7 Conclusions and scope for future work

This chapter presents the key findings of the thesis work based on the tribological study of mineral and vegetable oil–based lithium greases with and without nanoadditives. Finally, the chapter sums up the scope of future work for further development.

7.1 Conclusions

The formulations, usage, and disposal of lubricants in a sustainable manner are gaining increasing attention to avoid their adverse effects on the eco–system. The vegetable oil–based lubricants show immense interest as a green and clean alternative to the mineral oil–based system because of their inherently high lubrication properties, excellent biodegradability, large viscosity index, good affinity towards metal surfaces, and low volatility. Therefore, the present work is intended to develop vegetable oil–based greases to provide an energy–efficient and sustainable alternative to conventional grease.

The objective of the dissertation is focused on the comparative tribological study of mineral and vegetable oil–based greases thickened with lithium soap dispersion. The thickener concentration was fixed at 14 wt%. The high mechanical strength, low shearing properties, and good affinity to interact with tribo–interfaces under the high contact–stress, make the nanomaterials as potential additives to a diversified range of lubricating oils/greases for enhancement of tribological properties. In this context, the nanostructured materials of different shapes and sizes have been synthesized and used as nanoadditives to mineral and vegetable oils–based greases.

The variable concentrations (i.e., 0.01–0.05 wt%) of nanoadditives (i.e., MoS_2, MoS_2–ODT, GO, rGO, and GO–ODA) were used in paraffin oil–based grease, and their effect on physicochemical and tribological properties was evaluated as per ASTM standards. The AW and load–bearing capacity of formulated grease samples were evaluated using the four–ball tester under the boundary lubrication regime. Thereafter, the variable concentrations of same nanoadditives were also used in castor oil–based grease and probed the effect of nanoadditives on the physicochemical and tribological properties as per ASTM standards.

In the next part of the work, vegetable oil–based grease was developed using coconut oil as a base stock and lithium soap as a gelling agent. The blends of spherical SiO_2 nanoparticles with MoS_2 and GO nanosheets in different weight ratio are thoroughly dispersed during the formulation of coconut oil–based greases. The dosage of the nanoadditives mixture was fixed at 0.05 wt% for all formulations. The synergistic effect of two different morphologies (SiO_2 nanospheres and MoS_2 or GO nanosheets) of nanoadditives on the physicochemical and tribological properties of greases was evaluated and demonstrated the lubrication mechanisms by emphasizing their roles.

The major conclusions based on present experimental studies are summarized in subsequent sections.

7.1.1 Conclusions on nanoadditives

The MoS_2, MoS_2–ODT, GO, rGO, GO–ODA, and SiO_2 nanoadditives have been synthesized successfully. The various characterization techniques confirmed the synthesis of these nanoadditives. The MoS_2 and MoS_2–ODT nanomaterials have hair–like thin sheets in stacking of 4–12 thick molecular lamellae and their interlayer spacing was estimated to 0.623 nm. The GO, rGO, and GO–ODA nanomaterials have also sheet like structure, and their interlayer spacing was estimated to 0.81, 0.35, and 0.42 nm, respectively. The shape of SiO_2 nanomaterials was almost spherical, and its diameter was ranged from 20 to 35 nm.

7.1.2 Conclusions on tribological study of greases without nanoadditives

The comparative tribological study of mineral (paraffin) and vegetable oil–based (i.e., castor and coconut) greases thickened with lithium soap dispersion are presented. Paraffin oil–based grease is used as reference for comparing the various physicochemical and tribological properties with castor and coconut oil–based greases. The lubrication effect of all grease samples was assessed using the four–ball tester as per ASTM standard. The test results were compared and found the following observations.

- Based on calculated film thickness, it is observed that the tribo–pairs were operated under the boundary lubrication regime.
- There was no significant difference in drop point between castor grease, coconut grease, and paraffin grease. It suggests that castor grease and coconut grease have equivalent drop points as paraffin grease.
- The NLGI number of paraffin grease and castor grease was found to be one, and for coconut grease, it was two. This improvement suggests that the consistency of coconut grease is better than paraffin grease.
- The castor grease performed better than paraffin grease and showed reduction of COF, WSD, and MWV by ~24%, ~20%, and ~60% for steel tribo–pair. Likewise, coconut grease showed ~10%, ~2%, and ~9% lower COF, WSD, and MWV, respectively compared to paraffin grease.
- The load–carrying capacity of castor, coconut greases was found equal to the paraffin grease. The non–seizure and weld loads for all grease samples were found 126 and 160 kgf, respectively.

7.1.3 Conclusions on tribological study of greases with nanoadditives

The comparative tribological study of paraffin oil and castor oil–based lithium greases having variable nanoadditives were carried out. The concentrations of nanoadditives were varied in a range of 0.01 to 0.05 wt%. Paraffin oil–based grease is used as reference grease for comparing the various physicochemical and tribological properties of paraffin and castor greases enriched with nanoadditives. The four–ball tester was used to assess the lubrication behavior of all grease samples as per ASTM standard. The overall comparative improvement in antifriction (AF) and antiwear (AW) performance of all grease samples are summarized in **Table 7.1**. Further, some other important observations were found on comparing the physicochemical and tribological properties of all the grease samples, which are as follows:

- The consistency of paraffin grease was deteriorated in the presence of MoS_2 and MoS_2–ODT nanosheets, while it was improved slightly in the presence of GO, rGO, and GO–ODA nanosheets than paraffin grease.
- The consistency of castor grease deteriorated in the presence of MoS_2, MoS_2–ODT, GO, rGO, and GO–ODA nanosheets than castor grease.
- The addition of nanoadditives does not show any significant improvement in drop point of paraffin grease and castor grease.
- No change was observed in the EP property of paraffin grease and castor grease in the presence of MoS_2, MoS_2–ODT, GO, rGO, and GO–ODA nanosheets.
- The presence of optimized dosage of MoS_2, MoS_2–ODT, GO, rGO, and GO–ODA nanoadditives in paraffin grease conserved the energy by ~43%, ~43% ~34%, ~50%, and ~34%, respectively.

- The presence of optimized MoS_2, MoS_2–ODT, GO, rGO, and GO–ODA nanoadditives in castor grease conserved the energy by ~50%, ~38% ~65%, ~67%, and ~50%, respectively.
- The rGO nanosheets showed best performance among all nanoadditives for paraffin grease and castor grease.

Table 7.1: Summary of overall comparative improvement in AF and AW performance

Grease composition	Nanoadditives	AF performance		AW performance	
		% Improvement	Concentration (wt%)	% Improvement	Concentration (wt%)
Paraffin oil–based lithium grease	MoS_2	43	0.04	55	0.04
	MoS_2–ODT	43	0.01	61	0.04
	GO	34	0.01	87	0.01
	rGO	50	0.01	86	0.01
	GO–ODA	34	0.05	81	0.05
Castor oil–based lithium grease	MoS_2	50	0.02	11	0.02
	MoS_2–ODT	38	0.02	49	0.01
	GO	65	0.05	76	0.05
	rGO	66	0.01	83	0.01
	GO–ODA	50	0.03	83	0.04

7.1.4 Conclusions on tribological study of greases with synergistic effect of nanoadditives

The comparative tribological study of coconut oil–based lithium grease enriched with the blend of spherical SiO_2 nanoparticles with MoS_2 or GO nanosheets in different weight ratios as additives is addressed. The concentration of nanoadditives mixture was fixed at 0.05 wt%. The synergistic effect of two different morphologies (SiO_2 nanospheres and MoS_2 or GO nanosheets) of nanoadditives on the physicochemical and tribological properties of coconut grease was investigated as per ASTM standards. The tribological performance of all grease samples was evaluated using the four–ball tester. The physicochemical and tribological properties of coconut grease with and without blend of nanoadditives were compared the following observations are made:

- The consistency and drop point of coconut grease did not improve in the presence of blend of nanoadditives.
- The addition of blend of nanoadditives did not show any change in the extreme pressure property of coconut grease.
- The optimized blend of MoS_2/SiO_2 (30:70) and GO/SiO_2 (50:50) showed a significant reduction in COF, WSD, and MWV, driven by the synergistic their effect.
- The MoS_2/SiO_2 (30:70), and GO/SiO_2 (50:50) blends in coconut grease conserved the energy by ~20% and ~19%, respectively.

7.1.5 Overall general conclusions

The overall conclusions of the thesis work are as follows:

- The promising physicochemical and tribological results of castor and coconut grease suggest that vegetable oil–based greases can be suitable alternatives to conventional greases. Additionally, the vegetable oils are superior lubricants at boundary lubrication conditions.
- The addition of infinitesimal concentration of nanoadditives in grease does not significantly improve the physicochemical properties.
- No change was observed in the extreme pressure property of coconut grease by adding an infinitesimal concentration of nanoadditives.
- The presence of minute dosage of nanoadditives in grease has shown remarkable improvements in AF and AW properties.
- Comparisons of energy–saving results revealed that a minute dosage of nanoadditives in grease has a promising ability to conserve the energy.
- The formation of MoS_2–based and graphene–based tribo–film on interacting surfaces as deduced from microscopic and spectroscopic analyses facilitated the shearing under tribo–stress and protected the tribo–interfaces against the wear.
- The finding promises the potential of graphene–based nanoadditives for the formulation of new generation grease, which can even replace the conventional FMs and AW additives.

7.2 Scope for the future work

The global demand and advancement in lubrication technologies, particularly environment viewpoint, are gaining increasing attention for the development of new formulations. In this context, efforts are made to minimize the dependence on crude oil–based lubricant products, which can inhibit the adverse effect on the environment. Therefore, a suitable substitute is required for conventional lubricants, which have at least equal or better lubrication performance and minimum environmental footprint. The present work systematically investigated the physicochemical and tribological performance of vegetable oil–based greases with and without nanoadditives. Nevertheless, adequate research work is required to enhance the tribological performance of the bio–greases. The recommendations for the future work which can be explored are as follows:

- Synthesis of biodegradable greases that replaces conventional thickener and then evaluation for tribological performance with the variable doses of various nanoadditives.
- The chemical modification (i.e., epoxidation, hydrogenation, or transesterification) can ameliorate the oxidation stability of the vegetable oils and refurbish them into a suitable lubricant application. The chemically modified vegetable oil can be explored as a base stock for grease formulation.
- The effects of various operating parameters on bio–greases with/without nanoadditives need to explored in a greater detail.
- The blending of different vegetable oils in the formulation of bio–greases to achieve a satisfactory level of performance.