TRIBOLOGICAL CHARACTERISTICS OF MINERAL AND PLANT OIL BLENDS

MOHAMMED HASSAN JABAL

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

MAY 2016

To:

My God, Allah ‘azza wa jalla

Then to My beloved family

ACKNOWLEDGEMENT

Thanks to ALLAH, the Most Gracious, the Most Merciful, the Most Bountiful who gave me the courage and patience to accomplish this research work. Without his help and mercy, this would not have come into reality.

I am deeply grateful to my supervisor, Prof Ir Dr. Farid Nasir Ani for his guidance, patience, and support. I have been extremely lucky to have a supervisor who cared so much about my work, and who responded to my questions and queries so promptly. I would like also to thank my co-supervisor, Asso. Prof. Dr. Syahrullail Bin Samion for his useful advices and encouragement. Without their valuable advice, kind encouragement and trust, I would not have reached this point.

I would like to acknowledge the Malaysian Ministry of Higher Education (MOHE), Iraqi Ministry of Higher Education & Scientific Research, Universiti Teknologi Malaysia and University of Technology/ Baghdad for providing the financial support and facilities for this research.

My thanks are also due to the staff, faculty members, and technicians of the Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, who contributed to my research.

I have been very providential to have the love and support of my family throughout my academic career. I am extremely grateful to my father Haj Hassan Jabal for his constant faith in me and for always supporting my efforts.

ABSTRACT

Due to the biodegradability, low toxicity, high viscosity index, reasonably cost to produce and environment friendly, the bio-lubricants such as vegetable oils are being commonly used as sustainable resources. However, vegetable oils are still suffering from low wear resistance (high wear scar) and low thermal stability (low flash temperature parameter), which led to limit their applications. In this research, the evaluations of tribological characteristics as a new source of bio-lubricant, namely, cactus oil besides other different types of vegetable oils that include refined, bleached, and deodorized (RBD) palm olein, castor oil and also jatropha oil were implemented. These types of oils were employed as an extensive substitute to mineral oil in the air compressors machines and with the intention to reduce the amount of mineral oil, which these are non-degradable, toxic properties, unfriendly to the environment and also high-priced in producing, the blends of vegetable oils were also applied as a partially bio-lubricant replacement for the mineral oil. According to ASTM D4172-B standard test of four-ball tribotester, the lubricity of the oils was examined in terms of kinematic viscosity, viscosity index, coefficient of friction (C_f), wear scar diameter (*WSD*), and flash temperature parameter (*FTP*). The results of normal load, rotation speed, and oil temperature were also evaluated for blended and neat oils, and then the results were compared to the mineral oil. The observations of the wear surfaces were attained utilizing an image processing that considered as a new technique in the tribological field, as well as the ball volumetric losses were also calculated. To optimise the blended oils based on the computed parameters, a design of experiments (DOE) method was used. The tribological performance characteristics, such as the wear losses, cylinder surface temperature, and kinematic viscosity were evaluated using a reciprocating air compressor for 60 hours as an intermittent operating time. As a comparison between the vegetable oils, the neat cactus oil shows a satisfaction tribological behaviour due to lowest value of ball volume losses and comparable results for wear scar diameter and flash temperature parameter after being used as an abundant bio-lubricant. It was also found that the cactus oil fulfilled a significantly better tribological performance as a partial bio-lubricant, as an illustration, the wear losses was 0.058 g/l for the optimum cactus blend codes as (E44.24/CC55.76), while the mineral oil was 0.09 g/l. The results also demonstrated that the wear scar diameter for the optimum cactus blend under 600 N shows a 37.83% reduction and the wear losses for the optimum RBD palm olein blend shows a 97.55% reduction. Furthermore, it was also observed that the flash temperature parameter values increased to be 135.35% and 114.07% for the E53.11/RB46.89 and E44.24/CC55.76, respectively, which therefore it is able to conclude that the blending process contributed towards improving of the tribological characteristics and the air compressor performance. With regards to the results of viscosity, the neat and optimised blends oils exhibit an essential consistency based upon the viscosity grade requirement of ISO VG32. Moreover, the results of image processing possesses appropriately represented the surface wear characteristics and provided precise details about the distribution of wear depth and wear shape together with the ball volumetric losses.

ABSTRAK

Disebabkan kebiodegradasian, ketoksikan rendah, indeks kelikatan yang tinggi, harga yang berpatutan untuk dihasilkan dan mesra alam sekitar, biopelincir seperti minyak sayuran lazim digunakan sebagai sumber kelestarian. Walau bagaimanapun, minyak sayuran masih mengalami rintangan hausan rendah (keparutan hausan tinggi) dan kestabilan rendah haba (parameter suhu kilat rendah), yang membataskan penggunaannya. Dalam kajian ini, penilaian ciri-ciri tribologi sebagai sumber baru biopelincir iaitu minyak kaktus di samping jenis minyak sayuran lain yang berbeza termasuk minyak sawit olein tapis, diluntur, dan dinyahbau (RBD), minyak kastor dan minyak jatropha telah dilaksanakan. Jenis-jenis minyak tersebut telah digunakan dengan meluas sebagai pengganti minyak mineral dalam mesin pemampat udara dan tujuan untuk mengurangkan jumlah minyak mineral yang tidak boleh terurai, bersifat toksik, tidak mesra alam dan juga mahal untuk penghasilannya. Campuran minyak sayuran juga digunakan sebagai penggantian separa biopelincir untuk minyak mineral. Mengikut ujian standard ASTM D4172-B penguji tribo empat bebola, kebolehpelinciran minyak telah diperiksa dari segi kelikatan kinematik, indeks kelikatan, pekali geseran (C_f), garispusat kehausan parut (*WSD*), dan parameter suhu kilat (*FTP*). Keputusan beban normal, kelajuan putaran, dan suhu minyak juga telah dinilai untuk minyak campuran dan tulen, dan kemudian keputusan dibandingkan dengan minyak mineral. Pemerhatian permukaan haus telah dicapai dengan menggunakan satu pemprosesan imej yang dianggap sebagai satu teknik baru dalam bidang tribologi, juga kehilangan isipadu bebola dikira. Untuk mengoptimumkan minyak campuran berdasarkan parameter yang dikira, satu kaedah reka bentuk eksperimen (DOE) telah digunakan. Ciri-ciri prestasi tribologi seperti kehilangan (berat) haus, suhu permukaan silinder, dan kelikatan kinematik telah dinilai menggunakan pemampat udara salingan selama 60 jam sebagai masa operasi yang berkala. Sebagai perbandingan antara minyak-minyak sayuran tersebut, minyak kaktus tulen menunjukkan ciri-ciri tribologi yang memuaskan kerana nilai terendah kehilangan jumlah isipadu bebola dan keputusan yang setanding untuk diameter kesan keparutan dan parameter suhu kilat selepas digunakan sebagai biopelincir. Didapati juga minyak kaktus memenuhi prestasi tribologi yang ketara lebih baik sebagai biopelincir separa, contohnya, kehilangan (berat) hausan adalah 0.058 g/l untuk kod campuran optimum minyak kaktus sebagai (E44.24/CC55.76), manakala minyak mineral adalah 0.09 g/l. Keputusan juga menunjukkan garispusat hausan parut untuk campuran kaktus optimum di bawah 600 N mengalami pengurangan sebanyak 37.83% dan kehilangan (berat) hausan untuk campuran olein sawit RBD optimum menunjukkan penurunan sebanyak 97.55%. Tambahan pula, nilai parameter suhu kilat didapati meningkat kepada 135.35% dan 114.07% bagi E53.11/RB46.89 dan E44.24/CC55.76. Dengan itu dapat disimpulkan bahawa proses pencampuran menyumbang kepada penambahbaikan ciri-ciri tribologi dan prestasi pemampat udara. Merujuk kepada ciri-ciri kelikatan yang diperolehi oleh minyak tulen dan minyak campuran yang telah dioptimumkan, ia mempamerkan suatu konsistensi yang penting berdasarkan kepada keperluan gred kelikatan ISO VG32. Selain itu, hasil pemprosesan imej mempunyai ciri hausan permukaan yang memgambarkan ciri kehausan permukaan dan memberikan butiran yang tepat mengenai taburan kehausan dalaman serta bentuk kehausan bersama kehilangan isipadu bebola.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

REFERENCES

Abdalla, H. S., Baines, W., McIntyre, G., and Slade, C. (2007). Development of Novel Sustainable Neat-Oil Metal Working Fluids for Stainless Steel and Titanium Alloy Machining. Part 1. Formulation development. *The International Journal of Advanced Manufacturing Technology*.34 (1):21-33.

Abdollah, M. F. B., Yamaguchi, Y., Akao, T., Inayoshi, N., Miyamoto, N., Tokoroyama, T., and Umehara, N. (2012). Deformation–Wear Transition Map of DLC Coating Under Cyclic Impact Loading. *Wear*.274: 435-441.

Abdulquadir, B.L., and Adeyemi, M.B. (2008). Evaluations of Vegetable Oil-Based As Lubricants for Metal-Forming Processes. *Industrial Lubrication and Tribology* . 60(5):242-248.

Adhvaryu, A., and Erhan, S. Z. (2002). Epoxidized Soybean Oil as A Potential Source of High-Temperature Lubricants. *Industrial Crops and Products*.15 (3):247-254.

Adhvaryu, A., Liu, Z., and Erhan, S. Z. (2005). Synthesis of Novel Alkoxylated Triacylglycerols and Their Lubricant Base Oil Properties. *Industrial Crops and Products*.21 (1):113-119.

Agarwal, D., and Agarwal, A. K. (2007). Performance and Emissions Characteristics of Jatropha Oil (Preheated and Blends) in a Direct Injection Compression Ignition Engine. *Applied Thermal Engineering*. 27(13):2314-2323.

Ajithkumar, G. (2009). *Analysis, Modification and Evaluation of the Cold Flow Properties of Vegetable Oils as Base Oils for Industrial Lubricants*. Doctoral dissertation, Cochin University of Science and Technology.

Aldrich. (2003). *Aldrich Handbook of Fine Chemicals and Laboratory Equipment*. United Kingdom: Sigma-Aldrich Company Limited.

Allawzi, M., Abu-Arabi, M. K., Al-Zoubi, H. S., and Tamimi, A. (1998). Physicochemical Characteristics and Thermal Stability of Jordanian Jojoba Oil. *Journal of the American Oil Chemists' Society*.75 (1):57-62.

Alves, S. M., and de Oliveira, J. F. G. (2006). Development of New Cutting Fluid for Grinding Process Adjusting Mechanical Performance and Environmental Impact. *Journal of Materials Processing Technology*.179(1):185-189.

Anderson, E. F. (2001). *The Cactus Family*. Portland, Oregon: Timber Press, ISBN 978-0-88192-498-5.

Antolin,G.,Tinaut,F.,Briceno,Y.,Castano,V.,Perez,C.,and Ramirez ,A. (2002) . Optimisation of Biodiesel Production by Sunflower Oil Transesterification. *Bioresouce technology* .83(2):111-114.

Arbain, N. H., and Salimon, J. (2011). Synthesis and Characterization of Ester Trimethylolpropane Based Jatropha Curcas Oil as Bio Lubricant Base Stocks. *Journal of Science and Technology*.2 (2):47-58.

Asadauskas, S., Perez, J. M., and Duda, J. L. (1996). Oxidative Stability and Antiwear Properties of High Oleic Vegetable Oils. *Lubrication Engineering*. 52(12): 877-882.

Asadauskas, S., Perez, J. M., and Duda, J. L. (1997). Lubrication Properties of Castor Oil-Potential Basestock for Biodegradable Lubricants. *Lubrication engineering*.53 (12): 35-41.

Bartz, W. J. (1998). Lubricants and the Environment. *Tribology International*.31 (1): 35-47.

Bartz, W. J. (2006). Eco tribology: Environmentally Acceptable Tribological Practices. *Tribology International.* 39(8):728-733.

Belluco, W., and De Chiffre, L. (2001). Testing of Vegetable-Based Cutting Fluids by Hole-Making Operations. *Lubrication Engineering- Illinois*. 57(1):12-16.

Bhattacharya, A., Singh, T., Verma, V. K., and Nakayama, K. (1990). The Role of Certain Substituted 2-Amino-Benzothiazolylbenzoylthiocarbamides as Additives in Extreme Pressure Lubrication of Steel Bearing Balls. *Wear*, *136*(2), 345-357.

Birova, A., Pavlovičová, A., and Cvenroš, J. (2002). Lubricating Oils Based on Chemically Modified Vegetable Oils. *Journal of Synthetic Lubrication*.18 (4): 291-299.

Bisht, R. P. S., Sivasankaran, G. A., and Bhatia, V. K. (1993). Additive Properties of Jojoba Oil for Lubricating Oil Formulations. *Wear*.161 (1): 193-197.

Bisio, A. L., and Xanthos, M. (1995). How to Manage Plastics Waste: Technology and Market Opportunities .*Hanser Gardner Publications*.253.

Boerlage, G. D. (1933). Four-ball Testing Apparatus for Extreme-Pressure Lubricants. *Engineering*.136:46-47.

Booser, E. R. (1984). CRC Handbook of Lubrication. Theory and Practice of Tribology: Volume II: Theory and design.

Bowden, F. P., and Tabor, D. (2001). The Friction and Lubrication of Solids, Oxford Classic Texts. *Oxford University Press*. 1: 200–227.

Box, G. E., Hunter, J. S., and Hunter, W. G. (2005). *Statistics for Experimenters: Design, Innovation, and Discovery*. (2nd ed). Hoboken, New Jersey: *A John Wiley & Sons, Inc., Publication*.

Bozzi, A. C., and De Mello, J. D. B. (1999). Wear Resistance and Wear Mechanisms of WC–12% Co Thermal Sprayed Coatings in Three-Body Abrasion. *Wear*.233:575-587.

Briscoe, B.J., Thomas, S., and Williams, D.R. (1992). Microscopic Origins of the Interface Friction of Organic Films: the Potential of Vibrational Spectroscopy. *Wear*, 153(1):263-275.

Bruns, R. E., Scarminio, I. S., and De Barros Neto, B. (2006). *Statistical Design-Chemometrics*. (Vol. 25). Amsterdam: Elsevier.

Busch, C., and Backe, W. (1994). Rapidly Biodegradable Hydraulic Fluids. *Tribol Schmid*. 41(1), 17-23.

Canoira, L., Galeán, J. G., Alcántara, R., Lapuerta, M., and García-Contreras, R. (2010). Fatty Acid Methyl Esters (FAMEs) from Castor Oil: Production Process Assessment and Synergistic Effects in its Properties. *Renewable Energy*. 35(1): 208-217.

Carcel, A. C., Palomares, D., Rodilla, E., and Puig, M. P. (2005). Evaluation of Vegetable Oils as Pre-Lube Oils for Stamping. *Materials and design*.26 (7):587-593.

Carnes, K. (2004). Offroad hydraulic fluids: Beyond biodegradability. *Tribology and Lubrication Technology*.60 (9):32-40.

Castro, W., Weller, D. E., Cheenkachorn, K., and Perez, J. M. (2005). The Effect of Chemical Structure of Base Fluids on Antiwear Effectiveness of Additives. *Tribology International*.38 (3):321-326.

Chauhan, P. S., and Chhibber, D. V. K. (2013). Non-Edible Oil as A Source of Bio-Lubricant for Industrial Applications: A Review. *International Journal of Engineering Science and Innovative Technology (IJESIT).*1(2):299-305.

Cheenkachorn, K., and Fungtammasan, B. (2010). Development of Engine Oil Using Palm Oil as a Base Stock for Four-Stroke Engines. *Energy*. 35(6): 2552-2556.

Cheng, V. M., Galiano-Roth, A. S., Marougy, T., and Berezinski, J.(1994) .Vegetable-Based Hydraulic Oil Performance in Piston Pumps. *Society of Automotive Engineers (SAE) Technical Paper* .SAE 941079.

Choi, U. S., Ahn, B. G., Kwon, O. K., and Chun, Y. J. (1997). Tribological Behavior of Some Antiwear Additives in Vegetable Oils. *Tribology International* .30 (9):677-683.

Cloin, J. (2005). Coconut Oil as a Biofuel in Pacific Islands. South Pacific Applied Geosciences Commission.*SOPAC*:1-5.

Dayou, S., Liew, W. Y. H., Ismail, M. A. B., and Dayou, J. (2011). Evaluation of Palm Oil Methyl Ester as Lubricant Additive Using Milling and Four-Ball Tests. *International Journal of Mechanical and Materials Engineering*. 6(3):374-379.

Demirbas, A. (2004).Combustion Characteristics of Different Biomass Fuels. *Progress in Energy and Combustion Science* .30(2):219-230.

Díaz, R. M., Bernardo, M. I., Fernández, A. M., and Folgueras, M. B. (1996). Prediction of the Viscosity of Lubricating Oil Blends at Any Temperature. *Fuel*.75 (5): 574-578.

Dowson, D. (1979). *History of Tribology*. London: Addison-Wesley Longman Limited.

Dowson, D. (1998). *History of Tribology*. London: Professional Engineering Publication Limited.

Earle, J., and Kuiry, S. (2012). Characterization of Lubricants for Research and Development, Quality Control and Application Engineering. *Bruker Nano Surfaces Division*: 1-6.

Eichenberger, H. F. (1991). Biodegradable Hydraulic Lubricant an Overview of Current Developments in Central Europe. *Society of Automotive Engineers (SAE) Technical Paper*.SAE 910962.

Erhan, S. Z., and Asadauskas, S. (2000). Lubricant Base stocks from Vegetable Oils. *Industrial Crops and Products*.11 (2):277-282.

Erhan, S. Z., Sharma, B. K., and Perez, J. M. (2006). Oxidation and low temperature stability of vegetable oil-based lubricants. *Industrial Crops and Products*. 24(3): 292-299.

Erhan, S., and Sharma, B. K. (2006). Vegetable Oil Based Biodegradable Lubricants for Industrial Applications. *Biotechnology*. 21.

Farhanah, A. N., and Bahak, M. Z. (2015). Engine Oil Wear Resistance. *Jurnal Tribologi*. 4: 10-20.

Fasina, O. O., and Colley, Z. (2008). Viscosity and Specific Heat of Vegetable Oils as a Function of Temperature: 35 ^{o}C to 180 ^{o}C. *International Journal of Food Properties*. 11(4):738-746.

Figueroa, M., García, E., Hernández, E. A., and Vite-Torres, M. (2014). Friction and Wear of Jatropha Curcas Oil Using a Four Balls Tester. *Advanced Materials Research*.902: 76-81.

Fox, N. J., and Stachowiak, G. W. (2007). Vegetable Oil-Based Lubricants—A review of Oxidation. *Tribology International*.*40* (7):1035-1046.

Francis, G., Edinger, R., and Becker, K. (2005). A Concept for Simultaneous Wasteland Reclamation, Fuel Production, and Socio-Economic Development in Degraded Areas in India: Need, potential and perspectives of Jatropha plantations. *In Natural Resources Forum. Blackwell Publishing, Ltd*. 29(1): 12-24.

Glaeser ,W.A., Erickson, R.C., Dufrane , K.F. and Kannel,J.W.(1992).Tribology :The Science of Combating Wear-Part III.*Lubrication Engineering* .48(12) : 949-952.

Glancey, J. L., Benson, E. R., and Knowlton, S. (1996). A Low Volume Fluid Power System for the Evaluation of Genetically Modified Vegetables as Industrial Fluids. *Society of Automotive Engineers (SAE) Technical Paper*. SAE961725.

Golshokouh, I. (2013). *Tribological Behavior of Pyrolysis Bio-Oil and Pure Plant Oils as Lubricant*. Doctoral dissertation, Universiti Teknologi Malaysia, Mechanical Engineering, Skudai.

Golshokouh, I., Ani, F. N., and Syahrullail, S. (2012). Wear Resistance Evaluation of Palm Fatty Acid Distillate Using Four-Ball Tribotester. *Proceedings in AIP Conference.* 3–4 October 2011. Melaka, Malaysia. Explore AIP's new open-access journal .928:928-935.

Golshokouh, I., Golshokouh, M., Ani, F. N., Kianpour, E., and Syahrullail, S. (2013b). Investigation of the Physical Properties for Jatropha Oil in Different Temperature as Lubricant Oil. *Life Science Journal*.10 (8):110-119.

Golshokouh, I., Syahrullail, S., and Ani, F. N. (2014b). Empty Fruit Bunches Oil as New Lubricant. *In Applied Mechanics and Materials*.660:352-356.

Golshokouh, I., Syahrullail, S., Ani, F. N., and Masjuki, H. H. (2014a). Investigation of Palm Fatty Acid Distillate Oil as an Alternative to Petrochemical Based Lubricant. *Journal of Oil Palm Research*.26 (1): 25-36.

Golshokouh, I., Syahrullail, S., Ani, F. N., and Masjuki, H. H. (2013a). Investigation of Palm Fatty Acid Distillate as an Alternative Lubricant of Petrochemical Based Lubricants, Tested at Various Speeds. *International Review of Mechanical Engineering*. 7(1):72-80.

Golshokouh, I., Wira, J. Y., Ani, F. N., and Syahrullail, S. (2013c). Palm Fatty Acid Distillate as an Alternative Source for Hydraulic Oil. *Applied Mechanics and Materials*.315:941-945.

Goodrum, J. W., Geller, D. P., and Adams, T. T. (2003). Rheological Characterization of Animal Fats and their Mixtures with # 2 Fuel Oil. *Biomass and Bioenergy*.24 (3):249-256.

Goswami, A. (2011). *An Alternative Eco-Friendly Avenue for Castor Oil Biodiesel: Use of Solid Supported Acidic Salt Catalyst*. *Intech Open Access Publisher*.

Goyan, R. L., Melley, R. E., Wissner, P. A., and Ong, W. C.(1998).Biodegradable Lubricants. *Lubrication Engineering*.54:10-17.

Hamm, W., and Hamilton, R. J. (2000). Edible Oil Processing.US: Taylor & Francis.

Haseeb, S. Y. S., Fazal, M. A., and Masjuki, H. H. (2010). Effect of Temperature on Tribological Properties of Palm Biodiesel. *Energy*.35:1460-1464.

Haycock, R., Caines, A. J., Haycock, R. F., and Hillier, J. E. (2004). Automotive Lubricants Reference Book. (2nd ed.): John Wiley & Sons.

Höhn, B. R., Michaelis, K., and Döbereiner, R. (1999). Load Carrying Capacity Properties of Fast Biodegradable Gear Lubricants. *Lubrication engineering*.55 (11):15-36.

Honary, L. A. (1996). An Investigation of the Use of Soybean Oil in Hydraulic Systems. *Bioresource Technology*.56 (1):41-47.

Hong, L., Wan, Y., and Jain, A. (1998). Fingerprint Image Enhancement: Algorithm and Performance Evaluation. Pattern Analysis and Machine Intelligence, *IEEE Transactions on*. 20(8):777-789.

Huang, W., Dong, J., Li, F., and Chen, B. (2000). The Performance and Antiwear Mechanism of (2-Sulfurone-Benzothiazole)-3-Methyl Esters as Additives in Synthetic Lubricant. *Tribology International*.33 (8):553-557.

Husnawan, M., Saifullah, M. G., and Masjuki, H. H. (2007). Development of Friction Force Model for Mineral Oil Basestock Containing Palm Olein and Antiwear Additive. *Tribology international*.40 (1):74-81.

Ing, T. C., Kadir, M. R. A., Sidik, N. A. C., and Syahrullail, S. (2011). Experimental Evaluation on Lubricity of RBD Palm Olein Using Four ball Tribotester. *Tribology-Lubricants and Lubrication, INTECH Open Access Publisher:* 175-184.

Ing, T. C., Rafiq, A. K. M., Azli, Y., and Syahrullail, S. (2012b). Tribological Behaviour of Refined Bleached and Deodorized Palm Olein in Different Loads Using a Four-Ball Tribotester. *Scientia Iranica*. 19(6):1487-1492.

Ing, T. C., Rafiq, A. K.M., Azli, Y., and Syahrullail, S. (2012a). The Effect of Temperature on the Tribological Behavior of RBD Palm Stearin.*Tribology Transactions*.55 (5):539-548.

Izhan , M. I., Rafiq, A.K. M., and Syahrullail, S. (2013a). Friction Resistance of Refined, Bleached and Deodorized (RBD) Palm Olein Using Modified Pin-On-Disk Tribotester. *Jurnal Teknologi*. 60(1): 27-33.

Izhan, M. I., Wira, J. Y., Kadir, A., Rafiq, M., and Syahrullail, S. (2013b). Experimental Study on the Effect of Different Speeds Applied with Palm Olein Using Pin-On-Disk Tester. *Applied Mechanics and Materials*.315: 946-950.

Jayadas, N. H., Nair, K. P., and Ajithkumar, G. (2007). Tribological Evaluation of Coconut Oil as An Environment-Friendly Lubricant. *Tribology International*. 40(2):350-354.

Kabuya, A., and Bozet, J. L. (1995). Comparative Analysis of the Lubricating Power Between a Pure Mineral Oil and Biodegradable Oils of the Same Mean ISO Grade. *Tribology Series*. 30: 25-30.

Kalam, M. A., and Masjuki, H. H. (2002). Biodiesel from Palm Oil—An Analysis of its Properties and Potential. *Biomass and Bioenergy*.23 (6):471-479.

Kalin, M., and Vižintin, J. (2006). A Comparison of the Tribological Behaviour of Steel/Steel, Steel/DLC and DLC / DLC Contacts When Lubricated with Mineral and Biodegradable Oils. *Wear*. 261(1): 22-31.

Kassfeldt, E. and Dave, G. (1997). Environmentally Adapted Hydraulic Oils. *Wear*. 207(1):41-45.

Klaus, E.E., Nagarajan, R., Duda, J, L., and Shah, K.M. (1987). The Adsorption of Tribochemical Reaction Products at Solid Surfaces. *Proceedings of the Institution of Mechanical Engineers*: 379-387.

Kreith, F., Manglik, R., and Bohn, M. (2010). *Principles of Heat Transfer*.USA, Stamford: Cengage Learning.

Kržan, B., and Vižintin, J. (2003a). Tribological Properties of an Environmentally Adopted Universal Tractor Transmission Oil Based on Vegetable Oil. *Tribology International*.36 (11): 827-833.

Kržan, B., and Vižintin, J. (2003b). Vegetable-Based Oil as a Gear Lubricant. *Gear Technology*.20 (4):28-33.

Lansdown, A. (2004). Lubricating Oils. In A. Lansdown, Lubrication and lubricant selection: a practical guide. ASME Press.

Lathi, P. S., and Mattiasson, B. (2007). Green Approach for the Preparation of Biodegradable Lubricant Base Stock from Epoxidized Vegetable Oil. *Applied Catalysis B: Environmental*.69 (3):207-212.

Lawal, S. A., Choudhury, I. A., and Nukman, Y. (2012). Application of Vegetable Oil-Based Metalworking Fluids in Machining Ferrous Metals .A Review. *International Journal of Machine Tools and Manufacture*. 52(1): 1-12.

Lee, C. S., Park, S. W., and Kwon, S. I. (2005). An experimental Study on the Atomization and Combustion Characteristics of Biodiesel-Blended Fuels. *Energy and Fuels*. 19(5): 2201-2208.

Li, F., Hanson, M. V., and Larock, R. C. (2001). Soybean Oil–Divinylbenzene Thermosetting Polymers: Synthesis, Structure, Properties and Their Relationships .*Polymer*.42 (4):1567-1579.

Liaquat, A. M., Masjuki, H. H., Kalam, M. A., and Rasyidi, A. (2012). Experimental Analysis of Wear and Friction Characteristics of Jatropha Oil Added Lubricants. *Applied Mechanics and Materials.*110: 914-919.

Liu, W., Hu, L., and Zhang, Z. (1995). Friction and Wear of the Film Formed in the Immersion Test of Oil Containing Antiwear and Extreme Pressure Additives. *Thin Solid Films*. 271(1): 88-91.

Lovell, M., Higgs, C. F., Deshmukh, P., and Mobley, A. (2006). Increasing Formability in Sheet Metal Stamping Operations Using Environmentally Friendly Lubricants. *Journal of Materials Processing Technology*.177(1):87-90.

Lubis, A. M. H. S., Sudin, M. B., and Ariwahjoed, B. (2011b). Investigation of Worn Surface Characteristics of Steel Influenced by jatropha Oil as Lubricant and Eco-Friendly Lubricant Substituent. *Journal of Applied Sciences*.11 (10):1797-1802.

Lubis, A. M. H. S., Sudin, M. B., and Ariwahjoedi, B. (2011a). Wear Preventive Characteristics of Esterified jatropha Oil. *In National Postgraduate Conference (NPC).IEEE:* 1- 5.

Maleque, M. A., Masjuki, H. H., and Haseeb, A. S. M. A. (2000). Effect of Mechanical Factors on Tribological Properties of Palm Oil Methyl Ester Blended Lubricant .*Wear*. 239 (1):117-125.

Mannekote, J. K., and Kailas, S. V. (2009). Performance Evaluation of Vegetable Oils as Lubricant in a Four Stroke Engine. *Proceedings of 4th World Tribology Conference*. 6–11 September. Kyoto, Japan: 331.

Mannekote, J. K., and Kailas, S. V. (2010). Influence of Chemical Structure on the Boundary Lubrication Properties of Vegetable Oils. *Proceedings of ASME 10th Biennial Conference on Engineering Systems Design and Analysis*. 12–14 July. Istanbul , Turkey: American Society of Mechanical Engineers: 633-637.

Mannekote, J. K., and Kailas, S. V. (2011). Experimental Investigation of Coconut and Palm Oils as Lubricants in Four-Stroke Engine. *Tribology Online*. 6(1): 76-82.

Mannekote, J. K., Kailas, S. V., and Naik, R. T. (2009). Condition Monitoring of Vegetable Oils Used in a 4 Stroke Engine as Lubricants. *Proceedings of Tribo-India Conference on Tribology of Automotive Systems*. 11, 12 Dec. India.

Masjuki, H. H., and Maleque, M. A. (1996). Wear, Performance and Emissions of a Two-Stroke Engine Running on Palm Oil Methyl Ester Blended Lubricant.

Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology.210 (4): 213-219.

Masjuki, H. H., Kalam, M. A., Nurul, M. F., Jayed, M. H., Liaquat, A. M., and Varman, M. (2011). Environmentally Friendly Bio-Lubricant Lubricity Testing. *Proceedings* in *Clean Energy and Technology (CET)*. 27-29 June *2011*. Kuala Lumpur, Malaysia.IEEE: 140-144.

Masjuki, H. H., Maleque, M. A., Kubo, A., and Nonaka, T. (1999). Palm Oil and Mineral Oil Based Lubricants—Their Tribological and Emission Performance. *Tribology International*.32 (6):305-314.

Masjuki,H.H.,and Maleque, M. (1997). Investigation of the Anti-Wear Characteristics of Palm Oil Methyl Ester Using a Four-Ball Tribometer Test. *Wear*. 206(1-2): 179-186.

Massart, D. L., Vandeginste, B. G., Buydens, L. M. C., Lewi, P. J., and Smeyers-Verbeke, J. (1997). *Handbook of Chemometrics and Qualimetrics: Part A*. Amsterdam: Elsevier Science Inc.

Mercurio, P., Burns, K. A., and Negri, A. (2004). Testing the Ecotoxicology of Vegetable Versus Mineral Based Lubricating Oils: 1. Degradation Rates Using Tropical Marine Microbes. *Environmental Pollution*. 129(2):165-173.

Mezger, T. G. (2006). *The rheology handbook: for users of rotational and oscillatory rheometers*. Vincentz Network GmbH & Co KG.

Mia, S., Hayashi, S., and Ohno, N. (2007). High pressure tribological behavior of vegetable oils as lubricant. *Proceedings of the International Conference on Mechanical Engineering.* 29- 31 December 2007. Dhaka, Bangladesh: pp. 29-31.

Muraki, M., and Tominaga, E. (2001). Frictional Properties of Some Additives for Sliding Guide Way Lubricants in a sliding Speed Range Between 0.002 and 1.5 m/s with A Thrust Collar Friction Tester. *Tribology International*.34 (7): 437-442.

Nagendramma, P., and Kaul, S. (2012). Development of Ecofriendly/Biodegradable Lubricants: An overview. *Renewable and Sustainable Energy Reviews*.16 (1):764-774.

Neff, W. E., El-Agaimy, M. A., and Mounts, T. L. (1994). Oxidative Stability of Blends and Interesterified Blends of Soybean Oil and Palm Olein . *Journal of the American Oil Chemists' Society* . 71(10):1111-1116.

Nie, J. (2012). *Synthesis and Evaluation of Polyol Based Bio Lubricants from Vegetable Oils*. Published Master thesis .University of Saskatchewan Saskatoon.

Noureddini, H., Teoh, B. C., and Clements, L. D. (1992). Viscosities of vegetable oils and fatty acids. *Journal of the American Oil Chemists Society*. 69(12): 1189-1191.

Ogunniyi, D. S. (2006). Castor oil: A Vital Industrial Raw Material. *Bioresource Technology*. 97(9):1086-1091.

Ohno, N., Shiratake, A., Kuwano, N., and Hirano, F. (1997).Behavior of Some Vegetable Oils in EHL Contacts. *Tribology Series*.32:243-251.

Ommen, T.V., and Claibone, C.C. (1999). Electrical Transformers Containing Electrical Insulation Fluid Comprising High Oliec Acid Compositions.*U.S. Patent No. 5,949,017*. Washington, DC: U.S. Patent and Trademark Office.

Ong, H. C., Mahlia, T. M. I., Masjuki, H. H., and Norhasyima, R. S. (2011). Comparison of Palm Oil, Jatropha Curcas and Calophyllum Inophyllum for Biodiesel: A Review. *Renewable and Sustainable Energy Reviews*. 15(8): 3501-3515.

Patil, P. D., and Deng, S. (2009). Optimization of Biodiesel Production from Edible and Non-edible Vegetable Oils. *Fuel*. 88(7):1302-1306.

Pearson, S. L., and Spagnoli, J. E. (2000). Environmental Lubricants an Overview of Onsite Applications and Experience. *Lubrication Engineering*.56 (4):40-45.

Persson, B. N. (2000). *Sliding Friction: Physical Principles and Applications*. *Springer Science and Business Media*.

Peterson, M. B., and Winer, W. O. (Eds.). (1980). *Wear Control Handbook*. New York: American society of mechanical engineers.

Quinchia, L. A., Delgado, M. A., Franco, J. M., Spikes, H. A., and Gallegos, C. (2012). Low-Temperature Flow Behaviour of Vegetable Oil-Based Lubricants. *Industrial Crops and Products*. 37(1):383-388.

Quinchia, L. A., Delgado, M. A., Valencia, C., Franco, J. M., and Gallegos, C. (2010). Viscosity Modification of Different Vegetable Oils with EVA Copolymer for Lubricant Applications. *Industrial Crops and Products.* 32(3): 607-612.

Rac, A., and Vencl, A. (2009). Performance Investigation of Chain Saw Lubricants Based on New Sunflower Oil (NSO). *Tribologie and Schmierungstechnik*. 56(3): 249-257.

Rac, A., and Vencl, A. (2012). Ecological and Technical Aspects of the Waste Oils Influence on Environment. *In The 3rd International Conference on Dipre* .12: 5-11.

Randles, S. J. (1992). Environmentally Considerate ester Lubricants for the Automotive and Engineering Industries. *Journal of Synthetic Lubrication* .9(2):145-161.

Rao, G., and Mohan, P.R. (2003).Effect of Supercharging on the Performance of a DI Diesel Engine with Cotton Seed Oil. *Energy conversion and management* .44(6):937-944.

Razak, D. M., Syahrullail, S., Yahya, A., Mahmud, N., Hashim, N. L. S., and Nugroho, K. (2013). Lubrication on the Curve Surface Structure Using Palm Oil and Mineral Oil. *Procedia Engineering*. 68:607-612.

Ren, S., Meng, J., Wang, J., Lu, J., and Yang, S. (2012). Tribo-Corrosion Behaviors of Ti 3 SiC 2/Si3N 4 Tribo-Pair in Hydrochloric Acid and Sodium Hydroxide Solutions. *Wear*.274: 8-14.

Ren, S., Meng, J., Wang, J., Lu, J.,and Yang, S.(2012). Tribo-Corrosion Behaviors of Ti3SiC2/Si3N4 Tribo-Pair in Hydrochloric Acid and Sodium Hydroxide Solutions. *Wear*.274-275:8-14.

Resul, M. F. M. G., Ghazi, T. I. M., and Idris, A. (2012). Kinetic Study of jatropha Bio Lubricant from Transesterification of jatropha Curcas Oil with Trimethylolpropane: Effects of Temperature. *Industrial Crops and Products*.38: 87-92.

Rhee, I. S. (1996). Evaluation of Environmentally Acceptable Hydraulic Fluids. *NLGI Spokesman*. 60(5): 28-35.

Rico, J. F., Battez, A. H., and Cuervo, D. G. (2002). Wear Prevention Characteristics of Binary Oil Mixtures. *Wear*. 253(7):827-831.

Rudnick, L. R. (2006). Automotives Gear Lubricants, Synthetics, Mineral Oils, and Bio-Based Lubricants: Chemistry and Technology. *Taylor and Francis*: 425–440.

Rudnick, L. R. (2009). *Lubricant Additives: Chemistry and Applications*.USA: CRC Press.

Rudnick, L. R. (Ed.). (2013). *Synthetics, Mineral Oils, and Bio-Based Lubricants: Chemistry and Technology*. New York: Taylor & Francis Group: CRC press.

Shahabuddin, M., Masjuki, H. H., and Kalam, M. A. (2013b). Development of Eco-Friendly Biodegradable Biolubricant Based on Jatropha Oil. *Tribology in Engineering*. 135-146.

Shahabuddin, M., Masjuki, H. H., Kalam, M. A., Bhuiya, M. M. K., and Mehat, H. (2013a). Comparative Tribological Investigation of Bio-Lubricant Formulated from a Non-Edible Oil Source (Jatropha oil). *Industrial Crops and Products*.47:323-330.

Sharma, B. K., Adhvaryu, A., Liu, Z., and Erhan, S. Z. (2006). Chemical Modification of Vegetable Oils for Lubricant Applications. *Journal of the American Oil Chemists' Society*.83 (2):129-136.

Sharma, B. K., Doll, K. M., and Erhan, S. Z. (2008). Ester Hydroxy Derivatives of Methyl Oleate: Tribological, Oxidation and Low Temperature Properties. *Bioresource technology*.99 (15):7333-7340.

Sharma, N. (2006). The Jatropha Experience. *Proceedings In Biodiesel Conference,Towards Energy Independence–Focus on Jatropha*.9–10 June, Andhra Pradesh:9-15.

Shashidhara, Y. M., and Jayaram, S. R. (2010). Vegetable Oils as a Potential Cutting Fluid—An Evolution. *Tribology International*. 43(5): 1073-1081.

Shashidhara, Y. M., and Jayaram, S. R. (2012). Tribological Studies on AISI 1040 with Raw and Modified Versions of Pongam and Jatropha Vegetable Oils as Lubricants. *Advances in Tribology*: 1- *6*.

Shrirame, H. Y., Panwar, N. L., and Bamniya, B. R. (2011). Bio Diesel from Castor Oil–A Green Energy Option. *Low Carbon Economy*. 2(01): 1-6.

Singh, H., and Gulati, I. (1991). Tribological Behaviour of Base Oils and Their Separated Fractions. *Wear*, 147(1): 207-218.

Singh, P. J., Khurma, J., and Singh, A. (2010). Preparation, Characterisation, Engine Performance and Emission Characteristics of Coconut Oil Based Hybrid Fuels. *Renewable Energy*. 35(9):2065-2070.

Siniawski, M. T., Saniei, N., Adhikari, B., and Doezema, L. A. (2007). Influence of Fatty Acid Composition on the Tribological Performance of Two Vegetable-Based Lubricants. *Journal of Synthetic Lubrication*. 24(2):101-110.

Sivasankaran, G. A., Bisht, R. P. S., Jain, V. K., Gupta, M., Sethuramiah, A., and Bhatia, V. K. (1988). Jojoba-Oil-Based Two-Stroke Gasoline Engine Lubricant. *Tribology International*.21 (6):327-333.

Şolea, I. C., Deleanu, I., and Georgescu, C.(2013). Evaluation of Olive Oil as Lubricant with the Help of Four-Ball Tester. *Mechanical Testing and Diagnosis*. 3:40-48.

Stachowiak, G., and Batchelor, A. W. (2013). *Engineering Tribology*. Fourth Edition. Butterworth-Heinemann.

Stokes, J., (2005). *The Theory and Application of the HVOF Thermal Spray Process*. Dublin: Dublin City University Press: 1-14.

Suhane, A., Sarviya, R.M., Rehman, A., and Khaira, H.K. (2014). Experimental Study of Castor Oil Based Lubricant for Automotive Applications. *Journal of Engineering Research and Applications*. 1(4):104-107.

Syahrullail, S., and Nuraliza, N. (2014). Friction and Wear Performance of Double Fraction Palm Olein Lubricant Using Pin-on-Disk Tribometer. *In Applied Mechanics and Materials* .554: 396-400.

Syahrullail, S., and Zulhanafi, P. (2014). The Oxidation Effect of Palm Oil Based Lubricant Using Four–Ball Tribotester. *In Applied Mechanics and Materials*. 554:281-285.

Syahrullail, S., Azmi, A. M., Sapawe, N., and Khalid, A. (2014c). Wear Characterization of Aluminum Lubricated with Palm Olein at Different Normal Load. In *Applied Mechanics and Materials*.554: 401-405.

Syahrullail, S., Kamitani, S., and Shakirin, A. (2013a). Performance of Vegetable Oil as Lubricant in Extreme Pressure Condition. *Procedia Engineering*. 68: 172-177.

Syahrullail, S., Kamitani, S., and Shakirin, A. (2014b). Tribological Evaluation of Mineral Oil and Vegetable Oil as a Lubricant. *Jurnal Teknologi (Sciences and Engineering)*.66(3):37- 44.

Syahrullail, S., Norhakem, H. M., Sapawe, N., and Khalid, A. (2014a). The Influence of Normal Load in Wear Resistance Characteristic of Palm Fatty Acid Distillate. *In Applied Mechanics and Materials* .554: 286-290.

Syahrullail, S., Wira, J. Y., Kameil, A. H. M., and Fawwaz, W. N. (2012). Wear Characteristic of RBD Palm Olein Using Four-Ball Tribotester. *In the 4th*

International Meeting of Advances in Thermofluids (IMAT 2011). *Aip Publishing*. 1440(1): 991-996.

Syahrullail, S., Wira, J. Y., Nik, W. W., and Fawwaz, W. N. (2013c). Friction Characteristics of RBD Palm Olein Using Four-Ball Tribotester. *Applied Mechanics and Materials*.315: 936-940.

Syahrullail, S., Wira, J. Y., Nik, W. W., and Tiong, C. I. (2013b). The Effect of Sliding Speed on Friction and Wear of RBD Palm Olein. *Applied Mechanics and Materials*.*315*: 951-955.

Talkit, K. M., Mahajan, D. T., and Masand, V. H. (2012). Study on Physicochemical Properties of Vegetable Oils and Their Blends Use as Possible Ecological Lubricant. *Journal of Chemical & Pharmaceutical Research*.4(12): 5139-5144.

Tiong, C. I., Azli, Y., Kadir, M. R. A., and Syahrullail, S. (2012). Tribological Evaluation of Refined, Bleached and Deodorized Palm Stearin Using Four-Ball Tribotester with Different Normal Loads. *Journal of Zhejiang University Science A*. 13(8):633-640.

Tissot, B. P., and Welte, D. H. (1978). *Petroleum Formation and Occurrence: a New Approach to Oil and Gas Exploration.* Berlin Heidelberg. New York: Springer-Verlag.

Tlili, N., Bargougui, A., Elfalleh, W., Triki, S., and Nasri, N. (2011). Phenolic Compounds, Protein, Lipid Content and Fatty Acids Compositions of Cactus Seeds. *Journal of Medicinal Plants Research*. 5(18): 4519-4524.

Vižintin, J., Arnšek, A., and Ploj, T. (2000). Lubricating Properties of Rapeseed Oils Compared to Mineral Oils Under a High Load Oscillating Movement. *Journal of Synthetic lubrication*.17 (3):201-217.

Wan Nik, W. B. (2005). *Thermal and Rheological Properties of Palm Based Oil as Hydraulic Fluid*.Doctor Philosophy, Universiti Teknologi Malaysia, Mechanical Engineering, Skudai.

Wan Nik, W. B., Ani, F. N., and Masjuki, H. H. (2005a). Thermal Stability Evaluation of Palm Oil as Energy Transport Media. Energy Conversion and Management.46 (13): 2198-2215.

Wan Nik, W. B., Ani, F. N., Masjuki, H. H., and Giap, S. E. (2005b). Rheology of Bio-Edible Oils According to Several Rheological Models and its Potential as Hydraulic Fluid *Industrial Crops and Products*.22 (3): 249-255.

Wan Nik, W. B., Zulkifli, F., Lam, S. S., Rahman, M. M., and Yusof, A. A. (2014). Experimental Studies on the Rheological and Hydraulic Performance of Palm Based Hydraulic Fluid. *Jurnal Teknologi*. 66(3):7-13.

Wessol, A. A., and Whitacre, B. (1993). Operating Hydraulics on" Green" Fluids. *Machine Design*.65 (2):73-77.

Wilson, B. (1998). Lubricants and Functional Fluids from Renewable Sources. *Industrial Lubrication and Tribology*. 50(1): 6-15.

Wu, X., Zhang, X., Yang, S., Chen, H., and Wang, D. (2000). The Study of Epoxidized Rapeseed Oil Used as A Potential Biodegradable Lubricant. *Journal of the American Oil Chemists' Society*, 77(5):561-563.

Yao, J. (1997). Evaluation of Sodium Acetylacetonate as a Synergist for Aryl amine Antioxidants in Synthetic Lubricants. *Tribology International*.30 (11):795-799.

Yuan, C. Q., Peng, Z., Yan, X. P., and Zhou, X. C. (2008). Surface Roughness Evolutions in Sliding Wear Process. *Wear*. 265(3):341-348.

Yunus, R., Fakhru'L Razi, A., Ooi, T. L., Omar, R., and Idris, A. (2005). Synthesis of Palm Oil Based Trimethylolpropane Esters with Improved Pour Points. *Industrial and Engineering Chemistry Research*.44:8178-8183.

Zaslavsky, Y. S., Berlin, A. A., Zaslavsky, R. N., Cherkashin, M. I., Beloserova, K. E., and Rusakova, V. A. (1972). Antiwear, Extreme Pressure and Antifriction Action of Friction Polymer Forming Additives. *Wear*. 20(3): 287-297.

Zeng, X., Wu, H., Yi, H., and Ren, T. (2007). Tribological Behavior of Three Novel Triazine Derivatives as Additives in Rapeseed Oil. *Wear*.262 (5):718-726.

Zulkifli, N. W. M., Kalam, M. A., Masjuki, H. H., Shahabuddin, M., and Yunus, R. (2013).Wear Prevention Characteristics of a Palm Oil-Based TMP (Trimethylolpropane) Ester as an Engine Lubricant. *Energy*. *54*:167-173.

Zulkifli, N. W. M., Masjuki, H. H., Kalam, M. A., Yunus, R., and Azman, S. S. N. (2014). Lubricity of Bio-Based Lubricant Derived from Chemically Modified jatropha Methyl Ester. *Jurnal Tribologi*.1: 18-39.