

# Contents

---

<b>Certificate .....</b>	<b>ii</b>
<b>Acknowledgements .....</b>	<b>v</b>
<b>Abstract.....</b>	<b>x</b>
<b>Contents .....</b>	<b>xiii</b>
<b>List of figures.....</b>	<b>xix</b>
<b>List of tables.....</b>	<b>xxviii</b>
<b>Abbreviations/symbols .....</b>	<b>xxxi</b>
<b>1 Introduction.....</b>	<b>1</b>
1.1 Tribology.....	1
1.2 Role of lubricants in tribology .....	2
1.3 Classification of lubricants .....	3
1.4 Current status of lubricant market.....	5
1.4.1 Global and domestic market of liquid lubricants.....	5
1.4.2 Global and domestic market of greases .....	6
1.5 Nanomaterials .....	7
1.6 2D lamellar materials.....	8
1.7 Green tribology .....	11
1.8 Need of green lubrication.....	12
1.9 Summary of the chapter .....	12
<b>2 Literature survey .....</b>	<b>15</b>
2.1 Introduction.....	15
2.2 Advantages of greases over lubricants.....	16

2.3	Grease composition.....	16
2.3.1	Lube base oil .....	17
2.3.1.1	Mineral oil.....	17
2.3.1.2	Synthetic oil .....	21
2.3.1.3	Vegetable oil .....	21
2.3.2	Thickener .....	23
2.3.2.1	Soap thickener.....	24
2.3.2.2	Non-soap thickener .....	26
2.3.2.3	Mixed thickener .....	26
2.3.3	Additives .....	27
2.4	Role of additives .....	29
2.5	Basic process for grease formulation.....	31
2.6	Grease structure .....	33
2.7	Bio-greases .....	35
2.8	Review on tribological studies of greases.....	36
2.8.1	Review based on mineral oil-based greases.....	37
2.8.2	Review based on synthetic oil-based greases.....	43
2.8.3	Review based on vegetable oil-based greases.....	46
2.9	Problem formulation .....	50
2.9.1	Motivation.....	50
2.9.2	Problem definition .....	51
2.10	Objective of work .....	52
2.11	Research plan methodology.....	54
2.12	Summary of the chapter .....	55

<b>3</b>	<b>Experimental details .....</b>	<b>57</b>
3.1	Materials .....	57
3.1.1	Base oil.....	57
3.1.2	Grease thickener.....	59
3.1.3	Chemical used in the synthesis of nanoadditives.....	59
3.2	Synthesis of nanoadditives.....	60
3.2.1	Synthesis of MoS <sub>2</sub> and MoS <sub>2</sub> -ODT nanosheets .....	60
3.2.2	Synthesis of GO, rGO, and GO-ODA nanosheets .....	63
3.2.3	Synthesis of SiO <sub>2</sub> nanoparticles.....	66
3.3	Characterization of nanomaterials .....	67
3.3.1	Transmission electron microscope (TEM).....	67
3.3.2	X-ray diffractometer (XRD) spectroscopy.....	67
3.3.3	Fourier transform infrared (FTIR) spectroscopy .....	68
3.4	Synthesis of grease.....	69
3.5	Characterization of greases .....	70
3.5.1	Characterization of physicochemical properties of greases.....	70
3.5.1.1	Consistency .....	70
3.5.1.2	Drop point.....	73
3.5.2	Thermogravimetric analysis (TGA) of greases.....	75
3.5.3	Microstructural study of greases .....	75
3.5.4	Rheological study of greases .....	76
3.5.5	Characterization of tribological properties of grease using four-ball tester.....	76
3.5.6	Characterization of tribological properties of grease using SRV-5 machine.....	79

3.6	Characterization of worn surfaces .....	81
3.6.1	Scanning electron microscope (SEM) and Energy–dispersive X–ray spectroscopy (EDS) .....	81
3.6.2	X–ray photoelectron spectroscopy (XPS).....	81
3.6.3	Scanning probe microscope (SPM) .....	82
3.7	Summary of the chapter .....	82
<b>4</b>	<b>Tribological evaluation of mineral oil–based greases.....</b>	<b>83</b>
4.1	Characterization of MoS <sub>2</sub> and MoS <sub>2</sub> –ODT nanosheets .....	83
4.2	Characterization of GO, rGO, and GO–ODA nanosheets .....	87
4.3	Physicochemical characterization of paraffin greases .....	93
4.4	Tribological performance of paraffin greases on four–ball tester .....	97
4.5	Microstructural properties of the paraffin grease.....	103
4.6	Rheological behavior of grease.....	104
4.7	Study of worn surfaces tested on four–ball tester .....	107
4.8	Tribological performance of greases on SRV–5 machine .....	116
4.9	Study of worn surfaces tested on SRV–5 machine.....	118
4.10	Discussion .....	123
4.11	Summary of the chapter .....	129
<b>5</b>	<b>Tribological evaluation of castor oil–based greases.....</b>	<b>131</b>
5.1	Characterization of nanoadditives.....	131
5.2	Physicochemical properties of castor grease .....	131
5.3	Tribological performance of castor greases on four–ball tester.....	134
5.4	Study of worn surfaces.....	139
5.5	Discussion .....	146
5.6	Summary of the chapter .....	149

<b>6</b>	<b>Tribological evaluation of coconut oil–based greases with synergistic effect of additives .....</b>	<b>151</b>
6.1	Characterization of nanoadditives.....	151
6.2	Physicochemical characterization of coconut greases .....	152
6.3	Tribological performance of greases on four–ball tester .....	155
6.4	Evaluation of worn surfaces.....	158
6.5	Discussion.....	165
6.6	Summary of the chapter .....	170
<b>7</b>	<b>Conclusions and scope for future work .....</b>	<b>171</b>
7.1	Conclusions.....	171
7.1.1	Conclusions on nanoadditives.....	172
7.1.2	Conclusions on tribological study of greases without nanoadditives .....	173
7.1.3	Conclusions on tribological study of greases with nanoadditives .....	174
7.1.4	Conclusions on tribological study of greases with synergistic effect of nanoadditives .....	176
7.1.5	Overall general conclusions.....	176
7.2	Scope for the future work .....	177
	<b>References.....</b>	<b>179</b>
	<b>Appendix–A.....</b>	<b>195</b>
	<b>Appendix–B .....</b>	<b>197</b>
	<b>Appendix–C.....</b>	<b>203</b>
	<b>Appendix–D.....</b>	<b>209</b>
	<b>Appendix–E.....</b>	<b>215</b>
	<b>Appendix–F .....</b>	<b>217</b>

<b>List of publications.....</b>	<b>221</b>
<b>Conferences/symposiums .....</b>	<b>223</b>

## List of figures

---

<b>Figure 1.1:</b> Classification of lubricants based on their physical state, sources, and applications .....	4
<b>Figure 1.2:</b> Structural model of MoS <sub>2</sub> , representing the van der Waals interaction between .....	9
<b>Figure 1.3:</b> Structural model of graphene, representing the van der Waals interaction ...	10
<b>Figure 2.1:</b> Structure of (a) straight chain paraffin (b) branched chain paraffin (c) naphthenic and (d) aromatic molecules, key constituents of mineral lube base oils .....	18
<b>Figure 2.2:</b> Schematic representation of triglyceride structure, a constituent of vegetable oil .....	22
<b>Figure 2.3:</b> Classification of thickeners .....	25
<b>Figure 2.4:</b> Schematic demonstration on the role of nanoadditives in grease lubrication (a) rolling effect (b) mending effect (c) protective film (d) polishing effect .....	30
<b>Figure 2.5:</b> The scanning electron microscope image of 12–lithium hydroxy stearate soap network after extraction of lube base oil.....	34
<b>Figure 2.6:</b> Research plan methodology of the present study.....	55
<b>Figure 3.1:</b> Contact angle of (a) paraffin oil, (b) castor oil, and (c) coconut oil on the steel surface .....	58

<b>Figure 3.2:</b> Flowchart for the synthesis process of MoS <sub>2</sub> nanosheets by hydrothermal reduction .....	61
<b>Figure 3.3:</b> A schematic illustration on functionalization of MoS <sub>2</sub> nanosheets with ODT .....	62
<b>Figure 3.4:</b> A schematic illustration on the reduction of GO into rGO using hydrazine hydrate as reducing agent.....	64
<b>Figure 3.5:</b> A schematic illustration on functionalization of GO nanosheets with ODA molecules .....	65
<b>Figure 3.6:</b> Flowchart for synthesis process of SiO <sub>2</sub> nanoparticles by modified sol–gel method.....	66
<b>Figure 3.7:</b> The schematic diagram of cone penetration test set–up.....	71
<b>Figure 3.8:</b> The image of ¼ scale grease worker .....	72
<b>Figure 3.9:</b> The image of drop point equipment .....	73
<b>Figure 3.10:</b> Effect of thickener on the drop point of the grease .....	74
<b>Figure 3.11:</b> Schematic diagram of four–ball tester .....	77
<b>Figure 3.12:</b> Schematic diagram of the SRV test machine .....	79
<b>Figure 4.1:</b> X–ray diffraction patterns (a) MoS <sub>2</sub> and (b) MoS <sub>2</sub> –ODT nanosheets .....	84
<b>Figure 4.2:</b> FTIR spectra (a) MoS <sub>2</sub> and (b) MoS <sub>2</sub> –ODT nanosheets along with the vibrational features.....	85

<b>Figure 4.3:</b> Low and high resolutions TEM images of (a–b) MoS <sub>2</sub> and (d–e) MoS <sub>2</sub> –ODT nanosheets. TEM micrographs of (c) MoS <sub>2</sub> and (f) MoS <sub>2</sub> –ODT along with corresponding area elemental mapping. The lamellar structure of MoS <sub>2</sub> along with interlayer spacing is explicitly seen in high–resolution images.....	86
<b>Figure 4.4:</b> XRD patterns of GO, rGO, and GO–ODA nanosheets.....	89
<b>Figure 4.5:</b> FTIR spectra of (a) GO, (b) rGO, and (c) GO–ODA nanosheets along with assignments of vibrational peaks .....	90
<b>Figure 4.6:</b> TEM images of (a–b) GO, (c–d) rGO, and (e–f) GO–ODA at low and high resolutions .....	91
<b>Figure 4.7:</b> Microscopic images of (a) GO, (b) rGO, and (c) GO–ODA along with corresponding area elemental distribution based on EDS measurement .....	92
<b>Figure 4.8:</b> Variation in unworked and worked penetration depth of paraffin grease with and without nanoadditives .....	93
<b>Figure 4.9:</b> Variation in drop point of paraffin grease with and without nanoadditives...	95
<b>Figure 4.10:</b> Thermal degradation patterns of paraffin grease with and without nanoadditives .....	96
<b>Figure 4.11:</b> Variation in average COF with variable concentration of nanoadditives blended with paraffin grease. (Applied load: 392 N, test duration: 60 min) .....	98
<b>Figure 4.12:</b> Variation in COF with time for paraffin grease and its blend with nanoadditives. (Applied load: 392 N, test duration: 60 min).....	99

**Figure 4.13:** Variation in mean WSD with variable concentration of nanoadditives blended with in paraffin grease. (Applied load: 392 N, test duration: 60 min)..... 101

**Figure 4.14:** Variation in MWV of steel balls lubricated with paraffin grease and its blend with variable concentration of nanoadditives. (Applied load: 392 N, test duration: 60 min) ..... 102

**Figure 4.15:** SEM micrographs of (a) paraffin (b) GO (c) rGO, and (d) GO–ODA greases after extraction of oil..... 103

**Figure 4.16:** Shear stress vs. shear strain curve for paraffin, GO, rGO, and GO–ODA greases along with fitting of experimental results as per the Herschel–Bulkley model .. 105

**Figure 4.17:** Viscosity of paraffin, GO, rGO, and GO–ODA greases as a function of shear strain..... 106

**Figure 4.18:** Storage and loss modulus of paraffin, GO, rGO, and GO–ODA greases .. 107

**Figure 4.19:** SEM images of worn surfaces of steel balls lubricated with (a–b) paraffin grease, (c–d) 0.04 wt% MoS<sub>2</sub> blended grease (e,f) 0.04 wt% MoS<sub>2</sub>–ODT blended grease. (Applied load: 392 N, test duration: 60 min)..... 108

**Figure 4.20:** SEM images of worn surfaces of steel balls lubricated with (a–b) 0.01 wt% GO blended grease (c–d) 0.01 wt% rGO blended grease (e–f) 0.05 wt% GO–ODA blended grease. (Applied load: 392 N, test duration: 60 min)..... 109

**Figure 4.21:** Topographic images of the worn surfaces of steel balls lubricated with (a–b) paraffin grease, (c–d) 0.04 wt% MoS<sub>2</sub> blended grease (e,f) 0.04 wt% MoS<sub>2</sub>–ODT blended grease (Applied load: 392 N, test duration: 60 min)..... 110

**Figure 4.22:** Topographic images of the worn surfaces of steel balls lubricated with (a–b) 0.01 wt% GO blended grease, (c–d) 0.01 wt% rGO blended grease (e–f) 0.05 wt% GO–ODA blended grease. (Applied load: 392 N, test duration: 60 min) ..... 112

**Figure 4.23:** EDS spectra with elemental mapping of worn surfaces of steel balls lubricated with (a–b) paraffin grease (c–d) 0.04 wt% MoS<sub>2</sub> blended grease (e–f) 0.04 wt% MoS<sub>2</sub>–ODT blended grease. (Applied load: 392 N, test duration: 60 min)..... 113

**Figure 4.24:** EDS spectra with elemental mapping of worn surfaces of steel balls lubricated with (a) 0.01 wt% GO blended grease, (b) 0.01 wt% rGO blended grease (c) 0.05 wt% GO–ODA blended grease. (Applied load: 392 N, test duration: 60 min) ..... 115

**Figure 4.25:** Variation in (a) average COF with variable doses of GO, rGO, and GO–ODA in the greases (b) friction profiles with time and (c) MWV of steel tribo–pair lubricated with GO, rGO and GO–ODA greases. (Applied load: 200 N, stroke length: 1 mm, test duration: 120 min)..... 116

**Figure 4.26:** Worn surfaces of steel discs lubricated with (a) paraffin grease (b) 0.04 wt% GO blended grease, (c) 0.03 wt% rGO blended grease, and (d) 0.03 wt% GO–ODA blended grease. (Applied load: 200 N, stroke length: 1 mm, test duration: 120 min)..... 119

**Figure 4.27:** Worn surfaces of steel balls lubricated with (a) paraffin grease (b) 0.04 wt% GO blended grease, (c) 0.03 wt% rGO blended grease, and (d) 0.03 wt% GO–ODA blended grease. (Applied load: 200 N, stroke length: 1 mm, test duration: 120 min)..... 120

**Figure 4.28:** Surface profile of worn track developed on steel discs lubricated with (a) paraffin grease, (b) 0.04 wt% GO blended grease, (c) 0.03 wt% rGO blended grease, and

(d) 0.03 wt% GO–ODA blended grease. (Applied load: 200 N, stroke length: 1 mm, test duration: 120 min)..... 121

**Figure 4.29:** EDS spectra along with elemental mapping of worn steel discs lubricated with (a1–a5) paraffin grease, (b1–b5) 0.04 wt% GO blended grease, (c1–c5) 0.03 wt% rGO blended grease, and (d1–d6) 0.03 wt% GO–ODA blended grease. (Applied load: 200 N, stroke length: 1 mm, test duration: 120 min)..... 122

**Figure 4.30:** EDS spectra along with elemental mapping of worn scars of steel balls lubricated with (a1–a5) paraffin grease, (b1–b5) 0.04 wt% GO blended grease, (c1–c5) 0.03 wt% rGO blended grease, and (d1–d6) 0.03 wt% GO–ODA blended grease. (Applied load: 200 N, stroke length: 1 mm, test duration: 120 min)..... 123

**Figure 4.31:** Plausible lubrication mechanism revealing the role of nanosheets under the tribo–stress ..... 128

**Figure 5.1:** Variation in unworked and worked penetration depth of castor grease with and without nanoadditives ..... 132

**Figure 5.2:** Variation in drop point of castor grease with and without nanoadditives.... 133

**Figure 5.3:** Variation in average COF with variable concentration of nanoadditives in castor grease. (Applied load: 392 N, test duration: 60 min) ..... 134

**Figure 5.4:** Variation in COF for castor grease with and without nanoadditives with run time. (Applied load: 392 N, test duration: 60 min)..... 135

**Figure 5.5:** Variation in mean WSD with variable concentration of nanoadditives in castor grease. (Applied load: 392 N, test duration: 60 min)..... 137

**Figure 5.6:** Variation in MWV with variable concentration of nanoadditives in castor grease. (Applied load: 392 N, test duration: 60 min)..... 138

**Figure 5.7:** SEM images of worn surfaces of steel balls lubricated with (a–b) castor grease (c–d) 0.02 wt% MoS<sub>2</sub> nanosheets in grease (e–f) 0.01 wt% MoS<sub>2</sub>–ODT nanosheets in grease. (Applied load: 392 N, test duration: 60 min)..... 139

**Figure 5.8:** SEM images of worn surfaces of steel balls lubricated with (a–b) 0.05 wt% GO nanosheets in grease (c–d) 0.01 wt% rGO nanosheets in grease (e–f) 0.04 wt% GO–ODA nanosheets in grease. (Applied load: 392 N, test duration: 60 min)..... 140

**Figure 5.9:** Topographic images of the worn surfaces of steel balls used in the tribo–tests in the presence of (a–b) castor grease, (c–d) 0.02 wt% MoS<sub>2</sub> nanosheets in grease (e–f) 0.01 wt% MoS<sub>2</sub>–ODT nanosheets in grease. (Applied load: 392 N, test duration: 60 min) ... 141

**Figure 5.10:** Topographic images of the worn surfaces of steel balls used in the tribo–tests in the presence of (a–b) 0.05 wt% GO nanosheets in grease, (c–d) 0.01 wt% rGO nanosheets in grease (e–f) 0.04 wt% GO–ODA nanosheets in grease. (Applied load: 392 N, test duration: 60 min)..... 143

**Figure 5.11:** EDS spectra with elemental mapping of corresponding worn surfaces of (a– b) castor grease (c–d) 0.02 wt% MoS<sub>2</sub> nanosheets in grease (e–f) 0.01 wt% MoS<sub>2</sub>–ODT nanosheets in grease. (Applied load: 392 N, test duration: 60 min)..... 144

**Figure 5.12:** EDS spectra with elemental mapping of corresponding worn surfaces of (a– b) 0.05 wt% GO nanosheets in grease (c–d) 0.01 wt% rGO nanosheets in grease (e–f) 0.04 wt% GO–ODA nanosheets in grease. (Applied load: 392 N, test duration: 60 min) ..... 145

**Figure 5.13:** Plausible interaction between the fatty acids of castor grease and contact interfaces of steel balls. The fatty acids molecules formed the organized thin film over the steel surfaces, driven by tribo–stress ..... 147

**Figure 6.1:** Low and high–resolution TEM images of (a–b) SiO<sub>2</sub> nanoparticles ..... 152

**Figure 6.2:** (a) XRD pattern (b) FTIR spectrum of SiO<sub>2</sub> nanoparticles..... 152

**Figure 6.3:** Unworked and worked penetration measurements of coconut grease, having 0.05 wt% nanoadditives. The combinations of (a) MoS<sub>2</sub>/SiO<sub>2</sub>, and (b) GO/SiO<sub>2</sub> in their variable ratios are used as nanoadditives to coconut grease ..... 153

**Figure 6.4:** Dropping point measurement of coconut grease having 0.05 wt% of nanoadditives. The combinations of MoS<sub>2</sub>/SiO<sub>2</sub>, and (b) GO/SiO<sub>2</sub> in their variable ratios are used as nanoadditives to coconut grease..... 154

**Figure 6.5:** Changes in (a) COF, (b) WSD, and (c) MWV for steel balls using the coconut grease blended with binary combinations of MoS<sub>2</sub>/SiO<sub>2</sub> and GO/SiO<sub>2</sub> as nanoadditives. The wt% ratio of individual nanomaterials in each combination is varied to obtain the optimized tribo–performance. (Applied load: 392 N, test duration: 60 min) ..... 156

**Figure 6.6:** SEM images of worn steel balls lubricated with (a–b) coconut grease, (c–d) MoS<sub>2</sub>/SiO<sub>2</sub> blended grease, and (e–f) GO/SiO<sub>2</sub> blended grease. (Applied load: 392 N, test duration: 60 min)..... 158

**Figure 6.7:** (a) Quantitative estimation of different elements in the tribo–film deposited over the worn scars lubricated with coconut grease and nanoadditives blended grease samples. Microscopic images along with the corresponding area elemental distribution of

worn scars of steel balls lubricated with (b) coconut grease, (c) MoS<sub>2</sub>/SiO<sub>2</sub> blended grease, (d) GO/SiO<sub>2</sub> blended grease. (Applied load: 392 N, test duration: 60 min)..... 159

**Figure 6.8:** XPS (a) survey and (b) C 1s spectra of worn surfaces of steel balls lubricated with coconut grease, GO/SiO<sub>2</sub> blended grease, and MoS<sub>2</sub>/SiO<sub>2</sub> blended grease. The binding energy range of 287–291 eV is emphasized as Inset graphs of each C 1s spectrum to reveal the role of carboxylic groups in thin film formation..... 160

**Figure 6.9:** (a) Mo 3d and (b) S 2p spectra of worn steel balls lubricated with coconut grease, GO/SiO<sub>2</sub> blended grease, and MoS<sub>2</sub>/SiO<sub>2</sub> blended grease..... 162

**Figure 6.10:** (a–c) 3D and (d–f) 2D topographic images, (g–i) roughness profiles, and (j–l) bearing area ratio curve of worn steel balls lubricated with coconut grease, GO/SiO<sub>2</sub> blended greases, and MoS<sub>2</sub>/SiO<sub>2</sub> blended grease. (Applied load: 392 N, test duration: 60 min)..... 164

**Figure 6.11:** (a) Schematic representation of the plausible synergistic effect of nanoadditives in coconut grease. (b) Low–shearing property by nanosheets of MoS<sub>2</sub> and GO, (c) rolling effect by spherical SiO<sub>2</sub> nanoparticles, (d) synergistic effects by SiO<sub>2</sub> nanoparticles along with MoS<sub>2</sub> or GO nanosheets ..... 167

## List of tables

---

<b>Table 1.1:</b> Categorization of lube base oil as per API guidelines .....	4
<b>Table 1.2:</b> Forecast medium–term oil demand for period 2018–2024.....	5
<b>Table 1.3:</b> Percentage share of different types of grease production based on the type of thickeners .....	6
<b>Table 1.4:</b> Percentage excerpt of different kinds of base oils used for the production of lubricating greases .....	7
<b>Table 1.5:</b> Mechanical properties of 2D materials .....	10
<b>Table 2.1:</b> Basic physicochemical properties of different hydrocarbons–based mineral oils .....	20
<b>Table 2.2:</b> Comparison between physicochemical properties of mineral oil and vegetable oil .....	23
<b>Table 2.3:</b> Common examples of various kinds of additives used in the greases.....	28
<b>Table 2.4:</b> Tribological performance of mineral oil–based greases with numerous nanoadditives .....	39
<b>Table 2.5:</b> Tribological performance of synthetic oil–based greases with numerous nanoadditives .....	44
<b>Table 2.6:</b> Tribological performance of vegetable oil–based greases.....	48
<b>Table 3.1:</b> The physicochemical properties of paraffin, castor, and coconut oils.....	58

<b>Table 3.2:</b> List of chemicals used in the synthesis of nanoadditives .....	60
<b>Table 3.3:</b> Prescribed test conditions used for determination of the grease consistency ..	72
<b>Table 3.4:</b> Grades of grease classified by NLGI.....	72
<b>Table 3.5:</b> The details of specimens and test conditions used in four–ball tester .....	77
<b>Table 3.6:</b> The details of specimens and test conditions used in SRV–5machine .....	80
<b>Table 4.1:</b> Thermogravimetric analysis of various paraffin oil–based greases.....	97
<b>Table 4.2:</b> Energy saving with the use of MoS <sub>2</sub> , MoS <sub>2</sub> –ODT, GO, rGO, and GO–ODA nanoadditives in paraffin grease .....	100
<b>Table 4.3:</b> Rheological parameters calculated through the Herschel–Bulkley model by fitting the experimental results of shear stress vs. strain for paraffin, GO, rGO, and GO–ODA greases .....	105
<b>Table 4.4:</b> Roughness of worn surfaces of the steel balls lubricated with various paraffin greases.....	111
<b>Table 4.5:</b> Wear coefficient of paraffin grease with variable concentration of GO, rGO, and GO–ODA nanosheets.....	118
<b>Table 5.1:</b> Energy saving with the use of MoS <sub>2</sub> , MoS <sub>2</sub> –ODT, GO, rGO, and GO–ODA nanoadditives in castor grease .....	136
<b>Table 5.2:</b> Roughness of worn surfaces of the steel balls lubricated with various castor greases.....	142

**Table 6.1:** Energy saving by use of binary combinations of MoS<sub>2</sub>/SiO<sub>2</sub> and GO/SiO<sub>2</sub> as nanoadditives to coconut grease. .... 157

**Table 6.2:** Surface roughness parameters of worn surfaces of steel balls lubricated with coconut grease, MoS<sub>2</sub>/SiO<sub>2</sub> blended grease, and GO/SiO<sub>2</sub> blended grease ..... 164

**Table 7.1:** Summary of overall comparative improvement in AF and AW performance ..... 175