

**THE SIMULTANEOUS ADSORPTION AND
PHOTOCATALYTIC DEGRADATION OF
PHENOL USING ELECTROSPUN P(3HB)-TiO₂
NANOCOMPOSITE FIBERS**

AINIL HAWA BINTI JASNI

**MASTER OF SCIENCE
UNIVERSITI PERTAHANAN
NASIONAL MALAYSIA**

JANUARY 2017

**THE SIMULTANEOUS ADSORPTION AND
PHOTOCATALYTIC DEGRADATION OF PHENOL USING
ELECTROSPUN P(3HB)-TiO₂ NANOCOMPOSITE FIBERS**

AINIL HAWA BINTI JASNI

**Thesis Submitted to the Centre for Graduate Studies, Universiti Pertahanan
Nasional Malaysia, in Fulfilment of the Requirements for Master of Science
(Biology)**

January 2017

ABSTRACT

Introduction: Photocatalytic degradation and adsorption of crude oil on poly-3-hydroxybutyrate P(3HB) electrospun nanofiber immobilized with nanosized titanium dioxide (TiO₂) for phenol cleanup was evaluated in this study. The P(3HB) used in this study which is made from renewable sources is cost effective and biodegradable. It is hydrophobic and thus was proven to show simultaneous adsorption of phenol while TiO₂ photocatalytically degrades the adsorbed phenol molecules. **Objectives:** This study aims to develop a nanocomposite fibrous material using the environmentally friendly PHA and inert TiO₂ to simultaneously adsorb and degrade phenol. **Methodology:** Palm oil based sources of palm olein (PO), crude palm kernel oil (CPKO), waste cooking oil (WCO) had been used in this study to produce poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) [P(3HB-co-3HHx) bioplastics from wild type *Cupriavidus necator* and recombinant *Cupriavidus necator* Re2058/pCB113. Meanwhile, P(3HB) homopolymer was extracted from mice pellets (mice fed with lyophilized cells of *C. necator* H16 containing 39 wt% PHB). Kaneka Commercial P(3HB-co-3HHx) with 11.8% and 8.4% of 3HHx monomer composition were used as comparison. Different applied voltages, polymer concentrations and mixed solvent ratios were tested and optimized for the fabrication of electrospun nanofiber. Electrospun P(3HB)-TiO₂ films were successfully fabricated and were used in adsorption studies. Phenol was used as crude oil model as it is organic and stable. The fabricated nanofibers were characterized by FESEM, EDX, DSC, GPC and TGA and used for degradation of phenol under different parameters of contact time, pH, initial concentration, temperature and light condition. **Results:** It is apparent that high electrospinning voltage of 25kV produced homogenous strands and better fibrous networks of the nanocomposite films. The intrusion rate of electrospinning was found to be optimum at 40 μ L/min, meanwhile the concentration of polymer solution for electrospinning was set at 10 wt. % for all sample types. The maximum adsorption capacities was 59.047 mg/g. Langmuir and Freundlich isotherm models had been generated to provide reasonable fittings for this sorption data of oil and the sorbent. The trend of adsorptions were in a good agreement with Freundlich which R²= 0.99. The optimal contact time was 270 minutes of nearly 99.9% phenol removal. The equilibrium time was 10 minutes. The effects of photocatalyst-TiO₂ loading on the rates of photocatalytic degradation of phenol had increased in four different light conditions: solar>UV>fluorescent>dark. The experimental results illustrate that the kinetics of degradation of phenol are pseudo-2nd order. Phenol was effectively removed at pH 4 and at 60 °C and higher. **Conclusion:** In view of the results, the P(3HB)-TiO₂ nanocomposite films were proven to act as an effective material to simultaneously adsorb and degrade phenol in aquatic environment.

ABSTRAK

Pengenalan: Penjerapan fotokatalisis minyak mentah oleh poli-3-hidroksibutirata P(3HB) gentian pemintalan elektro digabung dengan titanium dioksida (TiO_2) bersaiz nano bagi penjerapan minyak telah dikaji dalam kajian ini. P(3HB) yang digunakan di dalam kajian ini disintesis daripada sumber yang boleh diperbaharui yang murah dan terbiodegradasi. Sifatnya yang hidrofobik telah membuktikan bahawa penjerapan dan degradasi fotokatalis minyak mentah secara serentak adalah berkesan. **Objektif:** Kajian ini bertujuan membangunkan sebuah bahan berfiber nanokomposit menggunakan PHA yang mesra alam dan TiO_2 yang stabil untuk menjerap sekaligus mendegradasi minyak mentah. **Kaedah:** Minyak kelapa sawit daripada sumber olein sawit (PO), isirung kelapa sawit mentah (CPKO), minyak masak terpakai (WCO) telah digunakan untuk menghasilkan bioplastik poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) [P(3HB-co-3HHx)] daripada *strain* liar *Cupriavidus necator* dan *Cupriavidus necator* Re2058/pCB113 rekombinan. Homopolimer P(3HB) pula telah diekstrak daripada tinja tikus (tikus yang diberi makan dengan sel *C. necator* H16 yang mengandungi 39% kandungan PHB). Komersial Kaneka P(3HB-co-3HHx) dengan kepekatan 11.8% and 8.4% monomer 3HHx komposisinya telah digunakan sebagai kajian komparatif. Penggunaan kadar voltan yang berlainan, kepekatan polimer dan nisbah campuran pelarut telah dijalankan dan dioptimumkan. Gentian pemintalan elektro P(3HB)- TiO_2 telah berjaya difabrikasi and digunakan di dalam kajian penjerapan. Fenol telah digunakan sebagai model minyak mentah kerana sifatnya yang organik dan stabil. Gentian-gentian pemintalan elektro telah dikaji sifatnya dengan analisa FESEM, EDX, DSC, GPC dan TGA dan digunakan untuk penjerapan fenol di bawah parameter berlainan seperti; masa penjerapan, pH, kepekatan asal, suhu dan sumber cahaya. **Keputusan:** Kajian membuktikan bahawa pada voltan tinggi iaitu 25kV telah menghasilkan jalinan gentian yang berluas permukaan tinggi pada gentian nanokomposit. Kadar penyempitan telah dioptimumkan dan ditetapkan pada 40 $\mu\text{L}/\text{min}$, selain itu kepekatan polimer telah diformulasi sebanyak 10 wt. % untuk semua jenis sampel. Kapasiti penjerapan maksima adalah 59.047 mg/g. Model isoterma Langmuir dan Freundlich telah dijana untuk menyediakan penanda yang sesuai untuk data minyak dan penjerap. Corak penjerapannya mempunyai korelasi baik dengan Freundlich iaitu $R^2 = 0.99$. Tempoh penjerapan optimum adalah selama 270 minit iaitu sebanyak 99.9% penyingkiran fenol. Manakala masa ekuilibrium adalah 10 minit. Efek integrasi fotokatalisis- TiO_2 terhadap kadar degradasi fotokatalisis fenol telah meningkat di bawah pencahayaan 4 jenis keadaan sumber cahaya: solar>UV>kalimantan>gelap. Keputusan eksperimen menyatakan degradasi kinetik fenol adalah bersamaan dengan perintah pseudo-kedua. Fenol telah disingkirkan secara efektif di dalam pH 4 dan pada suhu 60 $^{\circ}\text{C}$ dan ke atas. **Kesimpulan:** Keputusan menunjukkan P (3HB) filem- TiO_2 nanokomposit telah terbukti bertindak sebagai bahan yang berkesan pada masa yang sama menjerap dan mendegradasi fenol di persekitaran akuatik.

ACKNOWLEDGEMENTS

First of all, I would like to express my utmost gratitude to my supervisor Dr. Nanthini Sridewi a/p Appan for her kind guidance and supervision during the preparation of this report. Her encouragement, guidance, and support enabled me to develop a very detailed understanding of the subject thus ensured the success of all the work involved. I have achieved a lot of positive personal growth during my master's degree period. In addition, I would also like to take this opportunity to thank those who have made this report possible. Special thanks to my parents and spouse who provide me with valuable moral supports during the course of completing this report. I really appreciate the facilities support, advices and guidance from my co-supervisor, Prof. Dr. K. Sudesh Kumar (Professor of Microbiology and Biotechnology at the School of Biological Sciences, Universiti Sains Malaysia (USM) from 2013- 2015. I learned a lot and develop new skills in his facilities. I am also very grateful to the helpful Ecobiomaterial Lab 409 members in USM Penang Campus for their willingness to assist me theoretically and practically in the lab and guide me in the way to use all the valuable equipment. Thanks to my colleague in USM, Dr. Hanisah Kamilah Razak for the accommodation and tremendous assistance during my stay there. Thanks to Ms. Kasturi from Nottingham University, Semenyih for the high tech analysis and financial support. A warm thanks to my colleagues Ms. Filzah, Mdm. Khairani Hasuna Jaapar and Ms. Fatihah Suhaimi (lab technicians) from Nottingham University for the assistance in running my samples for characterization tests of FESEM and TGA. Thanks also to Madam Jamilah Afandi of Electron Microscopy Unit, School of Biological Sciences, USM for technical assistance during SEM analyses. This study had been presented in ICMSM 2015 in poster exhibition. Last but not least, million thanks to my National Defence University of Malaysia peers for the moral supports and concern. The process of completing this report would not be so smooth and inspiring without their cooperation and encouragement from everybody around me. This work has been funded by Ministry of Higher Education (MOHE) Malaysia under the Research Grant of FRGS/1/2013/SG05/UPNM/03/1.

APPROVAL

I certify that an Examination Committee has met on 2nd November 2016 to conduct the final examination of **Ainil Hawa Binti Jasni** on his degree thesis **The Simultaneous Adsorption And Photocatalytic Degradation Of Phenol Using Electrospun P(3HB)-TiO₂ Nanocomposite Fibers'**. The committee recommends that the student be awarded the **Master of Science (Biology)**.

Members of the Examination Committee were as follows.

Abdul Ghapor bin Hussin, PhD

Professor

Centre for Academic Development

Universiti Pertahanan Nasional Malaysia

(Chairman)

Wan Md Zin Bin Wan Yunus, PhD

Professor Emeritus Dato'

Centre for Tropicalization

Universiti Pertahanan Nasional Malaysia

(Internal Examiner)

Bassim H. Hameed, PhD

Professor

School of Chemical Engineering

Universiti Sains Malaysia

(External Examiner)

APPROVAL

This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Science (Biology)**. The members of the Supervisory Committee were as follows.

Nanthini Sridewi Appan, PhD
Department of Science and Maritime Technology
Faculty of Defence Science and Technology
Universiti Pertahanan Nasional Malaysia
(Main Supervisor)

K. Sudesh Kumar, PhD
Professor Dato'
School of Biological Sciences
Universiti Sains Malaysia
(Co-Supervisor)

UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

DECLARATION OF THESIS

Author's full name : Ainil Hawa Binti Jasni

Date of birth : 19th November 1988

Title : The Simultaneous Adsorption And Photocatalytic Degradation Of Phenol Using Electrospun P(3HB)-TiO₂ Nanocomposite Fibers

Academic Session : 2014/2015

I declare that this thesis is classified as:

- CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*
- RESTRICTED** (Contains restricted information as specified by the organisation where research was done)*
- OPEN ACCESS** I agree that my thesis to be published as online open access (full text)

I acknowledge that Universiti Pertahanan Nasional Malaysia reserves the right as follows.

1. The thesis is the property of Universiti Pertahanan Nasional Malaysia.
2. The library of Universiti Pertahanan Nasional Malaysia has the right to make copies for the purpose of research only.
3. The library has the right to make copies of the thesis for academic exchange.

Signature

881119-56-6216
IC/Passport No.

Date: _____

Signature of Main Supervisor

DR. NANTHINI SRIDEWI A/P APPAN
Name of Main Supervisor

Date: _____

Note : * If the thesis is CONFIDENTIAL OR RESTRICTED, please attach the letter from the organisation stating the period and reasons for confidentiality and restriction.

TABLE OF CONTENTS

	Page
ABSTRACT	ii
ABSTRAK	iii
ACKNOWLEDGMENTS	iv
APPROVAL	v
DECLARATION	vii
TABLE OF CONTENTS	viii
LIST OF TABLES	xvii
LIST OF FIGURES	xix
LIST OF ABBREVIATIONS	xxiii
CHAPTER	INTRODUCTION
1	1.1 Background 1
	1.2 Problem statement 3
	1.3 Objectives of this study 3
	1.4 Scope of research 4
	1.5 Thesis organization 4
CHAPTER	LITERATURE REVIEW
2	2.1 Biopolymers 5
	2.1.1 Polyhydroxyalkanoate (PHA) 6

2.1.2 Polylactic acid (PLA)	8
2.1.3 Starch-based polymers	10
2.2 Structure and characteristics of PHAs	11
2.2.1 Poly (3- hydroxybutyrate (3-HB)	11
2.2.2 Poly(3-hydroxybutyrate- <i>co</i> -3- hydroxyhexanoate), [P(3HB)- <i>co</i> -3HHx]	13
2.2.3 Substance Absorbability	14
2.3 Wastewater	16
2.3.1 Phenol polluted wastewater	16
2.3.1.1 Phenol	16
2.4 Current techniques	19
2.4.1 Sustainable palm oil products as substrates	19
2.4.1.1 Crude Palm Kernel Oil (CPKO)	21
2.4.1.2 Palm Olein (PO)	21
2.4.1.3 Waste Cooking Oil (WCO)	22
2.5 Polymer-photocatalyst nanocomposite materials	23
2.6 Applications of electrospun nanofibers	25
2.6.1 Polymer –Titanium Dioxide (TiO ₂) nanocomposite fibers for environmental application	25

2.6.2 PHA-based nanocomposite fibers for wastewater treatment	28
2.7 Electrospinning	28
2.7.1 Optimization of electrospinning conditions	31
2.7.1.1 Effect of solvents on electrospinnability	32
2.7.1.2 Effect of applied voltage and polymer solution viscosity on electrospinnability	33
2.7.2 The advantages of electrospun nanocomposite fibers	33
2.7.3 Effect of light conditions	33
2.8 Incorporation of titanium dioxide (TiO ₂) with the nanofibers	34
2.8.1 Case study on the use of electrospun PHA nanofibers - TiO ₂ for wastewater treatment	37

CHAPTER

MATERIALS AND METHODS

3

3.1 General techniques 40

3.1.1 Weighing of materials 41

3.1.2 Basic Chemicals	41
3.1.3 Absorbance value of phenol	41
3.1.4 pH determination	41
3.2 PHA sources	42
3.2.1 Polymer extraction	42
3.2.2 Photocatalyst	43
3.3 Preparation for electrospinning	44
3.3.1 Fabrication process via electrospinning	45
3.4 Analytical procedures	46
3.4.1 Solutions preparation	46
3.4.1.1 Preparation of methanolysis solution	46
3.4.1.2 Preparation of caprylate methyl ester (CME) solution	46
3.4.1.3 Methanolysis process	47
3.5 Quantitative analysis	47
3.5.1 Gas Chromatography (GC) analysis	47
3.5.2 Gel permeation chromatography (GPC) analysis	50

3.5.3 Differential scanning calorimetric (DSC) analysis	51
3.5.4 Thermogravimetric analysis (TGA)	51
3.5.5 Fibers thickness	52
3.6 Qualitative tests	52
3.6.1 Field Emission Scanning electron microscopy (FESEM)	52
3.6.2 Energy Dispersive X-ray (EDX)	52
3.7 Adsorption studies	53
3.7.1 Sorbate	53
3.7.2 Electrospun P(3HB) nanofiber	53

3.8 Calibration curve	54
3.8.1 Phenol Adsorption Batch experiments	55
3.8.1.1 Determination of adsorption capacity and percentage adsorption of phenol	55
3.8.2 Effect of contact time on adsorption capacity	56
3.8.3 Effect of temperature on adsorption capacity	57
3.8.4 Effect of light condition on photocatalytic degradation	57
3.8.5 Effect of pH on adsorption capacity	59
3.8.6 Effect of initial phenol concentration on adsorption capacity	59

	3.9 Determination of the adsorption	60
	isotherms and kinetic order models	
	3.9.1 Langmuir isotherm	60
	3.9.2 Freundlich isotherm	61
	3.9.3 Kinetic models	62
CHAPTER	RESULTS AND DISCUSSION	63
4	4.1 Preliminary studies to determine optimum electrospinning parameters	63
	4.2 Nanofiber Morphology	79
	4.3 Characterization of PHA results	81
	4.3.1 GC results	81
	4.3.2 Thermal analyses	84
	4.3.2.1 DSC results	84
	4.3.3 GPC results	87
	4.3.4 TGA results	90
	4.3.5 Summary of characterization results	93
	4.4 The optimization of electrospinning parameters	97
	4.4.1 Effect of applied voltage on the fabrication of PHA electrospun film	97
	4.4.2 Effect of solution concentration on	99

the fabrication of PHA electrospun film	
4.4.3 Effect of solvent ratio on the fabrication of PHA electrospun film	100
4.4.4 Effect of TiO ₂ loading on the fabrication of PHA electrospun film	102
4.4.5 Effect of extrusion rate on the fabrication of PHA electrospun film	104
4.5 Adsorption results	105
4.5.1 Effect of Contact time result on the degradation of PHA polymer films	105
4.5.2 Adsorption kinetics	108
4.5.3 Effect of temperature	112
4.5.4 Effect of light condition on photocatalytic degradation of phenol	113
4.5.5 Effect of different pH on phenol adsorption	120
4.5.6 Effect of initial concentration on phenol adsorption	122
4.5.7 Energy dispersive X-ray (EDX) analysis	129
4.6 Results summary of this study	138

CHAPTER	CONCLUSION	139
5	5.1 Future work and recommendations	140
	REFERENCES	141
	BIODATA OF STUDENT	157
	LIST OF PUBLICATIONS	158

LIST OF TABLES

No.	Table title	Page
Table 4.1	Raw data of GC analysis	82
Table 4.2	Summary of TGA results. All polymer concentrations were set at 10 wt. %.	91
Table 4.3	Molecular weight, thermal characteristics and PHA composition of all nanofibers determined by GPC, DSC, TGA and GC.	93
Table 4.4	Pseudo 1 st and 2 nd kinetic order results.	111
Table 4.5	The SEM micrographs of before and after adsorption of TiO ₂ immobilized nanofibers	119
Table 4.6	Raw data for the construction of Langmuir and Freundlich isotherm plot.	124
Table 4.7	Langmuir and Freundlich isotherm results	127
Table 4.8	Elemental result and morphology of Commercial Kaneka [P(3HB)- <i>co</i> -8.4 mol % 3HHx] before phenol adsorption	131
Table 4.9	Elemental result and morphology of Commercial Kaneka [P(3HB)- <i>co</i> -8.4 mol % 3HHx] after phenol adsorption of TiO ₂ immobilized nanofibers	132
Table 4.10	Elemental result and morphology of Commercial Kaneka [P(3HB)- <i>co</i> -8.4	133

	mol % 3HHx] + TiO ₂ 30 wt% before phenol adsorption	
Table 4.11	Elemental result and morphology of Commercial Kaneka [P(3HB)- <i>co</i> -8.4 mol % 3HHx] + TiO ₂ 30 wt% after phenol adsorption	134
Table 4.12	Elemental result and morphology of Commercial Kaneka [P(3HB)- <i>co</i> -8.4 mol % 3HHx] + TiO ₂ 30 wt% after phenol adsorption	135
Table 4.13	Elemental result and morphology of P(3HB) - 30 wt% TiO ₂ before phenol adsorption	136
Table 4.14	Elemental result and morphology of P(3HB) - 30 wt% TiO ₂ after phenol adsorption	137
Table 4.15	Optimized conditions for the adsorption of phenol from aqueous solution of this study	138

LIST OF FIGURES

No.	Figure title	Page
Figure 2.1	Chemical structure of PLA	8
Figure 2.2	General chemical structures of PHA and some representative members	11
Figure 2.3	Summary of polymers used in electrospinning studies	31
Figure 2.4	Primary processes in semiconductor photocatalysis	36
Figure 3.1	Schematic flow of overall experimental design	40
Figure 3.2	Chemical structure of titanium dioxide	43
Figure 3.3	SEM micrograph of titanium dioxide powder under the 240k magnification.	44
Figure 3.4	Chemical structure of phenol	53
Figure 3.5	Calibration curve of adsorption study	54
Figure 3.6	The experimental setup for studying the effects of the irradiation of fluorescence, dark and ultra violet-A light condition, a) image of ballast and light bulb installation	58

unit b) polystyrene box used for the effect of light condition batch experiment, c) diagram of experimental setup.

Figure 4.1	Digital photographs of 5 wt. % [P(3HB- <i>co</i> -14.7 mol % 3HHx)] in CHCl ₃ :DMF (ratio:8:2) electrospun at varying voltages	65
Figure 4.2	Digital photographs of 10 wt. % [P(3HB- <i>co</i> -24.8 % mol 3HHx)] in CHCl ₃ :DMF (ratio:8:2) electrospun at varying voltages	67
Figure 4.3	Digital photographs of 10 wt. % P(3HB)-39 wt% in CHCl ₃ :DMF (ratio:8:2) electrospun at varying voltages	68
Figure 4.4	Morphological features of 5 wt.% [P(3HB- <i>co</i> - 24.8 mol % 3HHx)] in CHCl ₃ :DMF (ratio:8:2) electrospun at varying voltages	71
Figure 4.5	Morphological features of 5 wt.% [P(3HB- <i>co</i> -14.7 mol % 3HHx)] in CHCl ₃ :DMF (ratio:8:2) electrospun varying voltages	73
Figure 4.6	Morphological features of 10 wt. % P(3HB) mice pellets in CHCl ₃ :DMF mixed solvent (ratio:8:2) electrospun at varying voltages	74
Figure 4.7	Morphological features of 10 wt. % [P(3HB- <i>co</i> - 11.8 mol % 3HHx)] in CHCl ₃ :DMF mixed solvent (ratio:8:2)	76
Figure 4.8	Morphological features of Commercial P(3HB)- <i>co</i> -8.4 mol % 3HHx + 30 wt. % TiO ₂	77
Figure 4.9	Photographs of images of the P(3HB)- 30 wt% TiO ₂ and P(3HB)- <i>co</i> -3HHx- 30 wt. %	78
Figure 4.10	SEM micrograph of sample with and without TiO ₂	80

Figure 4.11	The DSC thermogram of [P(3HB- <i>co</i> -3HHx)] polymer	85
Figure 4.12	The DSC thermogram of [P(3HB- <i>co</i> -3HHx)] + TiO ₂ .	85
Figure 4.13	Graph of molecular weight of polymer samples used in this study	89
Figure 4.14	The thermogram of P(3HB- <i>co</i> - 24.8 % mol 3HHx)]	90
Figure 4.15	Graph of percentage of adsorption versus contact time of the most optimized sample.	105
Figure 4.16	Photograph image of phenol solution	106
Figure 4.17	Graph of percentage of adsorption versus contact time of the all sample	108
Figure 4.18	Pseudo 1 st order kinetic model on phenol adsorption capacity of [P(3HB - <i>co</i> -8.4 % mol 3HHx)] electrospun nanofiber	109
Figure 4.19	Pseudo 2 nd order kinetic model on phenol adsorption capacity of [P(3HB - <i>co</i> -8.4 % mol 3HHx)] electrospun nanofiber	110
Figure 4.20	Comparative plot of adsorption percentage of all samples versus temperature of aqueous solution	112
Figure 4.21	Degradation of phenol by different types of PHA-TiO ₂ nanofiber films under fluorescent light illumination	115

Figure 4.22	Degradation of phenol by different types of PHA-TiO ₂ nanofiber films under UV light illumination	115
Figure 4.23	Degradation of phenol by different types of PHA-TiO ₂ nanofiber films in dark condition	116
Figure 4.24	Degradation of phenol by different types of PHA-TiO ₂ nanofiber films under solar irradiation	116
Figure 4.25	Digital photographs of electrospun nanofiber film[P(3HB -co -8.4 % mol 3HHx) + TiO ₂ 30 wt%	117
Figure 4.26	Comparative bar graph of phenol degradation percentage versus various samples under different light conditions	118
Figure 4.27	Graph of phenol adsorption percentage of all samples versus pH	120
Figure 4.28	Formation of formamide ion when phenol is mixed with water	121
Figure 4.29	Graph of adsorption percentage versus initial phenol concentration of all nanofiber samples	123
Figure 4.30	Langmuir isotherm model	125
Figure 4.31	Freundlich isotherm model	126

LIST OF ABBREVIATIONS

a.m.	Ante meridiem
AOP	Advance Oxidation Process
cm	Centimeter
CME	Caprylate Methyl Ester
CPKO	Crude Palm Kernel Oil
CPO	Crude Palm Oil
DCM	Dichloromethane
DMF	Dimethylformamide
DSC	Differential Scanning Calorimetry
DOC	Dissolve Organic Carbon
ED	Oxidizing potential unit
EDX	Energy dispersive X-ray
eV	Electron Volt
FESEM	Field Emission Scanning Electron Microscope
GBP	Graphene + Bismuth Phosphate composite
GC	Gas Chromatography
GPa	Giga Pascal
GPC	Gel permeation chromatography
g	Gram
g / cm ³	Gram per centimeter cubic
HAs	Hydroxyalkanoates
HPLC	High performance liquid chromatography

ICI	Imperial Chemical Industries
kg	kilogram
kLux	kiloLux
kV	kiloVolt
L-H	Langmuir - Hinselwood
MCL	Medium chain-length
MPa	Mega Pascal
mg	Miligram
mg/g	Miligram per gram
mg/L	Miligram per litre
mg/mL	Miligram per millilitre
mL	Mililitre
mL/min	Mililitre per minute
mm	Millimetre
mWcm ²	Milliwatt square centimeter
m ² /g	Square meter per gram
μg/L	microgram per Litre
μL	Microliter
μl/min	Microliter per minute
μM	Micro Molarity
M _n	Number -average molecular weight
M _w	Weight-average molecular weight
M _w /M _n	Polydispersity index
nm	Nanometer