**UNIVERSITI PUTRA MALAYSIA**

# *DEVELOPMENT OF BIOCOMPOSITES FROM POLY(LACTIC ACID) AND OIL PALM EMPTY FRUIT BUNCH FIBER*

**MARWAH BINTI RAYUNG**

**FS 2014 74**

# DEVELOPMENT OF BIOCOMPOSITES FROM POLY(LACTIC ACID) AND OIL PALM EMPTY FRUIT BUNCH FIBER

**MARWAH BINTI RAYUNG**

**MASTER OF SCIENCE**
**UNIVERSITI PUTRA MALAYSIA**

**2014**

© COPYRIGHT UPM

**DEVELOPMENT OF BIOCOMPOSITES FROM POLY(LACTIC ACID) AND OIL PALM EMPTY FRUIT BUNCH FIBER**

**By**

**MARWAH BINTI RAYUNG**

**Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science**

**October 2014**

© COPYRIGHT UPM

© COPYRIGHT UPM

**COPYRIGHT**

All material contained within the thesis, including without limitation, text, logos, icons, photographs and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use maybe made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of the material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia

# DEDICATION

*To my beloved parents and family*

*Thank you for everything*

© COPYRIGHT UPM

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

**DEVELOPMENT OF BIOCOMPOSITES FROM POLY(LACTIC ACID) AND OIL PALM EMPTY FRUIT BUNCH FIBER**

By

**MARWAH BINTI RAYUNG**

**October 2014**

**Chairman : Nor Azowa Binti Ibrahim, PhD**

**Faculty : Science**

The primary objective of this research was to develop fully biodegradable composite material based on poly(lactic acid) (PLA) and oil palm empty fruit bunch (OPEFB) fiber. However, the incompatibility between PLA and OPEFB fibers lead to poor fiber-matrix adhesion resulted in subpar composites performance. In addition, a typical hybridization of natural fiber/polymer matrix produced dark brown colour of product, a factor that limits its applications. Therefore, efforts had been made to treat the fibers by means of alkaline bleaching by using hydrogen peroxide to remove lignin, hemicellulose and surface impurities. The removal of these components is important to enhance the fiber/matrix interlocking system simultaneously increase the brightness of the composites. From the experimental studies, the optimum condition for bleaching process was obtained at pH 11, 70 °C for 90 minutes. Basically, the bleaching process produced brighter colour fiber with rougher surface as can be observed from Scanning Electron Microscopy (SEM). The Infrared (IR) spectra confirmed the removal of lignin and hemicellulose, while X-Ray Diffraction (XRD) result showed a change in fiber crystallinity from 36.8% to 60.6% after bleaching process due to the removal of these amorphous components.

The biocomposites were prepared by mixing PLA with the treated and untreated fiber at different ratio by using internal mixer at temperature 160 °C and 50 rpm. A bright colour biocomposites was successfully produced by using bleached fiber and the addition of colorant improved the appearance. The mechanical properties for bleached fiber biocomposites showed an improvement indicating better fiber-matrix adhesion which is proved by SEM micrographs. Thermal analysis study showed the composites have lower thermal stability compare to neat PLA itself. Water absorption study demonstrated the bleached fiber biocomposite was more water resistance compare to the untreated fiber. At 50% fiber loading, water uptake for bleached fiber biocomposites was recorded at 14.3% whereas 18.7% for untreated

© COPYRIGHT UPM

fiber biocomposites. Biodegradable study revealed with the addition of fiber into PLA increased the biodegradation rate of the biocomposites. As a matter of fact, the degradation increased because the fiber is more susceptible to microbial attacked, therefore the addition of fiber helps to accelerate the degradation of biocomposites. Besides, treatment of fiber increased the degradation from 6% to 9% after three months burial time. Conclusively, these results supported the role of PLA/OPEFB as environmental friendly composite and showed a great potential as an alternative to the non-biodegradable plastic.

© COPYRIGHT UPM

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

**PEMBANGUNAN BIOKOMPOSIT DARIPADA POLI(LAKTIK ASID) DAN SERAT TANDAN BUAH KELAPA SAWIT KOSONG**

Oleh

**MARWAH BINTI RAYUNG**

**Oktober 2014**

**Pengerusi : Nor Azowa Binti Ibrahim**

**Fakulti : Sains**

Objektif utama kajian ini adalah untuk membangunkan bahan komposit terbiodegradasi sepenuhnya berasaskan poli(laktik asid) (PLA) dan serat tandan buah kelapa sawit kosong (OPEFB). Walau bagaimanapun, ketidakserasian antara PLA dan serat OPEFB membawa kepada masalah lekatan serat/matriks menghasilkan prestasi komposit yang tidak memuaskan. Di samping itu, penghibridan serat/matriks semula jadi selalunya menghasilkan produk yang berwarna coklat gelap yang menghadkan aplikasinya. Oleh itu, kajian telah dilakukan untuk merawat gentian melalui pelunturan alkali dengan menggunakan hidrogen peroksida untuk membuang lignin, hemiselulosa dan benda asing di permukaan serat. Penyingkiran komponen ini adalah penting untuk meningkatkan sistem lekatan serat/matriks pada masa yang sama meningkatkan kecerahan komposit. Berdasarkan eksperimen yang dijalankan, keadaan optimum untuk proses pelunturan adalah pada pH 11, 70 °C dalam masa 90 minit. Proses rawatan telah menghasilkan serat berwarna cerah dengan permukaan kasar seperti yang dapat diperhatikan melalui mikrograf pengimbas elektron mikroskop (SEM). Spektra infra merah (IR) mengesahkan penyingkiran lignin dan hemiselulosa manakala keputusan pembelauan sinar-X (XRD) menunjukkan perubahan dalam penghabluran daripada 36.8% kepada 60.6% selepas proses pelunturan disebabkan penyingkiran komponen amorfus.

Bio-komposit telah disediakan dengan mencampurkan PLA dengan serat yang dirawat dan tidak dirawat pada nisbah yang berbeza dengan menggunakan pengadun dalaman pada suhu 160 °C dan 50 rpm. Komposit berwarna cerah telah berjaya dihasilkan menggunakan serat terluntur dan penambahan pewarna telah memperbaiki rupa fizikal komposit. Sifat-sifat mekanikal bagi komposit serat terluntur telah bertambah baik dengan ketara menunjukkan lekatan serat/matriks yang dibuktikan oleh mikrograf SEM. Kajian analisis terma menunjukkan biokomposit mempunyai



© COPYRIGHT UPM

kestabilan terma yang lebih rendah berbanding dengan PLA sendiri. Kajian penyerapan air menunjukkan serat biokomposit terluntur lebih tahan air berbanding dengan serat yang tidak dirawat. Pada 50% kandungan serat, penyerapan air bagi biokomposit daripada serat terluntur adalah sebanyak 14.3% manakala 18.7% untuk biokomposit daripada serat yang tidak dirawat. Kajian biodegradasi menunjukkan penambahan serat ke dalam PLA meningkatkan kadar biodegradasi bagi komposit. Realitinya, proses degradasi meningkat kerana gentian serat lebih mudah terdedah kepada serangan mikroorganisma, oleh itu penambahan serat membantu mempercepatkan degradasi biokomposit. Di samping itu, rawatan serat meningkatkan kadar degradasi daripada 6% kepada 9% selepas tempoh tiga bulan kajian dijalankan. Kesimpulannya, hasil kajian ini menyokong peranan PLA/OPEFB sebagai komposit mesra alam sekitar dan menunjukkan potensi yang besar sebagai alternatif kepada plastik yang tidak mesra alam.

© COPYRIGHT UPM

## ACKNOWLEDGEMENTS

*In the name of Allah, The Most Gracious, The Most Merciful.*

Firstly, I would like to take this opportunity to express my sincere gratitude to my supervisor Dr Nor Azowa who guide me throughout the path to complete this project. I also would like to thanks my supervisory committee, Dr Hazlin and Dr Wan Zuhainis for the guidance and help.

I owe greatest debt to Chieng, Then, Wei Kit, Zakiah, Masitah and Inani whom I bothered all the time to get information and help. Gratitude is also extended to all chemistry department staff, polymer research group especially from Lab BASL 101 and to all my friends for their help, advice and willingness to share knowledge with me. May Allah bless all of you.

Finally, I would like to show my greatest gratitude to my beloved parents and family for the freedom, support, advice and encouragement throughout these few years in university. Thanks to those I had forgotten to mention, but help me in my study directly or indirectly. Also, thank God for the wonderful experience and precious knowledge I gain from this university.

© COPYRIGHT UPM

# APPROVAL

I certify that a Thesis Examination Committee has met on 21st October 2014 to conduct the final examination of Marwah Binti Rayung on her Thesis entitled "Development of Biocomposites from Poly(Lactic Acid) and Oil Palm Empty Fruit Bunch Fiber" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

**Mansor Hj Ahmad, PhD**
Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

**Mohamad Zaki Abd Rahman, PhD**
Associate Professor
Centre of Foundation Studies for Agricultural Science
Universiti Putra Malaysia
(Internal Examiner)

**Khalina Abdan, PhD**
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

**Ishak Ahmad, PhD**
Professor
Faculty of Science and Technology
Universiti Kebangsaan Malaysia
Malaysia
(External Examiner)

**ZULKARNAIN ZAINAL, PhD**
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

© COPYRIGHT UPM

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

**Nor Azowa Ibrahim, PhD**
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Chairman)

**Norhazlin Binti Zainuddin, PhD**
Lecturer
Faculty of Science
Universiti Putra Malaysia
(Member)

**Wan Zuhainis Binti Saad, PhD**
Senior Lecturer
Faculty of Biotechnology and Biomolecular Science
Universiti Putra Malaysia
(Member)

© COPYRIGHT UPM

**BUJANG BIN KIM HUAT, PhD**
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

**Declaration by graduate student**

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ______________________________ Date: ____________________

Name and Matric No.: __________________________________________________

© COPYRIGHT UPM

**Declaration by Members of Supervisory Committee**

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ____________________
Name of
Chairman of
Supervisory
Committee: **Nor Azowa Ibrahim**

Signature: ____________________
Name of
Member of
Supervisory
Committee: **Norhazlin Zainuddin**

Signature: ____________________
Name of
Member of
Supervisory
Committee: **Wan Zuhainis Saad**

`



© COPYRIGHT UPM

## TABLE OF CONTENTS



© COPYRIGHT UPM

© COPYRIGHT UPM

‘

© COPYRIGHT UPM

# LIST OF TABLES



© COPYRIGHT UPM

# LIST OF FIGURES





© COPYRIGHT UPM

© COPYRIGHT UPM

## LIST OF ABBREVIATIONS

| | |
|---|---|
| ASTM | American Society for Testing of Materials |
| BF | Bleached fiber |
| DMA | Dynamic Mechanical Analysis |
| FTIR | Fourier Transform Infrared |
| HDPE | High density poly ethylene |
| ISO | International Standards Organization |
| LDPE | Low density poly ethylene |
| MB | Masterbatch |
| MPa | Mega Pascal |
| OPEFB | Oil Palm Empty Fruit Bunch |
| PBS | Poly(butylene succinate) |
| PCL | Polycaprolactone |
| PET | Polyethylene terephthalate |
| PGA | Poly(glycolide acid) |
| PHA | Poly(hydroxyalkanoate) |
| PHB | Poly(hydroxybutyrate) |
| PLA | Poly(lactic acid) |
| PLA/BF | Poly(lactic acid)/bleached fiber |
| PLA/BF/MB | Poly(lactic acid) /bleached fiber/masterbatch |
| PLA/UTF | Poly(lactic acid)/untreated fiber |
| PP | Poly propylene |
| PS | Poly styrene |
| PVC | Poly vinyl chloride |
| PVP | Poly(vynil pyrrolidone) |
| SEM | Scanning Electron Microscopy |
| SHS | Superheated steam |
| $T_g$ | Glass transition temperature |
| TGA | Thermogravimetric Analysis |
| UTF | Untreated fiber |
| XRD | X-ray Diffraction |



© COPYRIGHT UPM

# CHAPTER 1

# INTRODUCTION

## 1.1 General Background

Plastics have become an essential part of the modern lifestyle. Plastics are used extensively in various fields such as packaging, clothing, building and construction, automobiles, medical devices, electrical appliances, furniture and household goods and so forth. A wide range of products are made of plastics replacing the traditional materials because of their better physical properties, notably strength and toughness, lightness and barrier properties. In fact, production of plastics is also energy efficient and required low operational cost (Scott, 2002). It is safe to say that through plastics, everyday live were made easier and convenient.

The growing demands of plastics every year, shows the dependency of human being towards this materials. In one aspect this trend will lead to economy expansion while in another point of view, the growing bring along negative impact. It is a fact that most of the conventional plastics widely used today are derived from petroleum resources (Kim *et al.,* 2006), for example low and high density poly(ethylene) (LDPE, HDPE), poly(propylene) (PP), poly(styrene) (PS) and poly(vinyl chloride) (PVC). One of the constrain here is the natural resources cannot be sustain forever and subjected to price fluctuation and must eventually be depleted in the future. Since the source is non-renewable, the future of these materials seems unsure and cannot be predicted.

In a more severe scenario, plastics become a huge threat to human being, environment and the ecosystem. With the increasing production of plastic, the amount of waste generated from this industry also increase. The problems arise when these wastes cannot be degraded naturally; in fact they took thousand years to decompose. Since most of these wastes resist to biological degradation, they usually disposed-off using traditional methods such as land-fill and incineration techniques. However, in a long term the disposal methods are not viable option because land fill takes up valuable spaces, while incineration gives off toxic gaseous and affected human health and the environment.

A lot of effort had been done to find the proper plastic waste management system. Recycling is one of the techniques suggested to tackle the problem. Recycling is the process of collecting and processing waste material and turning them into new product. The implementation of this method will reduce the amount of waste sent to landfill and incinerators and help to conserve natural resources. However, recycling techniques is not economically wise since the recovered material has a low intrinsic value and the fact that the original polymers are easily produced cheaply (Scott and Wiles, 2002).

© COPYRIGHT UPM

The concern on preservation of natural resources, economic and ecological drawbacks of petroleum-based polymer stimulate interest in biodegradable polymer based on renewable resources. Bio-based polymers derive from agricultural stock are a piece of sustainability picture and they offer environmentally benefits. These polymers have the capability to degrade naturally into organic substances without releasing any toxic component (Wahit *et al.*, 2012). With many interesting features, bio-based polymers have a great potential to be used as an alternative and/or replacement to the existing conventional polymer in many area.

Research and development of biodegradable polymers have been widely conducted in past decades and a number of new bio-based polymers were synthesized. Poly(hydroxybutyrate) (PHB) was the first fully biodegradable polymer produced, derived from microbial fermentation of sugar. The discovery of this material has triggered researches to find other bio-based polymer (Scott, 2002). There are number of bio-based polymer that has been introduced commercially and available in the market nowadays such as poly(glycolide acid) (PGA), poly(lactic acid) (PLA), poly(hydroxyalkanoate) (PHA), polycaprolactone (PCL), poly(butylene succinate) (PBS) and so on. Among all, PLA attracts enormous attention because of its versatility, biocompatibility and biodegradability characteristic.

Poly(lactic acid) (PLA) is a type of linear aliphatic thermoplastic polyester derived from renewable agricultural raw materials (Yu *et al.*, 2009). PLA owns good stiffness, strength and transparency and shows comparable properties to the other petroleum based polymer. The unique characteristics of PLA which can be process similarly to polyolefin make it an attractive option as an alternative to the conventional polymer. There are many instances where PLA has been used in industrial application such as packaging, pharmaceutical and medical usage (Chee *et al.*, 2013). The commercial market for PLA based product has a bright future ahead as consumer demand for environmental friendly products increases.

## 1.2 Problem Statements

The utilization of bio-based polymer in place of petroleum based polymer gives positive effect in the sense of reduction on environmental impact and offsetting petroleum consumption. One of the major challenges to replace the conventional polymer is the high cost production of bio-based polymer. Another obstacle to deal with bio-based polymer is the fact that some of these materials exhibit limitation in their properties which cause them less preferable to be used as commodity plastic. A lot of studies had been conducted in order to reduce the cost and enhance the properties of the materials such as introducing suitable filler or reinforcement materials and compatiblizer into the system. Modification and enhancement of these polymers is a crucial step to be done to meet the expectation of developing eco-friendly materials that function in variety of commercial applications.

In the case of PLA, it has relatively high cost (RM25/kg) compare to conventional polymer (Mathew *et al.*, 2005). One way to solve this problem is through the incorporation of natural filler, which not only reduces cost but will also improve product performance. Researchers have been focusing on the prospective of natural



© COPYRIGHT UPM

fiber as filler. Natural fiber offers both economic and ecological advantages over commercial synthetic fiber, as they are renewable resources, cheap, widely available and non-abrasive. The combination of both bio-based polymer and natural fiber will produced fully biodegradable composites.

Oil Palm Empty Fruit Bunch (OPEFB) fiber has a great potential to be used as filler in polymer materials. OPEFB fiber is a waste product generated from oil palm industry, available abundantly in Malaysia and its surrounding South East Asia countries (Hassan *et al.*, 2010). The incorporation of OPEFB fiber into PLA will maximize the use of oil palm and turn it from waste to value added product. In particular, OPEFB fiber attracts interest because of its environmental friendly featured, abundance in nature, low density and most importantly low operational cost (Abdul Khalil *et al.*, 2008).

Though when combining PLA with OPEFB fiber produced composites materials that are fully degradable, lightweight and cheaper, the combination presents several limitations. For instance, the incompatible character between hydrophilic OPEFB and hydrophobic PLA matrix resulted to poor interfacial adhesion of the two components (Ibrahim *et al.*, 2009). In addition, a typical mixing of native fiber without treatment into PLA produces a dark brown colour of product, one of the factors that limits its application because the range of color that can be obtained is limited and makes it hard to be commercialized. Therefore, the matrix and/or fiber need modification for enhanced performance.

The properties of the composites can be improved by employing two approaches; treatment of fibers and the use of an appropriate additive (Avella *et al.*, 2009). Generally, modification of fiber can be classified into physical and chemical treatment. Physical methods such as super-heated steam, plasma and corona treatment change structural and surface properties of fiber. Chemical route modification of fiber like silane treatment, alkaline treatment, acetylation, maleated coupling and enzymatic treatment usually aimed to improve the fiber-matrix interaction (Faruk *et al.*, 2012). All of these methods only able to solve the incompatibility issues but did not contribute to the enhancement on the appearance of the composites.

Alkaline bleaching treatment by using hydrogen peroxide ($H_2O_2$) is another alternative that can be used for fiber treatment. This method has been extensively used in the paper and textile industries (Rosa *et al.*, 2009) but quite new in the polymeric composites field. Theoretically, as a bleaching agent, $H_2O_2$ has the capability to decolorize the fiber by removing chromophoric group in lignin that responsible for the color. In addition, hemicellulose which is the most hydrophilic group in the fiber and other surface impurities will be discarded during the process. The bleaching treatment will produce better physical appearance of the composites and simultaneously improves the fiber-matrix interaction. Interestingly, the treatment will also enables further modification of the composites with color additive to make it more attractive and acceptable. In this study, the effect of hydrogen peroxide treatment on the appearance and performance of the composites was investigated.

© COPYRIGHT UPM

## 1.3 Research Objectives

This study was conducted to synthesize fully biodegradable composites based on PLA and OPEFB fiber. Therefore, three main objectives were carried out, stated as follow:

1. To modify the OPEFB fiber by chemical treatment and study the effect of treatment on the properties of fiber.

2. To prepare PLA/OPEFB fiber composites and evaluate the effect of fiber loading, fiber treatment and color additive on the properties of composites.

3. To characterize the composites in terms of physical, mechanical, thermal stability and morphological properties.

© COPYRIGHT UPM

# REFERENCES


Abdul Khalil, H. P. S., Azura, M. N. and Issam, A. M. (2008). Oil Palm Empty Fruit Bunches (OPEFB) Reinforced in New Unsaturated Polyester Composites. *Journal of Reinforced Plastics and Composites*, 27(16-17): 1817-1826.

Abdul Razak, N. I., Ibrahim, N. A., Zainuddin, N., Rayung, M. and Saad, W. Z. (2014). The Influence of Chemical Surface Modification of Kenaf Fiber using Hydrogen Peroxide on the Mechanical Properties of Biodegradable Kenaf Fiber/Poly(Lactic Acid) Composites. *Molecules*, 19: 2957-2968.

Abu Bakar, A. and Baharulrazi, N. (2008). Mechanical Properties of Benzoylated Oil Palm Empty Fruit Bunch Short Fiber Reinforced Poly(vinyl chloride) Composites. *Polymer-Plastics Technology and Engineering*, 47: 1072–1079.

Abu Bakar, R., Darus, S. Z., Kulaseharan, S. and Jamaluddin, N. (2011). Effects of ten year application of empty fruit bunches in an oil palm plantation on soil chemical properties. *Nutr Cycl Agroecosyst*, 89:341–349.

Agrawal, R., Saxena, N. S., Sharma, K. B., Thomas, S. and Sreekala, M. S. (2000). Activation energy and crystallization kinetics of untreated and treated oil palm fiber reinforced phenol formaldehyde composites. *Materials and Science and Engineering*, A277: 77-82.

Ahmad Nordin, N. I. A., Ariffin, H., Andou, Y., Hassan, M. A., Shirai, Y., Nishida, H., Wan Yunus, W. M. Z., Karuppuchamy S. and Ibrahim N. A. (2013). Modification of Oil Palm Mesocarp Fiber Characteristics Using Superheated Steam Treatment. *Molecules*, 18: 9132-9146.

Alemdar, A. and Sain, M. (2007). Isolation and characterization of nanofibers from agricultural residues – wheat straw and soy hulls. *Bioresource Technology* 99(6): 1664-1671.

Amirou, S., Zerizer, A., Haddadou, I. and Merlin, A. (2013). Effects of corona discharge treatment on the mechanical properties of biocomposites from polylactic acid and Algerian date palm fibres. *Academic Journals*, 8(21): 946-952.

ASTM D256-10. (2010a). Standard Test Method For Determining the Izod Pendulum Impact Resistance of Plastics. ASTM International: West Conshohocken, PA, United States.




© COPYRIGHT UPM

ASTM D570-98. (2010b). Standard Test Method for Water Absorption of Plastics. ASTM International: West Conshohocken, PA, United States.

ASTM D638-10. (2010c). Standard Test Method for Tensile Properties of Plastics. ASTM International: West Conshohocken, PA, United States.

ASTM D790-10. (2010d). Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. ASTM International: West Conshohocken, PA, United States.

Auras, R., Harte, B. and Selke, S. (2004). An Overview of Polylactides as Packaging Materials. *Macromolecular Bioscience*, 4: 835–864.

Avella, M., Buzarovska, A., Errico, M. E., Gentile, G.and Grozdanov, A. (2009). Eco-challenges of bio-based polymer composites. *Materials*, 2: 911-925.

Bachtiar, D., Sapuan S. M. and Hamdan, M. M. (2008). The effect of alkaline treatment on tensile properties of sugar palm fiber reinforced epoxy composites. *Materials and Design*, 29: 1285-1290.

Basiron, Y. (2007). Palm oil production through sustainable plantations. *Eur. J. Lipid Science Technology*, 109: 289–295.

Bax, B. and Mussig, J. (2008). Impact and tensile properties of PLA/Cordenka and PLA/flax composites. *Composites Science and Technology*, 68: 1601–1607.

Bisanda, E. T. N. (2000). The Effect of Alkali Treatment on the Adhesion Characteristics of Sisal Fibres. *Applied Composite Materials,* 7: 331–339.

Bengtsson, M., Baillif, M. L. and Oskman, K. (2007). Extrusion and mechanical properties of highly filled cellulose fiber-polypropylene composites. *Composites Part A,* 38: 1922-1931.

Bledzki, A. K., A. Mamun, A., Jaszkiewicz, A. and Erdmann, K. (2010). Polypropylene composites with enzyme modified abaca fibre. *Composites Science and Technology,* 70: 854–860.

Byrne, F., Ward, P. G., Kennedy, J., Imaz, N., Huges, D. and Dowling D. P. (2009). The effect of masterbatch addition on the mechanical, thermal, optical and surface properties of poly(lactic acid). *Journal of Polymer Environment*, 17: 28-33.

© COPYRIGHT UPM

Chee, P. E., Talib, R. A., Yusof, Y. A., Chin, N. L., Ratnam, C. T., Khalid, M. and Chuah, T. G. (2010). Mechanical and physical properties of oil palm derived cellulose-LDPE biocomposites as packaging material. *International Journal of Engineering and Technology*, 7(1): 26-32.

Chee, W. K., Ibrahim, N. A., Zainuddin, N., A. Rahman, M. F. and Chieng, B. W. (2013). Impact Toughness and Ductility Enhancement of Biodegradable Poly(lactic acid)/Poly(ε-caprolactone) Blends via Addition of Glycidyl Methacrylate. *Advance in Materials Science and Engineering*, 1-8.

Cheng, S., Lau, K. T., Liu, T., Zhao, Y., Lam, P. M. and Yin, Y. (2009). Mechanical and thermal properties of chicken feather fiber/PLA green composites. *Composites Part B,* 40: 650-654.

Chiellini, E., Chiellini, F. and Cinelli, P. (2002). Polymers from renewable resources. In *Degradable Polymers Principles and Applications*, ed. Scott, G, pp. 163-233. Netherlands: Kluwer Academic Publisher.

Chowdhury, M. N. K., Beg, M. D. H. Khan, M. R. and Mina, M. F. (2013). Modification of oil palm empty fruit bunch fibers by nanoparticle impregnation and alkali treatment. *Cellulose*, 20:1477–1490.

Christensen, I. (2003). *Developments in colorant for plastics.* United Kingdom: iSmithers Rapra Publishing.

Chun, K. S. and Husseinsyah, S. (2013). Polylactic acid/corn cob eco-composites: Effect of new organic coupling agent. *Journal of Thermoplastic Composite Materials*, 1–12.

Chun, K. S., Husseinsyah, S. and Osman, H. (2013). Properties of coconut shell powder-filled polylactic acid eco-composites: effect of maleic acid. *Polymer Engineering and Science*, 1109-1116.

Dhakal, H. N., Zhang, Z. Y. and Richardson, M. O. W. (2006). Effect of water absorption on the mechanical properties of hemp fiber reinforced unsaturated polyester composites. *Composites Science and Technology*, 1-10.

European Bioplastics. Retreived 9 March 2014 from http://en.european-bioplastics.org/market/market-development/production-capacity/

Ewulonu, C. M. and Igwe, I. O. (2012). Properties of Oil Palm Empty Fruit Bunch Fibre Filled High Density Polyethylene. *International Journal of Engineering and Technology*, 3(6): 458-471.



© COPYRIGHT UPM

Faruk, O., Bledzki, A. K., Fink, H.P. and Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, 37: 1552– 1596.

Fisher, T., Hajaligol, M., Waymack, B. and Kellogg, D. (2002). Pyrolysis behaviour and kinetics of biomass derived materials. *Journal of Analytical and Appllied Pyrolysis*, 2(2):331-349.

Graupner, N. (2009). Improvement of the Mechanical Properties of Biodegradable Hemp Fiber Reinforced Poly(lactic acid) (PLA) Composites by the Admixture of Man-made Cellulose Fibers. *Journal of Composite Materials*, 43: 689-702.

Harmaen, A. S., Khalina, A., Faizal, A. R. and Jawaid, M. (2013). Effect of Triacetin on Tensile Properties of Oil Palm Empty Fruit Bunch Fiber-Reinforced Polylactic Acid Composites. *Polymer-Plastics Technology and Engineering*, 52: 400–406.

Harris, A. M. and Lee, E. C. (2006). Injection molded polylactide (PLA) composites for automotive application. *Materials Research and Advanced Engineering*, 1-9.

Hashim, M. Y., Roslan, M. N., M. Amin, A., Ahmad Zidi, A. M. and Ariffin, S. (2012). Mercerization treatment parameter effect on natural fiber reinforced polymer matrix composite: A brief review. World Academy Science, Engineering and Technology, 6: 1382-1388.

Hassan, A., Salema, A. A., Ani, F. N. and Abu Bakar, A. (2010). A review on oil palm empty fruit bunch fiber-reinforced polymer composite materials. *Polymer Composites*, 31(12): 2079-2101.

Hill, C.A.S. and Abdul Khalil, H.P.S. J. (2000). Effect of Fiber Treatments on Mechanical Properties of Coir or Oil Palm Fiber Reinforced Polyester Composites. *Journal of Applied Polymer Science*, 77: 1685-1697.

Huda, M. S., Drzal, L. T., Mohanty, A. K. and Misra, M. (2006). Chopped glass and recycled newspaper as reinforcement fibers in injection molded poly(lactic acid) (PLA) composites: A comparative study. *Composites Science and Technology*, 66: 1813–1824.

Huda, M. S., Lawrence, T. D., Mohanty, A. K. and Misra, M. (2008). Effect of fiber surface treatments on the properties of laminated biocomposites from poly(lactic acid) (PLA) and kenaf fibers. *Composites Science and Technology*, 68: 424-432.

© COPYRIGHT UPM

Husseinsyah, S., Koay, S. C. and Hakimah, O. (2013). Surface modification of coconut shell powder filled polylactic acid biocomposites. *Journal of Thermoplastic Composite Materials,* 26(6): 809–819.

Ibrahim, N.A., Ahmad, S. N. A., W. Yunus, W.M. Z. and Dahlan K. Z. M. (2009). Effect of electron beam radiation and poly(vinyl pyrrolidone) addition on mechanical properties of polycaprolactone with empty fruit bunch fibre (OPEFB) composite. *Express Polymer Letters*, 3(4): 226-234.

Ibrahim, N. A., Wan Yunus, W. M. Z., Othman, M., Abdan, K. and Hadithon, K. A. (2010). Poly(Lactic Acid) (PLA)-reinforced Kenaf Bast Fiber Composites: The Effect of Triacetin. *Journal of Reinforced Plastics and Composites*, 29: 1099-1111.

Jandas, P. J., Mohanty, S., Nayak, S. K., and Srivastava, H. (2011). Effect of surface treatments of banana fiber on mechanical, thermal, and biodegradability properties of PLA/Banana fiber biocomposites. *Polymer Composites*, 1689-1700.

John, M. J., Francis, B., Varughese, K. T. and Thomas, S. (2008). Effect of chemical modification on properties of hybrid fiber biocomposites. *Composites, Part A* 39: 353-363.

Joonobi, M., Harun, J., Shakeri, A., Misra, M. and Osman, K. (2009). Chemical composition, crystallinity and thermal degradation of bleached and unbleached Kenaf bast (Hibicus cannabinus) pulp and nanofibers. *Bioresource*, 4(2): 626-639.

Kalam, A., Berhan, M. N. and Ismail, H. (2010). Physical and mechanical characterizations of oil palm fruit bunch fiber filled polypropylene composites. *Journal of Reinforced Plastics and Composites,* 29(21): 3173-3184.

Khan, F., Ahmad, S R. and Kronfli, E. (2006). γ-Radiation Induced Changes in the Physical and Chemical Properties of Lignocellulose. *Biomacromolecules,* 7: 2303-2309.

Kim, H S., Hong, S. I. and Kim, S. J. (2001). On the rule of mixtures for predicting the mechanical properties of composites with homogenously distributed soft and hard particles. *Journal of Materials and Processing Technology,* 112: 109-113.



© COPYRIGHT UPM

Kim, H. S., Kim, H. J., Lee, J. W. and Choi I. G. (2006). Biodegradability of bio-flour filled biodegradable poly(butylene succinate) bio-composites in natural and compost soil. *Polymer Degradation and Stability,* 91: 1117-1127.

Kim, H. S., Lee, B. H., Lee, S., Kim, H. J. and Dorgan, J. R. (2011). Enhanced interfacial adhesion, mechanical, and thermal properties of natural flour-filled biodegradable polymer bio-composites. *J Therm Anal Calorim,* 104: 331–338.

Kolybaba, M., Tabil, L. G., Panighari, S., Crerar, W.J., Powell,T. and Wang, B. *Biodegradable polymers: Past, Present and Future.* Paper presented at the 2003 CSAE/ASAE Annual Intersectional Meeting, Fargo. October 2003.

Law, K. N., Wan Daud, W. R. and Ghazali, A. (2007). Morphological and chemical nature of fiber strands of oil palm empty fruit bunch (OPEFB). *Journal of Applied Polymer Science,* 66: 821–835.

Lee, K. Y., Delille, A. and Bismark, A. (2011). Greener Surface Treatments of Natural Fibres for the Production of Renewable Composite Materials. In *Cellulose Fibers: Bio- and Nano-Polymer Composites,* ed. S. Kalia, B. S. Kaith and I. Kaur, pp. 155-178, Springer.

Lee, Y. K. (2011). Colorant for composites. *Wiley Encyclopedia of Composites,* 1-5.

Leja, K. and Lewandowiez, G. (2010). Polymer degradation and biodegradable polymers- A review. *Polish Journal of Environmental Study*, 19(2): 255-266.

Li, Z., Zhou, X. and Pei, C. (2011). Effect of sisal fiber surface treatment on properties of sisal fiber reinforced polylactide composites. *International Journal of Polymer Science,* 1-7.

Ma, H. and Joo, C. W. (2010). Structure and mechanical properties of jute-polylactic acid biodegradable composites. *Journal of Composite Materials*, 45(14): 1451–1460.

Maekawa, M., Hashimato, A. and Tahara, M. (2007). Effects of pH in hydrogen peroxide bleaching on cotton fabrics pretreated with ferrous sulphate. *Textile Research Journal*, 77(4): 222-226.

Mandana, F. 2012. A Study of Fibre-Matrix Interactions in Biodegradable Kraft Pulp Fibre-Reinforced Polylactic Acid Composites, University of Toronto, Canada.

© COPYRIGHT UPM

Markarian, J. (2008). Biopolymers present new market oppurtunities for additives in packaging. *Plastics Additives and Compounding,* 1-25.

Mathew, A. P., Oksman, K. and Sain, M. (2005). Mechanical properties of biodegradable composites from poly lactic acid (PLA) and microcrystalline cellulose (MCC). *Journal of Applied Polymer Science*, 97(5): 2014-2025.

Miracle, D. B. and Donaldson, S. L. (2001). *Introduction to composites.* United States: ASM International.

Mohammed, M. A. A., Salmiaton, A., Wan Azlina, W. A. K. G. and Mohamad Amran, M. S. (2012). Gasification of oil palm empty fruit bunches: A characterization and kinetic study. *Bioresource Technology,* 110: 628–636.

Moshiul Alam, A. K. M., Beg, M. D. H., Prasad, D. M. R., Khan, M. R. and Mina, M. F. (2012). Structures and performances of simultaneous ultrasound and alkali treated oil palm empty fruit bunch fiber reinforced poly(lactic acid) composites. *Composites*, 43: 1921–1929.

Mostashari, S. M. and Fallah, M. H. (2007). Thermogravimetric analysis of a cellulosic fabric incorporated with ammonium iron (ii)-sulfate hexahydrate as a flame retardant. *Journal of Industrial Textiles,* 37(1): 31-42.

Nacos, M., Katapodis, P., Pappas, C., Daferera, D., Tarantilis, P. A., Christakopoulus, P. and Polissiou, M. (2006). Kenaf xylan-A source of biologically active oligosaccharides. *Carbohydrate Polymers,* 66(1): 126-134.

Othman, M., Ibrahim, N. A., Ruzaidi, C. M., Zakaria, N. and Halim, Z. (2012). Biodegradability analysis of KBF reinforced poly(lactic acid) biocomposites. *Advanced Materials Research*, 576: 434-437.

Petersson, L., Kvien, L. and Oskman, K. (2007) Structure and thermal properties of poly(lactic acid)/cellulose whiskers nanocomposite materials. *Composites Science and Technology,* 67:2535-2544.

Pielichowski, K. and Njuguna, J. (2005). *Thermal Degradation of Polymeric materials. United Kingdom*: Rapra Technology.

Raju, G., Ratnam, C. T., Ibrahim, N. A., Ab. Rahman, M. Z. and Wan Yunus, W. M. Z. (2008). Enhancement of PVC/ENR blend properties by poly(methyl acrylate) grafted oil palm empty fruit bunch fiber. *Journal of Applied Polymer Science*, 110: 368-375.

© COPYRIGHT UPM

Ramli, R., Yunus, R. M., Beg, M. D. H. and Prasad, D. M. R. (2011). Oil palm fiber reinforced polypropylene composites: effects of fiber loading and coupling agents on mechanical, thermal, and interfacial properties. *Journal of Composite Materials,* 46(11): 1275–1284.

Razak, N. W. and Kalam, A. (2012). Effect of OPEFB size on the mechanical properties and water absorption behaviour of OPEFB/PPnanoclay/PP hybrid composites. *Engineering Procedia,* 41: 1593-1599.

Rosa, M. F., Chiou, B., Medeiros, E. S., Wood, D. F., Williams, T. G., Mattoso, L. H. C., Orts, W. J. and Imam, S. H. (2009). Effect of fiber treatments on tensile and thermal properties of starch/ethylene vinyl alcohol copolymers/coir biocomposites. *Bioresource Technology,* 100: 5196-5202.

Rozman, H. D., Tay, G. S., Abubakar, A. and Kumar, R. N. (2001). Tensile properties of oil palm empty fruit bunch-polyurethene composites. *European Polymer Journal*, 37: 1759-1765.

Rozman, H.D., Mohd Ishak, Z.A. and Ishiaku, U.S. (2005). *In Natural Fibers: Biopolymers and Biocomposites,* ed. A. Mohanty, M. Misra, and L.T. Drzal, pp. 407. USA: Press LLC.

Saheb, D. N. and Jog, J. P. (1999). Natural Fiber Polymer Composites: A Review. *Advances in Polymer Technology*, 18(4): 351–363.

Satyanarayana, K. G., Monteiro, S. N., Duarte Lopes, F. P., Margem, F. M., Helvio P. G. S. Jr., and Lucas L. D. C. (2011). Dimensional Analysis and Surface Morphology as Selective Criteria of Lignocellulosic Fibers as Reinforcement in Polymeric Matrices. In *Cellulose Fibers: Bio- and Nano-Polymer Composites,* ed. S. Kalia, B. S. Kaith and I. Kaur, pp. 215-240, Springer.

Scott, G. (2002). Why biodegradable polymers. In *Degradable Polymers Principles and Applications*, ed. G. Scott, pp. 1-15. Netherlands: Kluwer Academic Publisher.

Scott, G. and Wiles, D. M. (2002). Degradable hydrocarbon polymers in waste and litter control. In *Degradable Polymers Principles and Applications,* ed. G. Scott, pp. 1-15. Netherlands: Kluwer Academic Publisher.

Senawi, R., Mohd Alauddin, S., Mohd Saleh, R. and Shueb, M. I. (2013). Polylactic Acid/Empty Fruit Bunch Fiber Biocomposite: Influence of Alkaline and Silane Treatment on the Mechanical Properties. *International Journal of Bioscience, Biochemistry and Bioinformatics,* 3(1): 59-61.

© COPYRIGHT UPM

Sgriccia, N., Hawley, M. and Misra, M. (2008). Characterization of natural fiber surfaces and natural fiber composites. *Composites, Part A* 39(10): 1632-1637.

Shinoj, S., Visvanathan, R., Panigrahi, S. and Kochubabu, M. (2011). Oil palm fiber (OPF) and its composites: A review. *Industrial Crops and Products*, 33: 7-22.

Silverajah, V. S. G., Ibrahim, N. A., Zainuddin, N., Wan Yunus, A. M. Z. and Abu Hassan, H. (2012). Mechanical, thermal and morphological properties of poly(lactic acid)/epoxidized palm olein blend. *Molecules*, 17: 11729-11747.

Sreekala, M.S. Kumaran, M. G. and Thomas, S. (1997). Oil Palm Fibers: Morphology, Chemical Composition, Surface Modification, and Mechanical Properties. *Journal of Applied Polymer Science*, 66, 821–835.

Sulaiman, F., Abdullah, N., Gerhauser, H. and Shariff, A. (2010). A Perspective of Oil Palm and Its Wastes. *Journal of Physical Science*, 21(1): 67–77.

Sundara, R. (1998). Hot peroxide bleaching. *Canadian Chem News*, 50(1): 15-17.

Swift, G. (2002). Environmentally biodegradable water-soluble polymers. In *Degradable Polymers Principles and Applications*, ed. G. Scott, pp. 379-412. Netherlands: Kluwer Academic Publisher.

Tao, Y., Yan, L. and Jie, R. (2009). Preparation and properties of short natural fiber reinforced poly(lactic acid) composites. *Transaction of Nonferrous Metals Society of China*, 19: 651-655.

Tappi Method T 236 cm-85 (1993). Kappa Number of Pulp. TAPPI Press, Atlanta, GA.

Tawakkal, I. S. M. A., A. Talib, R., Abdan, K. and Ling, C. N. (2012). Mechanical and Physical poeperties of kenaf-derived cellulose (KCD)-filled polylactic acid (PLA) composites. *BioResources*, 72: 1643-1655.

Thomas, S., Paul, S. A., Pothan, L. A. and Deepa, B. (2011). Natural Fibres: Structure, Properties and Applications. In *Cellulose Fibers: Bio- and Nano-Polymer Composites*, ed. S. Kalia, B. S. Kaith and I. Kaur, pp. 3-42, Springer.

Throedec, M., Sedan, D., Peyratout, C., Bonnet, J., Smith, A., Guinebretiere, R., Glaoguen, V. and Krausz, P. (2008). Influence of various chemical treatments on the composition and structure of hemp fibres. *Composites, Part A* 39(3): 514-522.



© COPYRIGHT UPM

Tserki, V., Zafeiropoulus, M. E., Simon, F. and Panayiotou, C. (2005). A study of the effect of acetylation and propionylation surface treatments on natural fibers. *Compososites, Part A* 36(8): 1110-1118.

Vink, E. T. H., Rabago, K. R., Glassner, D. A. and Glassner, P. R. (2003). Applications of life cycle assessment to NatureWorksTM polylactide (PLA) production. *Polymer Degradation and Stability,* 80: 403–419.

Vroman, I. and Tighzert, L. (2009). Biodegradable polymers. *Materials,* 2: 307-344.

Wahit, M. U., Akos, N. I. and Laftah, W. A. (2012). Influence of natural fibers on the mechanical properties and biodegradation of poly(lactic acid) and poly(ε-caprolactone) composites: A review. *Polymer Composites,* 33(7): 1045-1053.

Wang, K. H., Wu, T. M., Shih, Y. F. and Huang, C. M. (2008). Water Bamboo Husk Reinforced Poly(lactic acid) Green Composites. *Polymer engineering and science,* 1833-1839.

Wang, R., Wang, C. H. and Jiang, Z. H. (2010). Biodegradibility of flax noil fibers reinforced with poly(lactic acid) composites. *Journal of Fiber Bioengineering and Informatics,* 3(2): 75-79.

William, G. I. and Wool, R. P. (2000). Composites from Natural Fibers and Soy Oil Resins. *Applied Composite Materials,* 7: 421–432.

Yang, H., Yan, R., Chen, H., Lee, D. and Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel, 86: 1781-1788.

Yew, G. H., Mohd Yusof, A. M., Mohd Ishak, Z. A. and Isiaku, U. S. (2005). Water absorption and enzymatic degradation of poly(lactic acid)/rice starch composites. *Polymer degradation and Stability,* 90:488-500.

Yu, T., Li, Y. and Ren, J. (2009). Preparation and properties of short natural fiber reinforced poly(lactic acid) composites. *Transactions of Nonferrous Metals Society of China,* 19**:** 651-655.

Zimniewska, M., Przybylak, M. W. and Mankowski, J. (2011). Cellulosic Bast Fibers, Their Structure and Properties Suitable for Composite Applications. In *Cellulose Fibers: Bio- and Nano-Polymer Composites,* ed. S. Kalia, B. S. Kaith and I. Kaur, pp. 97-119, Springer.

© COPYRIGHT UPM