Chapter III

Castor oil as potential multifunctional additive in the formulation of eco-friendly lubricant

3.3.1 Introduction

The lubricants derived from petroleum based materials although exhibit satisfactory performance but create many environmental hazards due to their eco-toxicity and non-biodegradability. Moreover, the non-renewable sources of the commonly used lubricants are depleting and therefore their costs are increasing gradually. The use of bio-based resources for the preparation lubricant has solved this problem and simultaneously reduces environmental impacts significantly. Vegetable oils have potential advantages compared with synthetic petroleum resources owing to their biodegradable properties, low-toxicity and in many cases lower cost. They have excellent antiwear properties,[1–4] high viscosity index (VI),[5] low volatility,[5, 6] and enhanced extreme pressure (EP) additives performance.[7, 8] So, the use of vegetable oils or their derivatives as additives as well as base stocks to formulate environmental sustainable lubricant composition has attracted much attention recently. But, due to few drawbacks like poor fluidity at low temperature (pour point), poor oxidative stability, poor bio resistance and poor hydrolytic stability [9-12] the direct use of vegetable oils as lubricant base stock does not give satisfactory performance. However, these limitations can be mitigated by means of chemical derivatization e.g. epoxidation, metathesis, polymerization etc. of the oleo chemicals of the vegetable oils.[13-16] There are lots of examples where chemically modified vegetable oils have been used as additive or base stocks in the formulation of bio-lubricant.[17-22]

Castor oil from castor seeds contains high percentage of triacylglycerols of ricinoleic acid (85-95%) which is a C-18 fatty acid. It contains a double bond at C-9 and a hydroxyl group at C-12 (**figure 3.3.1**). The trifunctional nature of castor oil provides rigidity to the structure and the long fatty acid chain lends flexibility. Due to the unique oleo chemical properties castor oil can be used as a potential feedstock for a variety of end applications. It is widely used in diverse fields such as paints, adhesives, lubricants, pharmaceuticals, cosmetics, paper, rubber, agriculture etc. [23-28] The high flash point and polar functional groups of castor oil make it efficient in the application of automotive engine and gear box as lubricant.[28-30] Quinchia et al. studied tribological properties of sunflower, soybean and castor oil based lubricants and have found that castor oil showed the best tribological properties.[31] Chinchkar et al. have explained the application of castor oil as green lubricant.[32] The potential use of castor oil methyl esters as bio lubricants due to its high viscosity, low pour point, and good lubricity was explained by Madankar et al.[33] Copolymerization of castor oil with acrylates increase the polarity of the unit as well as enhance thermal and mechanical stability significantly.[34] However reports regarding the application of acrylate copolymers of castor oil as multifunctional additive for lubricant are very few.

Therefore, in this work the author have synthesized few polymeric materials by copolymerizing castor oil with dodecyl acrylate in different percentage ratios to get thermally stable, cost effective, better performing as well as eco-friendly lubricant additives. Dodecyl acrylate was chosen due to its long hydrocarbon chain which imparts better additive performance. The present work comprises preparation of copolymers of dodecyl acrylate with castor oil (CO) at different percentage compositions viz. 5%, 10%, 15%, 20% and 25% using AIBN initiator. Evaluation of the efficiency of the polymers as viscosity index improver (VII), pour point depressant (PPD) and antiwear additives in mineral base oil (paraffinic) were carried out according to respective standard ASTM methods. Similar experimental analysis with homopolymer of castor oil and dodecyl acrylate were also carried out to make a comparison with the co polymeric additives. Photo micrographic images were taken to study the action mechanism of the additives as pour point depressant.

3.3.2 Experimental section

3.3.2.1 Chemicals used

Refined castor oil (~85% unsaturation) was collected from local market and its fatty acid composition and properties are given in **table 3.3.1**. Toluene (GC 99.5%) was collected from Merck (Mumbai, India). AIBN (GC 98%), obtained from Spectrochem Pvt. Ltd. Mumbai (India) was recrystallized from $CHCl_3$-MeOH before use. Dodecyl acrylate (GC 90%, Aldrich, India) was used as received. Methanol (98%, Thomas Baker Pvt. Ltd.) was used after distillation. The mineral base oil (SN150) was collected from IOCL, Dhakuria, West Bengal, India and the properties are given in **table 3.3.2.**

3.3.2.2 Synthesis of the polymers

The copolymers were prepared through free radical polymerization method taking the monomers of castor oil and dodecyl acrylate (DDA) at different ratios (**table 3.3.3**) in presence of AIBN initiator. The polymerization was carried out in a three necked round bottom flask fitted with a magnetic stirrer, condenser, thermometer and an inlet for the introduction of nitrogen. In the flask, mixture of desired mass of castor oil and acrylate was heated to 90 ^{o} C and maintained for half an hour in minimum amount of toluene solvent.

Initiator AIBN (1% w/w, with respect to the total monomer) was then added and heated for 6 hour keeping the temperature constant at 90^{o}C. After the reaction is over, the product was poured into methanol with continuous stirring, filtered off and dried. The homopolymer of castor oil and DDA were also prepared in the similar procedure.

3.3.3 Measurements

3.3.3.1 Spectroscopic measurements

IR spectra were recorded on a Shimadzu FT-IR 8300 spectrometer using 0.1mm KBr cells at room temperature within the wave number range of 400 to 4000 cm^{-1}. NMR spectra were recorded in Bruker Avance 300 MHz FT-NMR spectrometer using a 5 mm BBO probe. $CDCl_3$ was used as solvent and tetramethylsilane (TMS) as reference material.

3.3.3.2 Molecular weight determination

The number average molecular weight (M_n) and weight average molecular weight (M_w) were measured by GPC method (polystyrene calibration) equipped with a 2414 detector, waters 515 HPLC pump and 717 plus auto sampler. Sample solutions (0.4% w/v in HPLC grade THF) are prepared by dissolving ~4 mg of polymer per ml THF and filtering (0.45-μm Millipore PTFE) to remove suspended particulates. The pump flow rate is 1.0 mL/min with THF as the carrier solvent, and injection volumes are set to 20 μL. The polydispersity index[35] which indicates the nature of the distribution of the molecular weights in the polymers was also calculated.

3.3.3.3 Thermo gravimetric analysis (TGA)

TGA data was measured on Shimadzu TGA-50 system, at a heating rate of 10^{o} C / min.

3.3.4 Performance evaluation

3.3.4.1 Evaluation of viscosity index (VI)

Viscosity index, an important parameter to determine the resistance of change of viscosity of the lubricant with temperature variation, was calculated according to ASTM D 2270-10. The kinematic viscosities which are essential to calculate the VI values of the lubricant composition were determined at 40^{o} C and 100^{o} C. Additives at different concentrations ranging from 1% - 5% (w/w) were blended with the lube oil to study the effect of concentration of additives on VI.

3.3.4.2 Evaluation of pour point

Pour points of the additive furnished base oils were determined according to the ASTM D 97-09 method using the cloud and pour point tester model WIL-471 (India).

3.3.4.3 Photographic images analysis

The photomicrograph showing wax behaviour of base oil (pour point = – 6° C) without and with polymers has been recorded. A Banbros polarizing microscope model BPL-400B was used for photographic analysis. The adopted magnification was 200X.

3.3.4.4 Evaluation of tribological performance

The antiwear performance in terms of wear scar diameter (WSD) and coefficient of friction (COF) of the lubricant compositions were evaluated by Four-ball wear test apparatus (FBWT) following the ASTM D 4172-94 method.[3] In this experiment 392 N (40 Kg) load at 75 ° C for 60 min was applied to measure the wear scar diameter (WSD). The diameter and rotating speed of the ball were 12.7 mm and 1200 rpm respectively. The coefficient of friction (COF) was also calculated by multiplication of the mean friction torque and spring constant.[35] The frictional torque on the lower balls may be expressed as;

$$\mu = T\sqrt{6}/3w \times r \qquad (1)$$

Where, μ = coefficient of friction, T = frictional torque in kg/mm, w = applied load in kg, r = distance from the centre of the contact surfaces on the lower balls to the axis of rotation, which is 3.67mm.

3.3.4.5 Biodegradability test

Biodegradability of the additives is tested through soil burial test (SBT) method as per ISO 846:1997 standard.[36] The soil sample was collected from North Bengal University campus having 25% moisture and pH 7.2. Percentage weight loss (PWL) of the polymer samples after a definite interval of times was calculated to determine the extent of degradation which was also confirmed by observing the shift in IR frequency of the ester carbonyl groups after the test. In the SBT method, a film was prepared by taking 1.5 g of each of the polymer samples separately and then buried in soil. Then the soils with the samples are incubated in a bacteriological incubator apparatus (Sigma Scientific Instruments Pvt. Ltd., Chennai, India) at 30° C with relative humidity of 60% for 3 months and thus subjected to the action of microorganisms present in the soil. After each regular interval of 15 days, the soil sample is taken out and washed with $CHCl_3$, purified and dried in an oven at 50 ° C. The dried samples weighed and decomposition was calculated in terms of percentage weight loss of the polymeric samples.[35]

3.3.5 Results and discussion

3.3.5.1 Spectroscopic data analysis

The homopolymer of DDA exhibited IR absorption band at 1722.5 cm^{-1} for the ester carbonyl group. The peaks at 2853.5 cm^{-1} and 2924 cm^{-1} are the characteristic of CH_3-CH_2- group. The peaks at 1456 cm^{-1} and 1164 cm^{-1} due to CO stretching vibration and absorption band at 720 cm^{-1} is due to bending of C-H bond (**figure 3.3.2**). The homopolymer of castor oil (CO) exhibited IR absorption band at 1735 cm^{-1} for the ester carbonyl group. The peaks at 2854 cm^{-1} and 2922 cm^{-1} are the stretching vibration of CH_3-CH_2- group. A broad peak at 3443 cm^{-1} is due to free –OH group present in castor oil (**figure 3.3.3**). The IR spectra of five copolymers (P-2 to P-6) are similar. The absorption band at 1732 cm^{-1} is due to ester carbonyl group. The peaks at 2853 cm^{-1} and 2924 cm^{-1} are the characteristic of CH_3-CH_2- group and a broad peak at 3445 cm^{-1} is due to –OH group (**figure 3.3.4**).

In the ^{1}H NMR spectra of homopolymer of DDA, the peaks at 3.63 ppm and 3.93 ppm indicate the protons of –OCH_2 group. The protons of CH_3 and CH_2 groups appear in the range of 0.88 - 1.81ppm (**figure 3.3.5**). In the ^{1}H NMR spectra of homopolymer of castor oil, the peaks in the range of 4.11- 4.32 ppm indicate the protons of –$COOCH_2$ group of castor oil. The peaks in the range of 3.60 – 3.71 ppm are for the –OH group of castor oil. The peaks ranging from 0.86 – 2.34 ppm are for the protons of sp^3 carbons. No peaks in the range of 5-6 ppm indicate the polymerization was carried out successfully (**figure 3.3.6**). In the ^{1}H NMR spectra of copolymers, the methyl protons appear in the range of 0.868 – 1.291 ppm, the methylene protons in the range of 1.466 – 1.596 ppm for all alkyl groups. The peaks in the range of 1.616 – 2.038 ppm appear for the protons of - COCH- group of alkyl acrylate. The peaks in the range of 2.215 – 2.318 ppm are for the – OH groups of ricinoleic acid present in castor oil. Peaks at 3.607 – 3.656 ppm indicate the protons of – OCH_2 of alkyl acrylate. The peaks in the range of 3.988 – 4.156 ppm indicate the protons of – $COOCH_2$ group of castor oil. No peaks in the range of 5-6 ppm indicate that polymerization was carried out successfully (**figure 3.3.7**).

In the ^{13}C NMR spectra of homopolymer of DDA, the ester carbonyl group appears in the range of 176.73-177.84 ppm and homopolymer of castor oil, the ester carbonyl group appears in the range of 172.93-177.41ppm. In the ^{13}C NMR spectra of copolymers (P-2 to P-6), the peaks in the range of 14.05 – 41.30 ppm appear due to carbons of all CH_3 and CH_2 groups. The peak at 58.11ppm represents the carbons of –OCH_2 groups of alkyl acrylate. The carbons of –$OOCH_2$ group of castor oil appear at 62.78-64.87 ppm. The peak at 71.50 ppm is the carbon which is joined to –OH group of castor oil. The peaks ranging from 166.31- 174.63 ppm confirm the carbons of ester groups. No peaks in the range of 120 – 150 ppm indicate that polymerization was carried out successfully (**figures 3.3.8, 3.3.9 and 3.3.10**).

3.3.5.2 Molecular weight data analysis

The experimental values of number average molecular weights (M_n), weight average molecular weights (M_w) and polydispersity indices (PDI) of the prepared polymers (P-1 to P-7) are given in **table 3.3.3**. From the experimental values, it is found that among the seven polymers, P-3 has highest molecular weight followed by P-4. This signifies that when the percentage of castor oil is 10, then degree of polymerization is highest and we get a long chain copolymer with narrow molecular weight distribution. Beyond this, with increasing CO in the backbone of DDA, the molecular weight values of the copolymers gradually decrease and the homopolymer of castor oil showed lowest molecular weight. Therefore, percentage of castor oil has a significant role during polymerization.

3.3.5.3 TGA data analysis

The TGA values of the seven polymers are given in **figure 3.3.11**. It is found that thermal stability of homopolymer of DDA (i.e. P-1) is higher among all the polymers and the stability decreases with increasing the percentage of castor oil in the copolymer composition. At 320^o C temperature the percentage of decomposition of the polymers from P-1 to P-7 are 20.48, 25.38, 29.11, 30.42, 35.48, 39.18 and 57.52 respectively. Whereas at 400 ^{o} C, the percentage weight loss of the polymers were 42.13, 47.19, 53.84, 55.47, 59.35, 66.72 and 98.79 respectively. The homopolymer of castor oil (P-7) showed highest degradation i.e. lowest thermal stability. Due to copolymerization of castor oil with DDA, the thermal stability increases. Therefore, copolymerization with DDA has a significant importance to improve thermal stability of castor oil.

3.3.5.4 Analysis of viscosity index (VI) data

VI was calculated by dissolving the prepared polymers (P-1 to P-7) at different concentrations from 1% to 5% (w/w) to the base oils. The experimental values of VI are given in **figure 3.3.12.** It is found that VI values increase with increasing the concentration of polymers in lube oil. The viscosity of lube oil decreases with increasing temperature but expansion of polymer molecules take place with increasing temperature. Because of this, the size of micelle increases. This increased in micelle size counterbalance the reduction of the viscosity of the polymer doped lube oil.[37] Therefore, with increasing the concentration of polymer in lube oil leads to an increase in the total volume of polymer micelle in lube oil, thus exerting higher thickening effect and improves the VI property.[38] It is also observed that the VI value increases by incorporation of castor oil in the backbone of homopolymer of DDA. This may be due to higher crosslink density of the copolymers.[39] The copolymer P-3

(DDA+10% CO) has highest effect on VI increment (76.5% ± 2 at 5% additive concentration) followed by P-4, P-5 and P-6 among the polymers. The higher VI values of the base oils blended with P-3 are due to greater volume of the solvated additive molecule i.e. micelle compared to others. This may be due to higher degree of polymerization of P-3 with a narrow molecular weight distribution compared to others which is reflected in its higher average molecular weights and lower PDI value.

3.3.5.5 Analysis of pour point data

The pour points of the lubricant compositions prepared by blending the additives at different concentration levels ranging from 1%–5% (w/w) are given in **figure 3.3.13**. All the polymers showed excellent results as PPD and the efficiency increases with increasing the concentration of polymers up to certain limit (4% concentration). This indicates that at this concentrations the polymer molecules interact with the paraffinic wax and decrease their crystals size.[40] The polymer P-2 has greater efficiency as PPD among the seven polymers followed by P-1 i.e. homopolymer of DDA. It may be due to smaller polymer molecules with polar alkyl side chains. The interaction between the short alkyl chain length and paraffin in the lube oil is more effective than long alkyl chain length and wax crystal formation is effectively inhibited.[41] Moreover, it is also found that with increasing the percentage of castor oil in copolymers, the efficiency as PPD decreases. It was further observed that when diluents like n-decane solvent (10% (w/w)) is added to the lubricant compositions, the pour point decreases to a certain extent. The decrease in pour point is due to dissolution of asphaltenes present in lube oil.[42, 43] Of course, due to addition of solvent (n-decane), the viscosity decreases to a certain extent, may be due to effect of dilution. The effect of solvent towards increment in pour points of the additive furnished lubricants is shown in **figure 3.3.14.**

3.3.5.6 Photo micrographic images analysis

Photo micrographic analysis was used to study the pour point and its mechanism of the lube oil without and with polymeric additives and is shown in **figure 3.3.15 (a-h).** The figure 3.3.15a is the photograph of lube oil (pour point = -6^{o} C) without any additives where there is large number of rod shaped wax crystals. The photo micrographic images of lube oil blended with different additives like P-1, P-2, P-3, P-4, P-5, P-6 and P-7 at 4% (w/w) concentration are shown in the figures 3.3.15 (b, c, d, e, f, g and h) along with the image of pure base oil. The results are in agreement with the pour point values determined by ASTM D97-09 method. A significant wax crystal modification is observed due to the addition of P-2, P-1 and P-3 in the base stock which are shown in figures 3.3.15c (pour point = -19^{o} C), 3.3.15b (pour point = − 17° C) and 3.3.15d ((pour point = − 17° C) respectively. The copolymers of DDA with 5% and 10% CO have greater pour point improvement capacities.

3.3.5.7 Analysis of tribological properties

The tribological properties of the lubricant compositions were determined by measuring WSD and COF values through FBWT apparatus applying 392 N load and shown in **figures 3.3.16** and **3.3.17** respectively. The anti wear performance of the base oil is significantly improved when the additives are blended with it and is reflected in the lower WSD and COF values of the lubricant compositions. The copolymers showed better result compared to the homopolymers of DDA and CO. The base oil blended with the copolymer of DDA with 10% CO i.e. P-3 at 5% concentration showed highest reduction in WSD (55.9±1.5%) and COF (60±1.5%) values compared to the other copolymers whereas the homopolymer of DDA showed minimal (43.8±1.4%). The film formed by the lubricant between the metal surfaces undergoing friction (through chemical and physical bonding between the functional groups of the additive molecules and metal atoms on the surface area of the rubbing zone) protect against wear during terbochemical process. The copolymers due to more polar ends which are definitely due to polar hydroxyl groups of CO counterpart formed stronger layer with metal atoms and perform better tribological performance compared to the homopolymer of DDA. The better antiwear performance of the copolymer P-3 in base oil indicated that the film formed by the lubricant is strengthened mostly. The higher degree of polymerization with narrow molecular weight distribution and higher number of polar side chains of the ester carbonyl groups and hydroxyl groups of P-3 are probably the reasons for exhibition of its better antiwear performance.[44-46]

3.3.5.8 Analysis of biodegradability test results

The results of SBT test are mentioned in **figure 3.3.18**. The degradation of homopolymer of DDA by the microbes in soil is very low and even after 90 days only 1.05 percent was decomposed. Significant biodegradation was observed due to copolymerization of DDA with castor oil and the percentage of decomposition increases with increasing castor oil in the copolymer composition. It was also found that the degradation of the recovered samples taken every 15 days increases with increasing time. The homopolymer of castor oil showed highest degradation and after 90 days' span the recovered sample showed 32.2±2 % weight loss. P-6 showed 20.21±2% weight loss after three months which is higher among the copolymers. Therefore, castor oil has a significant importance for inducing biodegradability of the additives. Moreover, molecular weight of the recovered samples after 90 days biodegradation was determined by GPC method and the results were compared with the respective samples before biodegradation and given in **table 3.3.4**. The IR spectra of the recovered samples after biodegradation are depicted in **figures 3.3.19** and **3.3.20**.

3.3.6 Conclusions

From the above study it was found that the copolymers of dodecyl acrylate and castor showed better performance as viscosity modifier, pour point depressant and antiwear additive for lube oil. Castor oil has a significant role in enhancing performances of the additives. The oxy-rich property of castor oil molecules along with long hydrocarbon chains with polar ends of DDA molecules are the key reasons for exhibiting better PPD and antiwear performance of the co polymeric additives. On the other hand, higher cross link density and molecular weight of the copolymers are responsible for showing higher viscosity index values. Moreover, due to biodegradability the additives are eco-friendly also. Therefore, the above study is definitely a potential approach to formulate a cost effective and sustainable lubricant composition.

3.3.7 References

References are given in bibliography section of chapter III of Part III (Page No. 199 - 202).

3.3.8 Tables and figures

Table 3.3.1 Properties of castor oil

Physical properties	
Density (g.cm^{-3}) at 40 ^{o}C	0.95
Kinematic Viscosity (c St) at 40 ^{o}C	225.7
Kinematic Viscosity (c St) at100 ^{o}C	18.5
Viscosity index	91
Flash point	210^{o} C
Pour point	−6^{o} C
Cloud point	−4^{o} C
Chemical composition	
Fatty acids	Average percentage range
Ricinoleic acid	83–85
Oleic acid	4–5
Linoleic acid	2–3
α – Linoleic acid	0.5–1
Stearic acid	0.5–1
Palmitic acid	0.5–1
Dihydroxystearic acid	0.3 – 0.5

Table 3.3.2 Physical properties of the mineral base oil

Properties	SN150
Density ($g.cm^{-3}$) at 40^0C	0.84
Viscosity at 40^0C in c St	23.502
Viscosity at 100^0C in c St	3.980
Viscosity Index	85.15
Cloud Point, ^oC	−4
Pour Point, ^oC	−6

Table 3.3.3 Percentage composition and molecular weight of the prepared polymers

Polymers	% of monomers		Average molecular weights		
	DDA	CO	M_n	M_w	PDI
P-1	100	0	17824	24588	1.38
P-2	95	5	8848	13515	1.53
P-3	90	10	35170	44644	1.27
P-4	85	15	15671	31312	1.99
P-5	80	20	16535	24538	1.48
P-6	75	25	8972	14700	1.64
P-7	0	100	7928	10022	1.26

M_n is number average molecular weight; M_w is weight average molecular weight; PDI is polydispersity index; DDA = Dodecyl acrylate; CO = Castor oil

Table 3.3.4 Comparative molecular weight (determined by GPC)

Polymer code	Before biodegradation		After biodegradation	
	M_n	M_w	M_n	M_w
P-1	17824	24588	17824	24588
P-2	8848	13515	8642	12898
P-3	35170	44644	34178	42975
P-4	15671	31312	15020	30526
P-5	16535	24538	15622	23534
P-6	8972	14700	7838	13170
P-7	7928	10022	5865	7225

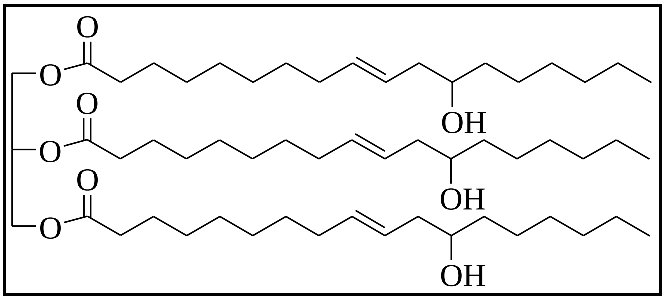


Figure 3.3.1 Triricinolein, the major component of castor oil

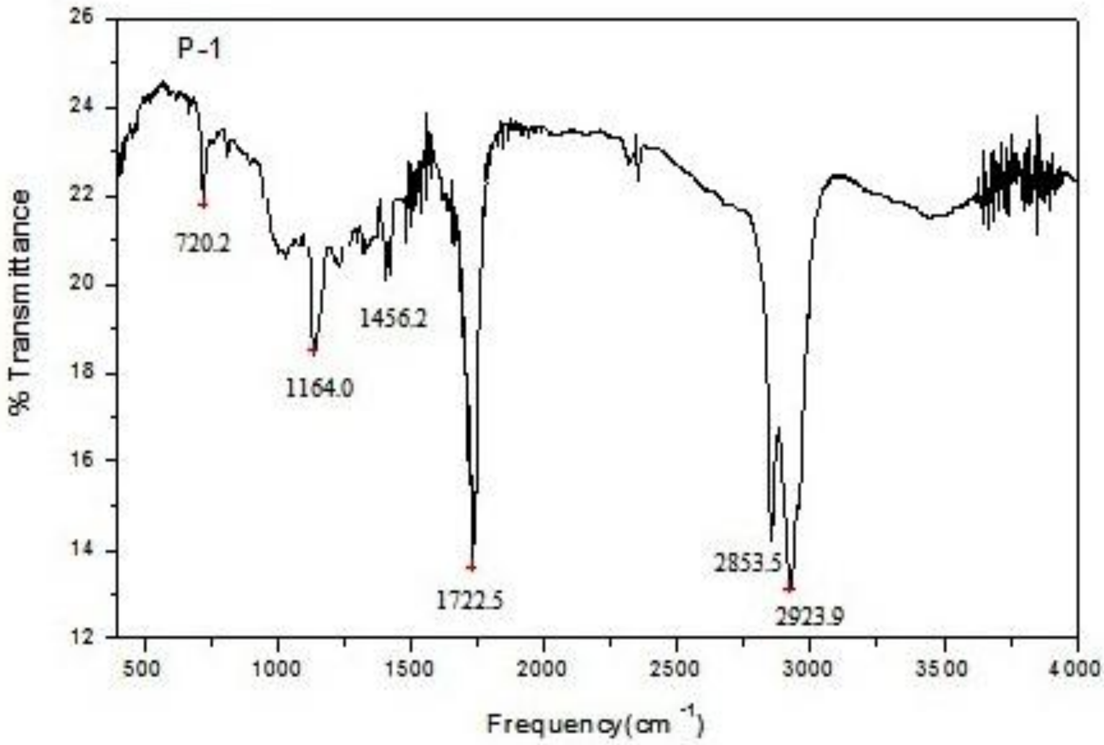


Figure 3.3.2 IR spectra of homopolymer of DDA (P-1)

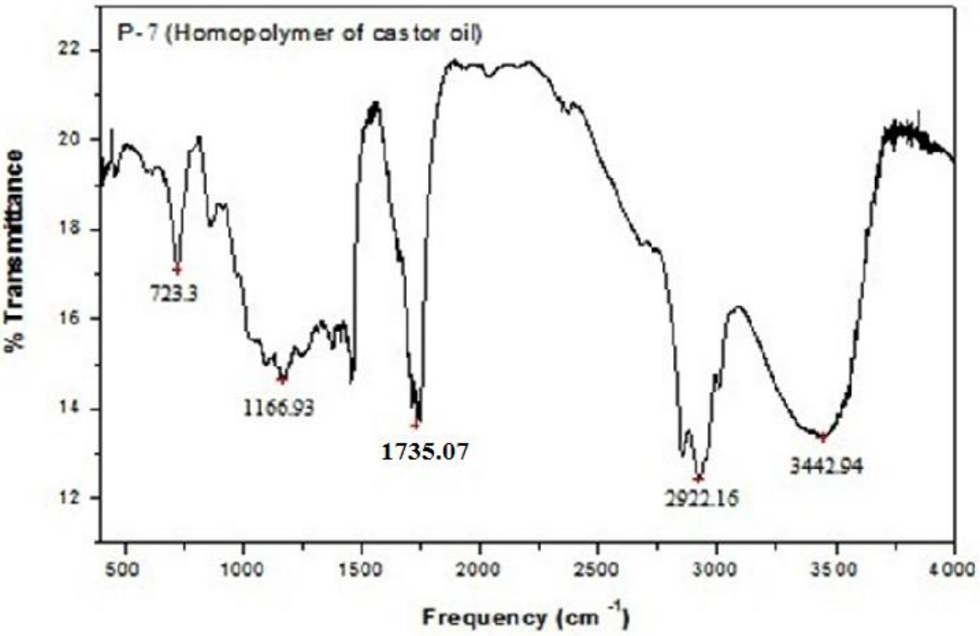


Figure 3.3.3 IR spectra of homopolymer of castor oil

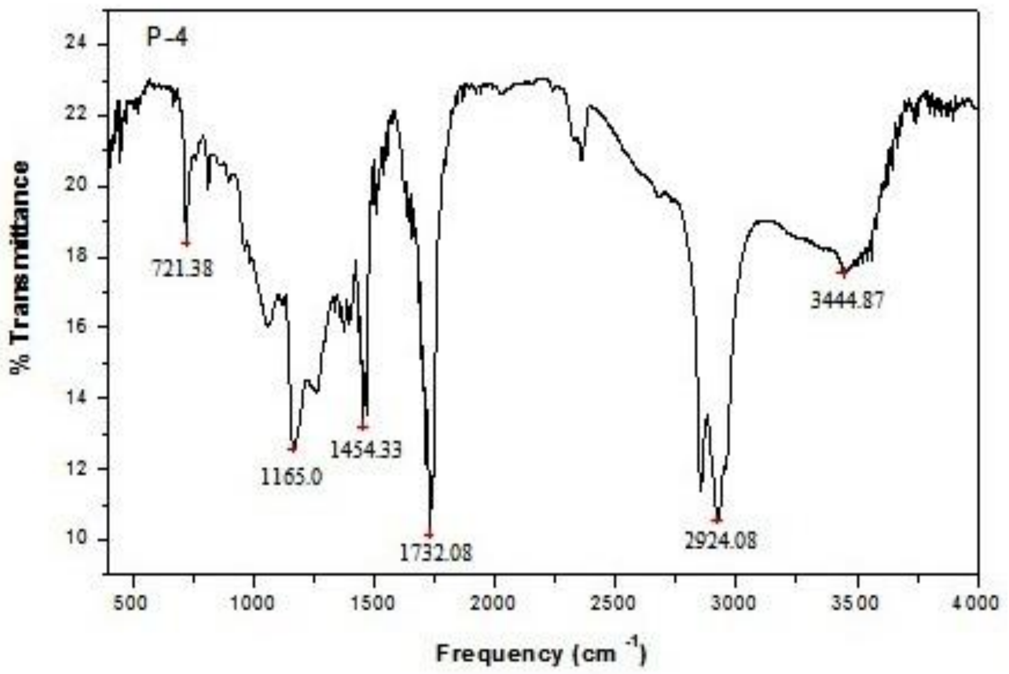


Figure 3.3.4 IR spectra of copolymer of DDA with 15% (w/w) of CO (P-4)

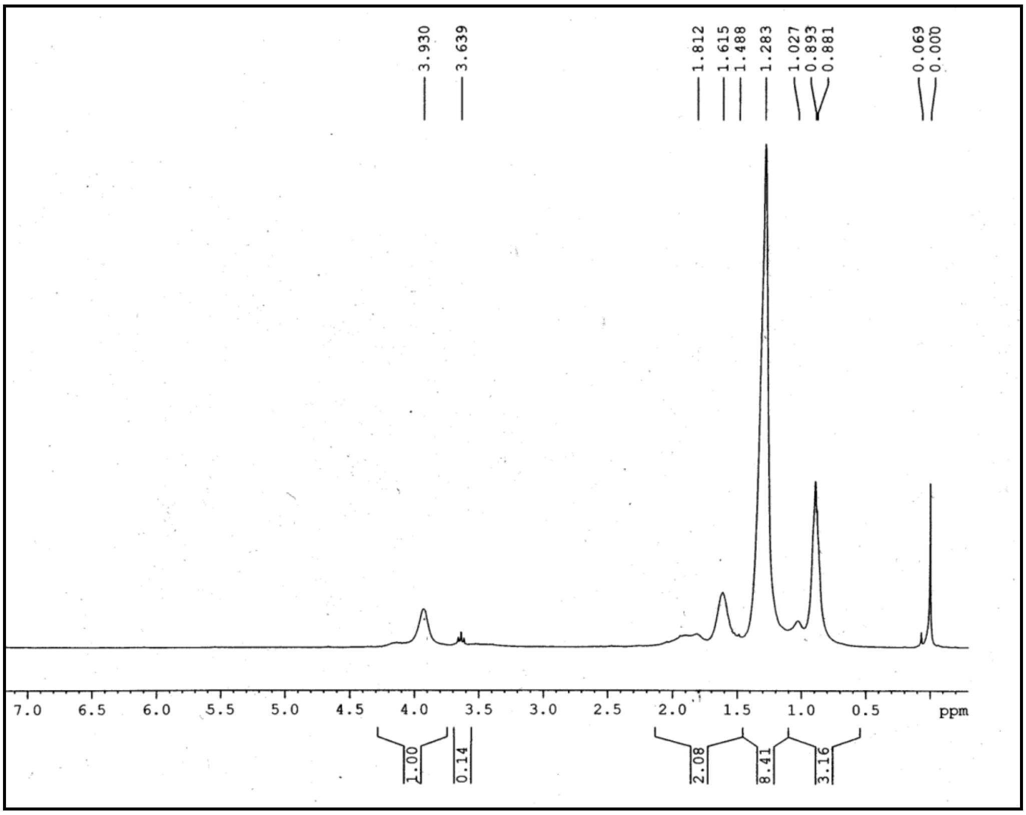


Figure 3.3.5 ^{1}H NMR spectra of homopolymer of DDA(P-1)

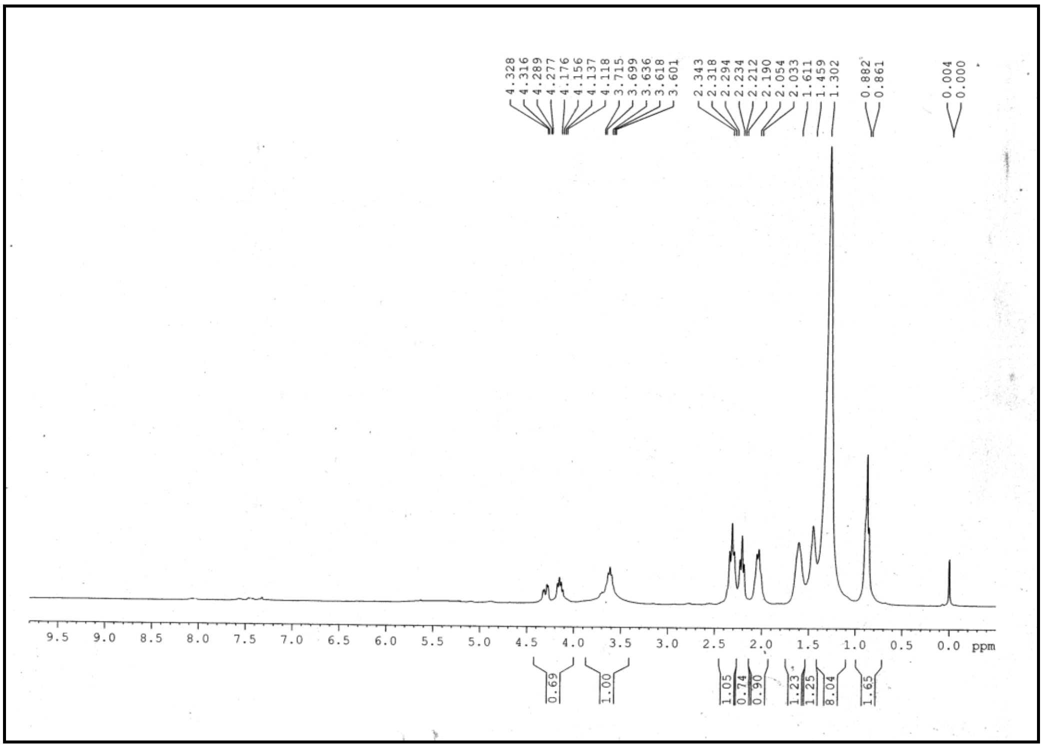


Figure 3.3.6 ^{1}H NMR spectra of homopolymer of castor oil

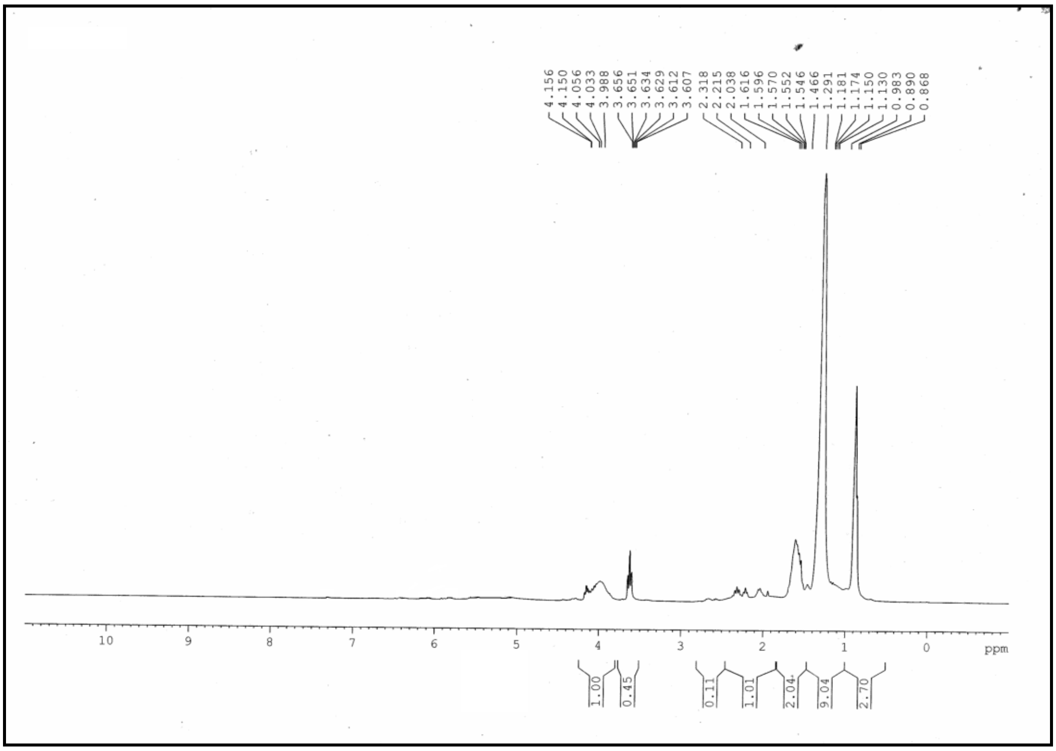


Figure 3.3.7 ^{1}H NMR spectra of copolymer of DDA with 15% (w/w) of CO (P-4)

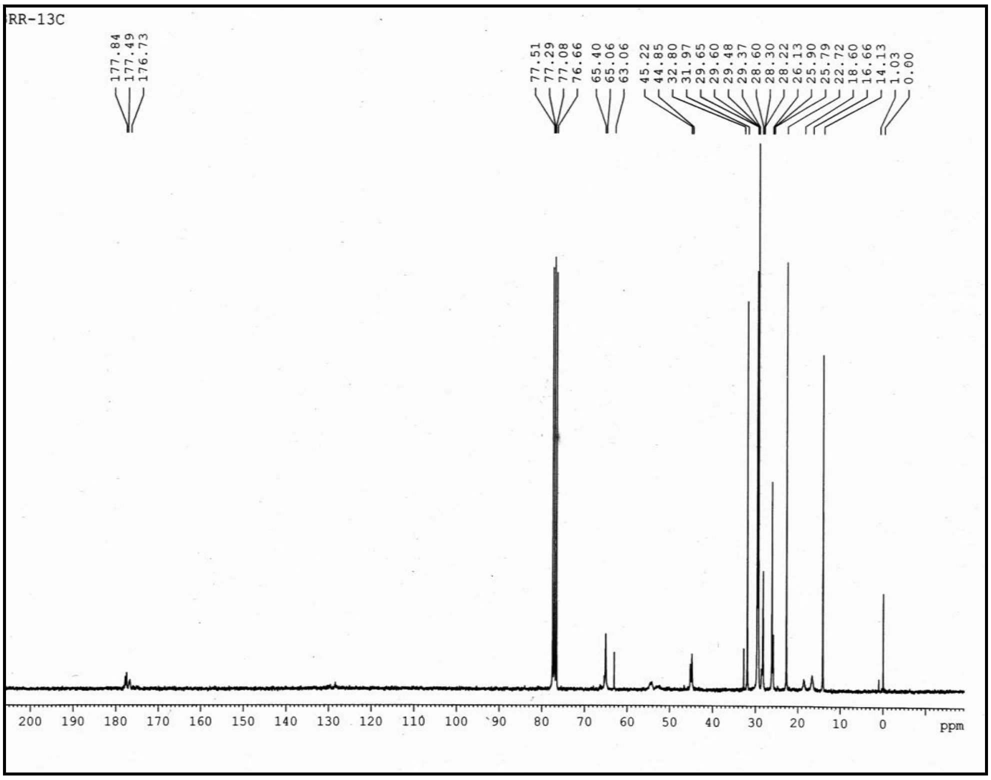


Figure 3.3.8 ^{13}C NMR spectra of homopolymer of DDA

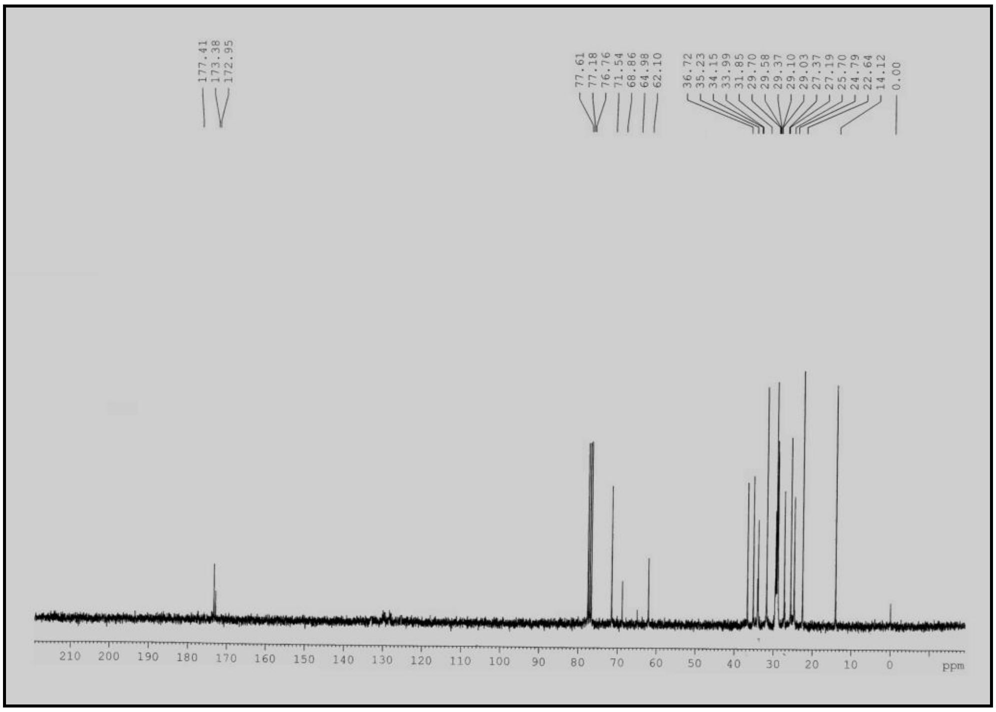


Figure 3.3.9 ^{13}C NMR spectra of homopolymer of castor oil

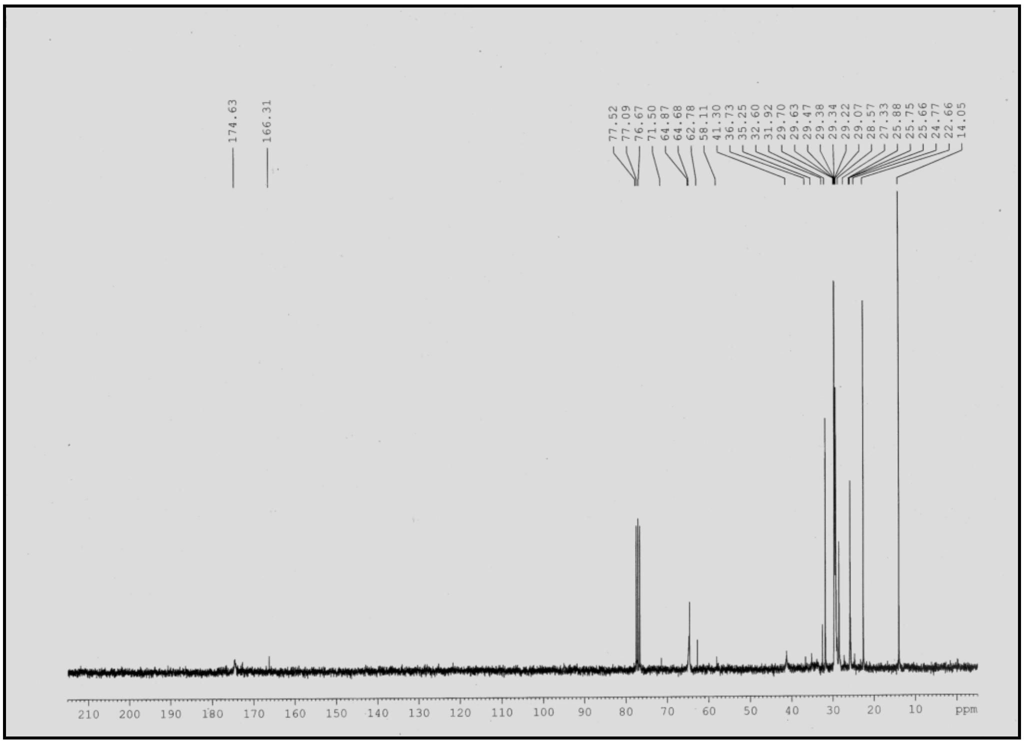


Figure 3.3.10 ^{13}C NMR spectra of copolymer of DDA with 15%(w/w) of CO

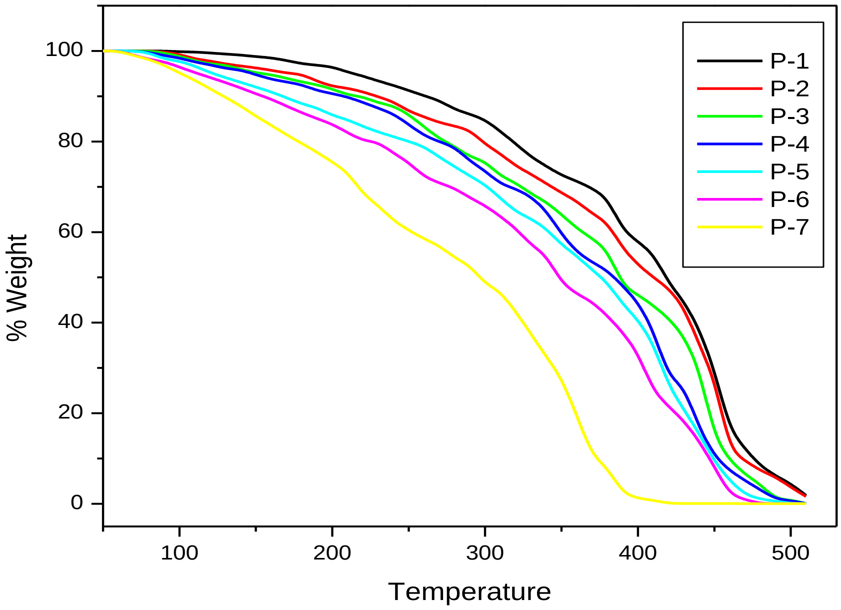


Figure 3.3.11 TGA of the additive furnished lubricant

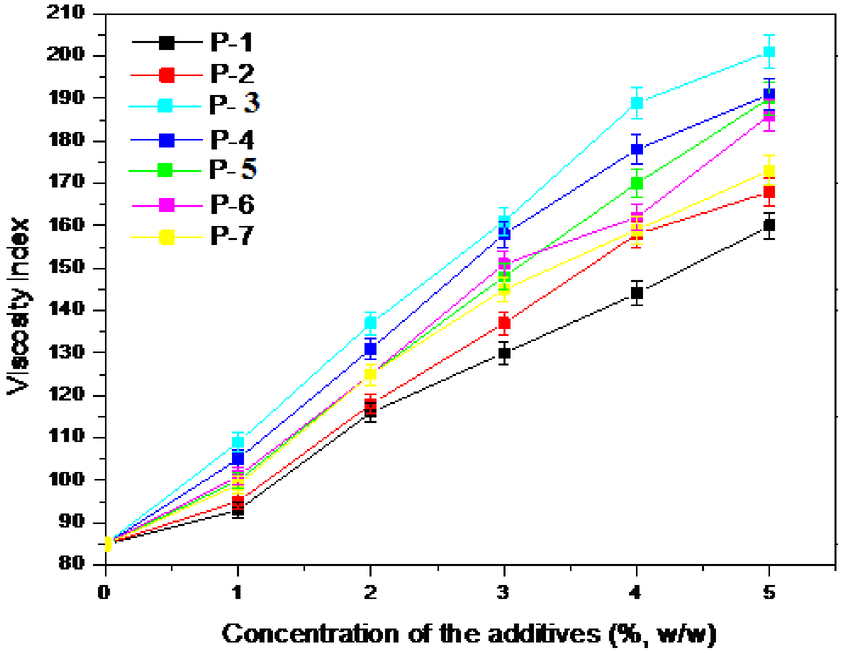


Figure 2.3.12 Variation of viscosity index of base oil blended with additives at different concentrations

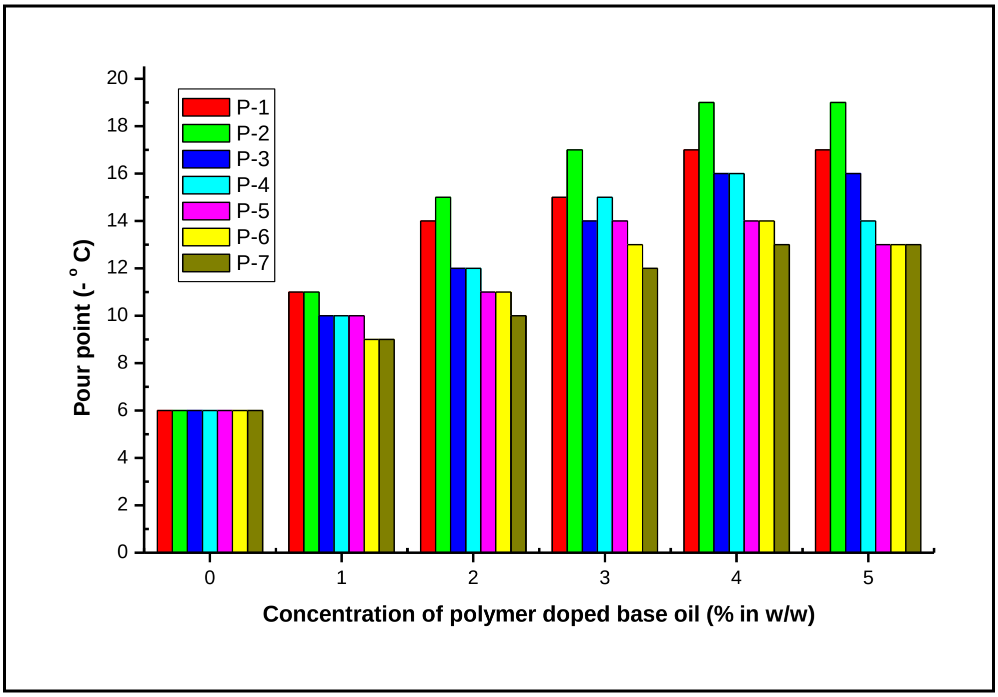


Figure 3.3.13 Pour points of the lubricant at different additive concentration levels

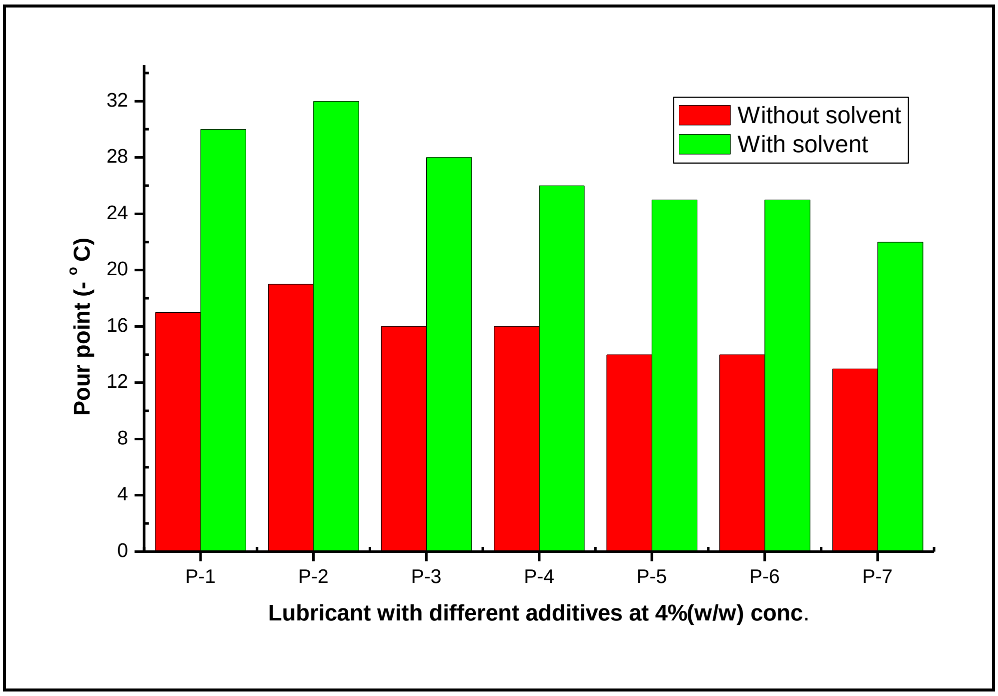
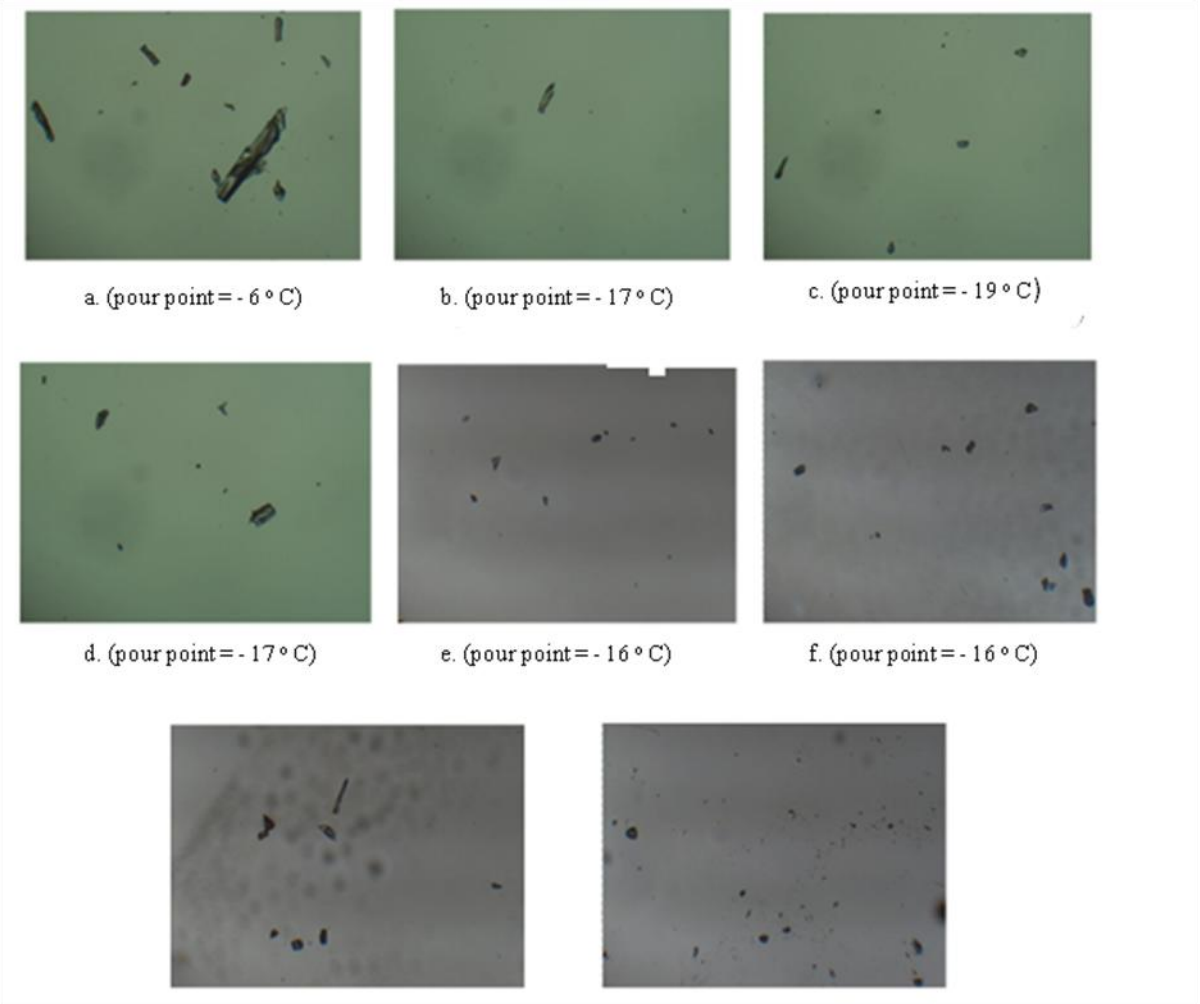


Figure 3.3.14 Pour point of lubricant at 4% (w/w) additive concentration before and after addition of 10% (w/w) n- decane solvent



a. (pour point = - 6 ° C)

b. (pour point = - 17 ° C)

c. (pour point = - 19 ° C)

d. (pour point = - 17 ° C)

e. (pour point = - 16 ° C)

f. (pour point = - 16 ° C)

g. (pour point = - 15 ° C)

h. (pour point = - 13 ° C)

Figure 3.3.15 Photomicrograph images of a) Pure lube oil b) Lube oil + 4% (w/w) of P-1 c) Lube oil + 4% (w/w) of P-2 d) Lube oil + 4% (w/w) of P-3 e) Lube oil + 4% (w/w) of P-4 f) Lube oil + 4% (w/w) of P-5 g) Lube oil + 4% (w/w) of P-6 h) Lube oil + 4% (w/w) of P-7

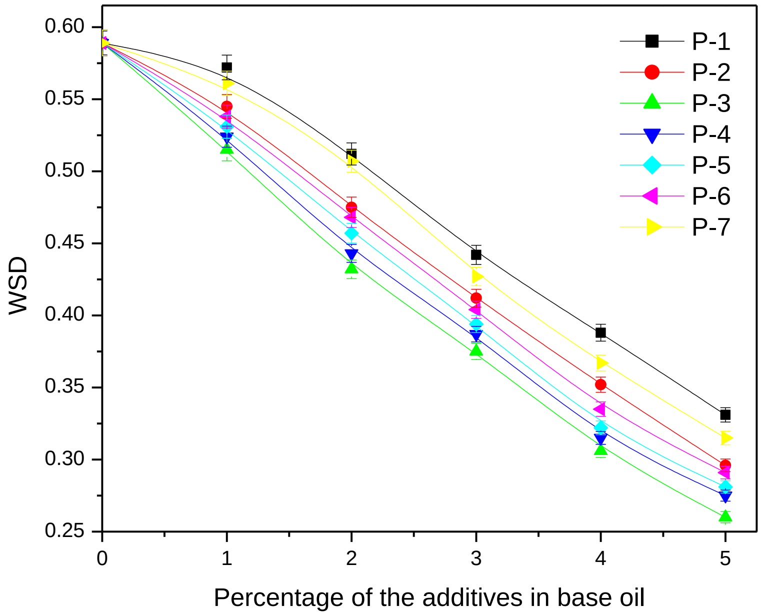


Figure 3.3.16 Wear scar diameter (WSD) of the lube oil blended with additives at different percentages (w/w)

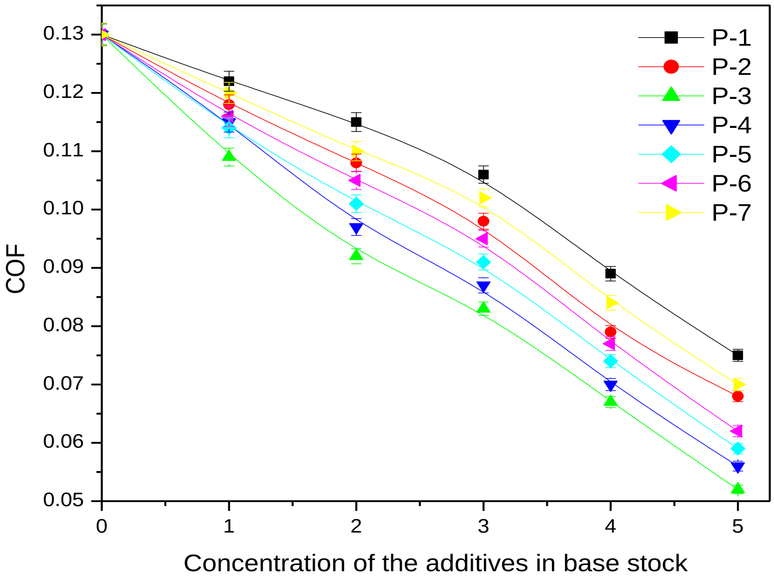


Figure 3.3.17 Coefficient of friction (COF) of the lube oil blended with additives at different percentages (w/w)

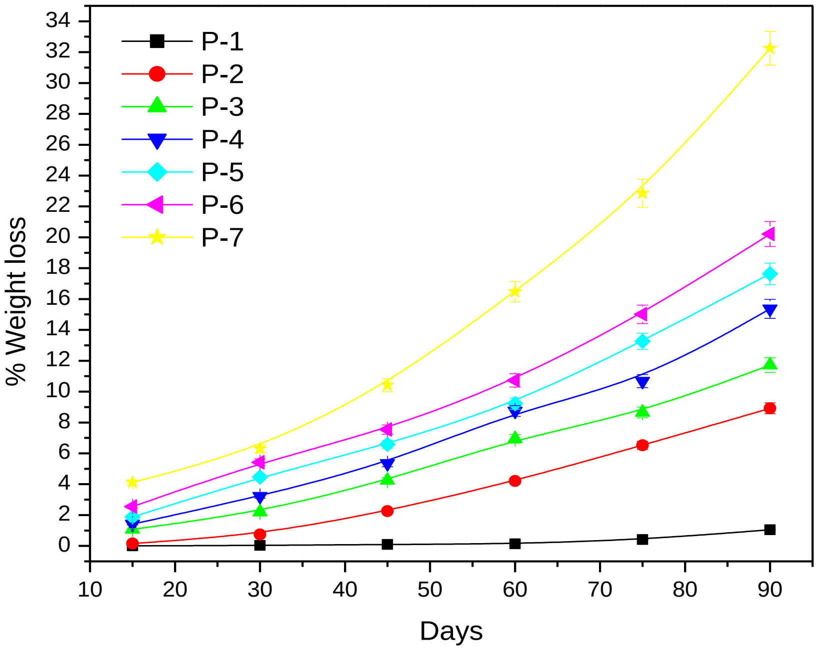


Figure 3.3.18 Biodegradability test (SBT) of the lubricant compositions

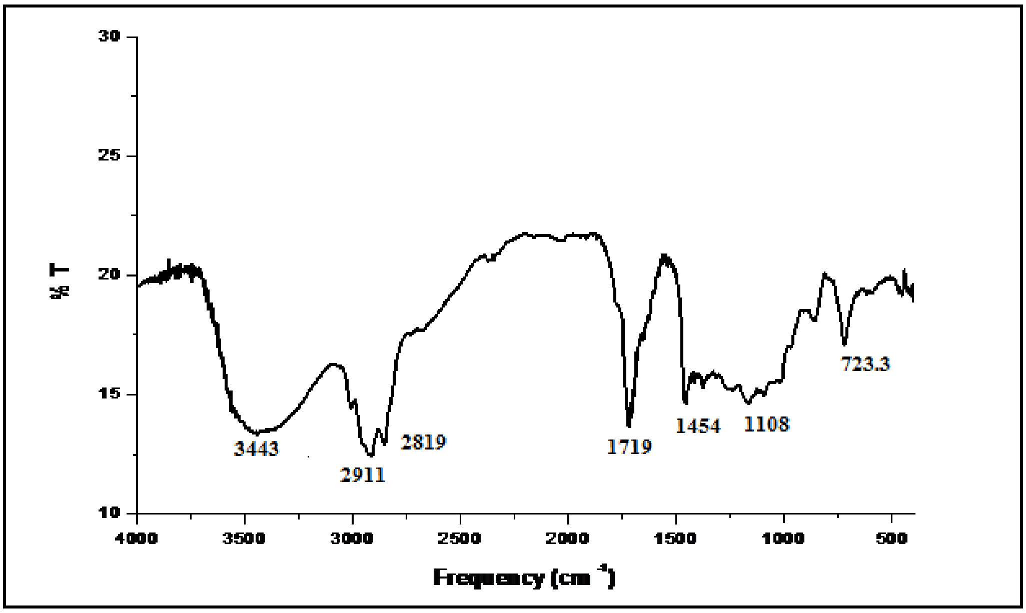


Figure 3.3.19 IR spectra of homopolymer of CO (P-7) after biodegradable

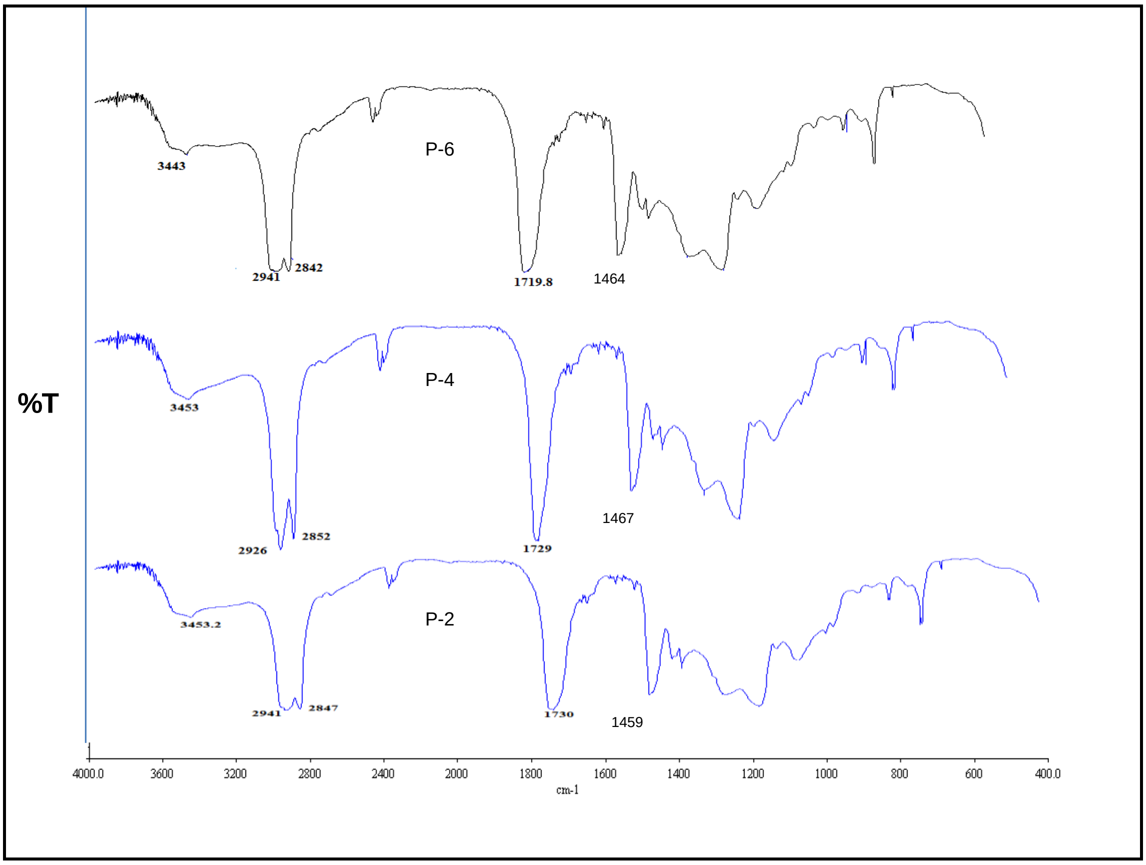


Figure 3.3.20 IR spectra of P-2, P-4 and P-6 after biodegradable