THERMAL, MECHANICAL AND DEGRADATION BEHAVIORS OF PLASTICIZED POLYLACTIC ACID/STARCH BLENDS

BY

RAINA JAMA AWALE

A dissertation submitted in fulfillment of the requirement for the degree of Master of Science (Biotechnology Engineering)

Kulliyyah of Engineering

International Islamic University Malaysia

AUGUST 2016

ABSTRACT

Petroleum based plastics have raised environmental concerns due to their non-degradable behaviour. To overcome this problem, biodegradable based materials have been researched extensively to be used as alternative materials. Polylactic acid (PLA) is a thermoplastic polymer produced from renewable resources. However, PLA's brittleness and slow degradation rate restricted its applications. The aim of this research is to improve the flexibility of PLA by using environmentally friendly plasticizer and filler. In this research, plasticized PLA/starch composites were developed using 5, 10, 15 and 20 wt% of epoxidized palm oil (EPO) contents. The blend was prepared using two methods ;(1) solution casting methods, where the blends were dissolved in chloroform and casted to evaporate the solvent and (2) melt blending method, where the blends were melt blended using internal mixer. Samples prepared in both methods were hot pressed for characterization purposes. The effects of the processing methods on the thermal behaviours of PLA/starch/EPO (PSE) prepared were evaluated using Differential Scanning Calorimetry (DSC). From DSC thermogram, the addition of 10wt% of EPO to PLA/starch (PSt) decreased the glass transition (T_g) from 58.5 °C to 52.5 °C and 54 °C for casted ad melt blended PSE respectively due to plasticizing effect of EPO. The crystallization temperature (T_{cc}) and melting temperature (T_m) of PSt decreased from 118.3°C and 151.5°C to 109°C and 147.1°C for casted PSE and 105°C and 145.5°C for melt blended PSE respectively, suggesting EPO facilitated easier crystallization for PSE. Based on the DSC result and processing condition, melt blending process was selected to further characterize PSE blends. From Thermogravimetric Analysis, the maximum degradation temperature of PSt from 346°C to 384°C was attributed to EPO acting as heat resistance. The mechanical testing revealed EPO at 5, 10 15 and 20 wt% decreased Young's Modulus from 2776 MPa for PSt to 797, 2496, 727 and 267 MPa, respectively. The elongation-at-break increased at all EPO content. This result indicated that EPO increased the ductility of PSE blends. The impact strength of PSt increased from 28 kJ/m^2 to 30, 51, 37, 38 kJ/m^2 at 5, 10, 15 and 20 wt% EPO which could be due EPO acting as energy distributer allowing more energy to be absorbed during sudden shock. The storage modulus decreased as the damping factor increased by the addition of EPO to PSt attributed to the increase in the elastic response of PSE blends. The shift of absorption band of PSt at 1748, and 1182 cm^{-1} to Fourier Transform Infrared Spectroscopy (FT-IR) to lower wavenumber in the presence of EPO could indicate the PSE blends were physically blended. The morphological study evidenced ductile fracture of PSE with 10 wt% EPO compared brittle morphology of PSt. As for the biodegradability study, the weight loss of PSt increased with the increases of EPO content which could be attributed to moisture penetration into PLA matrix and triggering hydrolysis in PLA chains. From these results it can be concluded that EPO enhanced the mechanical, thermal properties and increased the biodegradability of PLA.

خلاصة البحث

البلاستيك المصنع من المواد النفطية سبب هاجساً بيئياً بسبب انه غير قابل للتحلل. للتغلب على هذه المشكلة، تم البحث على نطاق واسع لمواد قابلة للتحلل لاستخدامها كمواد بديلة. عديد حمض اللبنيك (PLA)هو بوليمر لدن مصنع من مصادر متجددة. ومع ذلك، هشاشة وبطء معدل تحلل عديد حمض اللبنيك حد من استخداماته. والهدف من هذا البحث هو التحسين المرونة عديد حمض اللبنيك باستخدام الملدينات و حشو صديقة للبيئة. في هذا البحث، تم تطوير مزيج مركب من عديد حمض اللبنيك و النشا باستخدام ٥، ١٠، ١٥، ٢٠ ٪ بالوزن من زيت النخيل الايبوكسي (EPO) . تم إعداد المزيج باستخدام طريقتين، (١) طريقة الصب، حيث تم اذابة المزيج في الكلوروفورم ومن ثم سكبه للسماح للمذيب بالتبخر ;(٢) المزج بالصهر،حيث تم صهر المزيج باستخدام خلاط حراري. العينات التي أعدت بكلتا الطريقتين تم ضغطها باستخدام ضاغط ساخن لأغراض التوصيف. تم تقييم الآثار المترتبة على طرق المعالجة على السلوكيات الحرارية لمزيج عديد حمض اللبنيك/ نشا/ زيت النخيل الابوكسي (PSE) التي أعدت باستخدام التفاضل الضوئي الحراري (DSC). من منحنى التفاضل الضوئي الحراري تبين أن إضافة ١٠٪ بالوزن من زيت النخيل الايبوكسي إلى مزيج عديد حمض اللبنيك/نشا (PSt) أدى إلى انخفاض في درجة حرارة التحول الزجاجي (T_g) من ٥٨.٥ إلى ٥٢.٥ درجة مئوية و ٥٤ درجة مئوية لمزيج PSE المسكوب و المخلوط على التوالي نظرا لتأثير الملدن.كما انخفضت درجة حرارة التبلور (T_{cc}) و درجة حرارةالانصهار(T_m) لمزيج PSt من ١١٨.٣ و ١٥١.٥ درجة مئوية إلى ١٠٩ و١٤٧.١درجة مئوية للمزيج المسكوب و ١٠٥ و ١٤٥.٥ درجة مئوية للمزيج المخلوطة على التوالي، مما يشير إلى أن اضافة EPO سهل عملية التبلور لمزيج PSE بناء على نتيجة DSC و حالة المعالجة، تم اختيار عملية المزج الحراري كطريقة التحضير في هذا البحث. من نتيجة التحليل الوزني الحراري، تبين ان درجة الحرارة القصوى لخليط عديد حمض اللبنيك و النشا ارتفعت من ٣٤٦ درجة مئوية إلى ٣٨٤ درجة مئوية مما يدل على زيادة المقاومة الحرارية للمزيج الملدن. كشفت الاختبارات الميكانيكية ان اضافة مقدار ٥، ١٠، ١٥، ٢٠ ٪ بالوزن من زيت النخيل الايبوكسي أدى الى انخفاض معامل يونغ لمزيج PSt من ٢٧٧٦ ميغا باسكال إلى ٧٩٧، ٢٤٩٦، ٧٢٧ و ٢٦٧ ميجا باسكال، على التوالي. نسبة الاستطالة عند الكسر في جميع محتوى العينات الملدنة ازدادت عند إضافة زيت النخيل الايبوكسي. وأشارت هذه النتيجة الى زيادة ليونة مزيج PSE. زادت مقاومة الصدمة من ٢٨ kJ/m^2 إلى ٣٠، ٥١، ٣٧، ٣٨ kJ/m^2 عند اضافة ٥ و ١٠ و ١٥ و ٢٠ ٪ بالوزن من زيت النخيل الايبوكسي التي يمكن أن تكون بسبب EPO الذي قام بتوزيع الطاقة والسماح لاستيعاب المزيد من الطاقة خلال الاصطدام المفاجئ. انخفض معامل التخزين مع ازدياد معامل التخميد عند إضافة زيت النخيل الايبوكسي إلى مزيج عديد حمض اللبنيك و النشا و التي تعزى إلى زيادة في الاستجابة المرنة لمزيج PSE. انخفاض طول الموجة لمزيج عديد حمض اللبنيك و النشا من ١٧٤٨، و١١٨٢ سم$^{-1}$ عند استخدام مجهر المسح الطيفي تحت الأشعة الحمراء (FT–IR) عند إضافة زيت النخيل الايبوكسي مما يمكن ان يشير إلى ان مزيج PSE مخلوط جيدا. من دراسة مجهر المسح الضوئي يتضح ان اضافة ١٠ ٪ بالوزن من زيت النخيل الايبوكسي ادى الى تكسر مرن لمزيج PSE مقارنة بالتكسر الهش لمزيج PSt. أما بالنسبة لدراسة تحلل المزيج في التربة، فقد زادت نسبة فقدان الوزن لمزيج عديد حمض اللبنيك و النشا مع الزيادة في محتوى زيت النخيل الايبوكسي التي يمكن أن يعزى لاختراق الرطوبة بين سلاسل عديد حمض اللبنيك والذي اثار التحلل المائي. من هذه النتائج يمكن الاستنتاج بأن اضافة زيت النخيل الايبوكسي عزز من الخواص الميكانيكية والحرارية وزيادة التحلل لعديد حمض اللبنيك .

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion; it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Biotechnology Engineering)

……………………………..
Fathilah Binti Ali
Supervisor

………………………………..
Hazleen Anuar
Co-Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Biotechnology Engineering)

…………………………………
Ma'an Fahmi Rashid Alkhatib
Internal Examiner

………………………………..
Yose Fachmi Buys
Internal Examiner

This dissertation was submitted to the Department of Biotechnology Engineering and is accepted as a fulfillment of the requirements for the degree of Master of Science (Biotechnology Engineering)

………………………………..
Faridah Yusof
Head, Department of Biotechnology
Engineering

This dissertation was submitted to the Kulliyyah of Engineering and is accepted as a fulfillment of the requirements for the degree of Master of Science (Biotechnology Engineering)

…………………………………
Md Noor Hj Salleh
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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ACKNOWLEDGEMENT

In the name of God, the most Gracious, the most Merciful

I am highly appreciative of all the invaluable inputs of my supervisor Asst. Prof. Dr. Fathilah Binti Ali for her patience, motivation, enthusiasm and immense knowledge. Her guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my master study. I would like to thank Assoc. Prof. Dr. Hazleen Anuar for her constructive suggestions, advice and guidance through the research period.

I appreciate all the support from the staff of Biotechnology Engineering Department and International Institute for Halal Research and Training (INHART) for their valuable support during my research.

Last but not least, I would like to express my deepest appreciation to my parents and my beloved sister Hamidah, Wasindom, and my brothers, who have been a source of encouragement and inspiration to me throughout my life. My deepest gratitude and love for their dedication and the many years of support during my undergraduate and master's studies that provided the foundation for this work.

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LIST OF SYMBOLS

α	Alpha
β	Beta
ε	Epsilon
γ	Gamma
δ	Hildebrand Solubility Parameters
μm	Micrometre
μL	Microlitre

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimetry
ECO	Epoxidized Castor Oil
EPO	Epoxidized Palm Oil
ESO	Epoxidized Soybean oil
EVO	Epoxidized Vegetable Oil
FT-IR	Fourier Transform Infrared Spectroscopy
MgO	Magnesium Oxide
Mw	Molecular Weight
PBS	Poly (Butylene Succinate)
PCL	Poly ε-caprolactone
PDLA	Poly-D-lactic acid
PEG	poly ethylene glycol
PET	Polyethylene terephthalate
PGA	Polyglycolic acid
PHA	Poly hydroxyalkanoate
PHB	Poly (3-hydroxybutyrate)
PLA	Polylactic Acid
PLLA	Poly-L-Lactic Acid
PS	Polystyrene
PSE	Polylactic acid/starch/epoxidized palm oil
PSt	Polylactic acid/starch blend
ROP	Ring Open Polymerization
SEM	Scanning Electron Microscopy
$SnCl_2$	Tin chloride
TGA	Thermal Gravimetric Analysis
THF	Tetrahydrofuran
TPS	Thermoplastic Starch
UV	Ultra violet radiation

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Petroleum based plastics have contributed greatly to the packaging industry. The increasing reliance on plastics derived from fossil resource is mainly due to their durability and stability to biotic and abiotic stress (Jamshidian, Tehrany, Imran, Jacquot, & Desobry, 2010). In recent years, environmental concerns about petroleum plastic raised due to: (1) the accumulation of plastic waste in landfill, which over period of time will break down to small particles that end up precipitating in soil and water and (2) the huge fossil energy needed for the production and recycling of plastic with the depletion of petroleum resources will endanger the industrial development. For these reasons, researches on biodegradable and sustainable resources of plastics are needed as an alternative to commodity plastics (Sin, Rahmat, & Rahman, 2012).

Biodegradable plastic is a polymeric material that is converted to carbon dioxide, nitrogen and biomass when degrades (Balázs, 2013). Biodegradable polymers are categorized according to their sources; agro-polymer from biomass (e.g. protein and polysaccharide), biopolyesters which are synthesized by microorganisms (e.g. poly hydroxyalkanoates, PHA) and polymers synthesized from naturally occurring monomers (polylactic acid, PLA). The latter polymer has gained much attention due to its comparable qualities to fossil based polymer (Avérous & Pollet, 2012).

Polylactic acid was discovered in 1932 by Wallace Carothers and continued to be explored over time (Platt,2006). PLA was produced via polycondensation or ring opening polymerization of lactic acid or lactide respectively (Sedlarik et al., 2010).

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PLA is preferred due to its processability (Jiménez, Peltzer, & Ruseckaite, 2014), renewability (Auras, Lim, Selke, & Tsuji, 2011), and biocompatibility (Leng & Lau, 2010). However, brittleness, and slow degradation rate has limited the applications of PLA (Ren, 2011).

Many attempts have been approached to overcome these limitations. One of these approaches were physical blending of PLA with other additives and polymers to improve the mechanical properties, morphology, degradability, shelf life, reduce the cost, produce an eco-friendly material or mitigate of undesirable traits (Subramanian, 2013). PLA has been blended with starch (Xiong, Yang, et al., 2013), talc (Shakoor & Thomas, 2014), poly (ε-caprolactone) (Wu et al., 2011), chitosan (Zakaria et al., 2013), poly (3-hydroxybutyrate) (Abdelwahab et al., 2012), poly (ethylene glycol) (Sungsanit, 2011), and cellulose (Shumigin, Tarasova, Krumme, & Meier, 2011). There are different types of additives from organic and inorganic sources. The selection of the suitable additive depends on the polymer properties desired to be improved (Shirai et al., 2013).

Starch is a class of carbohydrate found in potatoes, cassava and corn with production of 70,000 tonnes of per annum (Oxford Business Group, 2014). The sustainability, renewability and low cost of starch allow it to be used as food additives, tablet filler, adhesive, cosmetic powder, cement additives, paper and polymer production (Ebnesajjad, 2012). The attractive features of PLA and starch have been studied extensively (Xiong, Yang, et al., 2013; Xiong, Li, et al., 2013; Arroyo, Huneault, Favis, & Bureau, 2010). However, one of the challenges in PLA and starch blending system is compatibility due to the PLA's hydrophobicity and starch's hydrophilic behaviour; therefore other additives are needed as intermediate to improve the interaction between polymers (Liu & Zhang, 2011).

Since the last century, biodegradable vegetable oils have been used as plasticizers due to their low toxicity and high viscosity (Vieira, da Silva, dos Santos, & Beppu, 2011). Epoxidation of vegetable oils (EVO) such as palm oil and soybean oil widens their application in the industry. EVOs have been used as a plasticizer to improve the properties of the polymer and increase ductility, tacticity and biodegradability (Chieng, Ibrahim, Then, & Loo, 2014). Epoxidized palm oil was used as plasticizer in PLA and it enhanced its mechanical properties (Ali, Fakhruldin, Awale & Anuar, 2015). According to Malaysian Palm Oil Board (MPOB), palm oil production in 2012 was 19.4 million tonnes (Hansen, 2007). Thus, the sustainability of palm oil in Malaysia makes it a suitable choice for plasticizer.

In this research, PLA was blended with starch and epoxy palm oil (EPO) which functions as filler and plasticizer, respectively. This study focused on investigating the effect of EPO on PLA/starch properties using solution casting and melt blending process. The mechanical, thermal, morphological properties and the degradation rate were studied for samples prepared via melt blending method.

1.2 PROBLEM STATEMENT

In 2014, Petroleum based plastic from packaging sector composed 62% of total plastic waste (Tawatsin, 2014). Petroleum based plastics tend to accumulate in landfill, increase carbon footprint, pollute water resources as well as exhausting limited petroleum resources. These concerns, called for the need of plastics from renewable materials as an alternative to commodity plastic (Wool & Sun, 2011).

PLA is a biopolymer produced from renewable source and widely used in textile and medical field. The availability, processability and the lower energy requirement made PLA the most outstanding polymer compared to other biopolymers.

However, PLA is brittle and has slow degradation rate which limited its applications (Auras et al., 2011). Thus, PLA was blended with natural filler such as starch to in order to increase its degradation rate.

Starch is hydrophilic polymer fond abundantly in nature, inexpensive and biodegradable, which promotes its application in industry. Even though, the addition of starch into PLA increased the biodegradation rate of PLA, it also increased PLA's toughness and further decreased its flexibility (Rodriguez, Ghosh, Jeng, & Sain, 2010).

Plasticizers are low molecular weight additive used to increase chain mobility in polymer matrix. Epoxidized palm oil (EPO) is renewable plasticizer used to increase the ductility of PLA. EPO found abundantly in Malaysia with production of approximately 20 million tonnes per annum (Hansen, 2007).

In this study, the properties of PLA were enhanced by blending with starch (filler) to increase biodegradability and epoxidized palm oil (plasticizer) to increase the ductility of PLA blends prepared via solution casting and melt blending method.

1.3 RESEARCH SIGNIFICANCE

The development of agro-based plastics is valuable solution toward environmental and resources concerns associated with petroleum-based. PLA is becoming the leading choice as bioplastic due to its comparable properties to some of the conventional plastics. The material used in this study PLA, starch and EPO are all degradable and renewable materials. In addition, starch (raw), EPO and PLA are sustainable resources in Malaysia that will reduce PLA production cost and increase PLA's application in the agro-based plastic industry.

1.4 RESEARCH OBJECTIVES

The objectives of this research are as follow;

1. To evaluate the effect of processing method on PLA/starch/EPO thermal behaviour prepared via solution casting and melt blending methods

2. To investigate the effect of EPO contents on thermal, mechanical, structural and morphological properties of PLA/starch/ EPO blends.

3. To study the biodegradability of PSE blends in soil.

1.5 RESEARCH SCOPE

1. Plasticization of PLA/starch blends by two methods; solvent casting and melt blending.

1. Properties of PLA/starch/EPO composites were evaluated by;

- Differential Scanning Calorimetry (DSC) and Thermal Gravimetric Analysis (TGA) were used to analyze thermal properties.

- Tensile testing was used to evaluate elongation-at -break, yield strength and modulus of PSE blends.

- Impact testing was used to study the impact strength of PSE blends.

- Dynamic Mechanical Analysis (DMA) was used to evaluate the stiffness of PSE blends.

- Fourier Transform Infrared Spectroscopy (FT-IR) was used to observe functional groups.

- Degradation in soil method was used to study the biodegradability of the blends in the environment.

1.6 DISSERTATION ORGANIZATION

This dissertation consists of five chapters; Chapter One commenced on a brief background about the research including, the issue arises from petroleum based plastic waste and bioplastic can be used to substitute it. In addition, this chapter also includes a brief highlight on PLA, starch and EPO as material choice of this project. Also, problem statement, research objectives, scope and the significance of the study were described in this chapter.

Chapter Two started with an overview of biopolymers and properties of PLA, preparation methods and applications of PLA. This chapter also include literature review on modification the properties of PLA using additives and degradation of PLA.

Chapter Three explains in detail the materials and equipment used in this study. The experimental procedures followed in this research are step-by-step described starting from screening, preparation of blends in different ratios through solution casting and melt blending methods, characterization, and finally the biodegradability study of the blends conducted in soil.

The results and discussion of this research are described in Chapter Four; begin with the screening of solvents and finding the suitable solvent for solution casting method. Solution casted sample of PLA/starch/EPO were prepared using one solvent and characterized using DSC. Melt blending method was also used to prepare PLA/starch/EPO blends with different EPO ratios to investigate the effect of plasticization on the mechanical, thermal, morphology, structural properties, and degradability of the blends.

Finally, research works are concluded and recommendations to improve this study and future works are outlined in chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Petroleum based plastics have an important role in the packaging sector. However, the life span of waste generated from plastic industry has become a serious concern to the environment. A study conducted by Plastic Management in Peninsular Malaysia in 2011, reported that 24% of solid waste composition is plastic where 11% is generated from single use packaging (Moh and Manaf, 2014)

In the environment, conventional plastics waste breakdown into small sizes and accumulate in lands for decades. To minimize plastics' resistance in the environment, the waste is buried in landfill, incinerated or recycled which need a lot of time, land and money (Moura, 2006). On the other hand, bioplastic is abundant and naturally degrades as a result of biotic stress such as bacteria and fungi or by abiotic stress oxidization and hydroxylation (Tokiwa, Calabia, Ugwu, & Aiba, 2009).

With the growing plastic waste accumulation, degradability of plastics is a crucial trait. The degradability is defined by American Society for Testing of Materials (ASTM) as alteration to the chemical structure of the plastic under specific environmental condition, in which alterations are characterized by the loss of mechanical and physical properties (Kijchavengkul et al., 2010). Depending on the source of plastics; plastics materials can be degraded biologically by microorganism, chemically by hydrolysis or physically by reducing the matrix size (Kumar, Karthick, & Arumugam, 2011). Biodegradability is a preferable method as the polymer will be

metabolized by naturally occurring microorganism which is more environmentally friendly, low cost and energy saving (Rydz, Sikorska, Kyulavska, & Christova, 2014).

Biopolymers are categorized based on their origin into natural or synthetic. Naturally existing biopolymers are produced through cell cycle of living organism such as protein, nucleic acid, cellulous, and starches. Another category of biopolymers is synthesized from renewable resources. Aliphatic polyesters such as poly(glycolic acid) (PGA), poly(hydroxyalkanoate) (Jamshidian et al., 2010) and poly(lactic acid) (Sin, Rahmat, & Rahman, 2012) are examples of synthetic biopolymers (Vroman & Tighzert, 2009)

PLA has attractive characteristics such as ; (i) biocompatibility to living cells due to its non-toxic nature (Leng & Lau, 2010), (ii) processability, PLA can be processed via injection moulding, film extrusion, blow moulding, fibre spinning, and film forming (Jiménez et al., 2014), (iii) PLA has low carbon fingerprint, as carbon dioxide produce from the degradation of PLA is consumed back in the production of PLA (Bruice, 2013), and (iv) the production of PLA requires less energy (25-55%) to that of conventional plastic (Baird & Cann, 2012). However, major drawbacks of PLA are brittleness, slow degradation rate and hydrophobicity that hinder its applications (Rasal, Janorkar, & Hirt, 2010).

Starch and polyester like PLA (Tsou et al., 2014; Toosi, 2010; Chabrat, Abdillahi, Rouilly, & Rigal, 2012), PCL (Shen & Wang, 2011; Kim, Jang, Park, & Min, 2010), and PHB (Zhang & Thomas, 2010; Ma et al., 2014) have been studied extensively. PLA and starch each are distinguishable polymers and have its own characteristics. However the PLA and starch blends have poor mechanical properties due to incomparability between the polymers (Kiangkitiwan & Srikulkit 2013; Silva,

2011). The frame work of this research contained the developing of flexible and biodegradable packaging material of plasticized PLA/ starch blend using EPO.

2.2 BIODEGRADABLE POLYMERS

The application of plant based polymer has been used since ancient times. The term "biodegradation" refers to the degradation of polymeric material solely via the enzymatic action of microorganism to produce carbon dioxide, inorganic compounds, water and biomass (Kumar et al., 2011). Based on this definition, biodegradable polymers are divided into two major groups: natural biopolymers and synthetic biopolymers.

Natural biopolymers are found abundantly in nature in macromolecular form such as polysaccharides. Polysaccharides are complex carbohydrates found in plants and animals. Major classes of plant polysaccharides are cellulose and starch. Cellulose is insoluble linear polymer of repeated cellobiose linked by β (1, 4) glycosidic linkage. Because of the insolubility of cellulose, it is chemically modified to be used in industry as ether, ester and acetals cellulose. Another class of polysaccharides is starch that is found in starchy corn, potato, cassava and rice. Starch are hydrophilic molecules consisting of amylose and amylopectin molecules linked in α (1,4) glycosidic linkage. Due to the hydrophilicity of starch, native starch based materials are sensitive to moisture and unstable under stress. Thus, researches were conducted where starch was blended with other polymer as filler (Awale,Mirghani, Anuar, Samat & Ali, 2016) or copolymer (Prusty & Swain, 2013) in order to improve its properties.

The second group of biopolymer is synthetic biopolymers. Synthetic biopolymers are polymers produced from renewable resources. Aliphatic polyester such as poly(glycolic acid) (PGA), poly(hydroxyalkonate) (Jamshidian et al., 2010),

and poly(lactic acid) (Saidi, Rahman, & Majid, 2013) have been extensively explored for their potential as biopolymers. This class of polymers have high molecular weight and produced mainly through ring opening polymerization method (Vroman & Tighzert, 2009). PGA is a hydrophilic type of polymer with high crystallinity (40-55 %) and produced through fermentation as an outside cellular product in bacteria. The polymer has excellent mechanical properties but its hydrophilicity and high degradation rate limited its application within the medical field. PHA is naturally occurring polymer in microorganism and produced commercially via fermentation as intercellular product in bacteria when the carbon is high and other essential nutrient are depleting. It has glass transition temperature (T_g) between -40 to 5 ˚C with melting point of 50 to 180 ˚C depending in its composition leading to brittleness and thermal instability of PHA. However due to its hydrophobicity, it has high biocompatibility and various application in medical field (Varsha, 2011).

In comparison to other biopolymers, PLA stands out with distinguished mechanical properties such as semicrystallinity, thermal stability, toughness and durability (Ehrenstein & Pongratz, 2013). In addition to the mechanical properties of PLA which is comparable to conventional plastics (e.g. Polystyrene (PS) and Polyethylene terephthalate (PET)), PLA based bioplastics is environmentally friendly alternative polymer (Silva, 2011).

2.3 POLYLACTIC ACID PROPERTIES

Polylactic acid belongs to aliphatic polyester family with properties of linear structure derived from natural resources. Lactic acid is the monomer used for polymerization of PLA with two isomers D-lactic acid (PDLA) and L-lactic acid (PLLA) or combination (Figure 2.1). At room temperature, PLA is in the form of white powder with glass

transition temperature (T_g) of 58 ˚C and melting temperature (T_m) of 175 ˚C (Mooney, 2009).

The behaviour and properties differ depending on the PLA composition. PLLA is semi-crystalline with density of 1.24 g/cm^3. PDLA is an amorphous type polymer with 1.2 g/cm^3. Both PLLA and PDLA have the T_g, T_m, decomposition temperature, elongation-at-break (%) of 50-60 ˚C, 150-180 ˚C, 200 ˚C and 20-30 % respectively. Crystallization of PLA is between 90-110˚C. The mixture of both isomers will result in amorphous crystal structure (Rasal et al., 2010).
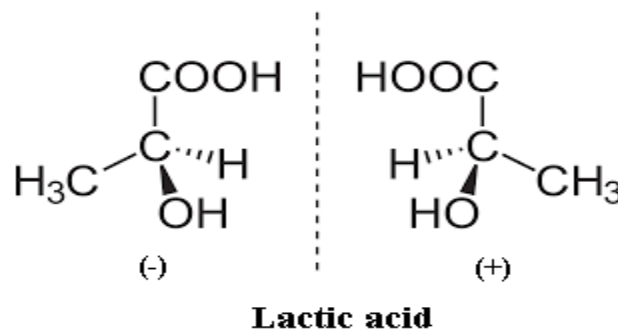

Figure 2.1 Chemical structures of Lactic acid isomer

Lactic acid is hydroxyl carboxylic acid naturally produced as metabolite by human, animal and microorganism as a result of carbohydrate fermentation. The production process of lactic acid for industrial application consists of five steps: (1) fermentation of starch, (2) cell lysis and protein removal, (3) purification, (4) concentration, and (5) pigmentation removal (Karimi & Srinivasan, 2012). The purity of lactic acid produced depends on its applications. For example, in food, pharmaceutical, and analytical application, a higher purity of lactic acid is required (Jamshidian et al., 2010).

PLA has several advantages over petroleum-derived polymers in terms of renewability, degradability, lower energy requirement, and stability. Firstly, PLA