Faculty of Engineering

Accelerated Thermal Ageing on Electrical and Physicochemical Performance of Palm Oil Methyl Ester-Based Nanofluids as Liquid Insulation in Transformers

Sharifah Masniah Wan Masra

Doctor of Philosophy
2024

Accelerated Thermal Ageing on Electrical and Physicochemical Performance of Palm Oil Methyl Ester-Based Nanofluids as Liquid Insulation in Transformers

Sharifah Masniah Wan Masra

A thesis submitted

In fulfillment of the requirements for the degree of Doctor of Philosophy

(Electrical Engineering)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2024

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

………………………………

Signature

Name: Sharifah Masniah Wan Masra

Matric No.: 20010186

Faculty of Engineering

Universiti Malaysia Sarawak

Date : 28th June 2024

ACKNOWLEDGEMENT

First and foremost, all praises go to Allah for giving me the opportunity, determination, and strength to complete my studies. Thank you UNIMAS for the scholarship. I want to express my profound appreciation to my supervisor, Ir Ts Dr Yanuar Zulardiansyah Arief for his continuous support, encouragement, and invaluable expertise throughout this study. To my co-supervisors, Prof Ir Dr Andrew Ragai Henry Rigit, Assoc Prof Ir Ts Dr Siti Kudnie Sahari, and Assoc Prof Dr Md. Rezaur Rahman, I am highly grateful for their motivation, insightful feedback, constructive criticism, and encouragement during the various stages of my study. Their collective expertise and dedication have undoubtedly enriched the quality of my work.

I am indebted to all my colleagues, friends, and lab mates for their support and exciting discussions, which have fostered an environment of intellectual exchange and growth. I want to extend my gratitude to En Wahap Marni, En Shafri Senawi, and En Benedict Samling from the Faculty of Resource Science and Technology (FRTS) and En Airul Azhar Jitai from the Department of Chemical Engineering and Energy Sustainability for their valuable assistance in operating the equipment in the laboratory. I would like to thank the staff and technicians of the Faculty of Engineering for assisting me throughout my study.

My heartfelt thanks go to my husband, Mohd Saufee Muhammad; my daughters, Sofea Miyuki and Shaza Mizuki; and my parents and siblings for their love, understanding, belief, and moral support throughout this long journey. Thank you all for being an integral part of my pursuit of a PhD.

ABSTRACT

The paradigm shift from non-biodegradable and non-renewable mineral oil to acceptable biodegradable, renewable, and safer alternatives has prominently emerged in response to the United Nations Sustainable Development Goal (SDG)-7. However, their high viscosity, low dielectric strength, and poor oxidation stability prevent the broader usage as a replacement for dielectric liquid in transformers. Driven by the need for elevated properties of vegetable oils to align with the industry standards, the conversion process of the triglycerides, combined with modifications through the addition of nanoparticles and a surfactant, has been investigated. This thesis proposes enhancing the properties of refined, bleached, and deodorised palm oil olein ($RBDPO_o$) through chemical modification using a transesterification process to produce palm oil methyl ester (POME) as the base fluid. Additionally, semiconductive titanium dioxide (TiO_2) and conductive multi-walled carbon nanotube (MWCNT) nanoparticles, along with the hexadecyltrimethylammonium bromide (CTAB) surfactant, are added. Accelerated ageing experiments were conducted in a sealed condition at a temperature of 130 ^{o}C over a duration ranging from 0 to 1000 h for 0.01−0.10-g/L concentrations to understand their degradation behaviour. Overall, the findings demonstrated that all POME-based nanofluids showed an increase in AC BDV during the accelerated thermal ageing study, with the highest average value recorded at 57.08 kV, indicating a remarkable increment of 157.7% for POME-based TiO_2 nanofluid at a concentration of 0.05-g/L. After being subjected to accelerated thermal ageing, the BDV of POME-based TiO_2 nanofluids revealed a consistent trend across various doping concentrations. It was demonstrated that the proposed POME-based nanofluids performed comparably with other types of methyl ester oils in terms of breakdown voltage, kinematic viscosity, and flash point.

Keywords: Chemical modification, nanofluids, palm oil methyl ester, thermal ageing, transesterification

Penuaan Terma Dipercepat ke atas Sifat-sifat Elektrik dan Kimiafizik Nanobendalir Berasaskan Ester Metil Minyak Sawit sebagai Cecair Penebat di dalam Transformer

ABSTRAK

Anjakan paradigma dari minyak galian yang tidak terurai secara biologi dan tidak diperbaharui kepada alternatif yang boleh terurai secara biologi, boleh diperbaharui dan lebih selamat telah muncul sebagai tindak balas kepada Matlamat Pembangunan Mampan ke-7 (SDG-7) Pertubuhan Bangsa-bangsa Bersatu (PBB). Walaubagaimanapun, kelikatan tinggi, kekuatan elektrik rendah, dan kestabilan oksidasi yang lemah menghalang penggunaan meluas sebagai pengganti cecair dielektrik di dalam transformer. Dipacu oleh keperluan untuk meningkatkan sifat-sifat minyak sayuran agar selaras dengan piawaian industri, proses penukaran trigliserida, digabungkan dengan pengubahsuaian melalui penambahan nanopartikel dan surfaktan telah dikaji. Tesis ini mencadangkan peningkatan sifat-sifat olein minyak sawit ditapis, diluntur, dan dinyahbau ($RBDPO_o$), melalui pengubahsuaian kimia menggunakan proses transesterifikasi untuk menghasilkan ester metil minyak sawit (POME) sebagai cecair asas. Selain itu, nanopartikel semikonduktif titanium dioksida (TiO_2) dan nanopartikel konduktif nanotiub karbon berbilang dinding (MWCNT), beserta surfaktan CTAB, ditambahkan. Eksperimen penuaan dipercepat telah dijalankan dalam keadaan tertutup pada suhu 130 ^{o}C selama tempoh antara 0 sehingga 1000 jam pada kelikatan 0.01−0.10-g/L untuk memahami tingkah-laku degradasi mereka. Secara keseluruhan, dapatan kajian menunjukkan bahawa semua nanobendalir berasaskan POME menunjukkan peningkatan dalam AC BDV semasa kajian penuaan terma dipercepat, dengan nilai purata tertinggi yang direkodkan pada 57.08 kV, menunjukkan peningkatan luar biasa sebanyak 157.7% bagi nanobendalir berasakan POME-TiO_2 pada kelikatan 0.05-g/L. Setelah menjalani penuaan terma dipercepat, BDV nanobendalir berasaskan POME-

TiO_2 mendedahkan trend yang konsisten pada pelbagai kelikatan. Ini telah ditunjukkan bahawa nanofluid berasaskan POME yang dicadangkan menunjukkan prestasi yang standing dengan jenis minyak ester metal yang lain dari segi voltan keruntuhan, kelikatan kinematik, dan titik kilat.

Kata kunci: *Pengubahsuain kimia, nanobendalir, metil ester minyak sawit, penuaan terma, transesterifikasi*

TABLE OF CONTENTS

	Page
DECLARATION	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
ABSTRAK	v
TABLE OF CONTENTS	vii
LIST OF TABLES	xii
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS	xvii
CHAPTER 1 INTRODUCTION	1
1.1 Study Background	1
1.2 Problem Statement	5
1.3 Research Questions	6
1.4 Research Hypothesis	7
1.5 Research Objectives	7
1.6 Scopes and Limitations of Study	8
1.7 Significance of Research	9
1.8 Thesis Outline	10
CHAPTER 2 LITERATURE REVIEW	12

2.1	Overview	12
2.2	Transformer Insulating Liquids	13
2.2.1	Mineral Oil	14
2.2.2	Synthetic Ester Oil	14
2.2.3	Natural Ester Oil	14
2.3	Methods to Improve Natural Ester Oils	16
2.3.1	Chemical Conversion of Triglycerides	16
2.3.2	Addition of Nanoparticles	19
2.3.3	Addition of Chemical Additives	26
2.4	Properties and Performance Characteristics for Transformer Oil	30
2.5	History of Palm Oil as Insulating Liquid	31
2.6	Properties of Palm Oil	32
2.7	Research Trends in Using Palm Oil as an Alternative to Mineral Oil	33
2.8	Properties of Palm Oil as Insulating Liquid	34
2.8.1	Physical Properties	35
2.8.2	Chemical Properties	37
2.8.3	Electrical Properties	44
2.9	Palm Oil-based Nanofluids	46
2.9.1	Development and Progress of Palm Oil-based Nanofluids	47
2.10	Preparation of Nanofluids	51

2.10.1 One-step Method 51

2.10.2 Two-step Method 51

2.11 Synthesis of Methyl Ester as the Base Fluid 53

2.12 Chapter Summary 56

CHAPTER 3 METHODOLOGY 59

3.1 Overview 59

3.2 Materials and Chemicals 61

3.2.1 Synthesis of the Understudy POME as the Base Fluids 61

3.2.2 Preparation of Nanofluids 62

3.3 Synthesis of POME by Transesterification Process 63

3.4 Characterisation of POME 66

3.4.1 FTIR Spectra Analysis for Functional Group Characterisation 66

3.4.2 GC−MS Analysis for Fatty Acid Composition 68

3.5 Characterisation of Nanoparticles 69

3.6 Preparation of POME-based Nanofluids 71

3.7 Methodology of Accelerated Thermal Ageing 74

3.8 Characterisation of Aged POME-based Nanofluids 75

3.8.1 FTIR Spectra Analysis 75

3.8.2 Ultraviolet−Visible Analysis 76

3.9 Experimental Setup 76

3.9.1 AC Breakdown Voltage Test 77

3.9.2 Characterising AC Breakdown Voltage Data Using a Probability Function 79

3.9.3 Resistivity 80

3.10 Measurement of Physicochemical Properties of Thermally Aged Nanofluids 81

3.10.1 Flash Point 82

3.10.2 Density 82

3.10.3 Kinematic Viscosity 83

3.10.4 Water Content 83

3.10.5 Acidity 84

3.10.6 Dissolved Gas Analysis (DGA) 84

3.11 Chapter Summary 84

CHAPTER 4 RESULTS AND DISCUSSION 85

4.1 Overview 85

4.2 Characterisation of Laboratory-Synthesised POME 85

4.2.1 FTIR Spectra Analysis 85

4.2.2 Gas Chromatography−Mass Spectra Analysis 86

4.3 Characterisation of Used Nanoparticles 88

4.4 Characterisation of Aged Nanofluids 90

4.4.1 FTIR Spectra Analysis of Aged Nanofluids 91

4.4.2 Ultraviolet−Visible Analysis 93

4.5 Effects of Accelerated Thermal Ageing on Electrical Properties of POME-based Nanofluids 95
4.5.1 Analysis of Average AC Breakdown Voltage 95
4.5.2 Statistical Analysis of AC Breakdown Voltage 99
4.5.3 Resistivity 110
4.6 Effects of Accelerated Thermal Ageing on Physicochemical Properties of POME-based Nanofluids 111
4.6.1 Flash Point 111
4.6.2 Density 112
4.6.3 Kinematic Viscosity 112
4.6.4 Water Content 114
4.6.5 Total Acid Number (TAN) 116
4.6.6 Change of Gases Concentration Over Ageing Durations 118
4.7 Chapter Summary 126
CHAPTER 5 CONCLUSION AND RECOMMENDATIONS 128
5.1 Conclusion 128
5.2 Recommendations for Future Work 131
REFERENCES 132
APPENDICES 156

LIST OF TABLES

Page

Table 2.1 Natural ester oil-based nanofluids research works and their findings 21

Table 2.2 Summary of surfactants investigated as reported in the literature 28

Table 2.3 Basic characteristics of mineral oil vs natural ester oil [adapted from (Jacob et al., 2020; Raof, 2021; Rozga, 2013)] 30

Table 2.4 Fatty acids composition of CPO (Mohd et al., 2021) and $RBDPO_o$ (Mohamad et al., 2018) 33

Table 2.5 International standards and specification of natural ester oils and mineral oil properties [adapted from (IEEE Std C57.147-2018, 2018; Judendorfer et al., 2014; Reffas et al., 2016; Sitorus et al., 2016)] 35

Table 2.6 Comparison of flash and fire points of palm oil with mineral oil and other types of natural ester oils (Abdullahi et al., 2004; Kanoh et al., 2008; Lewand, 2004; Suwarno et al., 2003) 37

Table 2.7 Fault types in the Rogers Ratio Method (RRM) (Golarz, 2016) 40

Table 2.8 Fault types in the gas ratio method as per IEC 60599 (Golarz, 2016; Piotrowski et al., 2019) 40

Table 2.9 Previous research on palm oil-based nanofluids and their findings 48

Table 2.10 Previous studies on methyl ester synthesis 54

Table 3.1 Properties of POME 62

Table 3.2 Selected nanoparticles used and their properties 63

Table 3.3 Nanofluids samples with different concentrations 72

Table 3.4 Test standards and equipment 82

Table 4.1 Major compositions of POME 87

Table 4.2 Average size of used nanoparticles 89

Table 4.3 Descriptive statistics of 36 measurements of 1000-h-aged nanofluids 99

Table 4.4 Hypothesis test of conformity to a normal distribution of 1000-h-aged nanofluids 102

Table 4.5 Skewness and kurtosis of AC BDV of 1000-h-aged nanofluids 103

Table 4.6	Hypothesis test of conformity to Weibull distribution of aged nanofluid samples	106
Table 4.7	Weibull parameters of 1000-h-aged oil samples	107
Table 4.8	AC BDV at 1%, 10%, and 50% probability levels	109
Table 4.9	Resistivity of oil 1000-h-aged nanofluid samples	110
Table 4.10	Comparison of flash points of different insulating oils	111
Table 4.11	Kinematic viscosity of nanofluid samples	114
Table 4.12	Gas concentration ratios based on RRM and IEC	120
Table 4.13	Results of fault prediction using various methods	124
Table 4.14	Comparative analysis of dielectric strength, kinematic viscosity, and flash point of POME with other methyl ester oils	125

LIST OF FIGURES

		Page
Figure 1.1	UN’s SDG-7 (https://www.globalgoals.org/goals/7-affordable-and-clean-energy)	2
Figure 1.2	Number of publications related to vegetables- and natural ester oils-based transformer oil [adapted from (Suhaimi et al., 2022a)]	3
Figure 2.1	Bodies of literature and focus in this study	12
Figure 2.2	Transformer insulation system: (a) Solid insulation [adapted from (Montero et al., 2022)], and (b) Liquid insulation [adapted from https://www.electricalindia.in/transformer-oil-trends/]	13
Figure 2.3	Triglycerides molecular structure (where R_1, R_2, and R_3 is hydrocarbon chain containing saturated and unsaturated carbon) (Mohd et al., 2021)	15
Figure 2.4	Research progress on developing methyl ester from natural ester oils	17
Figure 2.5	Production process of palm oil products [adapted from (Masra et al., 2022; Suhaimi et al., 2022a)]	32
Figure 2.6	Hydrolysis reaction of natural ester oil	38
Figure 2.7	Duval Triangle Method (Duval, 2002)	41
Figure 2.8	(a) Duval pentagon 1, and (b) Duval pentagon 2 (Duval and Lamarre, 2014)	43
Figure 2.9	Process of the preparation of nanofluids based on the two-step method	52
Figure 2.10	Transesterification reaction	55
Figure 2.11	Esterification reaction (Decarpigny et al., 2022)	55
Figure 2.12	Epoxidation reaction of $MTCKO^t$ to obtain $EMTCKO^o$ (Agu et al., 2019)	56
Figure 2.13	Chronology of palm oil-based insulating liquid development	58
Figure 3.1	Flowchart of the methodology	60
Figure 3.2	Separating methyl ester from glycerol in transesterification process	65
Figure 3.3	POME production process in the laboratory	65

Figure 3.4	Thermo Scientific Nicolet iS10 FTIR spectrometer	66
Figure 3.5	Flowchart of FTIR spectra analysis	67
Figure 3.6	QP2010 Plus GC spectrometer	68
Figure 3.7	Flowchart of GC−MS analysis	69
Figure 3.8	A JEOL JSM-IT5000HR FESEM equipment	70
Figure 3.9	A JEOL JEC-3000FC auto-fine coater	70
Figure 3.10	Flowchart of POME-based nanofluids preparation	72
Figure 3.11	Ultrasonication of POME-based NFs	73
Figure 3.12	Illustration of POME-based nanofluids preparation in the laboratory	73
Figure 3.13	Accelerated thermal ageing experiment using a convection oven	74
Figure 3.14	Agilent Cary 60 UV−Vis spectrophotometer	76
Figure 3.15	HZJQ-1B transformer oil BDV tester	78
Figure 3.16	Flowchart of AC BDV measurement	80
Figure 3.17	ADTR-2K PLUS test apparatus (Suhaimi et al. 2021)	81
Figure 3.18	DMA 35 Anton Paar handheld density meter	83
Figure 4.1	FTIR spectra of $RBDPO_o$ and POME	86
Figure 4.2	GC−MS chromatogram of laboratory-synthesised POME	87
Figure 4.3	FESEM images of (a) TiO_2 and (b) MWCNT nanoparticles showing their morphology at different magnifications	89
Figure 4.4	Visual observation of (a) TiO_2 and (b) MWCNT nanofluid samples before (left) and after (right) the 1000-h accelerated ageing	90
Figure 4.5	FTIR spectra of (a) TiO_2 and (b) MWCNT nanoparticles at varied concentrations and ageing durations	92
Figure 4.6	UV−Vis spectra of (a) TiO_2 and (b) MWCNT nanofluids at varied concentrations and ageing durations	95
Figure 4.7	Scatter plots of AC BDV of pure POME, fresh, and 1000-h-aged POME-based (a) TiO_2 and (b) MWCNT nanofluids at varied concentrations	96
Figure 4.8	Average AC BDV of 1000-h-aged POME-based nanofluids	98

Figure 4.9 Histograms of 1000-hour-aged POME-based TiO_2 at (i) 0.01-g/L, (ii) 0.02-g/L, (iii) 0.05-g/L, and (iv) 0.10-g/L concentrations 100

Figure 4.10 Histograms of 1000-h-aged POME-based MWCNT at (i) 0.01-g/L, (ii) 0.02-g/L, (iii) 0.05-g/L, and (iv) 0.10-g/L concentrations 101

Figure 4.11 Weibull probability plots of AC BDV for aged POME-based (a) TiO_2 and (b) MWCNT nanofluids 105

Figure 4.12 Change of kinematic viscosity at different ageing durations for POME-based (a) TiO_2 and (b) MWCNT nanofluids 113

Figure 4.13 Change of water content at different ageing durations for POME-based (a) TiO_2 and (b) MWCNT nanofluids 116

Figure 4.14 Change in TAN at different ageing durations for POME-based (a) TiO_2 and (b) MWCNT nanofluids 117

Figure 4.15 Variation of gas content in 1000-h-aged POME-based nanofluids 119

Figure 4.16 Result analysis using DTM for POME-based TiO_2 nanofluids 121

Figure 4.17 Result analysis using DTM for POME-based MWCNT nanofluids 122

Figure 4.18 Result analysis using DPM for 1000-h-aged POME-based (a) TiO_2, and (b) MWCNT nanofluids 123

LIST OF ABBREVIATIONS

AC BDV	Alternating Current Breakdown Voltage
Al_2O_3	Aluminum Oxide
ASTM	American Society for Testing and Materials
$BaTiO_3$	Barium Titanate
BDS	Breakdown Strength
BDV	Breakdown Voltage
GC−MS	Gas Chromatography−Mass Spectrometry
CH_3OH	Methanol
CJCO	Crude Jatropha Curcas Oil
CKO	Crude Karanji Oil
CO	Castor Oil
COME	Castor Oil Methyl Ester
CPKO	Crude Palm Kernel Oil
CPO	Crude Palm Oil
CP8	Crude Palm Oil Category 8
CP10	Crude Palm Oil Category 10
CSO	Cottonseed Oil
CTAB	Hexadecyltrimethylammonium Bromide
CuO	Copper (II) Oxide
DC BDV	Direct Current Breakdown Voltage
DGA	Dissolved Gas Analysis
DTM	Duval Triangle Method
Eh-BN	Exfoliated Hexagonal Boron Nitride

$EMTCKO^{o}$	Epoxyl Methyl Ester of *Terminalia Catappa* Kernel Oil
FAME	Fatty Acid Methyl Ester
FESEM	Finite Element Scanning Electron Microscopy
Fe_2O_3	Iron (III) Oxide
Fe_3O_4	Iron (II, III) Oxide
FTIR	Fourier Transform Infrared
HMWH	High Molecular Weight Hydrocarbons
H_2SO_4	Sulfuric Acid
IEC	International Electrotechnical Commission
IFT	Interfacial Tension
JCO	Jatropha Curcas Oil
JMEO	Jatropha Curcas Methyl Ester
KO	Karanji Oil
KOH	Potassium Hydroxide
KOME	Karanji Oil Methyl Ester
LI BDV	Lightning Impulse Breakdown Voltage
MEPKO	Methyl Ester of Palm Kernel Oil
MESSO	Methyl Ester of Sesbania Seed Oil
MPO	Modified Punga oil
MTCKO	Modified *Terminalia Catappa* Kernel Oil
$MTCKO^{t}$	Transesterified Modified *Terminalia Catappa* Kernel Oil
MWCNT	Multi-walled Carbon Nanotube
NaOH	Sodium Hydroxide
PCB	Polychlorinated Biphenyl
PDEV	Partial Discharge Extinction Voltage

PDIV	Partial Discharge Inception Voltage
PFAE	Palm Fatty Acid Ester
PKO	Palm Kernel Oil
PKOAE	Palm Kernel Oil Alkyl Ester
PKOME	Palm Kernel Oil Methyl Ester
POME	Palm Oil Methyl Ester
R&D	Research and Development
$RBDPO_o$	Refined, Bleached, and Deodorised Palm Oil Olein
RRM	Rogers Ratios Method
SDBS	Sodium dodecylbenzene sulfonate
SDG	Sustainable Development Goal
SDS	Sodium Lauryl Sulphate
SEO	Synthetic Ester Oil
SiO_2	Silicon Dioxide
TAN	Total Acid Number
Tan δ	Dielectric Dissipation Factor
TBHQ	Tert Butyl Hydroxyquinone
TCKO	*Terminalia Catappa* Kernel Oil
TiO_2	Titanium Dioxide
UN	United Nations
UV−Vis	Ultraviolet–Visible
ZnO	Zinc Oxide
ZrO_2	Zirconium Dioxide

CHAPTER 1

INTRODUCTION

1.1 Study Background

Petroleum-based oil, so-called mineral oil, has been utilised conventionally as a transformer liquid for decades and is widely established (Asano and Page, 2014; Fofana, 2013; Lv et al., 2017). It has emerged as the predominant insulating liquid of transformers due to its availability, good performance, low viscosity, and low cost. It is excellent as both a cooling and insulating liquid. However, the usage of mineral oil derived from non-renewable energy sources is affecting the environment because of its non-biodegradability properties, inflammable, and toxicity owing to its polyaromatic hydrocarbons content, which are potentially carcinogenic (Fofana, 2013; Jacob et al, 2020; Srivastava et al., 2021). In pursuit of a safer, non-flammable, and environmentally friendly insulating liquid for transformer applications, scholars and researchers have explored innumerable alternatives to mineral oil and have demonstrated significant results (Abdelmalik, 2014; Boss and Oommen, 1999; Mentlik et al., 2018; Stockton et al., 2007; Tokunaga et al., 2019; Totzauer and Trnka, 2019).

The shift of researchers’ interest from conventionally nonbiodegradable mineral oil to biodegradable and renewable alternatives has greatly stood out as the most promising and directly relevant initiative in supporting the United Nations (UN) Sustainable Development Goal (SDG)-7, which aims to provide access to affordable, clean, and modern energy services, as illustrated in Figure 1.1.

Figure 1.1: UN's SDG-7 (https://www.globalgoals.org/goals/7-affordable-and-clean-energy)

Researchers have recently made notable attempts to develop high-performance, eco-friendly, or fully biodegradable insulating liquids that can substitute conventional mineral oil. A paradigm shift is sufficiently evident with tremendous attention, and many researchers redirecting their interests to biodegradable and renewable alternatives. Most biodegradable oil research for transformer applications has focused on vegetable oil or natural ester oil derived from seeds or other parts of plants. According to Suhaimi et al. (2022a), an aggregate of 900 articles was obtained between 2013 and 2022 from the IEEE *X*plore database related to transformer oil based on vegetable or natural ester oils, as shown in Figure 1.2.

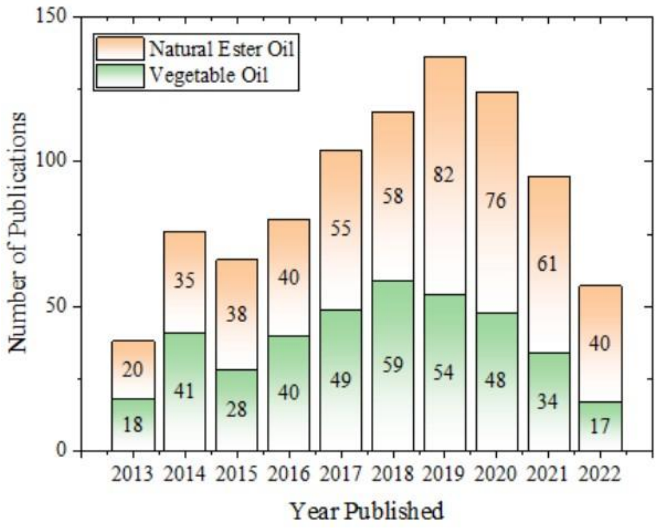

Figure 1.2: Number of publications related to vegetables- and natural ester oils-based transformer oil [adapted from (Suhaimi et al., 2022a)]

Around the early 1900s, experimental exploration of vegetable oils as dielectric coolants began (Fofana, 2013; McShane, 2002). Meanwhile, in the mid-1990s, Research and Development (R&D) laboratories commenced investigations to develop a fully biodegradable liquid (Oommen, 2002). Vegetable oil was considered the leading candidate and most promising option for such an insulating liquid (Fofana, 2013; Rafiq et al., 2015). As a non-fossil liquid alternative, vegetable oil offers a renewable, cost-saving, environment-friendly, fully biodegradable, sustainable, and safer alternative for transformers as an insulating and cooling medium (Amin et al., 2019; Fofana, 2013; Mahanta and Laskar, 2017; Rafiq et al., 2015; Shen et al., 2021).

The first commercial ester-based insulating liquid was BIOTEMP®, which was derived from high oleic sunflower or rapeseed oil and patented in 1999 by ABB in the USA (Boss and Oommen, 1999; Oommen et al., 1997). It was followed by Envirotemp FR3® from soybean oil by Cooper Industries Inc. a year later (McShane et al., 2000). BIOTEMP®,