IJACT 15-2-11

Scale-Up of Polymerization Process of Biodegradable Polymer Poly(lactic acid) Synthesis Using Direct Polycondensation Method

Sommai Pivsa-Art[1], Sumonman Niamlang[1], Weraporn Pivsa-Art[1], Nutchapon Santipatee[1], Tossamon Wongborh[1], Sorapong Pavasupree[1], Kiyoaki Ishimoto[1], Hitomi Ohara[2]

[1]Rajamangala University of Technology Thanyaburi, Pathumthani, Thailand,
[2]Kyoto Institute of Technology, Kyoto, Japan
Email: sommai.p@en.rmutt.ac.th

ABSTRACT

Environmental problems from petroleum-based plastic wastes have been rapidly increasing in recent years. The alternative solution is focus on the development of environmental friendly plastic derived from renewable resource. Poly(lactic acid) (PLA) is a biodegradable polymer synthesized from biomass having potential to replace the petroleum-based non-degradable polymers utilizations. PLA can be synthesized by two methods: (1) ring-opening of lactide intermediate and (2) direct polycondensation of lactic acid processes. The latter process has advantages on high yields and high purity of polymer products, materials handling and ease of process treatments. The polymerization process of PLA synthesis has been widely studied in a laboratory scale. However, the mass scale production using direct polycondensation of lactic acid has not been reported. We have investigated the kinetics and scale-up process of direct polycondensation method to produce PLA in a pilot scale. The order of reaction is 2 and activation energy of lactic acid to lactic acid oligomers is 61.58 kJ/mol. The pre-polymer was further polymerized in a solid state polymerization (SSP) process. The synthesized PLA from both the laboratory and pilot scales show the comparable properties such as melting temperature and molecular weight. The appearance of synthesized PLA is yellow-white solid powder.

Keywords: poly(lactic acid), kinetics of lactic acid polymerization, scale-up polymerization, 2-steps direct polycondensation, solid state polymerization

1. Introduction

The recently research and investigation for plastic packaging materials have been focus on discover and development of new polymer that are friendly to environment. These phenomena are arisen from the limitation of non-degradable polymers synthesized from petroleum products [1]. The amount of packaging consumed has been increasing drastically due to the numbers of population. Wastes of those plastic products have been increasing as they need more than a hundred years to be degraded. Therefore, the alternative way to solve the environmental problems is the application of biodegradable polymers to plastic packaging

industry. Biodegradable polymers having high potential for processing application are polyesters such as poly(lactic acid) (PLA) or polylactide, a linear thermoplastic polyester synthesized from biomass [2].

The commercial production of PLA is produced by ring opening polymerization (ROP) of lactide, the dimer of lactic acid (LA). The process uses catalysts such as tin, zinc, aluminum and lead, initiators such as *n-*, *sec-*, *tert*-butyl lithium, and solvent such as diphenyl ether, toluene and chloroform. Many of these components are toxic or flammable. As a result, this process requires purification to remove the unwanted materials from the product, which requires complex facilities [3]. The alternative route to produced PLA is the direct polycondensation of lactic acid. However the synthesis of high molecular weight PLA by this method is considered to be difficult because of instability of the LA oligomer and the difficulty of removing water produced in polymerization, which can encourage the depolymerization [4,5]. Thus, PLA synthesized with organic solvent via 3 steps of polymerization: dehydration, polycondensation and solid state polymerization, have been investigated [6]. However, the use of solvent increases the difficulty of process control and polymer purification which increase the process cost and limits the process to small scale production [7]. To solve these limitations, the utilization of binary catalyst system of stannous (II) chloride dehydrate/*p*-toluenesulphonic acid monohydrate (SnCl$_2$/TSA) was studied. [8]. To reduce the production cost and time in large scale, the low number of steps in production line is required. Thus a 2-steps direct polycondensation is developed; (1) dehydration and polycondensation, and (2) solid state polymerization [9]. This process has potential to scale up to large scale of PLA production.

In this work, PLA was synthesized via 2-steps direct polycondensation in laboratory scale. The kinetic of direct polycondensation was investigated and reactor design equation was established for scale up of the polymerization process to determine the potential of production of PLA via environmental friendly and non-complex facilities process. The thermal properties and ^{1}H-NMR of synthesized PLA from both scales were investigated.

2. Experimental

Materials. L-lactic acid (Galactic) with a monomer concentration of 90% w/w was used as received. *p*-Toluenesulfonic acid, PTSA was used as catalyst and used as received. Chloroform was used as the eluent in gel permeation chromatography (GPC). The polystyrene standard for GPC calibration was supplied by Sigma Aldrich Chemical Co. (USA).

Synthesis of PLLA. PLLA were synthesized by 2-steps direct polycondensation in a laboratory scale and a mass scale.

Laboratory scale (5 g/ batch). Direct polycondensation of L-lactic acid was conducted in a 25 ml custom made test tube with a mechanical stirrer and condenser connected to an inline cold trap and a vacuum pump. Thermometer was used to measure the exterior oil temperatures of the test tube. The reactor pressure was measured and controlled by vacuum controller (VCN500, OKANO). The pressure in the reactor was reduced gradually using a vacuum pump (G-50DA, ULVAC-KIKO).

Five grams of L-LA and 0.5%w/w of PTSA were added to a test tube. The temperature and pressure during the polymerization were precisely controlled at 150 $^{\circ}$C, 30 torr for 4 h. At the end of the reaction, the products were poured in the aluminum mold and allowed to cool to room temperature. After solidification, the product was grinded and annealed at 100 $^{\circ}$C for 2 hr. Annealed product was further solid state polymerization to obtain high molecular weight PLLA.

Kinetic study using laboratory scale. Ten grams of L-LA and 0.5%w/w of PTSA were added to a round bottom flask equipped with stirrer, thermocouple and reflux condenser. The temperature and pressure during the polymerization were precisely controlled at 140 $^{\circ}$C, 30 torr for 5 h. The sample was taken every 30 min for 4 ml using syringe through septum. The sample 2 ml was dissolved in chloroform and titrated to calculate the conversion of lactic acid.

Mass scale (100 kg/ batch). The similar reaction conditions of laboratory scale were selected to compare the thermal properties and molecular weight of synthesized PLLA on the effect of reactor size. The reaction was conducted in a 200 liter reactor with a paddle and condenser connected to an inline cold trap and a vacuum pump. Thermocouple was used to measure the internal temperature of reactor and exterior oil temperature. The reactor pressure was measured and controlled by vacuum controller (VCN500, OKANO). The pressure in the reactor was lower incrementally using a rotary vacuum pump (K7503, OSAKA VACUUM Ltd.).

One hundred kilograms of L-LA and 0.5%w/w of PTSA were added to the reactor. The melt polymerization was done for 4 h at 30 torr after reaching 150°C. At the end of the reaction, the products were discharged at 150 $^{\circ}$C in stainless bats and allowed to cool to room temperature for 7 hr and were kept in dry ice. After solidification, the product was grinded and annealed at 90 $^{\circ}$C for 2 hr. Annealed product was further subjected to solid state polymerized to obtain high molecular weight PLLA. The reaction temperature must lower than melting temperature, T_m of sample to prevent the molten of PLLA [8,9,10]. The temperature was gradually increased step by step.

Analytical methods. The weight average molecular weight (Mw), number average molecular weight (Mn) and Mw/Mn ratio of synthesized PLA were determined using a gel permeation chromatography (GPC) system equipped with two chromatography columns and a RI detector. Chloroform was used as the eluent at a flow rate of 1 mL/min, and the molecular weight were calibrated to a polystyrene standard at 40 $^{\circ}$C. The thermal properties were measured using DSC at heating rate 20 $^{\circ}$C/min under N$_2$ atmosphere. ^{1}H-NMR was use to investigate the chemical structure of L-LA, LA oligomer and PLLA.
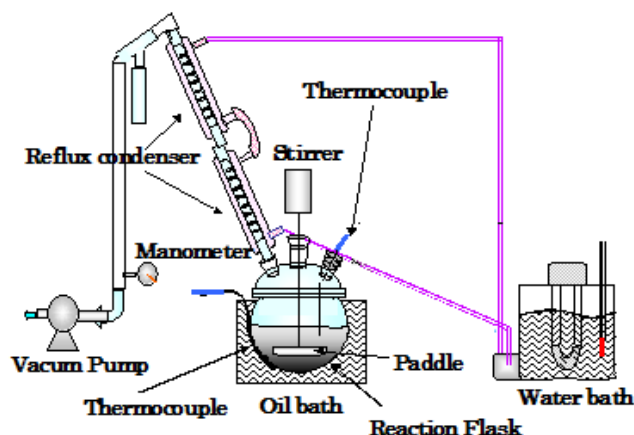

Fig. 1. Lab scale direct polycondensation of lactic acid

3. Results and Discussion

3.1 Kinetic study of direct polycondensation of lactic acid
The stepwise polycondensation reactions can be considered into 2 methods:

3.1.1 Self-catalyzed polymerization

In the absence of an exogenous strong acid, the acid monomer acts as its own catalyst in the esterification reaction. The condensation can be expected to be third order overall in the concentration of the –OH (or [OH]) and –COOH (or [$COOH$]) functional groups [11,12]:

$[OH] = [COOH] = [C]$

$$\frac{d[COOH]}{dt} = -k_3 \cdot [OH] \cdot [COOH]^2 \tag{1}$$

$$\frac{d[C]}{dt} = -k_3 \cdot [C]^3 \tag{2}$$

Integration of Eq. (2) yields:

$$\frac{[C]_0^2}{[C]^2} - 1 = 2[C]_0^2 \cdot k_3 \cdot t \tag{3}$$

However, the degree of polymerization (n) in a stepwise polymerization can be expressed by Eq. (4) (assuming no mass is lost):

$$n = \frac{[C]_0}{[C]} \tag{4}$$

Thus, Eq. (3) can be simplified to:

$$n^2 - 1 = 2[C]_0^2 \cdot k_3 \cdot t \tag{5}$$

Eq. (5) makes clear that the relationship between ($n^2 - 1$) and t should be linear if the polymerization follows this model of self-catalyzed polymerization.

Assume p = extent of reaction, the fraction of functional groups initially present that have undergone reaction at time t.

$$p = \frac{[C]_0 - [C]}{[C]_0} \tag{6}$$

The concentration [C] at time t of either carboxyl or hydroxyl groups is then given by

$$[C] = [C]_0 - [C]_0 p = [C]_0(1 - p) \tag{7}$$

Combination of Eq. (2) and Eq. (7) and integrate, yields:

$$\frac{1}{1 - p^2} = 2[C]_0^2 \cdot k_3 \cdot t + 1 \tag{8}$$

From Eq. (8) the relationship between $\frac{1}{1 - p^2}$ and t should be linear and $slope = 2[C]_0^2 \cdot k_3$.

3.1.2 External catalysis of polymerization

The stepwise polymerization involving an external catalyst follows the second order reaction [11,12]:

$$\frac{d[COOH]}{dt} = -k_2 \cdot [OH] \cdot [COOH] \tag{9}$$

where k_2 is the rate constant of the second order reaction. Setting $[OH] = [COOH] = [C]$ gives:

$$\frac{d[C]}{dt} = -k_2 \cdot [C]^2 \tag{10}$$

Integration of Eq. (10) gives:

$$\frac{[C]_0}{[C]} - 1 = [C]_0 \cdot k_2 \cdot t \tag{11}$$

Combining Eq.(4) and Eq. (11) yields:

$$n - 1 = [C]_0 \cdot k_2 \cdot t \tag{12}$$

Eq. (12) shows that the relationship between $(n-1)$ and t should be linear if the polymerization follows this model of external catalysis.

For the extent of reaction, combination of Eq. (2) and Eq. (12) and integrate, yields:

$$\frac{1}{1-p} = [C]_0 \cdot k_2 \cdot t + 1 \tag{13}$$

From Eq. (13) the relationship between $\dfrac{1}{1-p}$ and t should be linear and $slope = [C]_0 \cdot k_2$.

The activation energy (E_a) can be calculated from Arrhenius equation:

$$k = A \cdot e^{-E_a/RT} \tag{14}$$
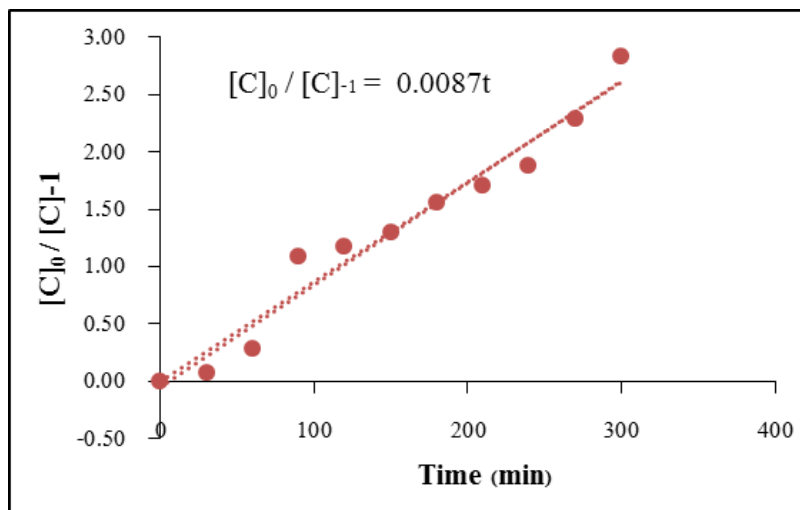
The polymerization reactions were carried out at 140 $^{\circ}$C and 170 $^{\circ}$C.

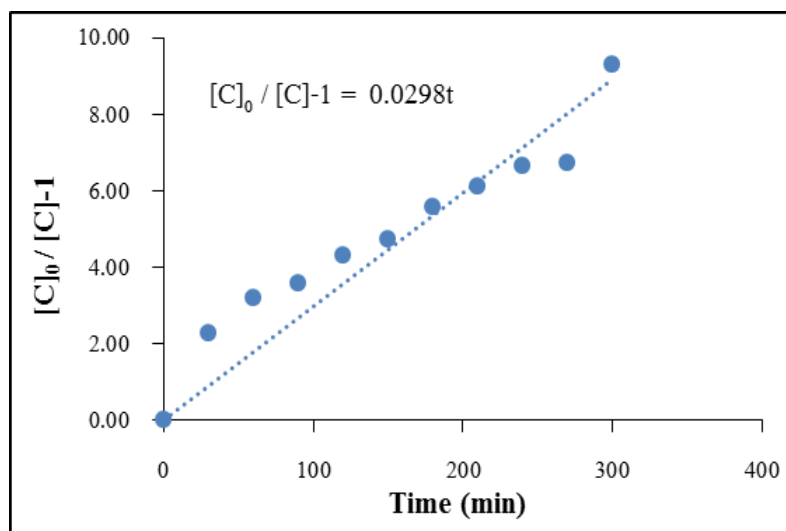**Fig. 2. Relation of $[C]_0/[C]$-1 and time (min) of direct polycondensation at 140 $^{\circ}$C**

Fig. 3 Relation of $[C]_0/[C]$-1 and time (min) of direct polycondensation at 170 °C

Therefore, the rate constant (k) of direct polycondensation of L-lactic acid at 140 °C (k_{140}) and 170 °C (k_{170}) are 8.7×10^{-3} mol^{-1} dm^3 nin^{-1} and 29.3×10^{-3} ^{3} mol^{-1} dm^3 min^{-1}, respectively. The activation energy of direct polycondensation of L-lactic acid is 61.58 kJ/mol.

3.2 Thermal and physical properties of synthesized PLLA

The PLLA oligomer obtained from melt state direct polycondensation were annealed and further polymerized by solid state polymerization (SSP) as previously described.   In SSP, the polymerization temperatures must be lower than melting temperature, T_m to maintain the reaction in solid phase. Thus the reactions were stopped to sampling the synthesized PLLA for determining T_m by DSC before further polymerization. The physical and thermal properties of synthesized PLLA from both laboratory scale and mass scale are tabulated in Table 1 and 2, respectively. For both scales, thermal and physical properties show the similar results. After direct polycondensation, the low molecular weight PLLA or PLLA oligomer were obtained and subjected to SSP at temperature below T_m. As longer SSP time, higher MW of PLLA is obtained due to the longer time and higher probability of oligomer to interact each other [8,9]. T_m of synthesized PLLA was gradually increased with increasing SSP time as shown in Fig. 1 and 2 for laboratory and mass scales, respectively. For laboratory scale, the T_m of polymerized PLLA are 137, 140, 150, 162 and 172 °C for direct polycondensation, annealing, SSP step 1, SSP step 2 and SSP step 3, respectively. For mass scale, T_m of polymerized PLLA are 130, 131, 130, 143, 150, 150 and 157 °C for direct polycondensation, annealing, SSP step 1, SSP step 2, SSP step 3 and SSP step 4, respectively. As longer SSP time, higher and shaper DSC thermograms are obtained due to the increasing of reaction time [13-14]. The Tm and MW values of the synthesized PLLA from laboratory scale and mass scale are comparable at the same conditions. Thus, the size of reactor does not show the effect on the T_m and MW of synthesized PLLA.

For mass scale, there are comments involved bumping of lactic acid during direct polycondensation and the agglomerations of molten PLLA during SSP due to low molecular weight of oligomers. To avoid bumping of lactic acid during direct polycondensation, gradually adjustment of temperature and pressure are required.
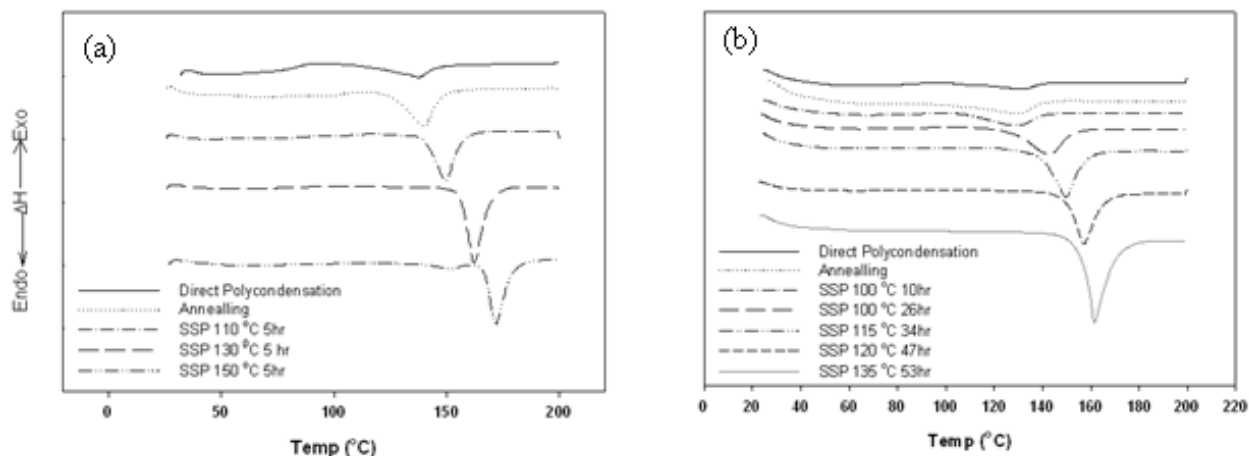
Fig. 4. DSC thermogram of synthesized PLLA: (a) laboratory scale (b) mass scale.

Table 1. Thermal and physical properties of laboratory scale (5 g) synthesized of PLLA

Step	Condition	Tm (°C)	Mw	PDI	Characteristics	
					Appearance	Color
Melt state	150 °C, 30 torr	137	3730	2.37	solid-powder	white
Annealing	100 °C, 1 atm	140	4220	2.08	solid-powder	white
SSP/5h	110°C, 10 torr, 5 h	150	7160	2.44	solid-powder	white
SSP/10h	130°C, 10 torr, 5 h	162	21300	2.17	solid-powder	white
SSP/15h	150°C, 10 torr, 5 h	172	32400	2.19	solid-powder	pale yellow

Note: Yield = 62.75%, Data from ref. [13]

Table 2. Thermal and physical properties of mass scale synthesized PLLA

Step	Condition	Tm (°C)	Mw	PDI	Characteristics	
					Appearance	Color
Melt state	150 °C, 30 torr	130	3160	2.41	solid-powder	White
Annealing	90 °C, 1 atm, 3 h	131	3570	1.93	solid-powder	White
SSP/10 hr	110°C, 10 torr, 7 h	130	3790	1.89	solid-powder*	brown yellow
SSP/26 hr	100°C, 10 torr, 16 h	143	7050	2.14	solid-powder*	pale yellow
SSP/34 hr	115°C, 10 torr, 8 h	150	10800	2.14	solid-powder*	pale yellow
SSP/47 hr	120°C, 10 torr, 13 h	150	20200	2.36	solid-powder*	pale yellow
SSP/53 hr	135°C, 10 torr, 6 h	157	24000	2.16	solid-powder*	pale yellow

* Partially melt, Yield = 72.25%, Data from ref. [13]

3.3 ¹H- NMR characterizations

To confirm the successful of synthesize of PLLA, ¹H-NMR of lactic acid, LA oligomer and synthesized PLLA were investigated. The PLLA from mass scale was successfully synthesized and the polymer products were confirmed by using ¹H-NMR as shown in Fig. 5. Peaks at 5.1-5.3 ppm are the methine protons in LA repeat units, while the signals of methine protons in the end groups of the polymers appear at 4.4 ppm. The peaks at 1.6 ppm represent to methyl protons, which often interfere with those of residual lactic acid monomer [14-18].
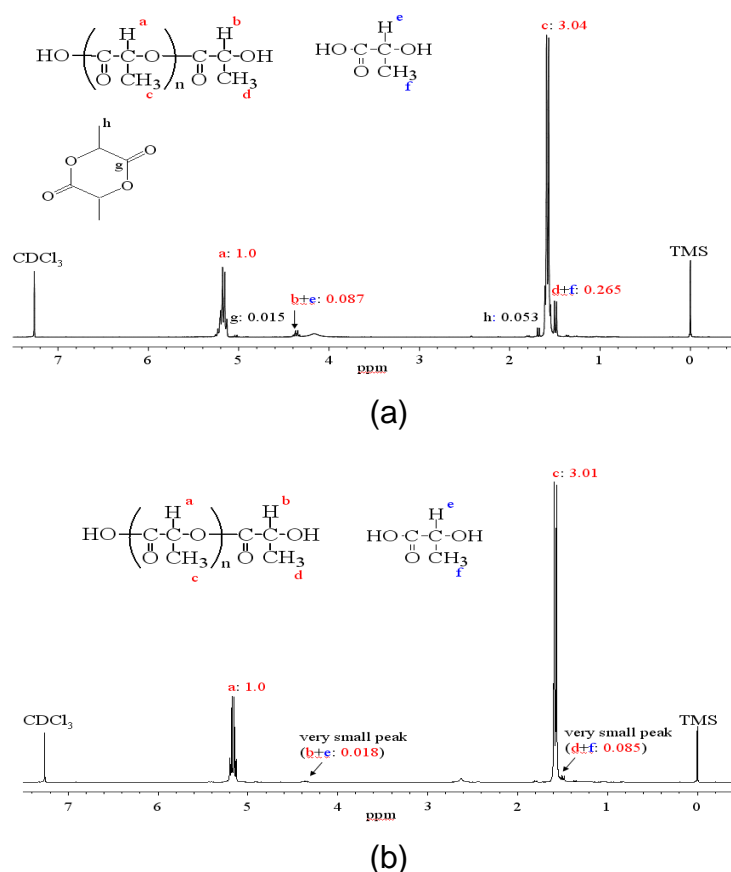

(a)

(b)

Fig. 5. ¹H NMR of a) PLLA oligomer and b) synthesized PPLA from mass scale direct polycondensation. Data from ref. [13]

4. Conclusions

Environmental friendly and non-complex facilities process of PLLA production was studied. PLLA was successfully synthesized via direct polycondensation and solid state polymerization in laboratory and mass scale and confirmed by ¹H-NMR. The kinetic study to find the rate constant and activation energy of direct polycondensation of L-lactic acid was studied. The synthesized PLLA from both laboratory and mass scales show comparable melting temperature and polymer physical properties. Thus there are high potential to produce PLLA using the new process. The investigations of effects of time and reaction condition for high efficiency and economized reaction are required in future works.

5. Acknowledgements

References

[1] S. Pivsa-Art, N. Srisawat, N. O-Charoen, S. Pavasupree and W. "Preparation of Knitting Socks from Poly (Lactic Acid) and Poly [(R)-3-Hydroxybutyrate-co-(R)-3-Hydroxyvalerate] (PHBV) Blends for Textile Industrials," *Pivsa-Art: Energy Procedia*, Vol. 9, pp. 589-597, 2011.
doi:10.1016/j.egypro.2011.09.069

[2] K.M. Nampoothiri, N.R. Nair, R.P. John, "An overview of the recent developments in polylactide (PLA) research," *Bioresource Technology*, Vol. 101, Issue 22, pp. 8493-8501, 2010.
doi:10.1016/j.biortech.2010.05.092

[3] T. Maharanaa, B. Mohantyb, Y.S. Negi, "Melt–solid polycondensation of lactic acid and its biodegradability," *Progress in Polymer Science*, Vol. 34, Issue 1, pp. 99-124, 2009.
doi:10.1016/j.progpolymsci.2008.10.001

[4] S. Yodaa, D. Brattonb, S.M. Howdleb, "Direct synthesis of poly(l-lactic acid) in supercritical carbon dioxide with dicyclohexyldimethylcarbodiimide and 4-dimethylaminopyridine," *Polymer*, Vol. 45, Issue 23, pp. 7839-7843, 2004.
doi:10.1016/j.polymer.2004.09.039

[5] F. Achmad, K. Yamane, S. Quan, T. Kokugan, "Synthesis of polylactic acid by direct polycondensation under vacuum without catalysts, solvents and initiators," *Chem. Eng. J.*, Vol. 151, Issue 1-3, pp. 342-350, 2009.
doi:10.1016/j.cej.2009.04.014

[6] M. Ajioka, K. Enomoto, K. Suzuki and A. Yamaguchi, "The basic properties of poly(lactic acid) produced by the direct condensation polymerization of lactic acid," *J. Envt. Polym. Degrad.*, Vol. 3, Issue 4, pp. 225-234, 1995.
DOI: 10.1007/BF02068677

[7] I. M. Sung, W. L . Chan, M. Miyamoto and Y. Kimura, "Melt polycondensation of L-lactic acid with Sn(II) catalysts activated by various proton acids: A direct manufacturing route to high molecular weight Poly(L-lactic acid)," *J. Polym. Sci.: Part A: Polym. Chem.*, Vol. 38, Issue 9, pp. 1673-1679, 2000.
DOI: 10.1002/(SICI)1099-0518(20000501)38:9<1673::AID-POLA33>3.0.CO;2-T

[8] Q. W. Gao, P. Lan, H. L. Shao and X. C. Hu, "Direct Synthesis with Melt Polycondensation and Microstructure Analysis of Poly(l-lactic acid-co-glycolic acid)," *Polym. J.*, Vol. 34, pp. 786-793, 2002.
doi:10.1295/polymj.34.786

[9] H. Fukuzaki, M. Yoshida, M. Asano and M. Kumakura, "Synthesis of copoly(d,l-lactic acid) with relatively low molecular weight and in vitro degradation," *Eur. Polym. J.*, Vol. 25, Issue 10, pp. 1019-1026, 1989.

doi:10.1016/0014-3057(89)90131-6

[10] S.I. Moon and Y. Kimura, "Melt polycondensation of L-lactic acid to poly(L-lactic acid) with Sn(II) catalysts combined with various metal alkoxides," *Polym. Int.*, Vol. 52, Issue 2, pp. 299-303, 2003.
DOI: 10.1002/pi.960

[11] G. Odian, *Principles of Polymerization, Fourth ed.*, John Wiley & Sons, NewYork, 2004.

[12] F.W. Billmeyer Jr., *Textbook of Polymer Science*, Wiley Int. Ed., Wiley Toppan, New York, 1962.

[13] S. Pivsa-Art, S. Niamlang, W. Pivsa-Art, S. Pavasupree, K. Ishimoto and H. Ohara, "The Production of Poly(L-lactic acid) from 2-Steps Direct Polycondensation in 100 Kg Scale," *Adv. Mater. Research.,* Vol. 418-420, pp. 1301-1306, 2012.
DOI: 10.4028/www.scientific.net/AMR.418-420.1301

[14] K. Fukushima and Y. Kimura, "Stereocomplexed polylactides (Neo-PLA) as high-performance bio-based polymers: their formation, properties, and application," *Polym. Int.*, Vol. 55, Issue 6, pp. 626-642, 2006.
DOI: 10.1002/pi.2010

[15] S.I. Moon, I. Taniguchi, M. Miyamoto , Y. Kimura and C.W. Lee, "Synthesis and Properties of High-Molecular-Weight Poly(L-Lactic Acid) by Melt/Solid Polycondensation under Different Reaction Conditions," *High Perform Polym.,* Vol.13, pp. S189-S196, June 2001.
doi:10.1088/0954-0083/13/2/317

[16] S.I. Moon, C.W. Lee, I. Taniguchi, M. Miyamoto and Y. Kimura., "Melt/solid polycondensation of l-lactic acid: an alternative route to poly(l-lactic acid) with high molecular weight," *Polymer*, Vol. 42, Issue 11, pp. 5059-5062, 2001.
doi:10.1016/S0032-3861(00)00889-2

[17] A. Celli and M. Scandolat, "Thermal properties and physical ageing of poly (l-lactic acid)," *Polymer*, Vol. 33, Issue 13, pp. 2699-2703, 1992.
doi:10.1016/0032-3861(92)90440-8

[18] J. L. Espartero, I. Rashkov , S. M. Li, N. Manolova, and N. Vert, "NMR Analysis of Low Molecular Weight Poly(lactic acid)s," *Macromolecules.*, Vol. 29, Issue 10, pp. 3535-3539, 1996.
DOI: 10.1021/ma950529u

[19] S. I. Moon, C. W. Lee, M. Miyamoto and Y. Kimura, "Melt polycondensation of L-lactic acid with Sn(II) catalysts activated by various proton acids: A direct manufacturing route to high molecular weight Poly(L-lactic acid)," *J Polym Sci, Part A: Polym Chem.*, Vol. 38, Issue 9, pp. 1673-1679, 2000.
DOI: 10.1002/(SICI)1099-0518(20000501)38:9<1673::AID-POLA33>3.0.CO;2-T