 0.063 for M1, M2 and M3, representing reductions of 40.50%, 43.80% and 47.93%, respectively.

The observed reduction in CoF upon the addition of MCC suggests that it may enhance the bio-based lubricant's frictional performance. By being stuck at the contact interface and partially filling surface flaws during sliding, MCC particles may lessen direct asperity interaction and lower frictional resistance. Improved tribological performance is compatible with contemporaneous decreases in CoF and WSD; however, SEM morphology alone cannot validate the underlying causes. Specifically, supplementary surface analyzes like EDS or XPS would be necessary to determine the formation, continuity, and chemical composition of any surface coating. As a result, any film-related process is merely taken into consideration as a potential explanation for the wear and friction patterns that have been observed.

Among the formulations under evaluation, M3, which contained 0.5 wt% MCC, performed the best, reducing CoF by over 48% as compared to the comparable neat RBCO formulation. Particle availability and dispersion at the contact surface may be responsible for this improvement. Previous reports on cellulose-based additions in vegetable oils [3,22] are in line with the observed trend. Because they were not directly studied, mechanisms such improved heat dissipation, tribofilm reinforcement, load bearing, surface mending, and viscosity preservation are thought to be potential rather than experimentally confirmed outcomes.

3.2 Effect of hybrid MCC/h-BN additives on wear scar diameter and coefficient of friction

The wear performance of the RBCO with the hybrid MCC/h-BN additive is shown in Figure 3 and Table 3. For each test, the three WSD values of the stationary lower balls were averaged but these three were not considered independent repetitions. The standard deviation of the independent tests is shown as error bars. Compared with neat RBCO (1159 μm), the WSD decreased to 1012, 938 and 892 μm for MB1, MB2 and MB3, corresponding to 12.68%, 19.07% and 23.04% reductions, respectively.

The hybrid formulation MB3 had the lowest WSD of all the formulations analyzed, and it was lower than that of the MCC-only formulations. Specifically, a 23.04% reduction was obtained for MB3, which is more than the 20.45% reduction for M3. The lower mean WSD observed for MB3 suggests improved performance under the tested conditions; however, the difference compared with M3 was not demonstrated to be statistically significant. In particular, MB3 showed a reduction in WSD of 23.04% as opposed to 20.45% for M3, suggesting that the hybrid formulation reduced worn scar diameter more under the examined conditions. The enhanced tribological performance seen in the hybrid formulation may be attributed to the lamellar crystal structure of h-BN, which is linked to its possible solid-lubricating activity. Additionally, h-BN may make it easier to accommodate surface asperities when sliding. However, the current SEM observations are insufficient to validate mechanisms including heat dissipation, tribofilm reinforcing, fracture inhibition, and boundary film stabilization. Previous tribological studies have found similar anti-wear behavior of h-BN-containing vegetable-oil lubricants [10,13], and decreases in WSD have also been linked to potential surface-film generation in vegetable-oil lubricants supplemented with nanoparticles [25]. Therefore, in the current investigation, these mechanisms are regarded as reasonable interpretations rather than events that have been experimentally proved.

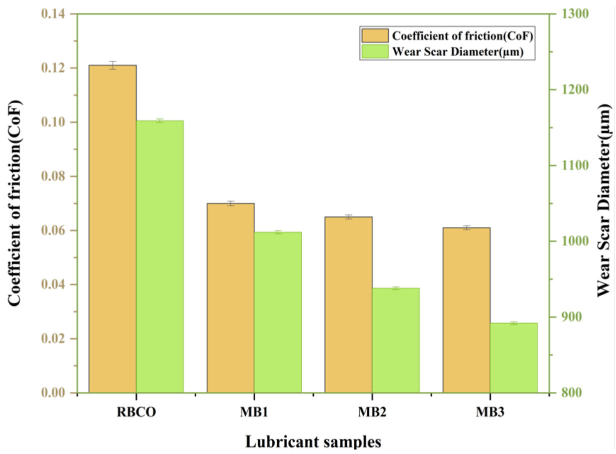

Fig. 3. Effect of hybrid MCC/h-BN content on CoF and WSD of RBCO bio-lubricant. Error bars indicate standard deviation (n = 2).

In Figure 3, the friction behaviour of the hybrid lubricants is presented. The CoF decreased from 0.121 for neat RBCO to 0.070, 0.065 and 0.061 for MB1, MB2 and MB3, corresponding to friction reductions of 42.15%, 46.28% and 49.59%, respectively.

The friction reduction of the hybrid additive system was best over the MCC-only formulations, with the lowest CoF for the MB3 system being 0.061. This enhanced performance is believed to be due to the creation of a hybrid protective layer composed of a mixture of MCC to increase the retention of particles and h-BN to provide an ultra-low shear sliding interface due to its graphite-like layered structure [10,16]. By lowering metal-to-metal contact and the production of abrasive wear debris, these additives enhance lubrication performance. Among the formulations examined, the hybrid formulation with lamellar h-BN and renewable cellulose particles showed the lowest CoF and WSD, with reductions of 23.04% and 49.59%, respectively, in comparison to neat RBCO. These findings show that the hybrid formulation performed better tribologically under the examined circumstances. The results agree with the latest reports where it has been shown that the cellulose based additives along with layered solid lubricants could improve the tribological performance of biolubricant based on vegetable oil by achieving a thin protective layer, load capacity and heat dissipation.

3.3 Wear Scar analysis and wear reduction mechanisms

Figures 4 and 5 show optical micrographs of the wear scars of the four-ball wear test. Figures 2 and 3 show the wear scar diameter (WSD) and coefficient of friction (CoF) values obtained from the four-ball wear test. The wear scar morphology results also support the quantitative tribological findings where it is evident that adding MCC, and hybrid MCC/h-BN additives to the RBCO biolubricant, is beneficial to the anti-wear properties of the biolubricant.

With the largest wear scar diameter (1159 μm) and noticeable abrasive wear, the neat RBCO showed more surface damage and significant asperity interaction. With the addition of MCC, the wear scar was gradually reduced to 1040, 950, and 922 μm for M1, M2 and M3, respectively, which represents 10.27%, 18.03%, and 20.45% reduction, respectively. Simultaneously, the CoF decreased from 0.121 for RBCO to 0.072, 0.068 and 0.063, representing friction reductions of 40.50%, 43.80% and 47.93%, respectively.

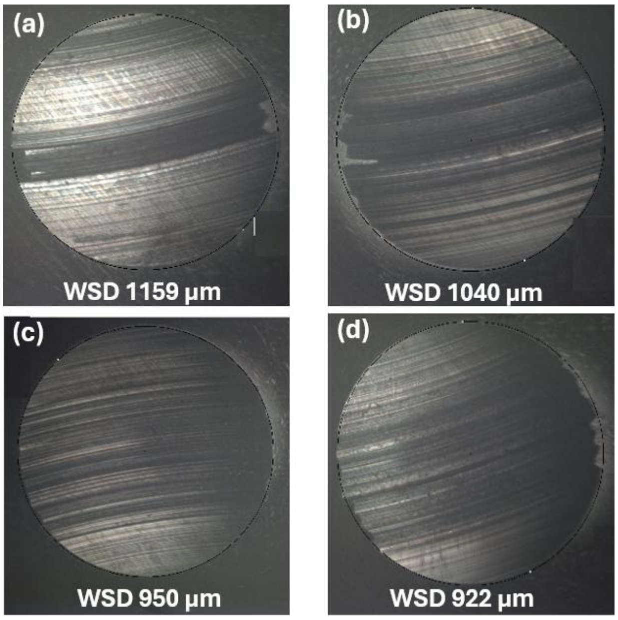

Fig. 4. Optical micrographs of wear scar diameter: (a) RBCO, (b) 0.1 wt%, (c) 0.3 wt%, (d) 0.5 wt% MCC modified RBCO; optical magnification: 200×.

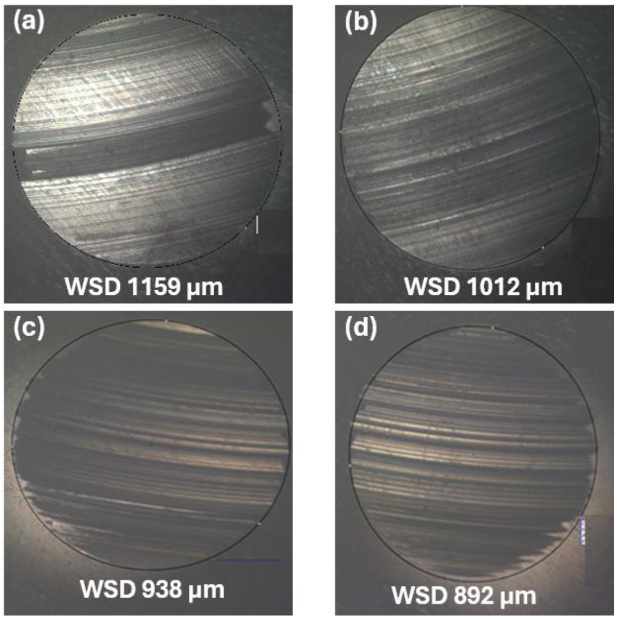

Fig. 5. Optical micrographs wear scar diameters: (a) RBCO, (b) 0.1 wt%, (c) 0.3 wt%, (d) 0.5 wt% hybrid (MCC +h-BN) additives modified RBCO; optical magnification: 200×.

The good correlation of the reduction in WSD and CoF implies that the wear improvement is due to the same lubrication mechanism. In order to reduce direct metal-to-metal contact and enhance wear performance, the hydroxyl functional groups of MCC could promote interactions with the steel surface and polar components of the vegetable oil. Additionally, the surface mending effect of the MCC particles enhances the load carrying capacity and reduces adhesive and abrasive wear by filling adhesive and micro-defects in the surface grooves. The reduction of friction and wear through similar thin film-assisted wear mechanisms for lubricant additives based on cellulose has been reported by Opia et al. [23] and Chen et al. [24] and the importance of the role of polar adsorption and boundary film formation in reducing friction and wear is highlighted in reviews of vegetable oil biolubricants.

Fig. 5 shows that the hybrid formulations of MCC/h-BN performed better than neat RBCO on the tribological performance. The WSD decreased from 1159 μm for neat RBCO to 1012, 938, and 892 μm for MB1, MB2, and MB3, corresponding to reductions of 12.68%, 19.07%, and 23.04%, respectively. The corresponding CoF values decreased to 0.070, 0.065, and 0.061, representing reductions of 42.15%, 46.28%, and 49.59%. MB3 had further decreases in both CoF (0.063 to 0.061) and WSD (922 to 892 μm) as compared to M3, which contained only MCC. These discrepancies were not found to be statistically significant but suggest an overall superior tribological behavior of MB3 in the conditions studied.

The lamellar structure of h-BN may enable low-shear sliding of MB3, in view of the weak interlayer interactions, while the polar functional groups of MCC may lead to interactions at the steel–lubricant interface. The simultaneous decrease of both CoF and WSD is in line with the better friction and wear properties but cannot be conclusively confirmed based on the observed SEM images alone. Anti-wear and friction-reducing effects of h-BN in vegetable-oil lubricants have been also reported in literature [10,16] and mechanisms such as rolling, surface filling and interfacial mechanisms have been proposed for the enhanced tribological properties of these lubricants containing nanoparticles previously [25,26]. These mechanisms are therefore taken as tentative interpretations, but not as phenomena that have been verified experimentally.

The overall results from the wear scar morphology and tribological results clearly show a correlation between lowering the WSD and CoF with increasing additive concentration. The success of the hybrid MCC/ h-BN formulations over the RBCO biolubricant demonstrates that the effect of the surface repair by the cellulose and the low-shear lamellar lubrication by the h-BN is very effective in reducing asperity interaction, increasing the stability of the boundary film and significantly improving the tribological performance of the RBCO biolubricant.

3.4 Wear mechanism analysis using scanning electron microscope

The SEM analysis of wear scar surfaces showed that the wear modes of the RBCO with MCC and hybrid MCC+h-BN additives are significantly different. The neat RBCO gave a relatively rough wear track with well-defined parallel grooves, heavy ploughing, stuck wear debris and some damage of the wear surfaces (Fig. 6). The features suggest that abrasive wear dominated the contact with the presence of adhesive interactions from direct contact between the asperities of the steels. Repeated metal-to-metal contact due to the lack of a stable lubricating film led to the highest friction (CoF = 0.121) and the greatest wear scar diameter (1159 μm).

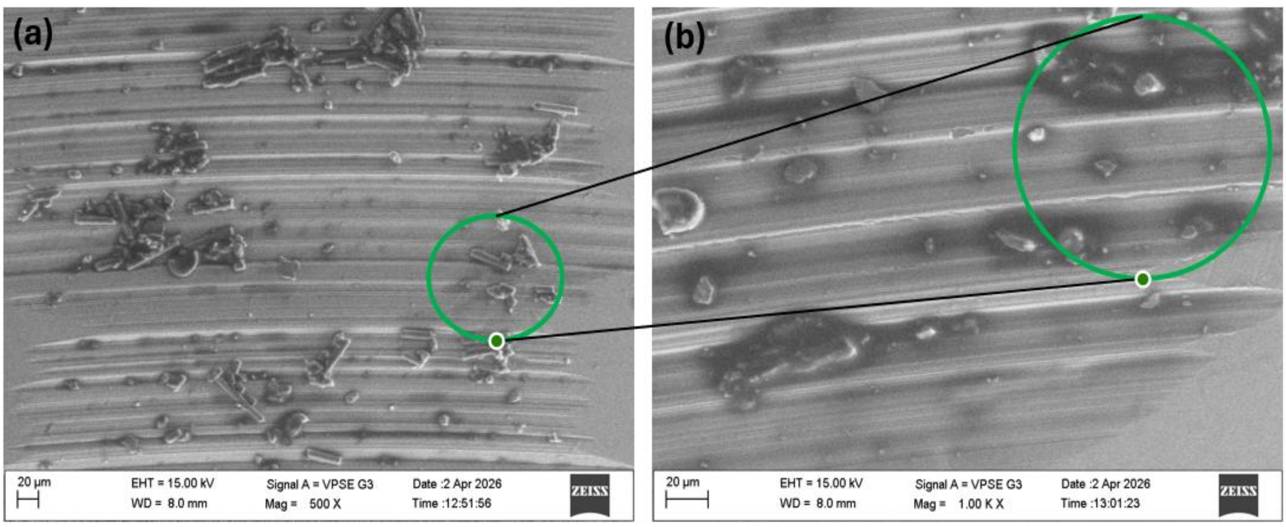

Fig. 6. SEM micrographs of the wear scar region of neat RBCO: (a) magnification 500× and (b) magnification 1 k×.

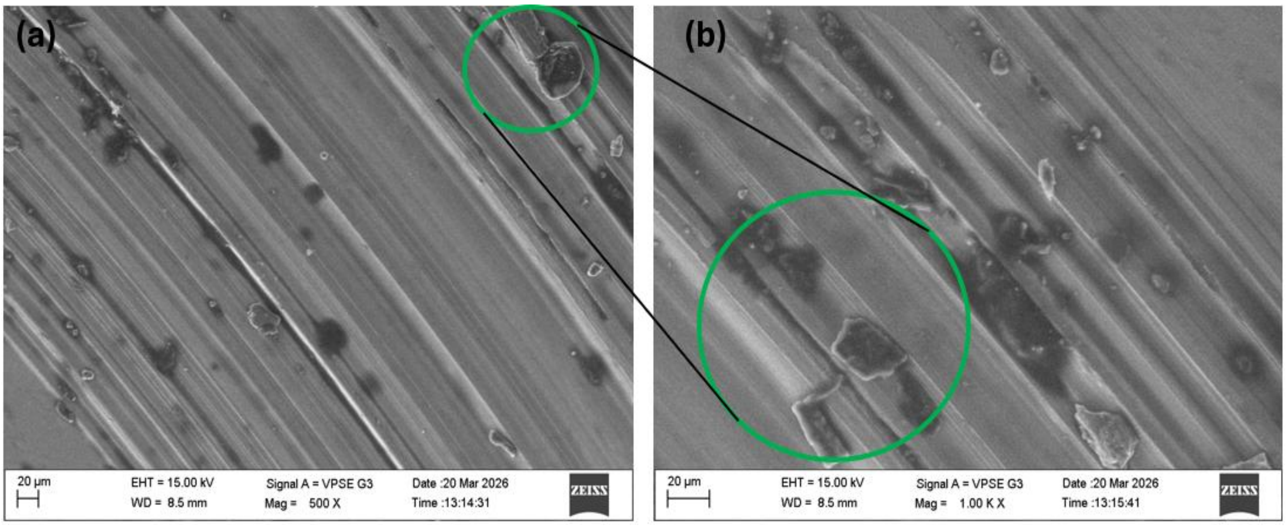

Fig. 7. SEM micrographs of the wear-scar region of MCC-modified RBCO lubricant (M3: 0.5 wt.% MCC): (a) 500× magnification and (b) 1 k× magnification.

The tribological response was enhanced by the incorporation of MCC. The SEM images (Fig. 7) show that the wear tracks are smoother and have shallower grooves, less plastically deformed areas and less loose wear debris than in neat RBCO. The less severe of the ploughing indicated that MCC particles acted to create a protective boundary layer, which was able to isolate the contacting asperities and spread the applied load. This protective action caused the wear mechanism to change from severe abrasive-adhesive wear to mild abrasive wear. The coefficient of friction, on the other hand, continuously lowered from RBCO to M3, a decrease of 47.93%, from 0.121 to 0.063, and the wear scar diameter reduced from 1159 to 922 µm (20.45%). These enhancements imply that a higher MCC concentration lowers surface degradation and frictional resistance brought on by direct asperity contact.

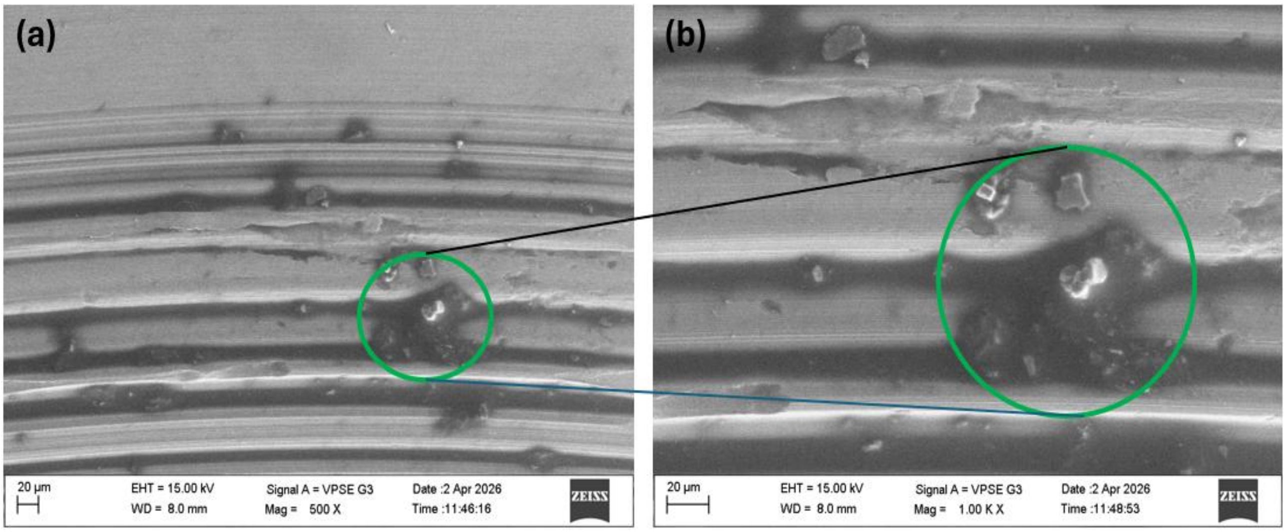

Fig. 8. SEM micrographs of the wear-scar region of hybrid MCC/h-BN-modified RBCO lubricant (MB3: 0.25 wt.% MCC + 0.25 wt.% h-BN): (a) 500× magnification and (b) 1 k× magnification.

The overall surface damage of the investigated formulations was lowest for MCC and h-BN hybrid additives, as seen from the wear scar morphology in Figure 8. The general parallel grooves seen in the worn surface are more pronounced and uniform, with localized removal of material and features that appear to be material adhered to the surface, or debris, which suggest that some abrasive and mild adhesive wear processes were still occurring during sliding. The wear track morphology was well organized, however, compared to the other formulations there was a reduction in severe surface damage. This enhanced tribological performance of the hybrid additive could be related to the combined lubrication effect of MCC and h-BN. The lamellar structure of h-BN can allow it to shear along the basal planes and decrease the shear resistance at the interfaces, and the MCC particles could help to form a protective boundary layer in the contact area. These two types of additives can affect the direct interaction of asperity and delay material removal during sliding, which can result in a combined effect.

The lowest coefficient of friction (0.061) and smallest wear scar diameter (892 μm) was recorded for MB3, which equates to a 49.59% and a 23.04% reduction from neat RBCO, respectively. The hybrid additive also decreased the CoF by ~3.2% (0.063 to 0.061) and the WSD by ~3.3% (922 to 892 μm) in comparison with the optimum MCC formulation (M3), showing that h-BN offers extra protection against friction and wear over MCC alone. The addition of MCC, especially when combined with h-BN, was linked to decreased surface damage and enhanced friction and wear performance, according to the SEM observations, which are generally in agreement with the observed tribological parameters. Although the observed surface characteristics are compatible with a less severe wear response, SEM measurements alone cannot validate the precise wear mechanisms and any related surface-film generation.

3.5 Limitations of the present work

There are various limitations to the current investigation. Robust inferential statistical analysis is limited because each formulation was subjected to only two independent four-ball tests. Since an h-BN-only formulation was not examined, its contribution to the hybrid system could not be independently evaluated. Important physicochemical characteristics, such as water content, acid value, density, viscosity, and viscosity index, were not measured experimentally. The chemical composition of the suggested tribofilm was not confirmed using methods like EDS, XPS, or Raman spectroscopy, even though SEM offered morphological observations of the worn surfaces. Furthermore, associated findings are outside the purview of this work because environmental performance, biodegradability, storage stability, and industrial applicability were not assessed experimentally.

4. CONCLUSIONS

The current study used the four-ball wear test under the designated experimental conditions to assess the tribological performance of microcrystalline cellulose (MCC) and hybrid MCC/h-BN additives added to the sustainable binary bio-lubricant, RBCO (85:15). The following conclusions can be made in light of the experimental results obtained under the examined test conditions and additive concentrations:

- The tribological performance of RBCO was greatly enhanced by MCC; in comparison to neat RBCO, 0.5 wt% MCC reduced CoF and WSD by 47.93% and 20.45%, respectively. With a CoF of 0.061 and a WSD of 892 μm, the hybrid 0.25 wt% MCC/0.25 wt% h-BN (MB3) performed the best. In comparison to the MCC-only formulation (M3), MB3 provided additional mean reductions of about 3.2% in CoF and 3.3% in WSD. The individual and interactive contributions of MCC and h-BN cannot be measured independently in the absence of an h-BN-only control, and these further reductions were not examined for statistical significance.
- In comparison to the neat RBCO formulation, the addition of MCC and hybrid MCC/h-BN additives decreased the wear scar diameter (WSD) and coefficient of friction (CoF) of RBCO under the designated four-ball test circumstances.
- The low-shear lamellar structure of h-BN, which can lessen direct asperity contact during sliding, and the complementary lubricating actions of MCC may have contributed to the enhanced tribological performance of the hybrid MCC/h-BN formulation.
- The observed wear behavior across the designed lubricant series may be caused by adhesive, abrasive, and/or delamination mechanisms.
- Under the examined additive concentrations and particular four-ball test conditions, the hybrid MCC/h-BN-modified RBCO showed enhanced anti-friction and anti-wear performance overall. The results do not prove biodegradability, environmental advantages, or industrial applicability because they are restricted to the measured CoF and WSD.
- Additional research should assess the performance under application-relevant operating conditions, oxidation and thermal stability, rheological characteristics, biodegradability, and corrosion behavior.

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