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Appendix A

Hertzian contact stress calculations in four ball tribometer

Equivalent radius (R’) => Ball (diameter 12.7 mm) AISI 52100 steel

$$\frac{1}{\text{R'}} = \left(\frac{1}{6.35} + \frac{1}{6.35}\right)$$

$$R' = 3.16\, mm$$

Reduced Youngs Modulus (E’) =>

$$\frac{1}{\text{E'}} = \frac{1}{2}\left(\frac{1 - 0.3^2}{210} + \frac{1 - 0.3^2}{210}\right)$$

$$E' = 231\, GPa$$

Applied normal load on single ball (W) = 0.40825P = 0.40825 × 392

$$W = 160.03\, N$$

Contact radius or Hertzian contact radius

Equation [*A.1*]

$$a = \left(\frac{3WR'}{2E'}\right)^{1/3}$$

$$a = \left(\frac{3 \times 160.03 \times 3.16 \times 10^{-3}}{2 \times 231 \times 10^{9}}\right)^{1/3}$$

a = 0.149 mm

Maximum contact pressure (Hertzian Stress)

Equation [*A.2*]

$$P_{max} = \frac{3W}{2\pi a^2}$$

$$P_{max} = \frac{3 \times 160.03}{2 \times \pi \times (0.149 \times 10^{-4})^2}$$

$$P_{max} = 3.4\, GPa$$

Stress distribution with depth of contacting body in four ball

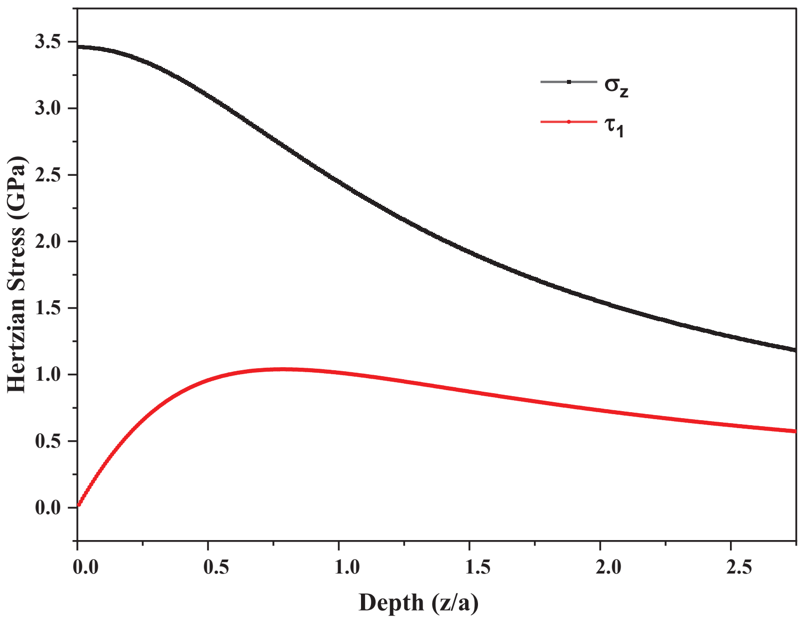

Figure A.1 Subsurface stresses along the axis of symmetry with depth (Where σ_z *is normal stress along z direction* τ_1 *is the principal shear stress at a given nondimensional depth)*

Maximum values of shear stress occur at 0.48*a*

$$z = 0.48 \times a$$

$$z = 0.48 \times 0.149$$

$$z = 0.07152\, mm$$

Wear volume calculations from wear scar diameter in four ball tester

Equation [*A.3*]

$$\mathrm{V} = \frac{\pi(\mathrm{d}_0)^4}{64\mathrm{R}'}\left\{\left(\frac{\mathrm{d}}{\mathrm{d}_0}\right)^4 - \left(\frac{\mathrm{d}}{\mathrm{d}_0}\right)\right\}$$

$$\mathrm{d}_0 = 2 \times a = 2 \times 0.149 = 0.298\, mm$$

Where given war scar diameter d = 930 µm

$$\mathrm{V} = \frac{\pi(0.298 \times 10^{-3})^4}{64 \times 3.16 \times 10^{-3}}\left\{\left(\frac{930 \times 10^{-6}}{0.298 \times 10^{-3}}\right)^4 - \left(\frac{930 \times 10^{-6}}{0.298 \times 10^{-3}}\right)\right\}$$

$$V = 1.124 \times 10^{-11}\, m^3$$

Appendix B

Hertzian contact stress calculations in MFT

Equivalent radius (R’) => Ball (diameter 6 mm) on Flat geometry steel disk (diameter 20 mm, thickness 8 mm) AISI 52100

$$\frac{1}{\mathrm{R'}} = \left(\frac{1}{\infty} + \frac{1}{3}\right)$$

$$R' = 3\,mm$$

Reduced Youngs Modulus (E’) =>

$$\frac{1}{\mathrm{E'}} = \frac{1}{2}\left(\frac{1-0.3^2}{210} + \frac{1-0.3^2}{210}\right)$$

$$E' = 231\,GPa$$

Contact radius or Hertzian contact radius

$$a = \left(\frac{3WR'}{2E'}\right)^{1/3}$$

$$a = \left(\frac{3 \times 50 \times 3 \times 10^{-3}}{2 \times 231 \times 10^{9}}\right)^{1/3}$$

a = 0.099 mm

Maximum contact pressure (Hertzian Stress)

Equation [*B.1*]

$$P_{max} = \frac{3W}{2\pi a^2}$$

$$P_{max} = \frac{3 \times 50}{2 \times \pi \times (0.099 \times 10^{-3})^2}$$

$$P_{max} = 2.44\,GPa$$

Appendix C

Film thickness calculations

Equation [*C.1*]

$$\frac{h_{min}}{R'} = 3.63\left(\frac{u\eta_0}{E'R'}\right)^{0.68}(\xi E')^{0.49}\left(\frac{W}{E'R'^2}\right)^{-0.073}(1 - e^{-0.68k})$$

Equation [*C.2*]

$$u = \frac{u_1 + u_2}{2}$$

Where u_1 and u_2 is velocity of body 1 and body 2

Pressure viscosity coefficient (ξ) is calculated using Wooster equation given below

Equation [*C.3*]

$$\xi = (0.6 + 0.965 \times \log_{10}\eta) \times 10^{-8}$$

For castor oil at 75 °C temperature

$$\xi = (0.6 + 0.965 \times \log_{10} 40.38) \times 10^{-8}$$

$$\xi = 2.14 \times 10^{-8}\ m^2/N$$

For Karanja Oil at 25 °C

$$\xi = (0.6 + 0.965 \times \log_{10} 73.56) \times 10^{-8}$$

$$\xi = 2.41 \times 10^{-8}\ m^2/N$$

Karanja oil at 75 °C temperature

$$\xi = (0.6 + 0.965 \times \log_{10} 12.43) \times 10^{-8}$$

$$\xi = 1.65 \times 10^{-8}\ m^2/N$$

Modified Karanja Oil at 25 °C

$$\xi = (0.6 + 0.965 \times \log_{10} 632.34) \times 10^{-8}$$

$$\xi = 3.30 \times 10^{-8}\ m^2/N$$

Modified Karanja Oil at 75 °C

$$\xi = (0.6 + 0.965 \times \log_{10} 37.20) \times 10^{-8}$$

$$\xi = 2.12 \times 10^{-8}\ m^2/N$$

Table C.1 Pressure viscosity coefficient values used for film thickness calculation

Oil	**Pure Karanja oil**	**25% MKO**	**50% MKO**	**75% MKO**	**100% MKO**	**Pure Castor oil**
@ 75 °C *ξ (10^{-8} m^2/N)*	1.65	1.77	1.86	1.94	2.12	2.14
@ 25 °C *ξ (10^{-8} m^2/N)*	2.41	2.61	2.74	3.06	3.30	-

List of Publication

Verma, Gulshan, A. P. Harsha, and Om Prakash Khatri. "The Effect of Spherical Hybrid Silica–Molybdenum Disulfide on the Lubricating Characteristics of Castor Oil." *Journal of Tribology* 145, no. 12 (2023).

Verma, Gulshan, A. P. Harsha, Ramesh N. Goshwami, and Om P. Khatri. "Performance Study of Graphene-Zinc Oxide Hybrid Nanolubricants under Various Test Conditions." *Journal of Materials Engineering and Performance* (2024): 1-17.

Verma, Gulshan, A. P. Harsha, Anchal Pandey, and Om P. Khatri. "The Friction, Wear, and Failure Behavior of Functionalized Hexagonal Boron Nitride with Karanja Oil Blends." *Tribology Transactions* 68, no. 1 (2025): 64-76.

Rajput, Arun, **Gulshan Verma**, A. P. Harsha, J. Ramkumar, K. Mondal, and K. Vishwanath. "Microstructural Tailoring for Enhanced Wear Resistance and Improved Mechanical Properties in High-Carbon Rail Steel." *Journal of Materials Engineering and Performance* (2025): 1-19.

Conference Attended

Tribological evaluation of Karanja oil based nanolubricants, oral presentation, in International conference on tribology and sustainability TriboIndia 2023 by TSI.

Tribological evaluation of multilayer polyimide coatings, oral presentation, in International conference on Tibology for sustainability IndiaTrib 2024 by TSI

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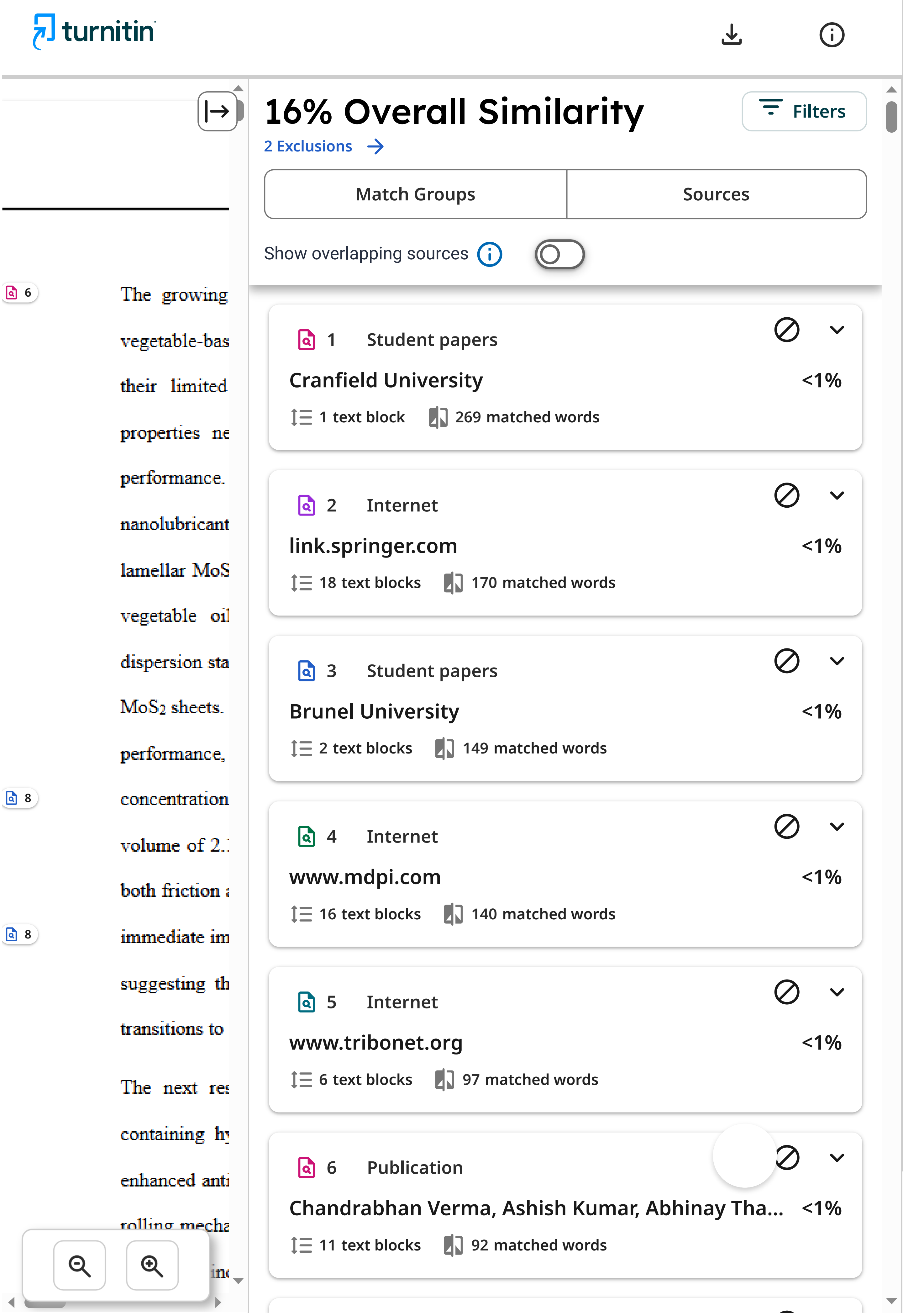

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Queries/Reply	Examiner 1
General comments	The literature review chapter effectively surveys the existing body of knowledge, identifies key research gaps, and provides a rationale and motivation for the research undertaken in the thesis. A strength of the literature review is its explicit identification of several research gaps, particularly in the use of hybrid nano-additives in vegetable based non-edible oils for lubrication and the synergistic effects of combining different nanoparticles in these oils. The sparsity of comparative studies on hybrid nano-additives in modified versus unmodified vegetable oils is also noted. This demonstrates an understanding of the existing literature by the candidate and justifies the need for the present research. The thesis demonstrates several strengths, including comprehensive material characterization (XRD, TEM, SEM, FTIR, Raman), application of statistical methods and modelling, and emphasis on sustainable and eco-friendly alternatives. In particular, I would like to acknowledge: • A comprehensive investigation into advanced lubricant additives, specifically exploring the use of various hybrid and chemically functionalized 2D nanomaterials; • An in-depth analysis of the lubrication mechanisms and failure behavior of the formulated nanolubricants. These factors indicate a solid piece of research work. Additionally, I have identified five research papers co-authored by the candidate, which further attest to the quality and impact of the work. I recommend the thesis to be accepted for the award of the Ph.D. degree subject to the clarification of the following points at the time of Viva-Voce:
Response	Thank you very much for your encouraging and thoughtful evaluation of my thesis. I am truly grateful for your recognition of the research contributions, particularly the comprehensive investigation into hybrid and chemically functionalized 2D nanomaterials, and the detailed analysis of lubrication mechanisms and failure behaviors. I also sincerely appreciate your acknowledgment of the research outputs through the co-authored publications, which reflect the broader impact and collaborative nature of the work. I look forward to the Viva-Voce and will be fully prepared to address the specific points raised, ensuring a clear and thorough discussion of the findings and their implications.
Query 1	The candidate mentions the potential for "Synergistic effects of combining different nanoparticles in non-edible oils" as a literature gap. A clarification on the specific synergistic mechanisms observed in the developed hybrid nanolubricants (e.g., SiO_2-MoS_2 and AZnOGO) and how these lead to improved tribological performance compared to individual nanoparticle additives would be interesting.
Response	The literature reveals limited exploration into the synergistic effects arising from the combination of different nanoparticles in non-edible oils, particularly regarding the underlying mechanisms contributing to enhanced tribological performance. In the

	developed hybrid nanolubricants such as SiO_2-MoS_2 and AZnOGO, distinct synergistic mechanisms were observed. For instance, in SiO_2-MoS_2 systems, the spherical morphology and hardness of SiO_2 contributed to a rolling effect that reduced friction, while the layered MoS_2 provided a lamellar shear mechanism and tribofilm formation, collectively lowering wear and friction beyond what either could achieve alone. Similarly, in AZnOGO systems, the anchoring of ZnO onto oxygen-functionalized graphene oxide (GO) sheets ensured better dispersion, thermal stability, and a dual function, ZnO contributed to anti-wear protection through localized tribo-chemical interactions, whereas GO ensured surface passivation and mechanical reinforcement at the sliding interface. These hybrid mechanisms, combining rolling, sliding, and surface reactivity, result in superior lubrication behavior, wear resistance, and load-carrying capacity compared to single nanoparticle systems, thus filling a significant knowledge gap in tribology and non-edible oil-based lubrication systems.
Query 2	The literature gap concerning the "interaction of nanoparticles with the base oil and surface asperities" in modified versus unmodified vegetable oils suggests a need to clarify how the specific fatty acid compositions of Karanja and castor oils (mentioned in Table 2.2) influence the dispersion, stability (as shown in Figures 4.7, 5.5, and 6.5), and tribological effectiveness of the incorporated hybrid nano additives.
Response	In the case of Karanja and castor oils, as highlighted in Table 2.2, their differing fatty acid profiles significantly influence nanoparticle dispersion and stability parameters crucial for tribological performance. Karanja oil, rich in oleic and linoleic acids, offers a relatively balanced viscosity and less oxidative stability due to presence of unsaturation, aiding uniform dispersion of hybrid nanoparticles, while castor oil, dominated by ricinoleic acid with hydroxyl functionality, provides high polarity and viscosity, which can both enhance nanoparticle anchoring and extreme performance. The modifications introduced to the oils alter their polarity and molecular structure, improving compatibility with surface-functionalized nanoparticles such as f-hBN and f-MXene. This leads to better colloidal stability, as evidenced in Figures 4.7, 5.5, and 6.5, and more effective interaction at surface asperities, facilitating the formation of protective tribofilms.

Query 3	While Chapter 2 broadly discusses general "limitations" of nanolubricants, the Viva-Voce could benefit from a more focused discussion on the specific challenges (e.g., dispersion issues, agglomeration observed in MXene. performance limitations under certain conditions) encountered during the experimental work of this thesis and how these might have influenced the results or interpretations.
Response	One of the major challenges was achieving and maintaining stable dispersion of nanoparticles in non-edible base oils, especially in the case of MXene, which exhibited a strong tendency to agglomerate due to its high surface energy and hydrophilic nature. Despite functionalization with trichloro(octadecyl)silane to improve steric stabilization, partial sedimentation and particle clustering were observed over extended periods, which is likely to influence repeatability and consistency in friction and wear measurements in an extended period of time. Similarly, the SiO_2-MoS_2 prepared by slow cooling creates a dense hybrid structure which sedimented before an hour. These particles do not play any role in lubrication after sedimentation. The problem becomes more severe when these particles get agglomerated at the tribological contact producing an uneven contact thus increasing wear by third body abrasion mechanism. Similar increase in frictional values can also be seen with other particles for the blends possessing poor stability of particles.
Query 4	The candidate discusses the use of "Friction induced vibration at failure" and "Analysis of nano-lubricant failure using vibration characteristics". Further clarification on how the specific changes in vibration signatures (e.g., shifts in dominant frequencies in STFT analysis shown in Figures 7.13, 7.14, and 7.15) directly correlate with the proposed lubricant failure mechanisms for the different nanolubricants would enhance understanding.
Response	Short-Time Fourier Transform (STFT), provided critical insights into the failure mechanisms of different nanolubricants studied in this thesis. The observed shifts in dominant frequencies in Figures 7.13, 7.14, and 7.15 correspond closely to transitions in lubrication regimes and surface interactions. For instance, in well-dispersed hybrid nanolubricant showed a uniform vibration signature at higher frequencies throughout the operation (i.e. before failure) as shown in Figure 7.15, whereas

	the pristine particle showed a fluctuating vibration signature clear from the thick band of frequencies formed with time as shown in Figure 7.14. This suggests the properly dispersed hybrid particles reduces the detrimental effects caused by frictional vibration thus enhance prolong performance and delays the failure.
	Examiner 2
General comments	Thesis title: Tribological evaluation of 2D nanomaterials and their hybrid in biolubricants This thesis provides research data and analysis on the design of vegetable oil-based lubricants with various 2D nanomaterials as the tribological performance enhancing agents. It is a Wel researched thesis with a range of new nanomaterials for vegetable oils which are Karanja oil and castor oil. The 2D nanomaterials which were experimented by the author are (1) hybrid silicon dioxide/molybdenum disulphide, (2) Zinc Oxide/graphene oxide hybrid particles, (3) functionalized MXene, and (4) hybrid polymerized SiO2/functionalized hexagonal boron nitride. It is noted that each of the nanomaterials were fabricated by the author and then characterized using a number of chemical and surface analytical techniques such as X-ray diffraction, TEM, FTIR. Each designed lubricant was subjected to four-ball and/or sliding reciprocation tests for the evaluation of the tribological performances. Conclusions are drawn based on the detailed tribological test data, friction vibrational data and scanning electron microscopy for each formulated lubricant. Some attempts were made by the author to provide friction model and wear mechanisms. It was found that, after many optimization experiments, each of the 2D nanomaterials added vegetable oil lubricants provided results which were better than the respective pure vegetable oil results. Overall, this PhD thesis has contributed to science and technology in tribology by proposing several new nanomaterial additives for vegetable oils. These modified oils can be used for several demanding tribological applications

	in the future. Most importantly, this work has contributed towards green tribology and sustainability by using renewable source of base oil rather than mineral oil. Some of the drawbacks which were found in the thesis are listed below
Query 1	In the abstract page xx, wear rate has been mentioned as mm which is incorrect units for wear rate. It should be presented as $mm^3/N\text{-}m$. Can author give the wear rate in proper units both in the abstract and in the chapters where the data are presented? Without this, a comparison with other lubricants is impossible.
Response	Thank you for the correction. The sliding reciprocating test results are presented in terms of wear rate, whereas the four-ball tests were conducted and reported in accordance with ASTM standards D4172, D5183, and D2783. As per ASTM guidelines, the results are represented in volumetric terms.
Query 2	Section 1.1.2, page 3:"The simplest classification of wear is mild or severe depending upon the severity of the loading conditions. " It is quite incorrect to say that wear classification is only mild wear. The author should list down all the types of wear processes.
Response	Thank you for the suggestions. Following section have been improved with addition of all types of wear processes.
Query 3	Section 2.2: Calling Animal fats-based lubricant as sustainable would be quite questionable. Author can just explain all the possible base oils, including mineral oils, and then mention which ones could be considered as sustainable or at least less harmful to the environment than others.
Response	Thank you for the suggestion. The section has been enhanced by including information on mineral oils, along with their advantages and disadvantages.
Query 4	Figure 2.1 seems to be quite unnecessary. If the author has included all the important papers in the literature survey, then it is not necessary to present this graph.
Response	Figure 2.1 has been removed from the thesis.

Query 5	Section 2.10: The objectives should not be written as "needed" or "required" etc. but rather What the author is going to conduct during this thesis work. It should be more like deliverables than a wish list.
Response	The objective section has been improved as per the examiner's suggestions.
Query 6	The author has presented and explained synthesis of the 2D materials. However, there is no evidence that these were done for the first time by the author, or, was already a published work by previous researchers? I cannot see his papers as first author for the synthesis work. If these synthesis methods were developed by other researchers, then proper credit should be given. I do not see any citation in sections 3.1.3.4, 3.1.3.5 etc.
Response	Thank you for pointing out missing points. The section has been improved with missing references. Some particles synthesized by author are not published yet these are in pipeline hence the references are not added for those particles.
Query 7	The schematic of the figure 3.5 is very different from the cone on plate geometry for the rheometer. The author should clarify if this geometry, as presented in the thesis, is correct. What is the reference? Please provide.
Response	Two different geometries are used for rheological studies. 1st viscosity has been measured with cone on plate arrangement and the Stribek characteristics of lubricant is measured using ball on 3 plate geometry which is presented in Figure 3.5. To ensure the clarification the figure caption have been modified.
Query 8	The calculation for Equation 3.6 should be provided with reference.
Response	All calculation has been given at the end in Appendix section. Section A of appendix shows the calculation of equation 3.6.
Query 9	Fig. 3.8 is not very clear or informative. A schematic would be better to explain how vibration signature is collected and analyzed.
Response	Author deeply acknowledges examiners remarks. Author has included schematic presentation of the setup for friction induced vibration measurement as per examiners suggestions.

Query 10	Magnification scale bar and the text in many of the SEM images are not clear. One can over write to make them clear.
Response	Thank you for pointing out corrections. All SEM figures have been improved by adding extra thick line so to make scale line visible.
Query 11	Figure 4.8: In figure (a), the typical pure oil COF shows throughout low. Hence, one would expect the average value to be lower when compared to SiO2/MoS2 But this is not the case in Fig (b). Can author explain why? These figure texts have very low resolution. Kindly improve.
Response	Figure 4.8 (a) shows the coefficient of friction (COF) versus time plot in which the green color line represents the pure oils COF and blue line represent SiO_2-MoS_2 COF. As depicted from the figure it is clear that COF of pure oil is all time higher than the hybrid's COF which is also shown in their average values.
Query 12	The AFM work presented in Section 4.4.2 is very hard to integrate in the thesis. The scan size for AFM is hardly 50x50 micron (not visible in figure 4.11). It cannot be compared to the macroscopic behavior of the lubrication study that has been performed using large sized specimens. The results at such a small scan size would be very subjective to the location one selects. Author should explain this.
Response	The author sincerely thanks the examiner for this valuable observation. It is indeed acknowledged that Atomic Force Microscopy (AFM) provides localized surface information over a very limited scan area (70 × 70 µm in this study), which cannot directly represent the entire wear scar, especially when macroscopic tests like the four-ball tribotest generate wear scars up to ~900 µm in diameter. To reduce location-specific bias and enhance representativeness, eight distinct AFM scans were performed across different regions of each wear scar. Although these scans still represent only a fraction of the total worn area, averaging the surface roughness parameters from these multiple locations helps in capturing broader trends. The AFM images presented in Figure 4.11 highlight the smoothest of the scanned regions to allow clearer visual comparison between different lubricant conditions. While the scale mismatch between AFM and macroscopic testing is recognized, the AFM results are

	intended to provide complementary nanoscale insight into surface features and wear mechanisms, supporting the broader tribological findings.
Query 13	Page 84: Author claims that SiO_2/MoS_2. particle would roll. However, for such a small particle size there is no evidence that they will roll at the interface. The particle, even though very round, are very rough. Author should provide any evidence of rolling or remove this claim from the explanation. In Section 5.8, the phrase "nano-rolling" has been used which is a misnomer. It can be simply rolling.
Response	Thank you for your valuable comment regarding the mention of the rolling behavior of SiO_2/MoS_2 nanoparticles at the tribo-interface. I agree that direct evidence of rolling at such small scales remains challenging to obtain experimentally due to limitations in in-situ characterization techniques. However, the claim of a rolling mechanism is supported by prior literature where spherical or near-spherical nanoparticles particularly hard oxide-based materials such as SiO_2 have been hypothesized to contribute to reduced friction through a rolling or micro-rolling effect. For example, studies have suggested that under appropriate load and surface energy conditions, such spherical particles can intermittently act like nano-ball bearings between contact surfaces (Ref: (Kim et al., 2009; Kotia et al., 2019; Wu et al., 2017)). In the present case, although direct visual confirmation is not available, the observed reduction in coefficient of friction and specific surface wear patterns are consistent with the hypothesized rolling contribution of the dispersed nanoparticles. The morphology and sphericity of the SiO_2 particles were confirmed via SEM/TEM, which further supports the plausibility of this mechanism. Additionally, in response to your observation, the term "nano-rolling" has been revised to "rolling" throughout the manuscript to avoid any ambiguity or misrepresentation. , I.-Y., Lee, J.-H., Lee, G.-S., Baik, S.-H., Kim, Y.-J., & Lee, Y.-Z. (2009). Friction and wear characteristics of the carbon nanotube–aluminum composites with different manufacturing conditions. *Wear*, *267*(1–4), 593–598.

	a, A., Ghosh, G. K., Srivastava, I., Deval, P., & Ghosh, S. K. (2019). Mechanism for improvement of friction/wear by using Al2O3 and SiO2/Gear oil nanolubricants. *Journal of Alloys and Compounds*, *782*, 592–599. https://doi.org/https://doi.org/10.1016/j.jallcom.2018.12.215 Wu, H., Zhao, J., Xia, W., Cheng, X., He, A., Yun, J. H., Wang, L., Huang, H., Jiao, S., Huang, L., Zhang, S., & Jiang, Z. (2017). A study of the tribological behaviour of TiO2 nano-additive water-based lubricants. *Tribology International*, *109*, 398–408. https://doi.org/https://doi.org/10.1016/j.triboint.2017.01.013
Query 14	Section 5.7: This statistical analysis seems to have very poor scientific basis. COF prediction using so many parameters is quite a challenge, One cannot predict COF for even slightly beyond those parametric values, Therefore, presentation of such a model in a scientific thesis is very questionable to this examiner
Response	We respectfully acknowledge the examiner's concern; however, the COF prediction using Response Surface Methodology (RSM) in our study is strictly limited to the local vicinity of the experimental design space and is not intended for extrapolation beyond tested ranges. RSM is a well-established empirical tool used in tribology to understand multi-factor interactions and optimize responses within a defined domain. The model was developed using a statistically designed experiment and validated through ANOVA, R^2, and residual analysis, confirming its adequacy within the experimental bounds. Its purpose is to provide engineering insights into parameter effects, not to claim universal predictability, and these limitations have been clearly stated in the updated thesis.
Query 15	Section 6.6: Author says that tribo-film formation was observed. However, no evidence has been shown. In Section 6.4.1, kindly show the evidence of film formation by the availability of such chemical species in abundance at the surface. When wear is high, formation of such a tribo-film can be difficult.
Response	Author deeply acknowledges examiners obervation. The following image has been updated with mapping along with the EDS spectra results of the worn surface as a proof of formation of tribofilm on the surface. The mapping shows the presence of Ti elements which shows the formation of MXene layer over the tribo-surface. Whereas additional Si and N elements are found on the surface of the wear scar which confirms the tribolayer formation of fMXene layers. At high load film break occurs

	which has been a major cause of lubrication failure in boundary regime which is been tested and analyzed using friction induced vibration in 7th chapter.
Query 16	Conclusion section at the end of Chapter 7 is missing.
Response	Author would like to express his sincere gratitude to examiner. The chapter summary (section 7.7) of the 7th chapter has been included in the updated thesis.
Query 17	This thesis work should have included a comparison study of the newly formulated oils with a typical mineral oil. Without this comparison, the claim about the effectiveness of the newly formulated oils could not be ascertained or claimed.
Response	The primary objective of this thesis is to explore and enhance the potential of bio-based oils as sustainable alternatives to conventional lubricants for green tribological applications. Accordingly, two bio-based oils currently in industrial or experimental use were selected chemically modified and 2D hybrid nanolubricant blended to improve their tribological performance. the tribological benchmarks of mineral oils have been referred to wherever relevant, including standard performance metrics available in the literature and ASTM standard values. Since the thesis is aligned with green lubrication, the core comparative value was placed between unmodified and modified biolubricants to evaluate how effectively green alternatives can be optimized, rather than proving them superior to mineral oils in absolute terms. However, it is acknowledged that a direct experimental comparison with a standard mineral oil could further substantiate the effectiveness of the proposed formulations. This could be considered a valuable extension for future work or a broader application-focused study.
Query 18	Chapter 8, Section 4: This section is not about conclusions. It just tells about the tests, so this section should be removed. Similarly, Section 5 should be removed.
Response	Following section has been removed in the revised thesis.
Query 19	Overall, this study lacks

	(a) a comparison with well-known mineral base oil (b) long term chemical stability data (c) extensive wear studied in terms of specific wear rate and long-term performances.
Response	Thank you for the valuable observations. The following points address the concerns raised: (a) Comparison with Mineral Base Oil: The core objective of this thesis is to investigate bio-based alternatives and their enhancement through chemical modifications and nano-additive addition. While a direct experimental comparison with conventional mineral oil was not included, standard benchmarks and tribological data of mineral oils from ASTM references and relevant literature have been incorporated for contextual understanding. The scope of this work primarily focused on comparing the base bio-oils with their modified versions to evaluate the extent of performance enhancement achievable within green lubrication paradigms. (b) Long-Term Chemical Stability: The long-term chemical stability of nanolubricants was studied in terms of visible agglomeration and sedimentation behavior, which was monitored over a period ranging from 120 to 280 hours. This period allowed the assessment of dispersion stability and practical handling feasibility of the nanolubricants. However, detailed degradation properties under prolonged storage and post-storage performance were not explored due to time and infrastructural constraints. These aspects are recognized as valuable areas for future study. (c) Extensive Wear and Long-Term Performance Tests: The long-term wear performance was evaluated using ASTM D 5183, a rigorous boundary lubrication test that runs continuously till failure, almost 3 to 5 hours (in our case). This method provides insight into frictional stability, surface protection, and seizure resistance under prolonged operating conditions. The study primarily emphasizes the initial and mid-term tribological performance of the nanolubricants, with following standard test methods and representation suggested by American Society of Testing and Material (ASTM). However, specific wear rate for sliding reciprocating test has been included.

	Some limitations are acknowledged, the thesis has attempted to address core aspects of tribological and chemical behavior within the targeted scope, and future work can further build upon these foundations.