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Synthesis and Performance Evaluation of Castor Oil-Styrene Copolymer: An Outstanding Multipurpose Directional Lubricant Additive

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ABSTRACT

Polymer and chemical industries are actively concentrating on the discovery and application of vegetable oils for polymer composites. In this work, castor oil homopolymers and their copolymers with styrene were made, as well as their assessment was done by spectroscopic methodology, thermo gravimetric analysis (TGA), and gel permeation chromatographic (GPC) strategy. The ASTM standard approach was employed to determine these polymers' efficiency in base oil. Photo-micrographic imaging was utilized to assess the efficacy of additives as pour point depressants by examining their impact on the microstructure. The biodegradability experiment for polymers was also conducted and outcomes are quite promising. Their performance comparisons have been further assessed and reported.

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KEYWORDS

Additives

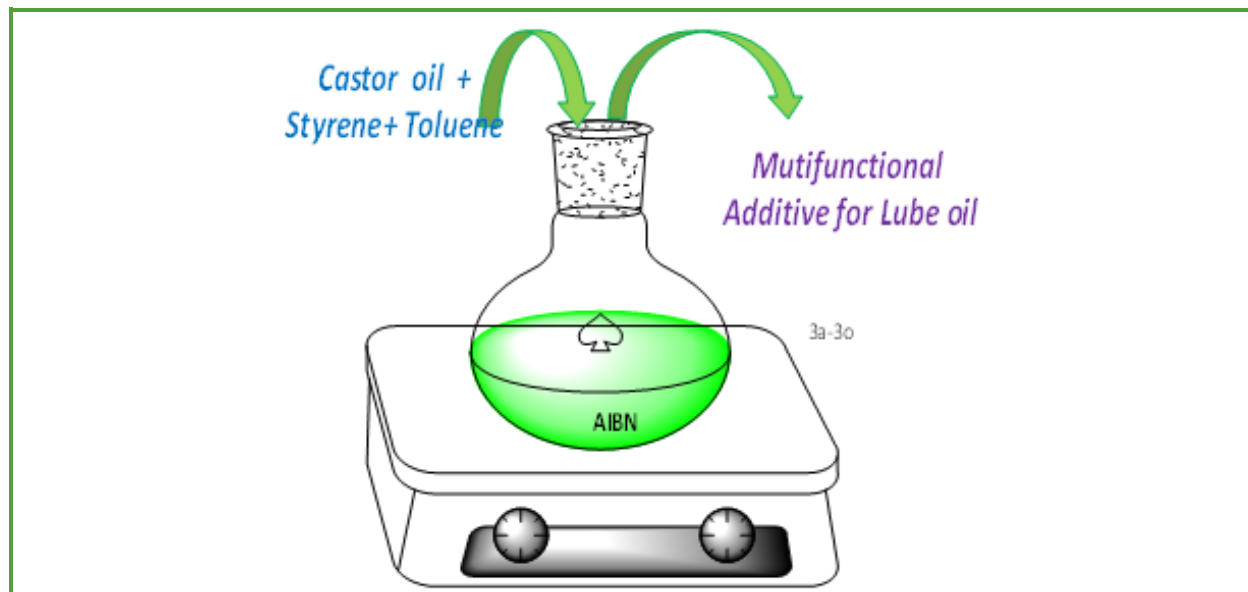
Pour Point Depressant

Viscosity Modifier

Castor oil

Styrene

Graphical Abstract



Introduction

There are many different base fluids and chemical additives used in the formulation of sophisticated lubricants.

The moving surfaces are kept separated from one another by the basal liquid, which creates a fluid zone between them to reduce friction. It reduces the amount of heat generated during operating condition and gets rid of the wear particles. Without sophisticated lubrication, additive chemistry and lubricant conceptualization, it would have been difficult to develop advanced engine and gearbox technologies. Contemporary engine oils are made up of various additives combined with base oils to create a comprehensive product that can meet even the most rigorous performance standards. The compounds, known as additives, satisfy the desired properties of lubricating and repelling the same.

In most cases, they are chemical compounds with a non-polar hydrocarbon chain and a polar head group. Numerous lubricating oil additives are employed, including detergent-

dispersants, corrosion inhibitors and substances for usage under extremely high pressures, viscosity index improvers (VIIs), antioxidants (AOs), and pour point depressants (PPDs).

The least temperature at which lubricating oil flows without interruption when refrigerated within defined parameters is known as the pour point. Paraffinic wax, a component of petroleum oils, crystallizes into stiff lattice-like frameworks at lower temperatures, obstructing flow. Hindering the production of wax crystal formations that would block passage of oil at low temperatures is how some high molecular weight polymers work. These chemical additives are also known as pour point depressants, flow improvers, paraffin antagonists, or wax moderators. Pour point depressants have no impact on the temperature or quantity of developed crystals.

The adsorption, co-crystallization, aggregation, and enhanced wax dissolution rate of these compounds are among their most generally acknowledged modes of action. Pour point depressants allow flowing at

temperatures underneath the pour point of unaltered lubricant, because they co-crystallize along with paraffinic wax; alter the development of the lattice-like organization.

Chlorinated polymers, wax alkylated phenol polymers, wax alkylated naphthalene polymers and polymethacrylates are examples of popular pour point depressants.

Another crucial lubricant property, viscosity is assessed using the arbitrary Viscosity Index (VI), which is derived through the measured viscosities within two different temperatures. This change in viscosity with temperature should be kept to a minimum for a lubricant to be effective. Thus, the lubricant performance is improved by a greater VI. Viscosity Index Improvers (VIIs) additives were incorporated into lubricating oils to regulate the rate at which viscosity changes in response to temperature fluctuations.

The behavior of polymer molecules in the oil affects how well VIIs work. The most crucial characteristics of these VIIs are their molecular weight, durability to strain breakdown, and polymer solubility. The lubricant causes the polymer molecule in solution, which is a randomized coil, to enlarge. As the polymer molecules shift from a tightly wound shape to an exposed framework, which has a larger volume, polymer solubility often rises with rising temperature. This volume addition makes the oil more viscous, counteracting the natural decline in viscosity with rising temperature.

The polymer capacity in an oil solution rises along with the polymer molecular weight. As a result, a polymer with a greater molecular weight will have a greater viscosity index than one with reduced molecular weight of similar kind. Acrylate-based polymers have been proved to be very good VIIs.

Some additives are antioxidants in nature. They can enhance the life span of a lubricant

through the raising of oxidative constrains of base oils. This is known as anti-wear (AW) property of lubricant, with which they can lower the friction extent in between the movable portions of those oils, by absorbing shock, reducing noise and minimization of the corrosion towards the portions. With decreasing the friction, decreases the extent of heat generation and thus reduction of most of the wear and tear portions occurs. Such additives are known as the anti-wear additives. They are known as extensive pressure additive and able to make a film or barrier or a protective layer on the wear surfaces.

Castor oil is one of the most popular vegetable oils, obtained from the seeds of the castor bean (Figure 1).

It has a wide range of industrial prospects and can be used medicinally as a purgative and an adhesive. Because of their low virulence, bio-absorbability, and outstanding wrangling qualities, such as excellent lubricity, minimal effervescence, great viscosity index [1], and cost effectiveness, this is one of the most commonly used recycled assets for manufacturing chemicals and polymers. Automotive technology [2, 3], medicine, the coatings industry [4], cosmetics, surface-active agents, nutrition, the food and beverage industry, inks [5], pesticides, and plasticizers [6] are just a few industries that use bio-dependent compositions extensively.

This oil is basically made up of triglycerides entity of fatty acids with long chain. These fatty acids consist of various triglyceride kinds, most of which are unsaturated. The fatty acid (FA) chain of this oil has a significant extent of unsaturation (-C=C-), which results in low thermal and oxidative stability and restricts such significance like lubricants into a moderate temperature [7].

To enhance the convenient rigidity and technical features, the synthetic modification of

triglyceride entity is necessary before its application to the field. For this accomplishment, polymerization of the oil is mandatory to enhance its molecular weight and extent of cross linking. Once more, copolymerization of this substance with the proper monomers can provide further benefits, such as ecological phenomenon of the currently prepared copolymer.

Polyacrylates and methacrylates are popular effective execution additives for lube oil. Methacrylates are frequently used as pour point depressant (PPD) and viscosity modifier (VM) of lube oil [8, 9].

However, in modern trend, the use of greener lubricants has brought some limitations to their vast application in automobile industries. In last few decades, to maintain the environmental sustainability and greener approach, the researchers have mainly focused to initiate production of environmentally benign lubricants or greener additives for inventing better fuel wealth, multi utilitarian skill development, and remove chemical threats [10, 11].

Castor oil was taken as a prospective element of copolymerization as it is

promotionally accessible for trading, cost effective, and contains satisfactory unsaturation. The current research performs an intense scanning onto the additive efficiency of produced polymeric ones with styrene and castor oil. Four varieties of copolymers of castor oil-styrene were constructed by different styrene concentrations in the mass (8%, 6%, 4%, and 2%).

The paper performs the polymers synthesis followed by their characterization, performance evaluation, and ecological explanation of all polymers.

With this framework, present study is governed to the copolymer production of castor oil-styrene succeed by their characterization (by thermogravimetric analysis to measure thermal stability of polymer and gel permeation chromatographic analysis [GPC] to determine their molecular weight and spectroscopic analysis [IR and NMR] for structural analysis) and estimation of their additive performance (as PPDs, AW, and VMs) in lubricating oil. Moreover, the extent of biodegradability was determined by GPC [12].

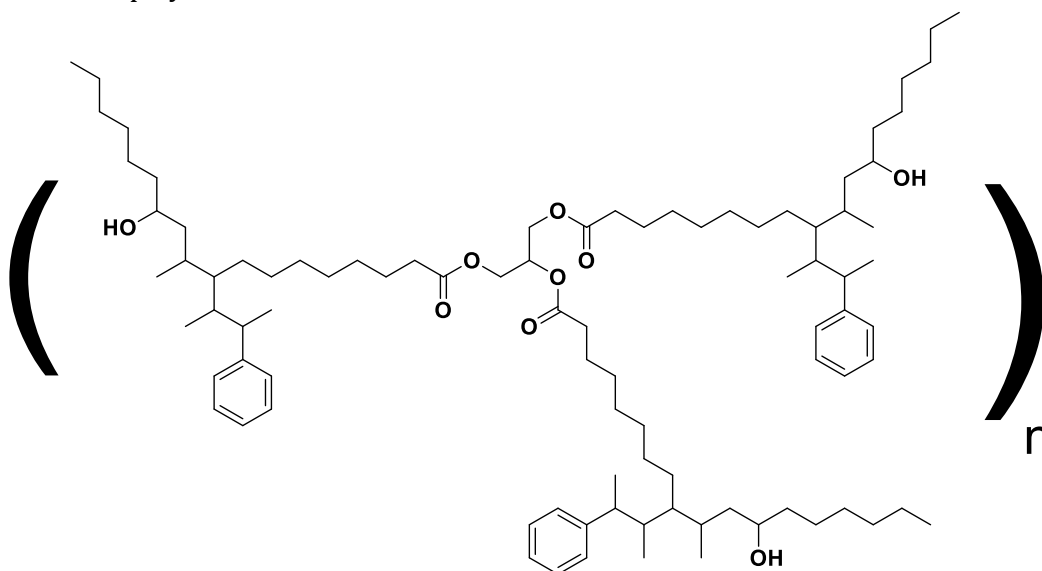


Figure 1. Structure of castor oil-styrene co-polymer

The outcomes of conducted biodegradability experiment for polymers are quite promising. Their performance comparisons have been also assessed and reported. The castor oil and styrene copolymer demonstrated biodegradability in combination to the effectiveness of multipurpose additives (PPD and VM), and as a result, is thought to be more beneficial in field activities than the current additives.

This study represents a challenging approach for constructing a novel lubricant composition with enhanced flexible additive properties. By increasing the polymer composition in the lubricating oil, the overall volume of polymer micelles is increased, leading to improved viscosity index (VI) properties and reduced wear scar diameter (WSD).

Experimental

Materials and Methods

Sigma-Aldrich, an Indian company, supplied the hydroquinone (> 99%) whereas Conc. H₂SO₄ (98%) and Toluene (GC 99.5%) was supplied by Merck Specialties Pvt. Ltd. The castor oil (CO) (see Table 1 for its fatty acid composition) was obtained from local suppliers whereas Styrene (GC 99.8%) and Methanol (GC 99.8%) was received from Thomas Baker Chemicals Pvt., Ltd., India. Azobisisobutyronitrile (AIBN, GC 98%) was obtained from Spectrochem Pvt. Ltd. in Mumbai, India, and was recrystallized from CHCl₃-MeOH. All other chemicals were utilized in its original form as received from the supplier without any additional purification. The fungal samples were cultured and obtained from the Microbiology Department of the affiliated organization and the Mineral base oils (BO₁ and BO₂) (see Table 2 for properties) used in the present study was provided by Indian Oil Corporation Ltd. (IOCL), India.

Table 1. Fatty acid components present in castor oil

Fatty acid	Percent composition in castor oil	
	Castor oil	
Palmitic(16:0)	3	
Stearic(18:0)	3	
Oleic acid(18:1)	9	
Ricinoleic acid(18:1)	75	
Linoleic acid(18:2)	10	

Table 2. Physical properties of base oils

Properties	Method	BO ₁	BO ₂
Viscosity at 40 °C in cSt	ASTM D445	7.229	23.472
Viscosity at 100 °C in cSt	ASTM D445	1.874	3.938
Viscosity Index	ASTM D2270	81	86
Pour Point, °C	ASTM D97	-3	-6
Density (g.cm ⁻³) at 40 °C	ASTM D4052	0.83689	0.85514

*BO collected from IOCL, Dhakuria, West Bengal.

Preparation of castor oil homo polymer

Following the same process outlined in the literature [13], homopolymer of castor oil was created at 90 °C by polymerization reaction in a three necked circularbase flask for 6 h.

Preparation of copolymers

The castor oil- styrene copolymer was constructed using various concentrations of styrene with castor oil. Four varieties of copolymers of castor oil-styrene were constructed with different castor oil concentrations in the mass (8%, 6%, 4%, and 2%). The radical polymerization was performed using the technique that has been previously reported [14].

Results and Discussion

Spectroscopic measurements

FT-IR and NMR techniques were used to characterize the polymers' and composites' spectrum properties. IR spectra in the 400-4000 cm^{-1} wave number region were captured using 0.1 mm KBr cells at room temperature on a Shimadzu FT-IR 8300 spectrometer. Using a 5 mm BBO probe and CDCl_3 solvent, NMR spectra were captured through a Bruker Advance NEO 400 MHz FT-NMR spectrometer. TMS was employed as a source of standard information.

Analysis of the spectroscopic data

The analysis of spectroscopic data for the prepared polymers confirmed the predicted structure of the additives.

For copolymers, the presence of ester carbonyl group of castor oil was verified by the characteristic IR absorption peak at 1743 cm^{-1} . In addition, peaks in the range of 2857-2931 cm^{-1} indicated the presence of other

components. The peaks at 695 cm^{-1} , 724 cm^{-1} , 756 cm^{-1} , and 810 cm^{-1} were indicative of the aromatic part of styrene (Figure S1, [supporting information](#)).

The ^1H -NMR spectra analysis revealed specific chemical shift ranges corresponding to different proton groups in the polymers. Protons in the methyl group were observed between 0.88-0.90 ppm. Protons in the methylene group were assigned peaks ranging from 1.28-1.63 ppm. The methine protons were observed within 2.04-2.30 ppm. The proton associated with $-\text{OCH}_2$ group appeared at 4.08 ppm. Protons from the $-\text{COOCH}_2$ group of castor oil peaks are represented by the peaks in the range of 4.10-4.15 ppm. The aromatic ring protons of styrene exhibited a broad peak spanning from 6.80-7.64 ppm (Figure S2, [supporting information](#)).

In ^{13}C -NMR spectra, different carbon groups in the copolymer exhibited specific chemical shift ranges, allowing for their identification. Carbon atoms in the CH_3 and CH_2 groups appeared within the range of 14.1-41.0 ppm. Peaks at 58.1 ppm testify the existence of methine carbons in the $-\text{CH}-$ of the $-\text{COCH}$ group. Peaks ranging from 60.0 to 62.1 ppm and 64.6-68.9 ppm represents carbon atoms in the $-\text{OCH}_2$ groups and $-\text{CH}_2$ carbons in the $-\text{OCOCH}_2-$ group respectively. The peaks in the range of 127.9-130.8 ppm and 165.6-173.0 ppm represent the aromatic carbons and ester carbonyl carbon (Figure S3, [supporting information](#)). The homopolymer of castor oil, showed IR absorption band at 1741 cm^{-1} (Figure S4, [supporting information file](#)).

The ^1H -NMR spectra of castor oil is presented in Figure S5 ([supporting information](#)). The peaks observed within 4.12-4.33 ppm, 0.86-0.90 ppm, 1.26-1.62 ppm and 2.29-2.34 ppm.

Figure S6 ([supporting information](#)), indicated the presence of protons from the -

COOCH₂ group in castor oil, methyl protons, the methylene protons, and methine protons specific to the alkyl chains.

The Figure S7 ([supporting information](#)) of supporting data represents the ¹³C-NMR spectra for the homopolymer of castor oil, where peak at 173.9 ppm represents ester carbonyl group and the peaks in the range 62.1-68.9 ppm represent the carbons of -OOCH₂ group.

Thermo gravimetric analysis (TGA)

Alumina crucible in air was used to measure the thermal stabilities of the synthesized copolymer and homo polymer using a thermo gravimetric evaluator (Shimadzu TGA-50). A 10 °C/min heating rate was used to operate the system. Calculations were made to determine the samples' percentage weight loss (PWL) as the temperature rose.

Thermo gravimetric analysis (TGA) study

The TGA (Thermo gravimetric Analysis) values of the five polymers are presented in [Table 3](#) and [Figure 2](#). Based on the provided information, several conclusions can be drawn. Polymer P-1 exhibits higher thermal degradation compared to the other polymers, indicating that it is less thermally stable. It begins significant decomposition at 180 °C, resulting in approximately 28% weight loss.

For Polymer P-2, major decomposition starting at around 220 °C, leading to approximately 25% weight loss. On the other hand, the thermal decomposition of polymers P-5, P-4, and P-3 is nearly similar, with major decomposition initiating at approximately 255 °C. Therefore, it can be concluded that the copolymerization process has enhanced the thermal stability of the castor oil-based polymers.

Determination of average molecular weights of the copolymer

The number average molecular weight (M_n) and weight average molecular weight (M_w) of the polymers were determined using the Gel Permeation Chromatography (GPC) method. The GPC system used was Water 2414 and polystyrene calibration was employed. The measurements were conducted in HPLC grade THF (Tetrahydrofuran) at room temperature, with a flow rate of 1 mL/min.

The experimental data in [Table 4](#) presents the weight average molecular weights (M_w) and number average molecular weights (M_n) of the prepared polymers (P-1 to P-5). Among all the polymers, P-5 exhibits the highest molecular weight, indicating a larger average molecular size. Enhancing styrene percentage of the castor oil skeleton, correlates with an increase in molecular weight.

Table 3. Percentage composition and TGA values of the prepared polymers

Polymer code	% Composition of monomer (w/w) in the feed		TGA values	
	Castor oil	Styrene	Decom. Temp	PWL
P1	100	0	180/350	28/85
P2	98	2	220/360	25/90
P3	96	4	245/385	20/82
P4	94	6	260/396	17/79
P5	92	8	270/402	16/75

*Decom. Temp.= Decomposition temperature and PWL=Percentage Weight Loss

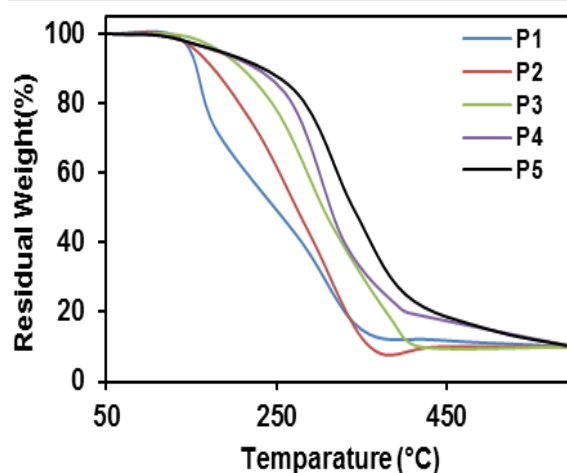


Figure 2. Plausible schematic diagram of thermo gravimetric analysis (TGA) values

Table 4. Molecular weight of the prepared polymers

Polymer code	Average Molecular weight (before biodegradation)			Average Molecular weight (after biodegradation)		
	M_n	M_w	PDI	M_n	M_w	PDI
P1	7911	10663	1.21	4561	5023	1.11
P2	16723	24792	1.11	13221	21325	1.63
P3	18563	30768	1.26	15342	26756	1.77
P4	20279	34908	1.35	16765	30289	1.79
P5	27068	40346	1.41	22390	33435	1.51

This suggests that the styrene proportion significantly influences the polymerization process. The observed trend highlights the significance of styrene percentage in determining the resulting molecular weight of the polymers.

Therefore, it can be concluded that the presence and proportion of styrene in the polymer backbone has a crucial impact on the molecular weight characteristics of prepared polymers.

Determination of viscosity index

To assess the effectiveness of the manufactured polymeric additives as viscosity modifiers, the viscosity index (VI) of the additives in a paraffinic base oil (VM) was determined (Table 5). The VI calculations were performed using the formulae provided by

Tanveer and Prasad, following the ASTM D2270 method. VI values were calculated for various concentrations of additives in the base oil, ranging from 1% to 5% (w/w). The experimental VI values are presented in Table 5. VI values enhance as the polymer concentration in the base oil increases.

This suggests that higher polymer concentrations have a positive impact on viscosity index. The viscosity of lubricating oil typically represents an inversely proportional relationship with temperature. However, with increasing temperature, polymer molecules expand, resulting in the enlargement of micelles. The increased micelle size hinders the viscosity reduction of the lubricant.

When the polymer concentration in lubricating oil is increased, it results in an augmentation of the volume of polymer

micelles. Consequently, this enhances the viscosity index (VI) property of the lubricating oil. Incorporating styrene in the homo-polymer skeleton of castor oil, leads to an increase in VI values which results in higher crosslink density of the copolymers. Among the copolymers, P-5 demonstrates the maximum impact on VI enhancement, followed by P-4, P-3, P-2, and P-1. Greater VI values observed in P-5 can be attributed to its larger solvated additive molecule (micelle) volume. This characteristic can be linked with greater average molecular weight and lower PDI (Polydispersity Index) value.

Determination of pour point

The pour points of the lubricants used in the present study was determined (in accordance with ASTM D97 standard) using a Cloud and Pour Point Tester model WIL-471 (India). The instrument can also be used for the measurement of pour point depressant characteristic of base oils with polymeric additives. In addition, five distinct additive concentrations were applied for every sample in this instance.

Table 6 displays the pour point values of the lubricants obtained by blending the polymers at different concentration levels ranging from 1% to 5% (w/w). All the polymers exhibit effectiveness as pour point depressants (PPD). This means that they are capable of reducing the pour point temperature of the lubricants. The efficiency of the polymers as pour point

depressants increases with an increase in the concentration of polymers, up to limit 4% concentration.

Beyond this concentration, further increases do not significantly enhance the pour point performance. The effective interaction between the polymer and the paraffinic wax present in the base oil is believed to be responsible for the improved pour point performance. At the optimal concentration (4%), the polymer effectively interacts with the paraffinic wax, leading to a reduction in the crystal size of the wax [17].

P-4 demonstrates the best efficiency as a pour point depressant. It exhibits superior efficiency in lowering the pour point temperature compared to the other polymers. To sum up, the experimental data suggests that all the polymers can be utilized as pour point depressants, till a certain threshold level. Furthermore, among the prepared polymers, P-4 stands out as the most effective pour point depressant.

Analysis of anti-wear properties

Table 7 lists the values of wear scar diameter (WSD) obtained through the FBWT (Four Ball Wear Test) apparatus, using a 392 N load, for the lubricant compositions. Blending the polymers with the lubricant leads to a significant improvement in the anti-wear performance, as represented by the lower WSD values of the lubricant compositions.

Table 5. Viscosity index (VI) values of polymer blended base oil

Polymer code	VI of polymer blended base oil at different concentrations(w/w)					
	0%	1%	2%	3%	4%	5%
P1	85/-6	92/-9	99/-12	108/-18	116/-24	125/-23
P2	85/-6	95/-12	105/-15	115/-15	121/-24	131/-22
P3	85/-6	102/-12	112/-15	122/-18	128/-25	138/-25
P4	85/-6	115/-15	122/-22	131/-25	135/-28	146/-28
P5	85/-6	118/-15	127/-18	139/-27	146/-30	147/-29

Table 6. Pour point (PPt) values of polymer blended base oil

Polymer code	PPt of polymer blended base oil at different concentrations(w/w)					
	0%	1%	2%	3%	4%	5%
P1	85/-6	92/-9	99/-12	108/-18	116/-24	125/-23
P2	85/-6	95/-12	105/-15	115/-15	121/-24	131/-22
P3	85/-6	102/-12	112/-15	122/-18	128/-25	138/-25
P4	85/-6	115/-15	122/-22	131/-25	135/-28	146/-28
P5	85/-6	118/-15	127/-18	139/-27	146/-30	147/-29

Table 7. Anti-wear property in terms of wear scar diameter (WSD in mm) values of different lubricant composition

Polymer code	Anti-wear property in terms of wear scar diameter (WSD in mm) of polymer blended base oil at different concentrations (w/w)					
	0%	1%	2%	3%	4%	5%
P1	1.107	1.045	1.025	1.016	1.009	1.001
P2	1.107	1.039	1.017	1.008	1.005	0.995
P3	1.107	1.034	1.011	1.002	0.994	0.983
P4	1.107	1.028	1.004	0.995	0.988	0.978
P5	1.107	1.022	0.998	0.986	0.981	0.969

This indicates that the addition of polymers enhances the lubricant's capability to reduce wear between moving metal surfaces. The copolymers exhibit better anti-wear performance compared to the homopolymer. This suggests that the presence of multiple monomers in the copolymers contributes to their improved tribological properties.

Among the polymers, P-5 at a concentration of 5% demonstrates the highest reduction in WSD values. The lubricant composition with P-5 forms a strong film amid the two moving metal surfaces; effectively reducing wear. The observed improvement in anti-wear performance is due to several factors. Initially, the higher molecular weight of the polymers, especially in the case of P-5, contributes to a greater number of polar side chains from ester carbonyl groups and hydroxyl groups present in rapeseed oil.

These polar groups enhance the lubricant's film-forming properties. Moreover, the higher percentage of styrene in the polymer feed, with

its aromatic ring structure, likely plays a substantial part in enhancing the tribological properties of lubricant composition.

Photo micrograph and wax modification

To investigate the impact of an additive on wax crystallization, the wax modification of the base fluid was examined using a Banbros polarizing microscope (BPL-400B, India) equipped with a cooling thermostat (Figure 3). The microscope provided a magnification of 200X, enabling detailed observation of the base fluid.

The temperature was controlled at 0 °C during the study to ensure consistent conditions for the examination of wax crystallization.

By capturing photo micrographic images of the base fluid under these controlled settings, the effectiveness of the additive in controlling wax crystallization could be evaluated.

Analysis of the photo micrographic image

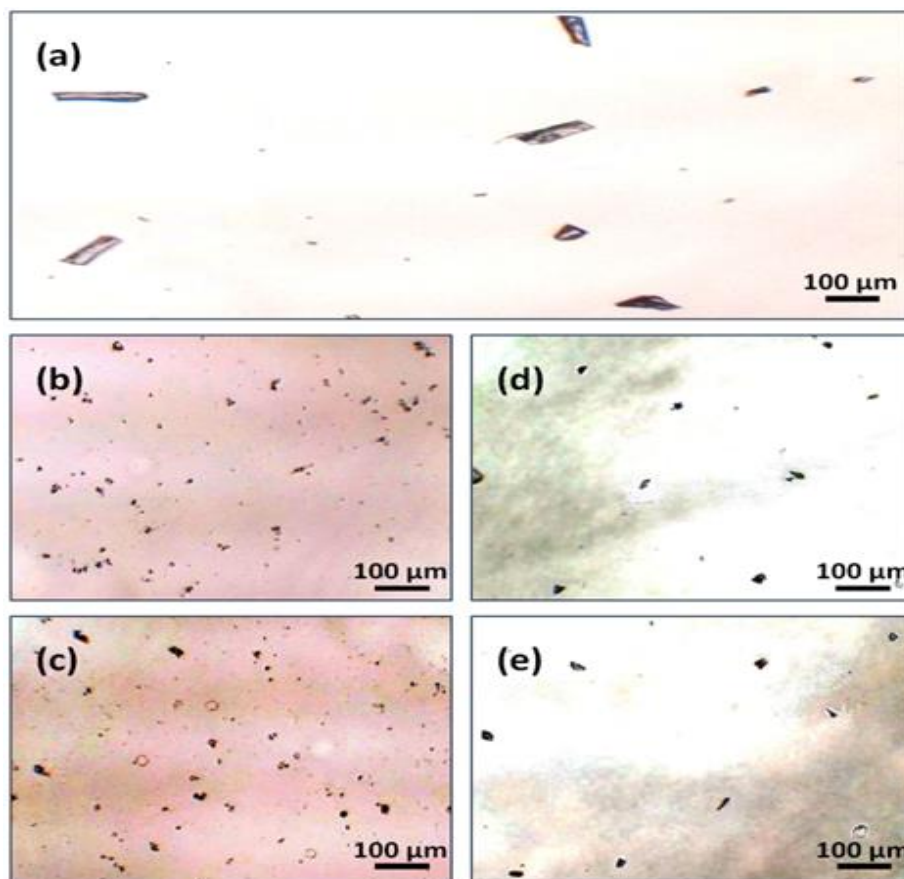


Figure 3. Photomicrograph of: (a) pure base fluid, (b) base fluid + additive P-1 (4%, w/w), (c) base fluid + additive P-3 (4%, w/w), (d) base fluid + additive P-4 (4%, w/w), and (e) base fluid + additive P-5 (4%, w/w)

Table 8. Result of biodegradability test by disc diffusion method and soil burial degradation

Sample	Weight loss in disc diffusion method in gm					Weight loss in soil burial degradation method in gm
	Pathogens used					
	[CC]	[FE]	[AA]	[CG]	[CE]	
P-1	0.56	0	0.59	0	0	0.55
P-2	0.44	0	0.51	0	0	0.48
P-3	0.35	0	0.46	0	0	0.39
P-4	0.31	0	0.34	0	0	0.33
P-5	0.27	0	0.26	0	0	0.28

*CC=*Calletotricheme camellia*, FE= *Fussarium equisetiae*, AA=*Alternaria alternata*

*CG=*Colletrichum gleosporoides*, and CE=*Curvularia aeragrostidis*.

The photomicrographs of the pure base fluid and the pure base fluid with added additives are presented in Figure 3. The photomicrograph (Figure 3a) of the original base fluid (pour point = -6 °C) reveals the presence of large rod-shaped wax crystals. These crystals contribute to the high pour point of the

base fluid. Upon adding additive P-2 (pour point = -24 °C, Figure 3b) and additive P-3 (pour point = -25 °C) (Figure 3c) to the base fluid at a concentration of 4% (w/w), a significant decrease in the volume and shape of the wax crystals is observed. The obtained crystals appear to be more dispersed

compared to the original base fluid. Similarly, additive P-4 (Figure 3d) (pour point = -28 °C) and additive P-5 (pour point = -30 °C, Figure 3e) also result in a substantial lessening in the size of the wax crystals. The crystals appear highly dispersed in the base fluid.

Biodegradability analysis

The extent of biodegradability was assessed using the ISO 846:1997 method for soil burial testing and the disc diffusion method against fungi. After the experiments, weight loss in the polymer samples was evaluated, and IR spectra were collected to look for any noticeable shifts in IR frequencies [18, 19]. With the recovered polymers, further GPC examination was undertaken in expectation of changes in Mn and Mw following biodegradation [12].

Disc diffusion method

In Petri dishes, culture media for fungi strains were made using the necessary quantity of agar, dextrose and potato extract mixture. Before usage, all the glass equipments underwent autoclaving. The test involved the use of five different fungal pathogens: *Curvularia aeragrostidis* (CE), *Colletotrichum gloeosporioides* (CG), *Alternaria alternata* (AA), *Fusarium equiseti* (FE), and *Colletotrichum camelliae* (CC). The culture media's transformation from yellow to black confirmed the fungus growth. One gram of specific polymer samples was placed to Petri dishes, where they were then cultured at 310 K for 30 days. After 30 days, rescued polymer samples were purified, chloroformed-cleaned, and dried in an open tank [18]. Dry sample masses were determined, and then FT-IR and GPC analyses were performed.

Soil burial degradation test

The ISO 846:1997 method was used to conduct the soil burial test. We buried polymer films in soil that was dug up from the university campus. In a humidity chamber, a thermostat was used to maintain a temperature of 303 K while adjusting the soil's humidity to between 50% and 60% prior to usage. After 60 days, the films that had been buried were found. Polymer samples were purified, dried, and chloroform washed [20]. After the dried samples were examined, FT-IR and GPC analyses were performed.

Analysis of biodegradability test

The results of the biodegradability tests, as presented in Table 8, indicate significant biodegradability for both the homopolymer (P-1) and copolymers (P-2 to P-5) when exposed to fungal pathogens, specifically *Colletotrichum camelliae* and *Alternaria alternata*. As expected, the homopolymer of castor oil (P-1) exhibited better biodegradability compared to the copolymers. Detailed analysis of the experimental data revealed noticeable biodegradation for all the samples. The results obtained from the Sequential Biodegradation (SBD) study indicate a progressively increasing trend for the degradation of polymeric additives with test duration. Moreover, both the homopolymer and copolymers exhibited substantial weight losses when exposed to the fungal pathogens, particularly *Alternaria alternata*, in the Direct Degradation (DD) test.

As anticipated, the homopolymer (P-1) with zero styrene content and the presence of natural monomer units displayed the highest level of biodegradability among all the additives, as observed in both tests. In the Fourier Transform Infrared (FT-IR) analysis, the peaks corresponding to the polymer P-1 exhibited shifts in their positions and a significant reduction in the height of peak and

its intensity after DD test. This confirms biodegradable nature of prepared polymers, as indicated by the changes in the IR peak positions, peak intensities, and the Polymer Weight Loss (PWL) values before and after the biodegradation tests.

Conclusion

Copolymers of castor oil and styrene have higher thermal stability than castor oil alone. Again, when styrene concentration in the copolymers rises, so does thermal stability. However, the shear stability of castor oil homopolymer is higher than that of their styrene copolymers, and shear stability declines as styrene concentrations in the copolymers rises. The castor oil-styrene copolymer functions as a much better PPD and viscosity modifier than the castor oil homopolymer, according to performance assessment of the additives. In addition, research shows that while castor oil homopolymer is significantly biodegradable, but very poor solubility in lube oil and showed low thermal stability and middling performances as a PPD and VM. In contrast, the castor oil and styrene copolymer demonstrated biodegradability in combination to the effectiveness of multipurpose additives (PPD and VM), and as a result, is thought to be more beneficial in field activities than the current additives. Indeed, the study mentioned above presents a promising approach for formulating a novel lubricant composition with enhanced flexible additive properties. By increasing the polymer composition in the lubricating oil, the overall volume of polymer micelles is increased, leading to improved viscosity index (VI) properties and reduced wear scar diameter (WSD). This approach can contribute to the development of environmentally friendly lubricants that offer enhanced performance and functional capabilities,

making them an attractive option for various applications.

Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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Supporting Information

Supporting information contains the experimental analysis, spectroscopic data, and scanned copies of ^1H -, ^{13}C -NMR and FT-IR spectra of some synthesized homopolymers and co-polymers.

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