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Research Article

Optimization of tribological performance of extracted waste banana peel oil reinforced with multi-layer graphene nanoparticles using response surface methodology

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Abstract
The incorporation of nanoparticles into bio-waste materials has recently gained attention in the field of tribology. Banana peel (BP), a promising bio-waste, shows potential for producing lubricant oil. While the performance of pure banana peel oil (BPO) has been promising, further enhancement is necessary to ensure stable performance. To address this, graphene nanoparticles (GNPs) are introduced as they are known to improve material characteristics and enhance oil performance. This study evaluates the coefficient of friction (COF) and wear scar diameter (WSD). The BPO-GNP mixture is optimized using response surface methodology (RSM) in Minitab software, employing a Box-Behnken design (BBD). The effects of factors such as homogenization time, volume percentage, and graphene type are examined in this study. The COF and WSD results are analyzed using Pareto charts and surface plots. The analysis reveals that the effects of each factor on COF are relatively minor. In contrast, homogenization time and graphene type have significant effects on WSD, with a p-value of 0.04. The results suggest that a homogenization time of 30 minutes and the use of research-grade graphene yield the optimal combination for minimizing WSD.

Keywords
Banana peel oil, Graphene nanoparticles, Bio-waste lubricant, Tribological performance, Wear scar diameter, Response surface methodology.

1.Introduction
The global emphasis on sustainability and green technology has transformed lubricant development, steering it away from petroleum-based oils toward renewable, bio-based resources [1]. Conventional lubricants, typically blended with additives such as zinc dialkyl dithiophosphate (ZDDP), have been criticised for their environmental toxicity and harmful effects on human health [2].

In response, industries and researchers are exploring biodegradable lubricants derived from agricultural waste and natural oils to reduce carbon footprints [3]. Malaysia's commitment to a 45% reduction in carbon emissions by 2030, along with the frameworks under the Green Technology Master Plan (2017–2030) and the National Policy on Industry 4.0, emphasises the integration of sustainable materials and energy-efficient technologies [4, 5]. Among potential bio-based resources, banana peel oil (BPO) has gained attention due to its rich bioactive composition and tribological potential, offering both environmental

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and economic advantages through waste valorization [6, 7].

Despite its eco-friendly properties, BPO still exhibits limited tribological performance under high-load, high-temperature conditions [8]. Studies have shown that while it demonstrates a relatively low coefficient of friction (COF), it does not reach a superlubricity range required for industrial applications [9]. Poor oxidative stability and inadequate film-forming ability further constrain its performance [10]. Additionally, achieving uniform dispersion of performance-enhancing additives, such as nanoparticles, within bio-based oils remains a significant challenge due to agglomeration issues [11]. To address these limitations, this study explores the incorporation of graphene nanoparticles (GNP) into BPO to enhance its friction-reducing and wear-resistant capabilities.

This study aims to investigate the tribological performance of BPO infused with GNP under varying operating parameters. The specific objectives are to evaluate the effects of graphene concentration on friction and wear, determine the optimal formulation for improved lubrication, and demonstrate the potential of graphene-enhanced BPO as a sustainable alternative to conventional lubricants.

This study contributes to the development of a sustainable lubricant by formulating BPO reinforced with GNP. The tribological behaviour, characterized by the COF and wear scar diameter (WSD), was systematically evaluated using the four-ball test under varying graphene loadings. The optimal nanoparticle concentration that minimized friction and wear was identified, demonstrating performance approaching superlubricity. Furthermore, the study elucidates the synergistic interaction between graphene's layered structure and BPO's bioactive compounds, offering insights into the design of high-performance, eco-friendly lubricants.

The remainder of this paper is organized as follows: Section 2 discusses the related work; Section 3 illustrates the methodology; Section 4 presents the tribological results and analysis along with surface characterization; and Section 5 concludes the study.

2.Literature review

The emergence of nanotechnology has led to transformative changes in lubricant formulation, especially in tribological applications where reducing friction and wear is critical. Among these advancements, the incorporation of nanoparticles into base oils has become an area of extensive research. Paul et al. (2019) outlined the growing application of nanolubricants in mechanical, automotive, and microelectromechanical systems (MEMS), where their ability to improve load-bearing capacity and reduce surface degradation is especially valuable [3]. These nanolubricants often include metal oxides, carbon allotropes, and hybrid particles, offering multifunctional tribological benefits. In addition, Zhang et al. (2021) demonstrated that titanium oxide (TiO2)-based nano-lubricants exhibited improved thermal stability and reduced WSD in high-speed steel contact compared with base oil alone, underscoring the potential of oxide nanoparticles in high-load regimes [12]. Ibrahim and Sulaiman (2024), found that magnesium oxide (MgO) demonstrated a significant reduction in forward and backward forces, revealing the least amount of fracture zones on the workpiece [13].

Uflyand et al. (2019) further emphasized that nanoparticles not only enhance tribological performance but are also seen as eco-friendly alternatives to traditional additives due to their low toxicity and biodegradability [14]. Their high surface area-to-volume ratio contributes to better film formation and the repair of worn surfaces during sliding contact [8]. However, dispersion remains a persistent challenge, particularly when suspending nanomaterials such as graphene in oil-based mediums. Ashraf et al. (2022) reported that silica nanoparticles required surfactant functionalization to prevent rapid agglomeration in hydrocarbon oils, which can otherwise undermine their tribological benefits [15]. Although numerous studies have investigated the influence of surfactant addition on enhancing dispersion stability, further research is still required to improve the long-term stability of both mono- and hybrid nanofluids and to elucidate the fundamental mechanisms governing their stabilization behaviour [16, 17].

Graphene-based nanolubricants have attracted considerable attention for their unique physicochemical properties, including high mechanical strength, excellent thermal conductivity, and a two-dimensional layered structure that facilitates easy shearing. Despite this, Liu et al. (2020) noted that superlubricity—a regime characterised by a COF below 0.01—has been achieved predominantly in aqueous systems rather than in oil-based systems [18]. The high viscosity of oil impedes the effective dispersion of graphene flakes, causing agglomeration and sedimentation that hinder consistent lubrication performance. Similar challenges were noted by Jafari et al. (2024), who found that unmodified graphene nanosheets tended to re-stack in mineral oil, leading to inconsistent friction reduction unless sterically stabilized [19].

To overcome these issues, researchers have explored hybrid nanomaterial systems. Beheshti et al. (2020) demonstrated that combining high-quality graphene with bio-oils resulted in a synergistic enhancement of lubrication behavior, though maintaining stable dispersion remained a challenge [20]. Hybridization of nanoparticles, such as combining carbon-based and ceramic materials, can exploit complementary effects, leading to improved wear resistance and thermal stability. For example, Abdullah et al. (2018) reported that a hybrid nanolubricant composed of graphite and zirconia (ZrO_2) nanoparticles dispersed in waste cooking oil achieved a COF of 0.05 under four-ball tribotesting. This value is competitive with commercial lubricants, suggesting that such formulations can bridge the gap between sustainability and performance [21].

Nassef et al. (2023) also showed that hybrid Zinc Oxide–graphene additives in rapeseed oil significantly reduced friction up to 20% [22]. Moreover, the broader implications of improved lubrication are significant. Holmberg and Erdemir (2017) estimated that friction-related energy losses account for approximately 23% of global energy consumption, with wear-induced mechanical failure a leading cause of machinery downtime [23]. Therefore, improving lubricant efficiency has both economic and environmental value.

From a methodological standpoint, statistical optimization techniques such as response surface methodology (RSM) have proven instrumental in studying the effect of key variables on tribological outcomes. Montgomery (2017) noted that the Box-Behnken design (BBD) allows for modelling nonlinear interactions among variables such as load, speed, and additive concentration with a minimal number of experimental runs [24]. RSM has been successfully used to optimise castor oil-based bio-lubricants, which showed lower COF values than those of other vegetable oils under controlled conditions [25]. Similarly, Ashok et al. (2022) demonstrated the utility of RSM in engine testing, where biodiesel blend parameters were tuned to minimize emissions while maintaining combustion efficiency [26]. This growing body of work provides a solid foundation for further investigations into BPO-based nanolubricants. The intersection of agricultural waste valorization, nanotechnology, and statistical optimization presents a promising frontier in the pursuit of high-performance, sustainable tribological systems.

3.Materials and methods

3.1Soxhlet extraction method

Banana peel (BP) waste is collected at a nearby Banana fritters stall. The peels are then rinsed with distilled water and cut into small pieces. BPs were sun-dried under natural conditions to maintain the eco-friendly approach of this study. The peels were spread evenly in a single layer on stainless-steel trays with an approximate loading of 2.0 kg·m^{-2} (wet basis). Each peel was sliced to a uniform thickness of 2–3 mm to ensure consistent drying. Ambient temperature and relative humidity during drying were approximately 30 ± 2 °C and 65 ± 5%, respectively, measured using a calibrated thermo-hygrometer. The drying process was continued until a constant mass was achieved, defined as a change of ≤ 0.5 mg between three consecutive weighings at 1-day intervals, a total of 3-4 days. No oven or thermogravimetric analyzer (TGA) verification was conducted, as the focus was on maintaining a natural drying process consistent with the research's sustainability principles. Dried peels were then crushed into small pieces using a coffee grinder. Oil extraction was carried out using a Soxhlet extraction fat analyzer (SZF-06A) with n-hexane (analytical grade, ≥99% purity) as the solvent (*Figure 1*). For each extraction, 5g of crushed BP and 50 mL of hexane (extract-to-solvent ratio of 1:10 w/v) were used. The extraction was conducted at 95 °C for 2 hours, equivalent to approximately 8–10 reflux cycles per hour. The collected extract was subsequently concentrated in a water bath at 95 °C for 20–30 minutes to remove residual solvent. The recovered BPO was transferred into amber glass bottles and stored at room temperature, protected from light and air exposure to minimize oxidation (*Figure 2*). A total of 150 mL of BPO was produced for the 4-ball tribological testing across 15 samples.

3.2Graphene nanoparticle

GNPs were purchased from BTCORP Generique Nano Pvt. Ltd., Bangalore, India. Three types of GNP are used in this research: research-grade, technical-grade and Industrial-grade. Each grade has its own specific density, as shown in *Table 1*.

Table 1 Graphene grade & density value

Graphene grade	Layer graphene	Density
Research	1 – 5	0.06 g/ml
Technical	15	0.45 g/ml
Industrial	25	0.60 g/ml

Figure 1 Soxhlet extraction fat analyzer SZF-06A

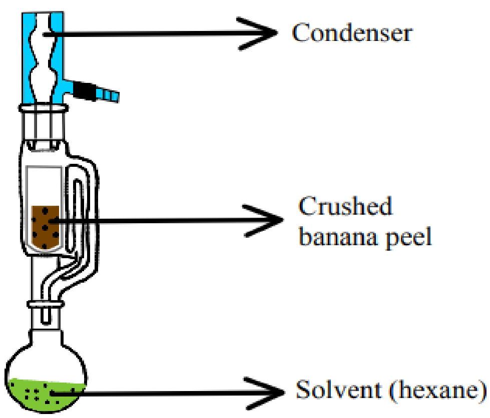


Figure 2 Schematic presentation of BPO oil extraction using soxhlet extraction

3.3Oil mixing using ultrasonic homogenizer

After the BPO was extracted and the GNP powders were obtained from a commercial supplier, the mixtures were prepared using an ultrasonic homogenizer (*Figure 3*). The homogenizer operated at a frequency of 60 Hz with a duty cycle of 0.5. Each sample contained 10 mL of BPO and varying concentrations of GNP, calculated using the density relationship described in Equation 1. The ultrasonication process was carried out for 30 minutes at ambient temperature (~28 ± 2 °C) to ensure uniform dispersion. No surfactant or dispersant was added to maintain the natural composition of the bio-based lubricant. After mixing, the prepared samples were immediately used for tribological testing to minimize any potential settling of the nanoparticles.

$$\rho = \frac{m}{v} \quad (1)$$

$\boldsymbol{\rho}$ Density ($\boldsymbol{g/cm^3}$) (1 ml = 1 cm³)
$\boldsymbol{m}$ Mass (g)
$\boldsymbol{v}$ Volume (ml)

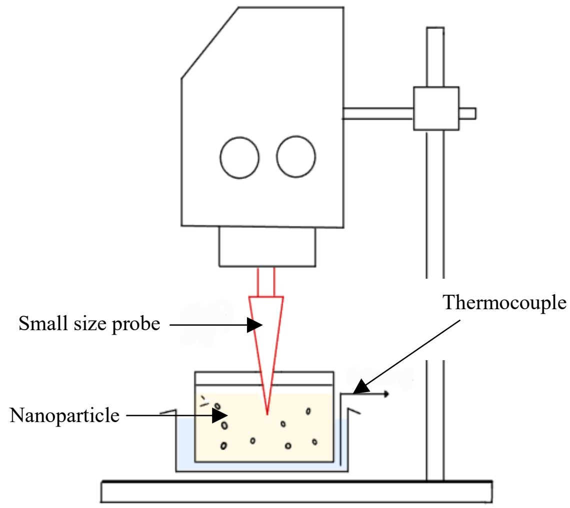


Figure 3 Ultrasonic homogenizer

3.4Response surface methodology

RSM is applied in this research to determine the optimal composition for the newly developed bio-oil. RSM is a mathematical and statistical which uses a second-degree polynomial model, employing both the univariate and multivariate models to study the relationship between two or more response variables and several independent variables. Equation 2 shows the RSM second order model equation.

$$y = y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum \sum_{i<j} \beta_{ij} X_i X_j + \varepsilon \quad (2)$$

y	response surface equation
β_0	Constant
$\beta_i, \beta_{ii}, \beta_{ij}$	Coefficient for the linear, quadratic and cross-product terms, respectively

RSM, using the Box-Behnken experimental design method is implemented to assess the significance of the input parameters. BBD suggests points from a three-level factorial arrangement, allowing for the efficient estimation of the first order and second-order coefficients of the mathematical model (*Figure 4*). Thus, the design is more efficient and economical compared to the corresponding 3^k designs which are mainly used for experiments involving a large number of variables.

Upon collecting the experimental data, response surface modelling is employed to develop mathematical models that depict the observed reactions. These models illustrate the correlation between variables and response components within a multidimensional framework. Commonly used models in this context include linear, quadratic, and higher-order polynomial models, as well as other specialized forms designed to the specific process. Firstly, linear models are expected to be produced, as they assume a direct and proportional relationship between the factors and the response. Hence, the linear equation is expressed in Equation 3 as follows:

$$Y_i = \beta_0 + \sum \beta_i X_i + \varepsilon_i \quad (3)$$

Y_i	Response Variable
$\beta_0 \beta_i$	Coefficient to be estimated
ε_i	Error term

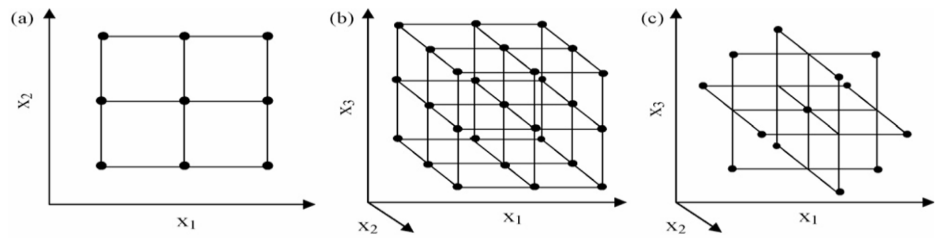


Figure 4 Experimental designs based (a) two-level variables and (b) three-level variables and (c) Box-Behnken design to optimize the three variables [27]

In addition to the linear equations, quadratic models are also anticipated in this study. Quadratic models include both linear and squared terms of the factors allowing for accommodation of non-linear relationships between the factors and the response. These models capture the curvature in the response surface. The quadratic model is presented in Equation 4 as:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad (4)$$

$\boldsymbol{Y_i}$	Response Variable
$\boldsymbol{\beta_0 \beta_i}$	Coefficient to be estimated
$\boldsymbol{\varepsilon_i}$	Error term

The tribological performance optimization was conducted using RSM with a BBD implemented in Minitab software. Three independent factors were selected based on preliminary trials and literature: GNP composition (0.1–0.5 vol%), homogeneous mixing time (10–30 minutes), and type of graphene grade (Research, Technical, Industrial), as shown in *Table 2*. The factors were coded as (−1, 0, +1) to represent the low, mid, and high levels, respectively. The experimental matrix consisted of 15 randomized trials, automatically generated by the Minitab software, as shown in *Table 3.* The randomization of the run order was applied to minimize systematic error due to external influences such as temperature or humidity variation. Three replications were performed at the center points (0.3 vol% composition, 20 min mixing time, Technical-grade graphene) to evaluate experimental error and assess model adequacy through lack-of-fit analysis. No blocking was applied, as all experiments were conducted under consistent laboratory conditions. A quadratic polynomial model was pre-specified to describe the interaction effects among the factors and to capture curvature in the response surface. The experimental responses COF and WSD were analyzed using analysis of variance (ANOVA) to determine the statistical significance of each factor and their interactions. Model adequacy was further validated through diagnostic residual plots and lack-of-fit tests, confirming that the quadratic model was statistically sound and suitable for optimization purposes.

Table 2 Parameter set for RSM box-behnken

Parameter	Unit	Low value	Mid value	High value
Composition,	Vol%	0.1	0.3	0.5
Hemogeneous Time	Minute	10	20	30
Type of Graphene	Grade	Research	Technical	Industrial

Table 3 Response data generated by Minitab software

Trials	Factors			Coded				Response	
	Composition (vol.%)	Homogeneous time (minutes)	Type of graphene (Grade)	A	B	C		COF	Wear scar diameter (WSD)
1	0.1	10	0	-1	-1	0		-	-
2	0.5	10	0	1	-1	0		-	-
3	0.1	30	0	-1	1	0		-	-
4	0.5	30	0	1	1	0		-	-
5	0.1	20	-1	-1	0	-1		-	-
6	0.5	20	-1	1	0	-1		-	-
7	0.1	20	1	-1	0	1		-	-
8	0.5	20	1	1	0	1		-	-
9	0.3	10	-1	0	-1	-1		-	-
10	0.3	30	-1	0	1	-1		-	-
11	0.3	10	1	0	-1	1		-	-
12	0.3	30	1	0	1	1		-	-
13	0.3	20	0	0	0	0		-	-
14	0.3	20	0	0	0	0		-	-
15	0.3	20	0	0	0	0		-	-

3.5Four-ball testing based on ASTM D4172

Based on the 15 samples generated by the Minitab Software, the tribo testing process is conducted to analyse the tribological behaviour of the BPO + GNP. Tribological testing utilises Koehler 4-ball testing Model K93190-M-CE as shown in *Figure 5*. In addition, the testing of the oil is based on American Society for Testing and Materials (ASTM D4172). *Table 4* shows the parameter setup for 4-ball testing.

Table 4 Parameter Setup for 4-ball testing

Parameter	Value
Speed	1200 rpm
Force	392 N
Time	3600 second
Temperature	75◦C

Figure 5 Koehler model K93190-M-CE 4-ball testing

Figure 6 shows the schematic of the 4-ball testing. Three 12.7mm steel balls are fixed and lubricated, while a unique collet on an AC motor-driven spindle holds the fourth ball with the same diameter. As the top ball rotates, it comes into contact with the three fixed balls submerged in the test oil. The ball container securely holds the balls in place, while the ball container clamp keeps the balls together, and a locking nut applies the force. Furthermore, a heating block at the bottom of the ball pot regulates the oil sample's temperature. The balls are loaded by moving a lever and placing fixed weights on a loading pan. The normal load is measured via a load cell attached to the loading lever. A push bearing and plunger support the ball pot above the loading lever. Additionally, a frictional force load cell measures the frictional torque of the three fixed balls. The data terminal processing system records the COF. An optical microscope (OM) is used to measure the WSD and to determine the average size.

A heating block at the base of the ball pot regulated the lubricant temperature. Before each test, the setup was preheated for 5 minutes to reach thermal equilibrium. Approximately 10 mL of the BPO–graphene mixture was used per test to ensure full submersion of the contact region. All test balls were ultrasonically cleaned in acetone and ethanol and air-dried before use to eliminate contaminants. Each experiment was conducted in triplicate (n = 3) to ensure repeatability. The WSD on the stationary balls was measured using an OM, and the average value from the three scars was recorded. Measurement uncertainties for both COF and WSD were determined based on the standard deviation of triplicate readings.

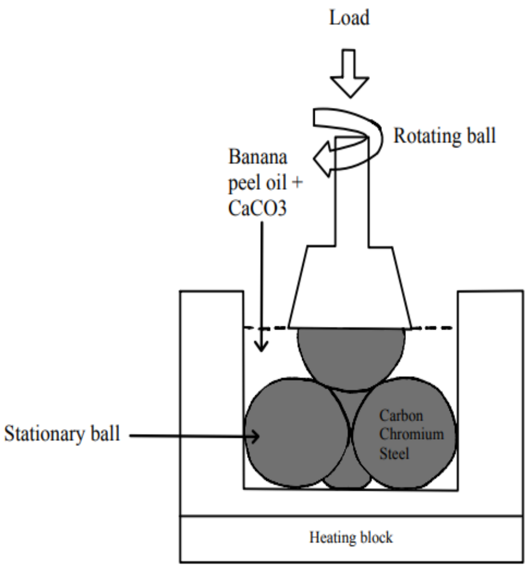


Figure 6 Schematic of four-ball testing

4.Results and discussion

4.1Effects of different factors on COF and WSD

Table 5 presents the results of 15 experimental runs conducted using the RSM BBD method in Minitab. The summary of the statistical testing results is expressed as a function of the input parameters.

The residual plots in *Figure 7* demonstrate the analysis for both the COF and WSD, which are essential for evaluating the validity and sufficiency of their corresponding regression models. The normal probability plot for COF reveals that the residuals closely align with a straight line, signifying compliance with the normality assumption [28]. The residuals vs. fitted values plot indicates a random distribution of residuals, implying that the model efficiently captures overall variability without discernible patterns [29]. This random dispersion suggests an opportunity to improve the model by incorporating additional relevant variables to enhance its predictive accuracy and clarity.

Similarly, the residual analysis for WSD validates the model's adequacy. The residuals vs. fitted values plot shows random dispersion of residuals around zero, indicating no significant concerns such as nonlinearity or heteroscedasticity [30]. Additionally, the normal probability plot (Q-Q Plot) for WSD corroborates the normality assumption, with low deviations indicating reliable residuals [31].

Overall, the residual plots confirm the suitability of both models. The absence of strong patterns suggests that the potential concerns related to non-linearity, variability, or influential data points are minimal and manageable [32]. Therefore, the model effectively captures the relationship between factors and the responses, providing an accurate representation of the input-output relationship.

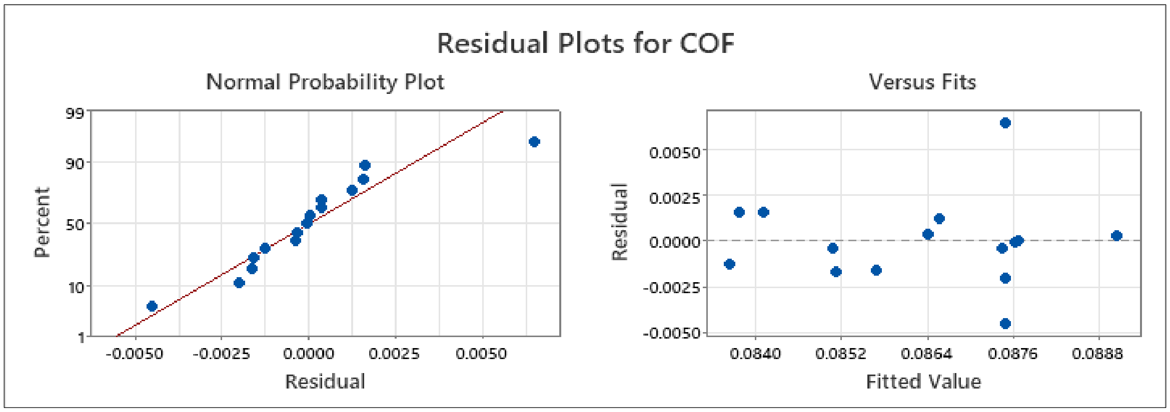
Table 5 Tribology testing results for BPO and GNP

Trials	**Factors**			**Coded**			**Response**	
	Composition (vol.%)	**Homogenous time (minutes)**	**Type of graphene (Grade)**	**A**	**B**	**C**	**COF**	**Wear scar diamater (WSD)**
1	0.1	10	0	-1	-1	0	0.0868	0.163
2	0.5	10	0	1	-1	0	0.0857	0.153
3	0.1	30	0	-1	1	0	0.0841	0.142
4	0.5	30	0	1	1	0	0.0847	0.149
5	0.1	20	-1	-1	0	-1	0.0878	0.151
6	0.5	20	-1	1	0	-1	0.0877	0.148
7	0.1	20	1	-1	0	1	0.0876	0.154
8	0.5	20	1	1	0	1	0.0824	**0.137**
9	0.3	10	-1	0	-1	-1	0.0835	**0.167**
10	0.3	30	-1	0		-1	0.0894	0.149
11	0.3	10	1	0	-1	1	0.0871	0.154
12	0.3	30	1	0	1	1	0.0854	0.166
13	0.3	20	0	0	0	0	**0.0940**	0.148
14	0.3	20	0	0	0	0	0.0855	0.157
15	0.3	20	0	0	0	0	0.0830	0.156

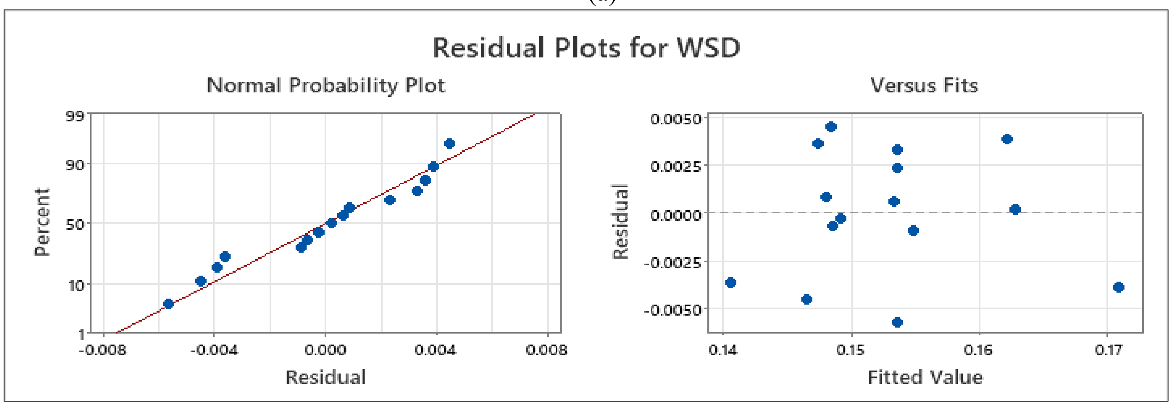
lowest COF and WSD

highest WSD

highest COF



(a)



(b)

Figure 7 Residual plots of data obtained for (a) COF and (b) WSD

The ANOVA results in *Tables 6* and *7* provide insights into the COF and WSD responses. For COF, none of the investigated factors—composition, homogenization time, or graphene grade—exhibited a statistically significant effect, as indicated by p-values greater than 0.05. In addition, the COF model showed no predictive capability, with an adjusted R^2 value of approximately 0% and a model p-value of 0.959. This suggests that within the current experimental range, the selected parameters did not exert a measurable influence on frictional behavior. In contrast, the ANOVA results for WSD reveal that homogenization time had a marginal influence ($p = 0.100$), while the interaction between homogenization time and graphene grade was statistically significant ($p = 0.040$), indicating a synergistic effect on the wear response. However, neither graphene composition ($p = 0.195$) nor graphene grade alone ($p = 0.805$) showed significant independent effects. The non-significant COF model likely reflects a narrow factor range or insensitivity of the frictional response under boundary lubrication conditions, where surface film formation dominates over compositional variations. As such, the COF model is considered non-predictive within the present design, and further refinement—such as expanding factor ranges, increasing experimental resolution, or applying response transformation techniques—is recommended for future work to enhance model adequacy and sensitivity.

Table 6 ANOVA for COF

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	9	0.000038	0.000004	0.27	0.959
Linear	3	0.000009	0.000003	0.18	0.907
Composition, vol.%	1	0.000004	0.000004	0.26	0.631
Homogeneous time, minutes	1	0.000000	0.000000	0.00	0.967
Type of Graphene, Grade	1	0.000004	0.000004	0.27	0.625
Square	3	0.000008	0.000003	0.17	0.913

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Composition, vol.%*Composition, vol.%	1	0.000004	0.000004	0.27	0.628
Homogeneous time, minutes*Homogeneous time, minutes	1	0.000004	0.000004	0.28	0.621
Type of Graphene, Grade*Type of Graphene, Grade	1	0.000000	0.000000	0.00	0.982
2-Way Interaction	3	0.000022	0.000007	0.45	0.729
Composition, vol.%*Homogeneous time, minutes	1	0.000001	0.000001	0.04	0.841
Composition, vol.%*Type of Graphene, Grade	1	0.000007	0.000007	0.40	0.553
Homogeneous time, minutes*Type of Graphene, Grade	1	0.000014	0.000014	0.90	0.387
Error	5	0.000080	0.000016		
Lack-of-Fit	3	0.000014	0.000005	0.14	0.928
Pure Error	2	0.000066	0.000033		
Total	14	0.000119			

Table 7 ANOVA for WSD

Source	DF	Adj SS	Adj MS	P-Value
Model	9	0.000807	0.000090	0.117
Linear	3	0.000188	0.000063	0.216
Composition, vol.%	1	0.000066	0.000066	0.195
Homogeneous time, minutes	1	0.000120	0.000120	0.100
Type of Graphene, Grade	1	0.000002	0.000002	0.805
Square	3	0.000273	0.000091	0.129
Composition, vol.%*Composition, vol.%	1	0.000166	0.000166	0.064
Homogeneous time, minutes*Homogeneous time, minutes	1	0.000085	0.000085	0.151
Type of Graphene, Grade*Type of Graphene, Grade	1	0.000001	0.000001	0.856
2-Way Interaction	3	0.000346	0.000115	0.088
Composition, vol.%*Homogeneous time, minutes	1	0.000072	0.000072	0.179
Composition, vol.%*Type of Graphene, Grade	1	0.000049	0.000049	0.254
Homogeneous time, minutes*Type of Graphene, Grade	1	0.000225	0.000225	0.040
Error	5	0.000148	0.000030	
Lack-of-Fit	3	0.000099	0.000033	0.450
Pure Error	2	0.000049	0.000024	
Total	14	0.000955		

Figures 8 and *Figure 9* illustrate how the COF and WSD of the BPO + GNP are affected by changes in the factors, composition, homogeneous time and graphene type. These plots can map only two dynamic variables at a time, requiring the third variable to be fixed. For example, *Figure 8(a)* shows the COF variation as a function of the composition and homogeneous time, with the graphene type held constant (grade: Research).

The surface plots for COF illustrate the relationship between two independent variables and their effect on the COF. The x-axis and y-axis represent the selected variables, while the z-axis or colour gradient indicates the corresponding COF values. The shape of the surface provides visual insights into these relationships. *Figure 8 (a*) illustrates the relationship between two independent variables, such as composition and homogeneous time, and their effects on the COF. The COF value is minimised when the composition is high, and the homogenization time is set at its lowest. *Figure 8 (b)* and *(c)* show that a high grade of graphene produces a low COF value. Moreover, no flat areas are observed in the surface plot, indicating that stability is not detected when the factor values are changed [33].

According to the three-dimensional surface plot in *Figure 9*, homogeneous time (in minutes), and the type or grade of graphene affect the WSD. The X-axis represents homogeneous time, ranging from about 10 to 30 minutes, while the Y-axis denotes the graphene grade, which varies between -1 (research) and 1 (industrial). The Z-axis indicates the WSD values, ranging from 0.15 to 0.17. The curved, "V"-shaped surface reveals that WSD is minimized when the homogeneous time is around 25 to 30 minutes, and the graphene grade is near 0 to -1. When the mixing time is short (around 10-15 minutes), the WSD increases. Similarly, graphene grades at the extreme ends (1) generally lead to higher WSD values. To achieve the lowest WSD, an optimal balance is found with a mixing time of between 25 to 30 minutes and a graphene grade between 0 and -1. Consequently, this provides valuable insight into determining the ideal conditions for enhancing the lubrication properties of BPO infused with different graphene types. Hence, a homogeneous time of 30 minutes and research-grade graphene provide the most effective mixture for minimizing WSD in this study.

Given the significant factor identified for WSD in Equation 5, further testing is performed to validate the result. To evaluate the sensitivity of each factor affecting the WSD, a dedicated sensitivity analysis is conducted for parameters A, B and C, as presented in Equations 6, 7 and 8. The formulation of this sensitivity analysis is based on the derivation of the response function outlined as follows:

$$WSD=0.1826 + 0.0438\,A - 0.00294\,B - 0.01025\,C - 0.1677\,A^2 + 0.000048\,B^2 + 0.00054\,C^2 + 0.00213\,AB - 0.0175\,AC + 0.000750\,BC \quad (5)$$

Derivation in terms of A, B and C:

$$\frac{\partial(wsd)}{\partial A} = 0.0438 - 0.3354\,A + 0.00213\,B - 0.0175\,C \quad (6)$$

$$\frac{\partial(wsd)}{\partial B} = -0.00294 + 0.000096\,B + 0.00213\,A + 0.00075\,C \quad (7)$$

$$\frac{\partial(wsd)}{\partial C} = -0.01025 + 0.00108\,C - 0.0175A + 0.00075B \quad (8)$$

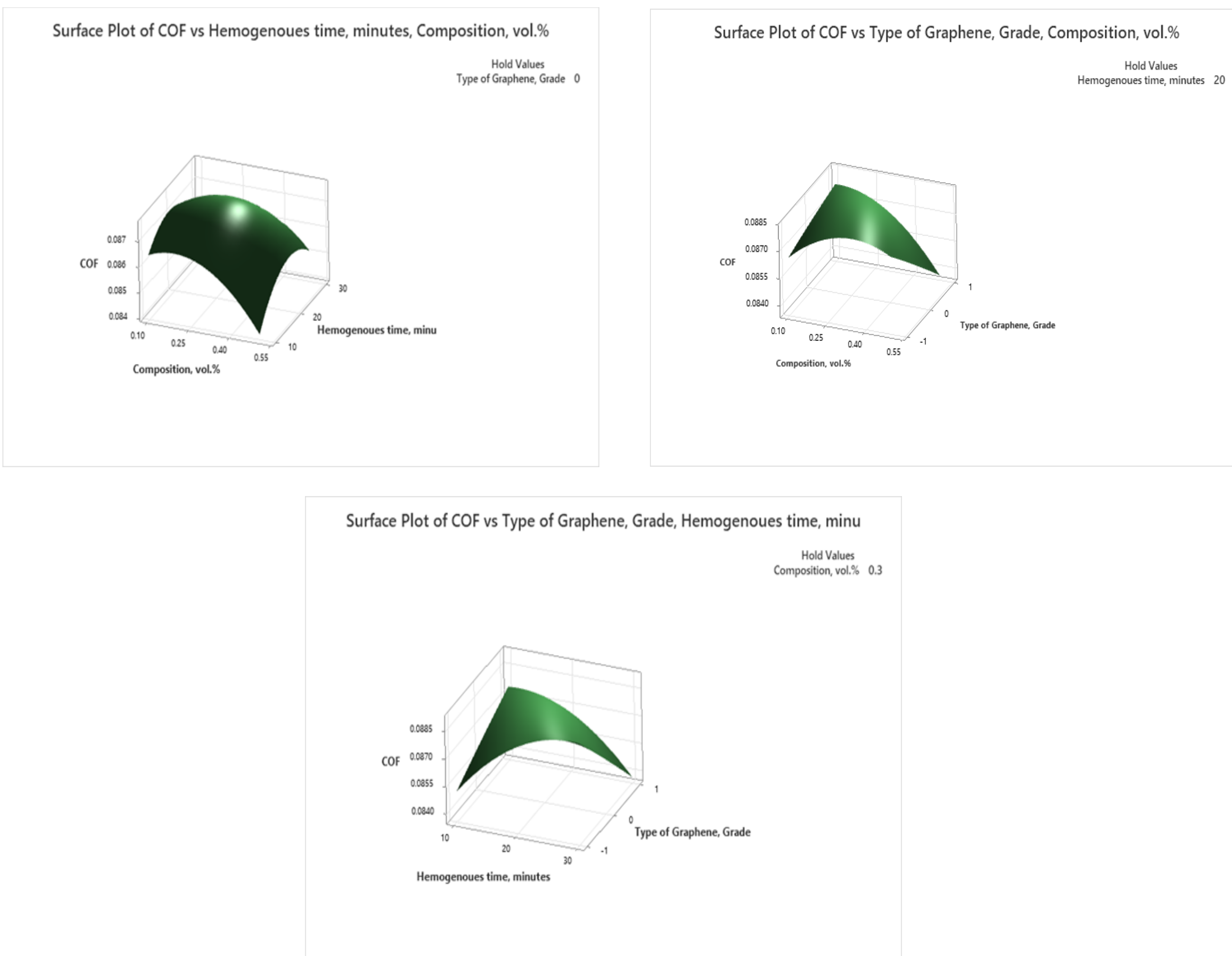


Figure 8 Contour plots of the combined effects of factors on COF

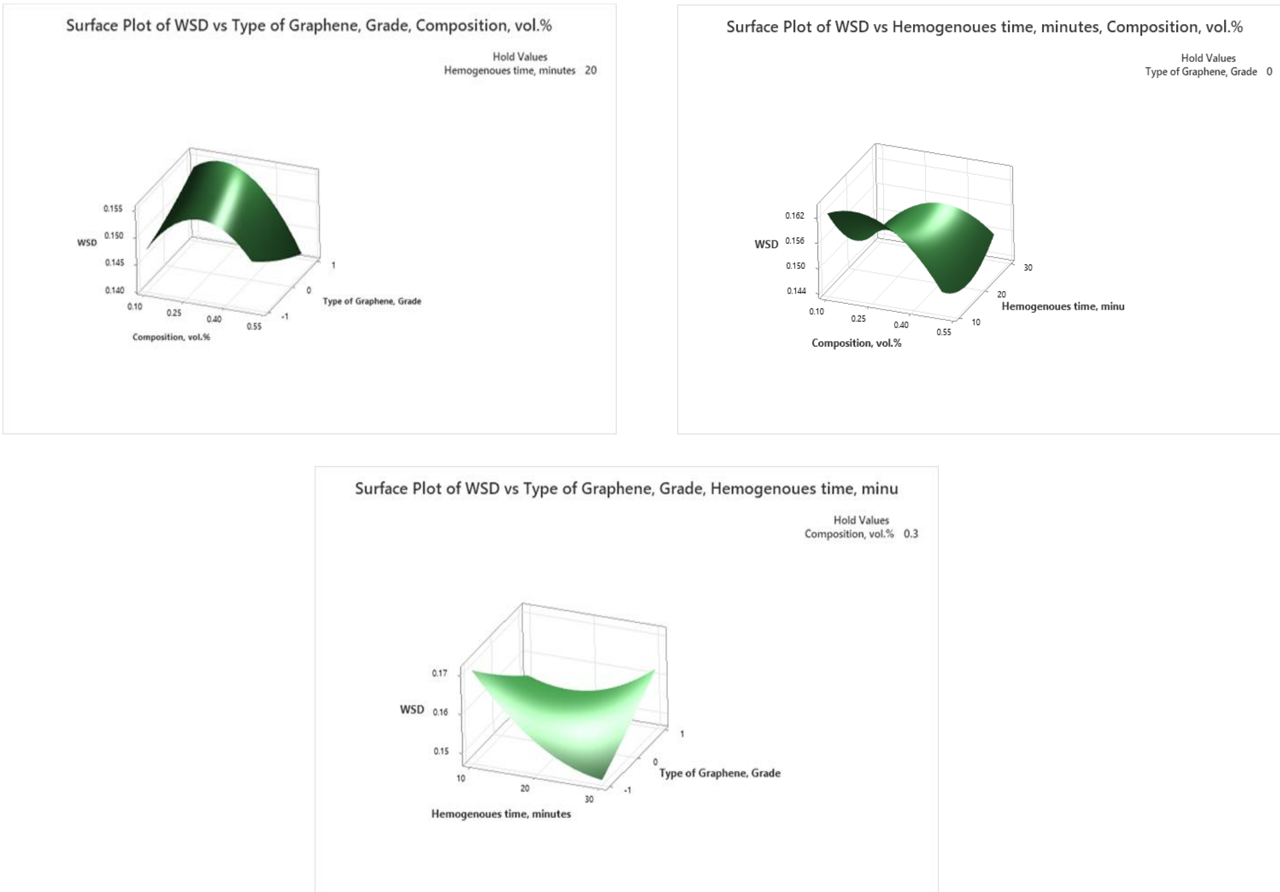


Figure 9 Contour plots of the combined effects of factors on WSD

Figures 10 and *11* present a comparison of the sensitivity analysis for factors A, B and C related to WSD. Higher bars denote higher sensitivity, while shorter bars indicate lower sensitivity. These results align with the ANOVA analysis, confirming that factors A and B are the most sensitive to changes towards the WSD. The result suggests that composition and homogeneous time are the two most influential factors affecting the WSD.

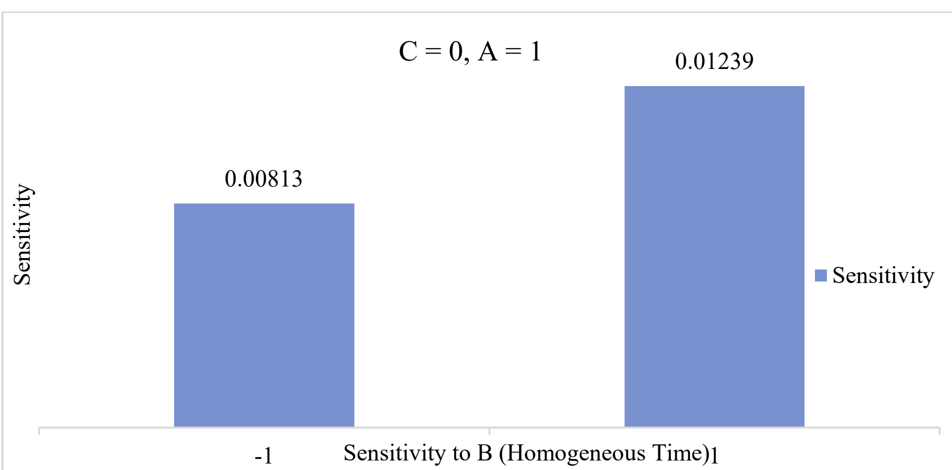


Figure 10 Sensitivity analysis when factor A (composition) is set to value 1

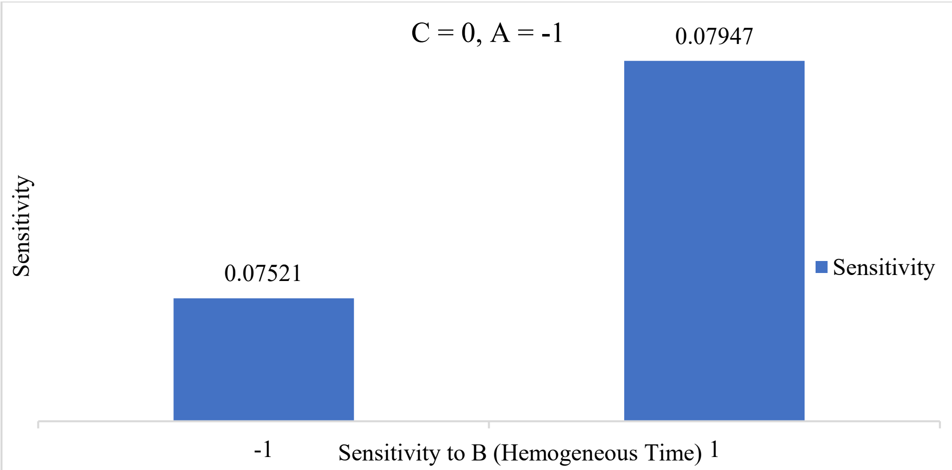


Figure 11 Sensitivity analysis when factor A (composition) is set to value -1

4.2Limitation

The present research is subject to several limitations that should be acknowledged. The physicochemical characterization of the extracted BPO, including viscosity, density, acid value, saponification value, iodine value, and Fourier transform infrared spectroscopy (FTIR), gas chromatography–mass spectrometry (GC–MS) profiling, was not conducted in this work, as the main objective was to optimize tribological performance parameters using RSM. Similarly, advanced characterization of the GNP grades, such as transmission electron microscopy (TEM) or atomic force microscopy (AFM) for flake size and thickness, Raman spectroscopy for structural assessment, zeta potential, and impurity evaluation, was not performed due to analytical facility constraints. In addition, detailed ultrasonication parameters—such as energy input, amplitude, and horn-tip specifications—were not recorded because a fixed-power bench-top homogenizer was employed. Dispersion stability evaluations, including zeta potential and sedimentation analyses, were also not undertaken; instead, visual inspection was used to ensure short-term homogeneity prior to testing. Control samples, including pure BPO and commercial reference lubricants, were not incorporated into the experimental matrix owing to limited oil yield and the defined research scope, which focused on graphene-infused formulations. The COF model yielded a non-significant result (p = 0.959), suggesting that the selected factor ranges and model structure may not have adequately captured the variability in the response. These constraints are recognized as limitations of the present study. Future work will therefore emphasize comprehensive physicochemical and microstructural characterization of materials, refinement of experimental factor ranges, detailed dispersion stability assessments, and validation of the predicted optimal conditions through confirmation experiments using appropriate control lubricants. A complete list of abbreviations is listed in *Appendix I.*

5.Conclusions

In this study, RSM was employed to evaluate the tribological performance of BPO blended with different types of GNPs. The effects of composition (vol.%), graphene type, and homogenization time were analyzed with respect to WSD and COF. The results indicate that the selected factors exhibit a more pronounced influence on WSD than on COF. The developed model for WSD demonstrated a good fit with the experimental data (R^2 = 84.51%); however, the predicted R^2 value of 0% indicates limited predictive capability. Among the investigated parameters, the interaction between homogenization time and graphene type was found to be statistically significant (p = 0.040), highlighting its critical role in influencing wear behavior. Although composition and homogenization time showed a tendency to reduce WSD, their individual effects were not statistically significant. These observations suggest that the model may be overfitting or that additional influencing parameters are not captured within the current experimental design. In contrast, the analysis of COF revealed no statistically significant effect of the considered factors, as confirmed by ANOVA results with p-values greater than 0.05. The model exhibited a weak fit (R^2 = 32.32%) and lacked predictive capability, indicating that the selected variables do not adequately explain variations in frictional performance. Furthermore, no significant interaction or quadratic effects were observed for

COF. Overall, the study demonstrates that graphene nanoparticle incorporation in BPO has a measurable impact on wear characteristics, particularly through interaction effects, while its influence on friction remains inconclusive under the investigated conditions.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

None.

Author's contribution statement

Fawzan Hanafi Bin Mohamad Fazdhli: Investigation, data collection, analysis, writing original draft manuscript. **Muhammad Ilman Hakimi Chua bin Abdullah:** Supervision, Challenges investigation, and Writing draft manuscript. **Mohammad Rafi bin Omar:** Data collection, Analysis, and Writing draft manuscript. **Mohd Fazdli bin Abdullah:** Challenges investigation and drafted the manuscript. **Mohd Fariduddin Mukhtar:** Challenges in the investigation and writing of the draft manuscript. **Effendi Bin Mohamad:** Writing draft manuscript. **Rohana Binti Abdullah:** Writing draft manuscript. **Iskandar Waini:** Writing draft manuscript. **Najiyah Safwa Khashi'ie:** Writing draft manuscript. **Poppy Puspitasari:** Writing draft manuscript. **Avita Ayu Permanasari:** Writing draft manuscript.

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Appendix I

S. No.	Abbreviation	Description
1	AFM	Atomic Force Microscopy
2	ANOVA	Analysis of Variance
3	ASTM D4172	American Society for Testing and Materials
4	BBD	Box-Behnken Design
5	BP	Banana Peel
6	BPO	Banana Peel Oil
7	COF	Coefficient of Friction
8	FTIR	Fourier Transform Infrared Spectroscopy
9	GC–MS	Gas Chromatography–Mass Spectrometry
10	GNP	Graphene Nanoparticles
11	MEMS	Microelectromechanical Systems
12	MgO	Magnesium Oxide
13	MOHE	Ministry of Higher Education
14	OM	Optical Microscope
15	RSM	Response Surface Methodology
16	SZF-06A	Soxhlet Extraction Fat Analyzer
17	TEM	Transmission Electron Microscopy
18	TGA	Thermogravimetric Analyzer
19	TiO_2	Titanium Oxide
20	WSD	Wear Scar Diameter
21	ZDDP	Zinc Dialkyl Dithiophosphate