

Preparation of Epoxidized Palm Oil by using Performic Acid

Nurazira Mohd Nor* and Jumat Salimon

Center for Advanced Materials and Renewable Resources, Faculty of Science and Technology,
Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

*Corresponding author (e-mail: nuraziramohdnor@yahoo.com)

The epoxidation process of palm oil was carried out using *in situ*-generated performic acid. Formic acid acts as an oxygen carrier and hydrogen peroxide acts as an oxygen donor in the reaction system. The epoxidation process was performed using a molecular ratio of 5.91 moles of formic acid to 3.60 moles of hydrogen peroxide, reaction temperature of 40°C and reaction time of 2.55 hours. The validation of the epoxidized palm oil (EPO) molecular structure was confirmed by Fourier Transformation Infra-Red (FTIR) and proton and carbon Nuclear Magnetic Resonance (¹H-NMR and ¹³C-NMR) spectroscopy. High conversion (99.43%) of oxirane ring was obtained with 86% (w/w) yield of EPO. The existence of epoxy group was evidenced by FTIR at 843 cm⁻¹, ¹H-NMR chemical shift at 2.89 ppm and ¹³C-NMR at 54.19-57.22 ppm. The physicochemical properties results show that EPO has higher oxidative stability (190°C), flash point (255°C) and viscosity index (133), which make EPO plausible to be used as an industrial fluid.

Key words: Epoxidation, epoxidized palm oil, oxygen oxirane content, performic acid

Received: May 2019; Accepted: September 2019

In recent years, renewable materials have been increasingly used in various industries to replace mineral oils due to increasing costs of mineral oils and rising concerns about environmental pollution [1]. Renewable sources such as plant oils and animal fats are used after appropriate chemical modification [2]. Among the chemical modifications of polyolefin, epoxidation is a simple and effective method of converting double bonds to form new and reactive functional compounds [3].

Epoxidation can be carried out from olefinic molecules through four methods: (a) epoxidation with percarboxylic acid [4], which is the most widely used in industry and can be catalyzed by acids or enzymes [5,6]; (b) epoxidation with organic and inorganic peroxide including alkaline and nitrile hydrogen peroxide epoxidation as well as transition metal-catalyzed epoxidation [7]; (c) epoxidation with halohydrins using hypohalous acids and their salts as reagents for the epoxidation of olefins with electron deficient double bonds [4]; and (d) epoxidation with molecular oxygen [4]. The most widely used process is the epoxidation of unsaturated compounds with either pre- or *in-situ*-formed organic per acids [8]. The epoxidation process is one of the most important functional reactions of the double bond to other stable functional groups to enhance the oxidative stability of plant oils [9,10]. It is also industry's most widely used process towards highly unsaturated plant oils to increase their industrial use [8].

Epoxidized oils have a wide range of industrial and commercial uses because of the richly varied chemical reactivity due to the high strain energy of the

three-membered oxirane rings [11, 12]. Due to the high reactivity of the oxirane rings in epoxidized oils, epoxidized oils are used as renewable raw materials to produce intermediate products such as alcohols, glycols, alcoxyalcohols, hydroxyesters, N-hydroxyalkylamides, mercaptoalcohols, hydroxynitriles, alkanolamines and carbonyl compounds [13, 14]. They are also widely used in lubricants, detergents, stabilizers and plasticizers in polyvinylchloride (PVC). Plant oils with high content of unsaturated fatty acids are used to produce high quality epoxy functional materials [15]. Epoxidized plant oil products from the epoxidation process can be used as high-temperature lubricants [16, 17], plasticizers [18] and high temperature coating materials [19].

Epoxidation of plant oils such as mahua oil [13], *Jatropha curcas* oil [11, 15, 20], soybean oil [15, 21, 22], rubber seed oil [23], canola oil [12], rapeseed oil [24], jojoba oil and castor oil [8] have been investigated. Recently, palm oil has become one of the potential plant oils to produce renewable materials [25, 26, 27]. Palm oil, which is abundantly available all over Malaysia contains a high percentage of unsaturated fatty acids (49.4%) [28], which serves as a good starting material for the epoxidation process. The epoxidation of palm oil was studied by Hoang and Kim [29]. This study focused on the effect of reaction time on palm oil epoxidation process. The conversion of double bond to oxirane group in palm oil was investigated in four different reaction times (120 min, 150 min, 180 min and 210 min). The mole ratio of unsaturated, formic acid and hydrogen peroxide was set at 1: 5: 4 and the reaction temperature was 50°C.

The optimized epoxidation time was obtained at 180 minutes with 98.9% double bond conversion to oxirane ring and 70% yield. In 2010, Derawi and Salimon [30] discussed the synthesis of epoxidized palm olein (PO) using performic acid and its characterization. Effects of formic acid (HCOOH) and hydrogen peroxide (H₂O₂) concentration, temperature, stirring effect and reaction time were studied. The optimum reaction conditions were 5 moles of HCOOH, 2 moles of H₂O₂, 45°C, 150 min and 350 rpm of stirring speed. At this optimum conditions, the reaction yield was 91.3% with 96.5% of oxirane conversion. Table 1 shows a summary of the research findings on epoxidation of palm oil and palm olein using performic acid.

The objective of this study is to produce epoxidized palm oil (EPO) through epoxidation of palm oil. Lower reaction temperature was used to produce higher percentage of epoxide yield and higher oxirane conversion. Epoxidized palm oil (EPO) was

characterized using Fourier Transformation Infra-red (FTIR) and proton and carbon Nuclear Magnetic Resonance (¹H-NMR and ¹³C-NMR), and the physicochemical properties were examined using several tests such as oxidative stability, pour point, flash point and viscosity index. Figure 1 shows the proposed schematic reaction for the epoxidation of palm oil represented by the 1,3-dipalmitoyl-2-oleoyl-glycerol (POP) structure as the dominant triacylglycerol content (30.2%) in palm oil.

MATERIALS AND METHODS

Materials

Palm oil was obtained from Jomalina Refinery, Teluk Panglima Garang, Selangor, Malaysia. Formic acid (88%) was obtained from Fisher Scientific and hydrogen peroxide (30%) from Merck. Sodium hydrogen carbonate and sodium chloride were purchased from System.

Table1. Summary of the research findings on epoxidation.

Study	Hoang and Kim ^[29]	Derawi and Salimon ^[30]
Yield (%)	70	91.3
Oxirane conversion (%)	98.9	96.5

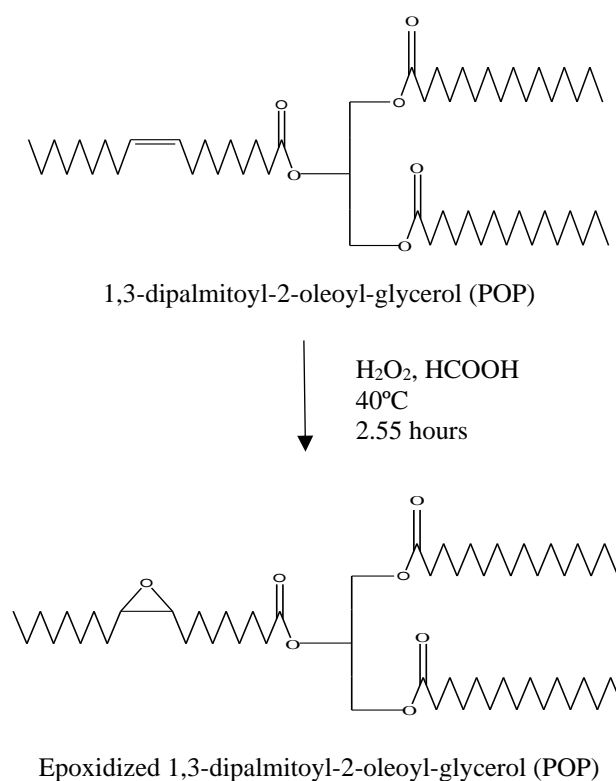


Figure 1. The schematic reaction of epoxidation of palm oil.

Epoxidation of Palm Oil

Epoxidation of palm oil was carried out at optimum conditions of: 5.91 moles of formic acid to 3.60 moles of hydrogen peroxide, reaction temperature of 40°C and reaction time of 2.55 hours, as reported by Nurazira et al. [26]. Epoxidation process began by adding palm oil with formic acid into a 250 mL three-neck round bottom flask equipped with mechanical stirrer, thermometer and reflux condenser. The mixture of palm oil and formic acid was heated and stirred continuously (900 rpm) using a magnetic stirrer. Hydrogen peroxide was slowly added. At the end of the reaction, the heating was stopped and the product was neutralized with sodium hydrogen carbonate solution (5%) and added with sodium chloride solution (5%) and distilled water. The product was kept overnight with the addition anhydrous sodium sulphate to remove water. Then, the product was filtered using Whatmann No. 1 filter paper.

Characterization of Palm Oil and Epoxidized Palm Oil

The unsaturation of PO was determined by iodine value (IV) test using Wijs method according to Kuntom et al. [31]. Oxirane oxygen content (OOC) was determined according to the AOCS Analysis Method Cd 9-57 [32]. Fatty acid and triacylglycerol compositions in PO were analyzed by Gas Chromatography equipped with a Flame Ionization Detector (GC-FID- Shimadzu 17A) and High Performance Liquid Chromatography (HPLC- Waters 1515). The PO and EPO structures were validated using Fourier Transformation Infra-red (FTIR) and

proton and carbon Nuclear Magnetic Resonance ($^1\text{H-NMR}$ and $^{13}\text{C-NMR}$). FTIR spectra were recorded on a Perkin Elmer Infrared Spectrophotometer in the range of 400-4000 cm^{-1} . ^1H and $^{13}\text{C-NMR}$ spectra were recorded on a JEOL-ECP 400 spectrometer (400 MHz $^1\text{H}/100.61$ MHz ^{13}C), using CDCl_3 as solvent. All physicochemical properties analyses were performed according to standard methods for pour point, flash point, oxidative stability and viscosity index.

RESULTS AND DISCUSSION

Palm oil (PO) is golden yellow and exists in semi-solid form at room temperature. The liquid fraction contains unsaturated triacylglycerol (TAG), whereas the solid fraction contains more saturated TAG. The epoxidation process is more likely to occur in unsaturated TAG.

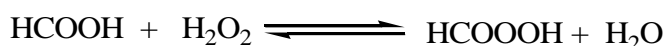
TAG and fatty acid composition analyses were performed to determine their main compositions in PO. Table 2 shows that the main TAG in PO are POP (39.89%), followed by POO (26.69%), PLP (7.43%), PLO (7.34%) and other TAGs. POP and POO show higher percentages because palmitic acid and oleic acid are the main fatty acids in PO. It is evidenced by the fatty acid composition shown in Table 3. The main fatty acid compositions of PO are oleic acid with 44.8%, followed by palmitic acid (41.9%), linoleic acid (9.1%), stearic acid (3.6%) and myristic acid (0.6%). The composition of fatty acids in PO is close to the value of PO fatty acid composition reported by Chowdhury et al. [33]. PO contains a high percentage of unsaturated fatty acids (53.9%), which serves as a good starting material for the epoxidation process.

Table 2. Triacylglycerol composition (percentage) of palm oil.

Triacylglycerol	Percentage (%)
Free fatty acid	7.03
Monoacylglycerol + Diacylglycerol	2.88
1-oleoyl-2,3-dilinoleoyl-glycerol (OLL)	0.04
1-palmitoyl-2,3-dilinoleoyl-glycerol (PLL)	0.68
1-miristoyl-2-linoleoyl-3-palmitoyl-glycerol (MLP)	0.07
1,3-dioleoyl-2-linoleoyl-glycerol (OLO)	0.45
1-palmitoyl-2-linoleoyl-3-oleoyl-glycerol (PLO)	7.34
1,3-dipalmitoyl-2-linoleoyl-glycerol (PLP)	7.43
1,2,3-tri-oleoyl-glycerol (OOO)	1.55
1-palmitoyl-2,3-dioleoyl-glycerol (POO)	26.69
1,3-dipalmitoyl-2-oleoyl-glycerol (POP)	39.89
1,2,3-tri-palmitoyl-glycerol (PPP)	3.11
1-sterioyl-2,3-dioleoyl-glycerol (SOO)	0.61
1-palmitoyl-2-oleoyl-3-sterioyl-glycerol (POS)	1.99
1,2-dipalmitoyl-3-sterioyl-glycerol (PPS)	0.24

Table 3. Fatty acid composition (percentage) of palm oil.

Fatty acid	Percentage (%)
Myristic acid (C14)	0.6
Palmitic acid (C16)	41.9
Stearic acid (C18)	3.6
Oleic acid (C18:1)	44.8
Linoleic acid (C18:2)	9.1
ΣSaturated fatty acid	46.1
ΣUnsaturated fatty acid	53.9

**Figure 2.** The performic acid generation reaction.

In epoxidation reaction, hydrogen peroxide acts as an oxygen donor, while formic acid acts as an oxygen carrier and regenerates once epoxidation reaction has occurred [12]. Formic acid also participates in the overall reaction as a catalyst in the formation of oxirane ring and as a reactant in the hydrolysis of the oxirane ring. To achieve maximum oxirane oxygen content, formic acid level should be such that both effects are balanced [13,20]. Epoxidation of palm oil is performed using *in situ*-generated performic acid (HCOOOH), which is produced by mixing formic acid (HCOOH) and hydrogen peroxide (H₂O₂). The performic acid generation reaction is given in Figure 2.

The epoxidation process involving the mechanism of electrophilic addition is shown in Figure 3. Peroxyacid transfers an oxygen atom to the alkene with syn stereochemistry - both C-O bonds form on the same face of double bond through a one-step mechanism without intermediates. The farthest oxygen atom from the carbonyl group is the one transferred. Peroxyacid is commonly used as epoxidizing agent. It has an extra oxygen atom between the carbonyl group and its acidic hydrogen, and is electrophilic at oxygen. Attack at this position by a nucleophile displaces carboxylate, which is a good leaving group. The mechanism is essentially an

electrophilic attack, with a proton being transferred from the epoxide oxygen to the carboxylic acid by-product. Firstly, the nucleophilic π bond donates its electrons to the oxygen, breaking the O-O bond to form a new carbonyl bond. The electrons from the old O-H bond form a new C-O bond and the original carbonyl group uses its electrons to pick up the proton. The transition state of the reaction makes the bond formation and bond breaking processes much clearer [34].

The results of the epoxidation of palm oil are shown in Table 4. The average percentage yield of epoxidation is 86% (w/w). The epoxidation process can be monitored through IV and OOC values. IV should be as small as possible after epoxidation while OOC should be as large as possible. There is a difference between IV before and after epoxidation. The initial IV of palm oil before epoxidation was 57.8 m/g while the IV for EPO after epoxidation was low, approaching zero (0.09 mg/g). EPO showed a high OOC value (3.46%) with 99.43% of relative conversion oxirane (RCO). The theoretical value of OOC is 3.48% as reported by Nurazira [35]. This means that almost all unsaturated fatty acids in PO were epoxidized and converted to oxirane rings to produce EPO.

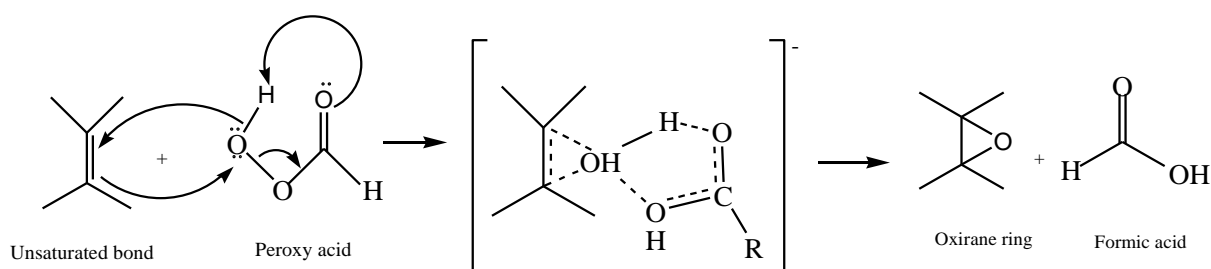
**Figure 3.** The mechanism of epoxidation reaction.

Table 4. Analysis results for epoxidation of PO.

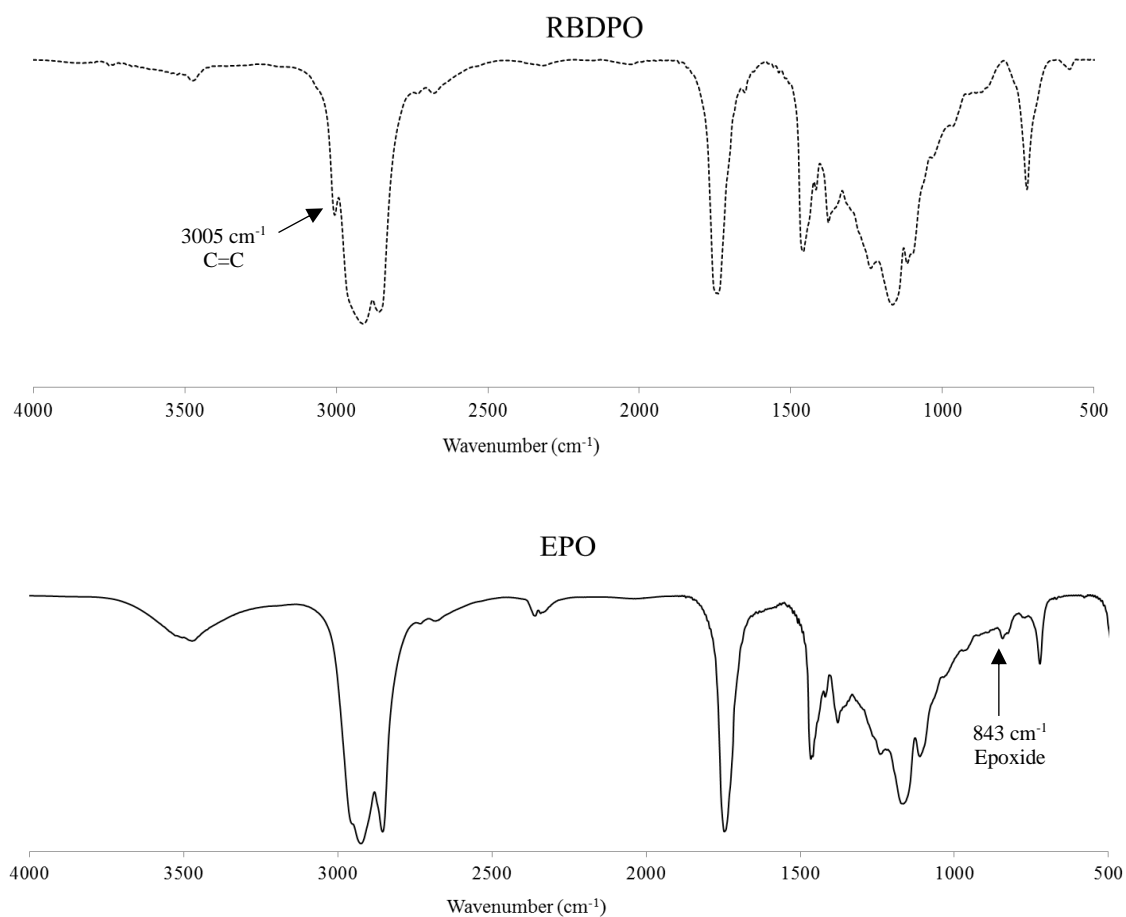
Compound	PO	EPO
Yield (%)	0	86
Iodin value (mg/g)	57.8	0.09
OOC value (%)	0	3.46
RCO (%)	0	99.43

Epoxide Identification and Characterization

FTIR spectroscopy was performed to identify and validate the presence of oxirane ring in EPO. Figure 4 shows the comparison between FTIR spectra of PO and EPO. The disappearance of double bond functional group (C=C) peak at 3005 cm^{-1} and weak peak (HC=CH) at $1500\text{-}1750\text{ cm}^{-1}$, which initially present in PO spectrum indicates the conversion of double bond to epoxy group. This can be proven by the presence of C-O-C oxirane peak at 843 cm^{-1} in EPO spectrum. Pavia et al. [36] reported that the presence of epoxy group can be monitored at wavenumber range of $815\text{-}950\text{ cm}^{-1}$ that corresponds well to this study.

The comparison of ^1H and ^{13}C -NMR spectra between PO and EPO is shown in Figure 5 and 6. In Figure 5(a), the signal at 5.34 ppm corresponds to the

vinyl proton ($-\text{CH}=\text{CH}-$), while the signal at $2.00\text{ - }2.05\text{ ppm}$ indicates the presence of allylic proton ($\text{C}=\text{C}-\text{H}$), both represent the peak of the double bond in PO. In EPO spectrum (Figure 5(b)), it can be seen clearly that there is a disappearance of both peaks (double bond), while new peaks appear at 2.89 ppm , that corresponds to the CH protons attached to the oxygen atom ($-\text{CHOCH}-$) and at 1.49 ppm , that corresponds to the epoxy protons ($-\text{CH}_2-\text{CHOCH}-\text{CH}_2$). The results indicate that the double bond in PO was converted to the epoxy group during the epoxidation reaction. Analysis of ^{13}C -NMR (Figure 6(a)) showed that the peaks at $127.85\text{-}130.17\text{ ppm}$ represent double bond (C=C). The conversion of double bond to oxirane ring can be evidenced by the disappearance of double bond peaks and the presence of epoxy carbon peaks (C-O) at $54.19\text{-}57.22\text{ ppm}$ (Figure 6(b)).

**Figure 4.** FTIR spectra of PO and EPO.

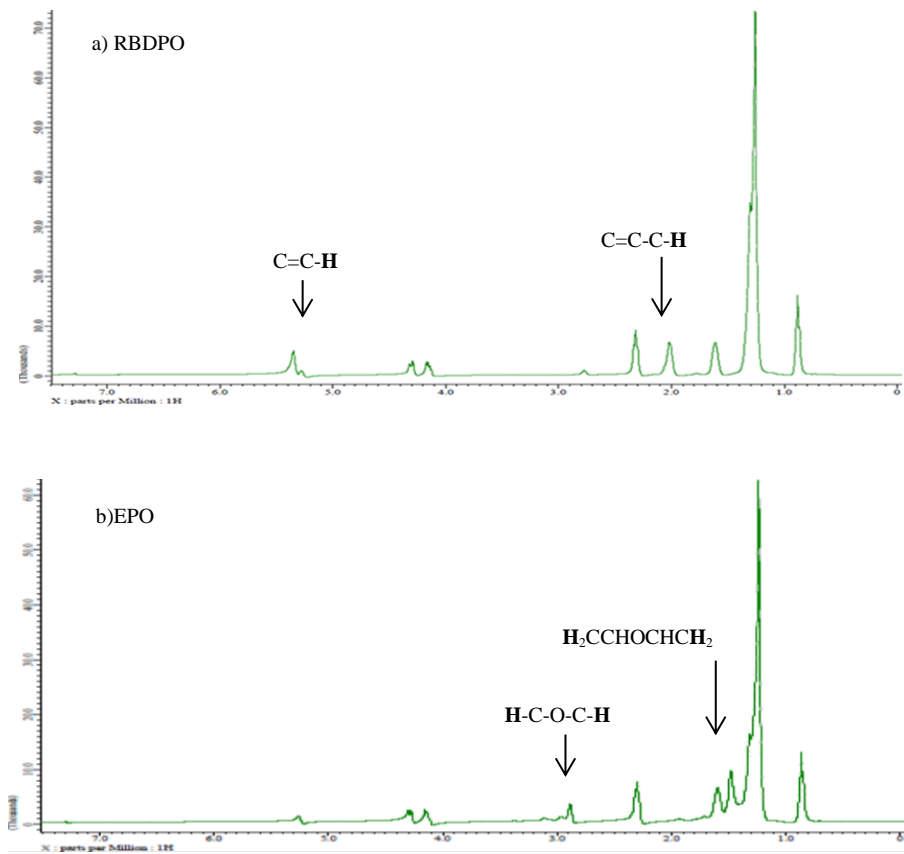


Figure 5. $^1\text{H-NMR}$ spectra for (a) PO; and (b) EPO.

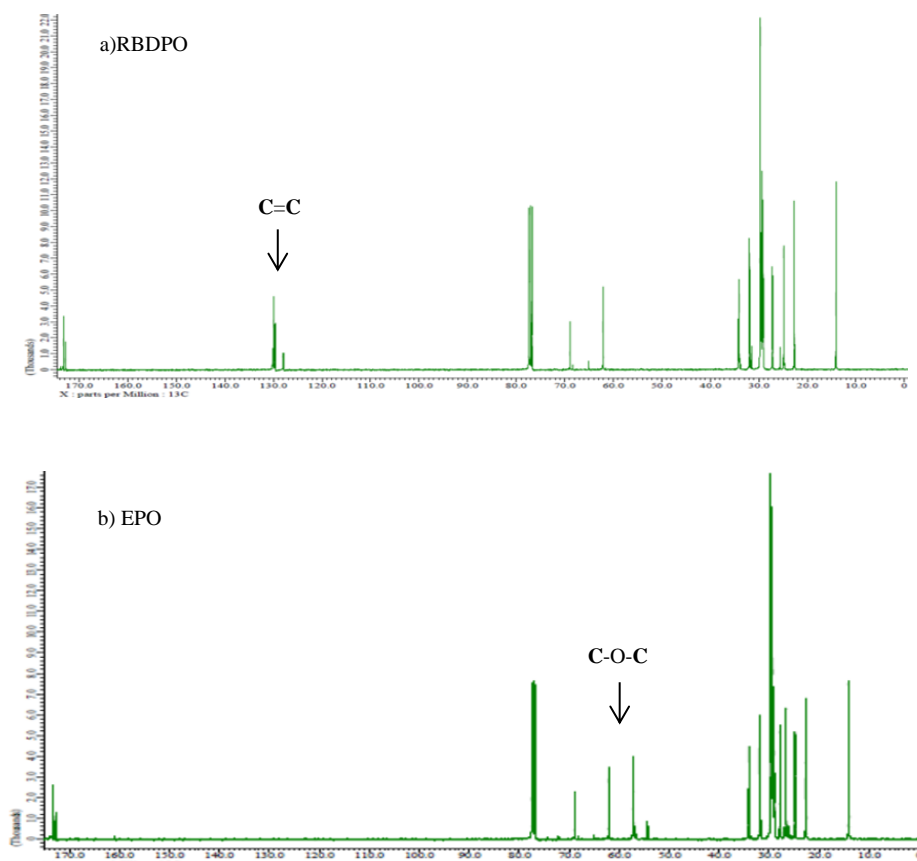


Figure 6. $^{13}\text{C-NMR}$ spectra for (a) PO; and (b) EPO.

Physicochemical Properties of Epoxidized Palm Oil

There were several tests that have been conducted to determine the physicochemical properties of PO and EPO. The results are summarized in Table 5. The ability of a substance to withstand oxidative degradation is an important property of industrial fluid. Oxidative stability is determined by onset temperature (OT) using Differential Scanning Calorimetry (DSC). OT is the temperature at which a rapid increase in the rate of oxidation is observed at a constant, high pressure (200 psi). A high OT would suggest high oxidation stability of the material [37]. In this study, there was an increase in oxidative stability of EPO (190°C) compared to PO (181°C). This is due to the conversion of double bond to epoxy which reduces the amount of unsaturated fatty acids. The removal of hydrogen atoms from the methyl group adjacent to the double bond will form free radicals. These free radicals can easily react with oxygen to form peroxy radicals. Peroxy radicals attack other fat molecules to remove one of their hydrogen atoms and form other hydroperoxides and free radicals. This condition will double the oxidation process [38]. The rate of oxidation process can be attributed to the amount of unsaturated fatty acids in its composition [39]. Therefore, reduction of the double bond content via epoxidation will enhance the oxidative stability of the oil.

Pour point is one of the important quality parameters to determine cold flow properties of the fluid. EPO showed higher pour point (18°C) compared to PO (7°C) due to the reduction of double bond in oil structure. The result shows that unsaturated carbons play an important role in decreasing pour point. Another important factor in assessing the performance of industrial fluids is flash point [37, 40]. Flash point refers to both flammable oils and combustible oils. Fluids with a flash point less than 43°C are flammable, while those with a flash point above this temperature are combustible [37]. Both PO and EPO have high flash points of 240°C and 255°C, respectively. High flash point is very important to

ensure fluid is not burned in the engine during operation.

Viscosity is also an important factor influencing fluid efficiency in reducing friction and wear [37]. In this study, the viscosity of PO is lower than EPO due to the existence of double bonds which give liquid lubrication properties by a degree of unsaturation. The viscosity of EPO is in the middle range. Generally, the least viscous fluid that still forces both moving surfaces is required [37]. If the fluid is too thin, the surfaces will rub and friction will increase, while if the fluid is too viscous, the surfaces will need a large amount of energy to move [37]. Increasing the temperature will reduce the viscosity. It can be observed when temperature rose from 40°C to 100°C for both fluids. Viscosity index shows the change of viscosity with temperature variation. The best fluid is a fluid that has a high viscosity index and does not change in viscosity over the temperature range and therefore works well [37]. EPO showed a high viscosity index. This shows that the viscosity of EPO is less affected by temperature change and does not drastically change as temperature changes. This is a good indicator and is suitable for use in large temperature ranges.

CONCLUSION

Epoxidized palm oil (EPO) was successfully synthesized with high yield (86%) and high oxirane conversion (99.43 %). The OOC value (3.46%) is close to the theoretical value (3.48%). There is an increase in the oxidative stability, flash point and viscosity index of EPO which makes EPO plausible to be used as industrial fluid.

ACKNOWLEDGEMENT

The authors would like to acknowledge Universiti Kebangsaan Malaysia for the financial support as well as research facilities provided and Ministry of Education, Malaysia for providing scholarship support for the author.

Table 5. Physicochemical properties of PO and EPO.

Fluid	PO	EPO
Oxidative stability (°C)	181	190 °C
Pour point (°C)	7	18
Kinematic viscosity at 40°C (cSt)	56.97	97.72
Kinematic viscosity at 100°C (cSt)	9.24	14.56
Viscosity index (VI)	130	133
Flash point (°C)	240°C	255°C

REFERENCES

- Trinh Thi Kim Hoang and Il Kim (2015) Epoxidation and ring-opening of palm oil to produce high-functionality polyols, *Australian Journal of Basic and Applied Sciences*, **9(8)**, 89-93.
- Salimon, J. and Salih, N. (2009) Substituted esters of octadecanoic acid as potential biolubricants, *European Journal of Scientific Research*, **31(2)**, 273-279.
- Wang, X., Zhang, H., Wang, Z. and Jiang, B. (1997) In situ epoxidation of ethylene propylene diene rubber by performic acid, *Polymer*, **38(21)**, 5407-5410.
- Guenter, S., Rieth, R. and Rowbottom, K. T. (2003) Ullmann's Encyclopedia of Industrial Chemistry, 6th edn., WileyVCH.
- Warwel, S. and Klaas, M. R. (1995) Chemo-enzymatic epoxidation of unsaturated carboxylic acids, *J. Mol. Cat. B: Enzym*, **1**, 29-35.
- Rios, L. A., Weckes, P., Schuster, H. and Hoelderich, W. F. (2005) Mesoporous and amorphous Ti-silicas on the epoxidation of vegetables oils, *J. Catal.*, **232**, 19-26.
- Sharpless, K. B., Woodard, S. S. and Finn, M. G. (1983) On the mechanism of titanium-tartrate catalyzed asymmetric epoxidation, *Pure Appl. Chem*, **55**, 1823-1836.
- El-Adly, R. A., Shoaib, A. M., Enas, A. I. and Modather, F. (2014) Optimum operating conditions for epoxidation reaction of jojoba and castor oils, *Int. Journal of Engineering Research and Applications*, **4(3)**, 816-822.
- Moser, B. R. and Erhan, S. Z. (2007) Preparation and evaluation of a series of α -hydroxy ethers from 9, 10-Epoxystreates, *Eur. J. Lipid Sci. Technol*, **109**, 206-213.
- Salimon, J., Ahmed, W. A., Salih, N., Yarmo, M. A. and Derawi, D. (2015) Lubricity and tribological properties of dicarboxylic acids and oleyl alcohol based esters, *Sains Malaysiana*, **44(3)**, 405-412.
- Rafiee-Moghaddam, R., Salimon, J., Jelas-Haron, M. D., Jahangirian, H., Shah Ismail, M. H., Hosseini, S. and Rezayi, M. (2014) Lipase epoxidation optimizing of *Jatropha curcas* oil using perlauric acid, *Digest Journal of Nanomaterials and Biostructures*, **9(3)**, 1159-1169.
- Mungroo, R., Pradhan, N. C, Goud, V. V. and Dalai, A. K. (2008) Epoxidation of canola oil with hydrogen peroxide catalyzed by acidic ion exchange resin, *J Am Oil Chem Soc.*, **85**, 887-896.
- Goud, V.V., Patwardhan, A.V. and Pradhan, N. C. (2006) Studies on the epoxidation of mahua oil (*Madhumica indica*) by hydrogen peroxide, *Bioresource Technology*, **97**, 1365-1371.
- Goud, V. V., Pradhan, N. C. and Patwardhan, A. V. (2006b) Epoxidation of karanja (*Pongamia glabra*) oil by H₂O₂, *J Am Oil Chem Soc*, **83**, 635-640.
- Meyer, P.P., Techaphattana, N., Manundawee, S., Sangkeaw, S., Junlakan, W. and Tongurai, C. (2008) Epoxidation of soybean oil and *Jatropha* oil, *Thammasat Int. J. Sc. Tech.*, **13**.
- Lathi, P.S. and Mattiasson, B. (2007) Green approach for the preparation of biodegradable lubricant base stock from epoxidised vegetable oil, *Applied Catalysis B: Environmental*, **69**, 207-212.
- Salimon, J., Dina Azleema, M. N., Nazriwati, A. T., Mohd Firdaus, M. Y. and Noraisah, A. (2010) Fatty acid composition and physicochemical properties of Malaysian castor bean *Ricinus communis* L. seed oil, *Sains Malaysiana*, **39(5)**, 761-764.
- Joseph, R., Madhusoodhanan, K. N., Alex, R., Varghese, S., George, K. E. and Kuriakose, B. (2014) Studies on epoxidised rubber seed oil as secondary plasticiser/stabiliser for polyvinyl chloride, *Plastics Rubber and Composites*, **33(5)**, 217-222.
- Derawi, D. and Salimon, J. (2016) Sintesis sebatian hidroksi-eter minyak sawit olein, *Sains Malaysiana*, **45(5)**, 817-823.
- Goud, V. V., Patwardhan, A. V., Dinda, S. and Pradhan, N. C. (2007) Kinetics of epoxidation of *Jatropha* oil with peroxyacetic and peroxyformic acid catalysed by acidic ion exchange resin, *Chemical Engineering Science*, **62**, 4065-4076.
- Kyu, W. L., Cheng, H., Jin, Y., Young, W. K. and Keun, W. C. (2008) Modification of soybean oil for intermediates by epoxidation, alcoholysis and amidation, *Korean Journal Chemical Engineering*, **25(3)**, 474-482.
- Wang, R. and Schuman, T. P. (2013) Vegetable oil-derived epoxy monomers and polymer blends: A comparative study with review, *Polymer Letters*, **7(3)**, 272-292.
- Okieimen, F. E., Bakare, O. I. and Okieimen, C. O. (2002) Studies on the epoxidation of rubber

- seed oil, *Industrial Crops and Products*, **15**: 139-144.
24. Milchert, E. and Smagowicz, A. (2009) The influence of reaction parameters on the epoxidation of rapeseed oil with peracetic acid, *J Am Oil Chem Soc*, **86**, 1227-1233.
 25. Nurazira Mohd Nor, Darfizzi Derawi and Jumat Salimon (2017) Chemical modification of epoxidized palm oil for biolubricant application, *Malaysian Journal of Analytical Sciences*, **21(6)**, 1423-1431.
 26. Nurazira Mohd Nor, Darfizzi Derawi and Jumat Salimon (2018) The optimization of RBD palm oil epoxidation process using D-Optimal design, *Sains Malaysiana*, **47(7)**, 1359-1367.
 27. Nurazira Mohd Nor, Darfizzi Derawi and Jumat Salimon (2019) Esterification and evaluation of palm oil as biolubricant base stock, *Malaysian Journal of Chemistry*, **21 (2)**, 28-35.
 28. Njoku, P. C., Egbukole, M. O. and Enenebeaku, C. K. (2010) Physio-chemical characteristics and dietary metal levels of oil from *Elaeis guineensis* species, *Pakistan Journal of Nutrition*, **9(2)**, 137-140.
 29. Hoang, T. T. K. and Kim, II (2015) Epoxidation and ring-opening of palm oil to produce high functionality polyols, *Australia Journal of Basic and Applied Sciences*, **9(8)**, 89-93.
 30. Derawi, D. and Salimon, J. (2010) Optimization on epoxidation of palm olein by using performic acid, *E-Journal of Chemistry 2010*, **7(4)**, 1440-1448
 31. Kuntom, A., Lin, S. W., Ai, T. Y., Idris, N. A., Yusof, M., Sue, T. T. and Ibrahim, N. A. (2004) MPOB test methods – a compendium of test on palm oil products, palm kernel products, fatty acids, food related products and others. Bangi: MPOB.
 32. American Oil Chemists Society (1998) Official Methods and Recommended Practices of The American Oil Chemists Society. AOCS Press.
 33. Chowdhury, K., Banu, L. A., Khan, S. and Latif, A. (2007) Studies on the fatty acid composition of edible oil, *Bangladesh Journal of Scientific and Industrial Research*, **42(3)**, 311-316.
 34. Derawi, D., Salimon, J. and Ahmed, W. A. (2014) Preparation of epoxidized palm olein as renewable material by using peroxy acids, *Malaysian Journal of Analytical Sciences*, **18(3)**, 584-591
 35. Nurazira Mohd Nor. (2019) Kajian pengubahsuaian minyak sawit mentah untuk penghasilan stok asas biopelincir, Ph.D.Thesis, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
 36. Pavia, D. L. (2001) Introduction to Spectroscopy, Thomson Learning, Inc., United States.
 37. Salimon, J., Salih, N. and Yousif, E. (2011) Chemically modified biolubricant basestocks from epoxidized oleic acid: improved low temperature properties and oxidative stability, *Journal of Saudi Chemical Society*, **15**:195-201.
 38. Fox, N. J. and Stachowiak, G. W. (2007) Vegetable oil-based lubricants-A review of oxidation, *Tribology International*, **40**, 1035-1046.
 39. Borugadda, V. B. and Goud, V. V. (2015) Response surface methodology for optimization of bio lubricant basestock synthesis from high free fatty acids castor oil, *Energy Science & Engineering*, **3(4)**, 371-383.
 40. Salimon, J. and Salih, N. (2009) Modification of epoxidized ricinoleic acid for biolubricant base oil with improved flash and pour points, *Asian Journal of Chemistry*, **22(7)**: 5468-5476.