EasyChair Preprint

№ 6121

Determination of Optimal Conditions for Obtaining Polylactic Acid by Microwave-Assisted Direct Polycondensation

Diego Alexander Cumbe Gordillo,
Michelle Alejandra Herrera Cortés, Linet Hernández Gil,
Augusta Jiménez Sánchez, Elianne Rodríguez Larraburu and
Carla María Gutiérrez Quiroz

July 20, 2021

Determination of optimal conditions for obtaining polylactic acid by microwave-assisted direct polycondensation

Diego Alexander Cumbe-Gordillo[1][0000-0002-4524-4442], Michelle Alejandra Herrera-Cortés [2][0000-0002-4590-1617], Linet Hernández-Gil[3][0000-0001-6390-4056], Augusta Jiménez-Sánchez[3][0000-0003-2143-7263], Elianne Rodríguez-Larraburu[4][0000-0003-1766-5626], Carla María Gutiérrez-Quiroz[4][0000-0002-3865-4718]

[1] Sociedad Nacional de Galápagos (SONGA C.A.), Galápagos, Ecuador.
[2] Galapesca, Galápagos, Ecuador.
[3] Universidad de Guayaquil, Guayaquil, Ecuador.
[4] Instituto Superior Universitario Bolivariano de Tecnología, Guayaquil, Ecuador.

erodriguez@bolivariano.edu.ec

Abstract. Introduction: An alternative to petrochemical polymers is polylactic acid. Objective: To determine the optimal polylactic acid conditions by microwave-assisted direct polycondensation to obtain the highest yield. Materials and methods: 28 lactic acid and 32 PLA studies were compared. Results: Food residues with sweet sorghum juice, *Bacillus coagulans* and *Lactobacillus rhamnosus* microorganisms, using Fed-Batch SSF, for 20-40 h, between 30-45ºC and pH 5-7. As a synthesis, commercial or fermented lactic acid between 25-50 mmHg under vacuum, SnCl2/p-TsOH at 0.1-0.6% for 15-45 min with 100-300W at 50-150°C. Conclusions: Several factors influence the performance and type of polymer, such as raw material, type of microorganisms, type of fermentation and pH.

Keywords: Biodegradable, fermentation, polylactic acid, polycondensation, microwave radiation.

1 Introduction

The production of plastic waste reaches approximately 8 million tons, polluting water, air and soil, either due to its slow degradation or due to the toxins it releases into the environment, which affects the health of humans and animals, especially aquatic ones. (ECODES, 2019). It is for this reason that the need arises to create biodegradable materials made from starches, sugars, lignocellulosic residues and residues from different industrial activities (Lopretti, 2017) in order to reduce the impact of materials from oil.

An alternative is polylactic acid (PLA), which improves the mechanical properties of a material since when combined with other polymers it provides advantages due to its biodegradability (Labeaga Viteri, & Aitziber, 2018). However, their properties and production performance differ depending on the synthesis method applied such as azeotropic distillation, ring opening polymerization (ROP) and direct polycondensation; These last two are the most used production techniques (Tejada, 2015), in addition, it depends on the catalyst, temperature, pH and concentration of the precursor or lactic acid and obtaining the latter depends on the fermentation conditions, type of microorganism, types and pH of the raw material.

According to studies by the European Bioplastics Association (2019), the production capacity of PLA worldwide has increased since 2012 with a production of 186,953 tons / year compared to the 353,800 tons / year produced until 2020, and it is forecast that reaches a total of 424,440 tons / year in 2023, although to date there is no PLA production in Ecuador. Therefore, it seeks to identify the optimal conditions in obtaining PLA by means of direct microwave-assisted polycondensation through a current bibliographic review for its possible elaboration at an industrial level in Ecuador.

2 Material and methods

Scientific publications are the guide to the scientific development, therefore, a non-experimental, descriptive research was used, collecting several studies from high-impact indexed journals through the use of platforms from reliable sources such as Springer, Science Direct, EBSCO, SciELO, doctoral thesis, between 2015 and 2020. The terms “Lactic Acid Production”, “Synthesis of lactic acid”, “Synthesis + Polylactic Acid + Microwave”, “Poly lactic acid synthesis”, “Production + Polycondensation”, “Polylactic acid synthesis” were used”, “Poly lactic Acid + Microwave”, “PLA Microwave”, “Poly lactic acid + microwave” and “Poly lactic acid synthesis”. Those scientific articles with the highest citation were considered with the virtual platform SJR (SCImago Journal Ranking), giving a total of 28 scientific articles on lactic acid and 32 articles referring to PLA, which were carefully analyzed establishing relationships, comparisons and discussions between each study to determine the best fermentation and synthesis conditions for PLA.

3 Results

Lactic acid or 2-hydroxypropanoic acid is the monomer of PLA, it exists in four forms: L, D, meso and racemic. The L (+) isomer is metabolized by the human organism while the D (-) is not. The racemic form is optically inactive and is the commercial form (Albán, 2003). At present, there is interest in obtaining lactic acid from agricultural waste and its subsequent transformation.

Table 1 shows the studies related to obtaining lactic acid using different raw materials, microorganisms and fermentation conditions. PLA is a thermoplastic polyester, made from lactic acid by different routes. One of them is the polycondensation of lactic acid, depolymerization to the dilactide dimer followed by polymerization opening the ring to form high molecular weight polymers. In the second route, lactic acid is polycondensed in the presence of a dysfunctional monomer, producing a teleketic polymer, which binds to others to produce high molecular weight polymers. In the third way, lactic acid is polycondensed directly into high molecular weight polymers. The reactions are produced by the action of heat or by the action of catalysts such as metal alkoxides and chiral methoxy-side aluminum complexes (Munilla & Carracedo, 2005). Similary, table 2 shows the studies regarding the obtaining of PLA from a commercial or fermented lactic acid by means of conventional heating or microwaves.

Table 1. Lactic acid production conditions.

1. Raw material	1.1. Origin	2. Microorganism	2.1. Substratum	2.2. Supplement	3. Type of fermentation	3.1. Conditions of fermentation			4. Final concentration of lactic acid (g/L)	4.1. Production performance (%)	5. References
						3.2. T (°C)	3.3. t (h)	3.4. pH			
Highly delignified hardwood kraft pulp	Japan	*Lactobacillus plantarum* ***Inoculum:*** *6% v/v*	N/A	Glucose: 0,4% Xylose: 0,1%	SSF	50	72	5,5	102,3	87,9	(Hama, et al., 2015)
Potato waste	N/A	*L. pentosus NRRL B-227* ***Inoculum:*** *10% v/v*	Hydrolyzed potato residues	YE: 10 g/L	N/A	30	72	7	47,2	99	(De Oliveira, 2016)
Pretreated sugarcane bagasse	Queensland, Australia	*B. coagulans DSM 2314* ***Inoculum:*** *5% v/v*	Pretreated sugarcane bagasse with 0.02% H_2SO_4	YE: 5g/L Peptone: 10 g/L Glucose: 20 g/L	Fed Bacth SSF	50	68	5,8	70,4	83,0	(Van Der Pol, Eggink & Weusthuis, 2016)
					SSF (Tow stages)	50	30	5	58,7	73,0	
Cellobiose	Sigma-Aldrich, Missouri, USA	*Bacillus coagulans WCP10-4* ***Inoculum:*** *2% v/v*	4-Nitrophenyl-β-D-glucopyranoside (pNPG)	β-glucosidase (Cellobiose)	SSF	50	28	6	N/A	97,8	(Ong, Ng & Wu, 2016)
Coffee pulp waste	CENICAFÉ, Colombia	*B. coagulans* ***Inoculum:*** *- Laboratory scale (6% v/v) - Pilot scale (5% v/v)*	**Sources of C:** Glucose, Xylose, Arabinose	YE: 10 g/L	**Batch** - Laboratory scale	52	40-44	6	48	54	(Pleissner, et al., 2016)
					- Pilot scale	52	23	6	45,3	78	
Green legume juice	Brandeburg, Germany	*B. coagulans AT107* ***Inoculum:*** *2% v/v*	120 g/L dextrose monohydrate	YE: 15 g/L	Fed batch	52	30	6	98,8	N/A	(Dietz, et al., 2016)
Sweet sorghum juice	Chinese Academy of Agricultural Sciences, Shunyi District, Beijing, China	*B. coagulans LA 1507 y L. rhamnosus LA-04-1* ***Inoculum:*** *5% v/v & 10% v/v*	**Source of N:** SCP **Source of C:** SSJ	SCP	Batch	42	24	5,6	118	92,10	(Wang, et al., 2016)
Cottonseed meal and corn cob residues	Tianyuan Food Processing CO., Ltd. (Xuzhou, China)	*Sporolactobacillus inulinis YBS 1-5* ***Inoculum:*** *10% v/v*	**Source of N:** CSM **Source of C:** CCR	YE Glucose, Xylose, Cellulase	Fed batch	37	16	5,5	107,2	85	(Bai, et al., 2016)
Food waste	Asia Pacific Catering, Hong Kong Science Park.	*Lactobacillus casei Shirota* ***Inoculum:*** *2% v/v*	Hydrolyzed food waste	YE: 10 g/L	SSF	37	36	N/A	94	94	(Kwan, Hu, & Lin, 2016)
Xylose	N/A	*G. stearothermophilus 16* ***Inoculum:*** *5% v/v*	**Source of C:** 5% p/v Xylose **Source of N:** 5% p/v YE	YE: 5% p/v ME Peptone	Batch	45	96	6	3,2	8,90	(Kunasundari, Naresh, & Chu, 2017)
Glucose	N/A	*Geobacillus stearothermophilus 15* ***Inoculum:*** *3% v/v*	**Source of C:** 5% Glucose **Source of N:** 3% YE	YE: 3%	Batch	40	24	8,5	10,4	N/A	(Kunasundari, Naresh, & Safie, 2017)
Mixed restaurant food waste	Institute for Agricultural Engineering and Bioeconomy	*Streptococcus sp. A620* ***Inoculum:*** *6% v/v*	**Source of C and N:** Pretreated food waste	YE: 15 g/L	SSF Laboratory and technical scale	35	28	6	58	N/A	(Navarro, et al., 2017)

	Potsdam, Germany										
Cassava starch	Termamyl Classic; Bagsværd, Denmark	*Rhizopus microspores DMKU 33*	Cassava starch liquefied pretreated with α-amylase	N/A	Fed Batch SSF	40	84	5,5	112,05	91,5	(Trakarnpaiboon, et al., 2017)
***Sophora flavescens* residues**	Shanxi Zhendong Pharmaceutical, Shanxi, China	*L. casei CICC 6056* ***Inoculum:*** *2% v/v*	SFR Pretreated with NaOH 1,2%	YE: 10 g/L K_2HPO_4: 2 g/L	Batch SSF	37	72	7	55,1	83,5	(Wang, et al., 2017)
Sugarcane bagasse and harvest residues	South Africa	*B. coagulans P38*	SCB y HR pretreated	Hydrolyzed of hemicellulose (75%v/v)	N/A	45	54	6	**SCB:** 4,18 **HR:** 20,42	N/A	(Koekemoer, 2018)
		B. coagulans MXL-9				50	54	6,5	**SCB:** 5 **HR:** 16	N/A	
		Lactobacillus lactis IO-1				37	54	6	**SCB:** 8 **HR:** 17	N/A	
Orange peel waste	Biopolis S.L, Valencia, Spain	*Lactobacillus delbrueckii ssp. delbrueckii CECT286.* ***Inoculum:*** *0.1% v/v*	Fructose + Galactose **Source of C:** OPW **Source of N:** FCL	FCL: 37 g/L YE: 22 g/L K_2HPO_4: 2g/L	Batch	40	24	5,8	7,07 10,6 N/A	49,94 49,23	(De la Torre, Ladero, & Santos, 2018)
Dried beans distilled with soluble	Vivergo bioethanol plant, Yorkshire, UK	*Lactobacillus coryniformis*	Hydrolyzed dried grains distilled with soluble	Glucose: 20 g/L	SHF	37	54	6	19,7	99,9	(Zaini, Chatzifragkou, & Charalampopoulos, 2018)
		Lactobacillus pentosus							18,87	62,1	
		Lactobacillus brevis						5	12,7	99,8	
		L. coryniformis		Glucose: 33 g/L	SSF	37	48	5	27,9	42,3	
Carob waste	Lebanese food industry	*L. rhamnosus ATCC 53103*	Saccharose + glucose	YE: 10 g/L	Fed batch SSF	37	24	5,5	22	76,90	(Bahry, et al., 2019)
Pretreated rice straw	Chenzhou, Hunan, China	*B. coagulans LA-15-2*	Bagasse of pretreated rice straw with EDA (10% p/v)	Glucose	Batch SSF	50	20	N/A	50	28,27	(Chen, et al., 2019)
			EDA	Bagasse and cellulose	Fed Batch SSF	50	46	6,2	92,5	57,81	
Mesquite seed (*Prosopis juliflora*)	Chidambaram, India	*L. delbrueckii* MTCC 911	HMSP: 10%	YE: 2% Peptone: 1%	N/A	37	96	6	38,23	N/A	(Kasirajan, et al., 2019)
Orange peel	Paterna, Valencia, Spain	*L. delbrueckii ssp delbrueckii*	Hydrolyzed orange peel	N/A	Fed Batch SSF	40	96	5,8	96,3	87,8	(De la Torre, Acedos, Ladero, & Santos, 2019)
Hydrolyzed municipal solid waste	IMECAL, S.A. Valencia, Spain	*B. coagulans A166* ***Inoculum:*** *3% v/v*	Hydrolyzed municipal solid waste	YE: 5 g/L	Homo-fermentative (pilot scale)	52	10-22	6	61,1	94,0	(López-Gómez, et al., 2019)
Inedible starchy biomass	Beijin, China	*B. coagulans IPE22*	**Source of C:** Glucose	Mesothermic α-amylase lucoamylase	SLSF	52	40	N/A	68.72	99	(Wang, et al., 2019)
Brewer's spent grain and malt rootlets	Rockville, USA	*Lactobacillus rhamnosus ATCC 7469* ***Inoculum:*** *5% v/v*	Hydrolyzed brewer's spent grain and malt rootlets	BYE: 19,12% SL: 0,19%	Batch	37	36	N/A	31,56	95,46	(Radosavljević, et al., 2019)
Residues of crust bread and green alfalfa juice	Barcelona y Potsdam	*B. coagulans* ***Inoculum:*** *2% v/v*	**Source of C:** Hydrolyzed crust bread waste **Source of N:** 15 g/L YE	N/A	Fed batch	52	24	6	62,2	N/A	(Alexandri, et al., 2020)

Beet pulp	Cádiz, Spain	*Lactobacillus casei 2246*	N/A	YE: 5 g/L ME: 10 g/L	Fed batch SSF	37	103,5	N/A	26,88	13	(Díaz, et al., 2020)
Agricultural straw	Wuhan, China	*B. coagulans LA204* ***Inoculum:*** *10% v/v*	Corncob	YE: 10 g/L	Fed batch SSF	50	48	N/A	N/A	54	(Liu, et al., 2020)
Cassava bagasse	Xiamen, China	*B. coagulans y L. rhamnosus* ***Inoculum:*** *5% v/v*	N/A	N/A	SSCF	50	41	6,5	112,5	88	(Chen, et al., 2020)

Source: Authors.

Note: T=Temperature; t=Time; SSF=Simultaneous saccharification and fermentation; YE=Yeast extract; H_2SO_4=Sulfuric acid; SCP=Steep Corn Powder; SSJ=Sweet Sorghum Juice; CSM=Cottonseed meal; CCR=Corncob residues; ME=Meat extract; SFR=Sophora flavescens residues; NaOH=Sodium hydroxide; K_2HPO_4=Potassium hydrogen phosphate; SCB=Sugarcane bagasse; HR=Harvest residues; OPW=Orange peel waste; FCL=Fermented corn liquor; SHF=Separate enzymatic hydrolysis and fermentation; EDA=Ethylenediamine; HMSP=Hydrolyzed Mesquite Seed Powder; C=Carbon; N=Nitrogen; SLSF=Simultaneous liquefaction, saccharification and fermentation; BYE=Brewer's yeast extract; SL=Soy lecithin; SSCF=Simultaneous saccharification and co-fermentation.

Table 2. Categories developed about obtaining polylactic acid (PLA).

1. Raw material	**2. PLA synthesis**	**2.1. Catalyst**	**2.2. Synthesis conditions**		**3. Heating method**	**4. PLA characterization**		**5. PLA properties**		**6. References**
			2.2.1. T (°C)	**2.2.2. t (h/min)**		**4.1. Physical**	**4.2. Chemicals**	**5.1. Molecular weight**	**5.2. Performance (%)**	
Commercial L, D lactic acid ***Purity:*** *85%*	RM	N/A	100	24 h	CH	N/A	MALDI-TOF	N/A	94,5	(Kéki, et al., 2001)
	RM	N/A	N/A	20 min	MR (650 W)	N/A			84,3	
Commercial L(+) lactic acid ***Purity:*** *85%*	DMP	$SnCl_2$ / TSA **[0,45% by weight]**	N/A	40 min	MR (528 W)	N/A	FTIR NMR GPC	**PLLA** **Mv:** 50800 g/mol	N/A	(Jing, Peng, Yingmin & Xiaojuan, 2006)
Commercial L(+) lactic acid ***Purity:*** *85%*	PD	$SnCl_2$ / p-TsOH **[0,6 %]**	200	30 min	MR (40 W)	N/A	GPC MALDI-TOF	**Mw:** 16000 Da	54	(Nagahata, Sano, Suzuki & Takeuchi, 2007)
Commercial L(+) lactic acid ***Purity:*** *98%*	PD	Zn **[1,5 %]**	180	30 h	MR	N/A	FTIR SEM / EDS	N/A	N/A	(Estupiñan Duran, et al., 2007)
Commercial L(+) lactic acid ***Purity:*** *85%*	PD	N/C	187	60 min 135 min 195 min	MR (130 W)	N/A	FTIR NMR (1H - NMR) GPC	**Mw:** 17000 Da	N/A	(Pandey & Aswath, 2008)
		$Sn(Oct)_2$ **Molar ratio** 1000:1	N/A	30 min 135 min				**Mw:** 29000 Da		
Commercial L(+) lactic acid	PD	N/A	200	100 h	CH	N/A	GPC FTIR	**Mw:** 90000 g/mol	34,52	(Achmad, Yamane, Quan & Kokugan, 2009)

Commercial L(+) lactic acid ***Purity:*** *80%*	DMP	$Al_2(SO_4)_3$ **[0,4 % by weight]**	260	1 h	MR	Viscometry method	FTIR TGA	**Mv:** 22176 g/mol	72,3	(Cao, Wang & Yuan, 2009)
Commercial lactic acid ***Purity:*** *90%*	PD	$SnCl_2$ / p-TsOH **[0,6 %]**	N/A	5 h	MR	N/A	NMR (1H y 13C) SEC	**Mw:** 9550 Da	98	(Nagahata, et al., 2010)
Commercial L, D lactic acid ***Purity:*** *98%*	ROP	$Sn(Oct)_2$ **Molar Ratio** 1/10000	100	30 min	MR (150 W)	N/A	GPC FTIR SEM	**Mn:** 112542 g/mol **Mw:** 309940 g/mol	95	(Nikolic, et al., 2010)
Commercial L(+) lactic acid ***Purity:*** *90%*	DMP	$SnCl_2$. $2H_2O$ / TSA **Molar ratio** 1:1	175	4 h	CH	Viscometry Polarimeter	GPC NMR	**PLLA** **Mw:** 44000 g/mol	80	(Song, & Wu, 2011)
Commercial lactic acid ***- D, L:*** *90% purity* ***- L(+):*** *89% purity*	PD	N/C (Compuesto DIC) **[0,2 mol / 8 ml]**	80	30 min	MR (500 W)	N/A	FTIR NMR (1H & 13C) DSC MALDI-TOF	6633 Da	85 - 90	(Brown, et al., 2012)
				8 h	UI			6327 Da		
		N/C (Polímero PVA) **[2,2 g / ml]**	50	10 min	MR (500 W)			N/A	N/A	
			N/A	N/A	UI					
Commercial L(+) lactic acid ***Purity:*** *90%*	RM / SSP	CR **[0,005 % mol]**	200	165 min	CH	N/A	GPC	**PDLA** **Mw:** 100000 Da **PLLA** **Mw:** 120000 Da	95	(Huang, et al., 2014)
Commercial L(+) lactic acid ***Purity:*** *85%*	DMP	$Sn(Oct)_2$ **[0,5 %]**	160	4,5 h	MR	Viscometry method AV	FTIR TGA	**PLLA** **Mv:** 7030 Da	> 90	(Jiménez, Salas, Esquivel & Vega, 2014)
		$Sn(Oct)_2$ **[1 %]**	170	15 h	CH	N/A	FTIR	**PLLA:** 10685 Da	> 90	
Commercial L(+) lactic acid ***Purity:*** *85%*	PAD	$Sc(OTf)_3$ **[0,1 % mol]**	N/A	6 h	MR (300 W)	N/A	GPC NMR SEC DSC	**PLLA** **Mn:** 4400 Da **Mw:** 11600 Da	> 99	(Yamada, et al., 2014)
		$SnCl_2$ **[1,0 % mol]**	160	6 h	CH	N/A		**PLLA** **Mw:** 19600 Da	> 99	
		$SnCl_2$ **[1,0 % mol]**	N/A	6 h	MR (300 W)	N/A		**PLLA** **Mn:** 9200 Da **Mw:** 46700 Da	> 99	
		$SnCl_2$ **[1,0 % mol]**	N/A	6 h	MR-EF (100 W)	N/A		**PLLA** **Mn:** 8800 Da **Mw:** 60200 Da	> 99	
Commercial L(+) lactic acid ***Purity:*** *88%*	ROP	$Sn(Oct)_2$ / $C_5H_{12}O$	N/A	10 min	MR (350 W)	N/A	GPC / SEC NMR FTIR TGA	**Mn:** 2972 Da **Mw:** 4012 Da	N/A	(Bakibaev, et al., 2015)
Commercial L(+) lactic acid ***Purity:*** *85%*	PD	ZnO **[0,50 %]**	< 120	30 min	MR	Shore A hardness	FTIR XRF	N/A	N/A	(Guzmán & Arana, 2015)

Commercial L(+) lactic acid ***Purity:*** *80%*	PC	MSA	160	24 h	CH	N/A	GPC	**Mn:** 8000 g/mol **Mw:** 13800 g/mol	N/A	(Di Martino, Kucharczyk, Zednik & Sedlarik, 2015)
Commercial L(+) lactic acid ***Purity:*** *98%*	PD	$ZnCl_2$ **[1,50 %]**	180	57 h	CH	N/A	FTIR	N/A	N/A	(Montañez, Peña & Estupiñán, 2015)
Fermented L, D lactic acid (Potato waste) ***- L(+):*** *95% purity* ***- D(-):*** *5% purity*	PD	N/A	140	90 min	MR (300 W)	Viscometry method AV	GPC SEM TGA DSC XRD	**Mv:** 1450 g/mol	49	(De Oliveira, 2016)
			140	90 min	MR (100 W)			**Mv:** 610 g/mol	76	
Commercial L(+) lactic acid ***Purity:*** *85%*			140	90 min	MR (300 W)			**Mv:** 2070 g/mol	45	
			140	90 min	MR (100 W)			**Mv:** 1190 g/mol	79	
Commercial lactic acid ***- L(+):*** *80 % purity* ***- D, L:*** *90% purity*	DMP	N/A	130	24 h	CH	N/A	GPC FTIR Spectroscopy NMR (1H-NMR / 13C-NMR) DSC	**Mn:** 3200 g/mol **Mw:** 4500 g/mol	**PLLA=**42,4	(Kucharcyk, Zednik & Sedlarik, 2016)
								Mn: 2400 g/mol **Mw:** 4100 g/mol	**PDLLA=**47,7	
Pure commercial lactic acid ***Purity:*** *100%*	PD	$SnCl_2$. $2H_2O$ / $C_8H_4O_3$ **[0,5 %]**	160	35 h	CH	N/A	FTIR GPC	**Mn:** 6900 Da **Mw:** 22100 Da	N/A	(Anthony, 2016)
		$SnCl_2$. $2H_2O$ / $C_4H_2O_3$ **[0,5 %]**						**Mn:** 13400 Da **Mw:** 61700 Da		
		$SnCl_2$. $2H_2O$ / $C_7H_8O_3S$ **[0,5 %]**						**Mn:** 18300 Da **Mw:** 81500 Da		
Commercial L(+) Lactide	ROP	$Sn(Oct)_2$ **[0,008 mol/L]**	160	16 min	MR	N/A	GPC Spectroscopy NMR (1H - NMR)	**Mn:** 38681 g/mol **Mw:** 57636 g/mol	N/A	(Dubey, et al., 2017)
			180	20 min				**Mn:** 34763 g/mol **Mw:** 50059 g/mol		
Fermented L(+) acid (*Food waste*) ***Purity:*** *96%*	ROP	$Sn(Oct)_2$ **[0,1 - 0,4 % by weight]**	200	25 min	CH	N/A	TGA DSC	**Mw:** 151127 g/mol	81,09	(Lin, et al., 2017)
Commercial L(+) lactic acid ***Purity:*** *86%*	ROP	$Sn(Oct)_2$ **[0,6 % by weight]**	140-200	8 h	CH	N/A	GPC TGA NMR DSC	1500 g/mol	N/A	

Commercial L(+) lactic acid ***Purity:*** *80%*	DMP	pTsOH **[0,3 % mM]**	180	60 min	MR (700 W)		GPC DSC	**Mn** = 2461 g/mol **Mw** = 4818 g/mol	25	(Temur & Bayramoğlu, 2018)
Commercial L(+) lactic acid ***Purity:*** *90%*	RM	p-XSA **[0,5 % mol]**	150	3	CH	N/A	GPC TGA	**Mn:** 20000 Da **Mw:** 40000 Da	N/A	(Takenaka, Kimura & Ohara, 2018)
	SSP		130	15 h				**Mn:** 68000 Da **Mw:** 160000 Da	N/A	
Fermented D(-) lactic acid ***(Dried distillery grains with soluble*****) Purity:** *91,8%*	PAD y PD	$Sn(Oct)_2$ **[0,2 g/L]**	140	80 h	CH	N/A	GPC	**PDLA:** 3010 Da	N/A	(Zaini, Chatzi-fragkou, & Chara-lampopoulos, 2018)
Commercial L(+) lactic acid ***Purity:*** *90%*	ROP	CRL **[2 % w/w]**	90	72 h	CH	N/A	GPC FTIR NMR XRD SEM DSC	**Mn:** 2854 g/mol **Mw:** 5428 g/mol	93	(Whulanza, et al., 2018)
Commercial L, D lactic acid ***Purity:*** *84,5%-85,5%*	PC	H_3PW/C **[20 % by weight]**	180	15 h	CH	N/A	XRD FTIR GPC NMR	**PLLA** **Mw:** 14900 Da	N/A	(Chafran, et al., 2019)
Commercial L(+) lactic acid ***Purity:*** *80%*	DH/PC	N/A	215	35 min	MR (360 W)	Viscometry method	GPC	**Mv:** 758 Da	N/A	(Guba, et al., 2019)
Fermented L(+) lactic acid (*Prosopis juliflora*) *Purity:* *85%*	ROP y PD	$SnCl_2$ **[0,01 %]**	145	48 h	CH	N/A	FTIR Mass spectroscopy (MALDI-TOF)	2065 Da	N/A	(Kasirajan, et al., 2019)

Source: Authors.

Note: *T=Temperature; t=Time; RM=Raw material; CH=Conventional heating; MR=Microwave radiation; MALDI-TOF=Mass spectrometry; DMP=Direct melt polycondensation; $SnCl_2$=Stannous chloride; TSA=Toluenesulfonic acid; FTIR=Fourier transform infrared spectroscopy; NMR=Nuclear magnetic resonance; ROP= Ring opening polycondensation; GPC=Gel permeation chromatography; PLLA=Poly L(+) Lactic Acid; Mv=Viscometric average molecular weight; DP=Policondensación directa; Mw=Weight average molecular weight; SSP=Solid state polycondensation; Zn=Zinc; SEM=Scanning electron microscopy; EDS= X-ray energy dispersion spectrometry; N/C= No catalyst; $Sn(Oct)_2$=Stannous octoate; $Al_2(SO_4)_3$=Aluminum sulfate; p-TsOH=p-toluenesulfonic acid; SEC=Size exclusion chromatography; PAD=Polycondensation by azeotropic distillation; $SnCl_2 . 2H_2O$=Dihydrated stannous chloride; DIC= N, N'-diisopropylcarbodiimide; UI=Ultrasonic irradiation; DSC=Differential scanning calorimetry; PVA=Polyvinyl acetate; CR=Creatinine; AV=Acid value; TGA=Thermogravimetric analysis; $Sc(OTf)_3$=Scandium trifluoromethanesulfonate; $C_5H_{12}O$=Isoamyl acid; ZnO=Zinc oxide; XRF=X-ray fluorescence; MSA=Methanesulfonic acid; XRD= X-ray diffraction; $C_8H_4O_3$=Phthalic anhydride; $C_4H_2O_3$=Maleic anhydride; $C_7H_8O_3S$=Methyl benzenesulfonate; p-XSA=p-xylenesulfonic acid; CRL=Candida rugosa lipase; H_3PW=Dodecatungstphosphoric acid.*

4 Discussion

4.1 Relevant studies on obtaining lactic acid

The microorganisms used range from *Lactobacillus* of various species, to fungi such as *Rhizopus microsporus* and also fermentation techniques; the most used are: simultaneous saccharification and fermentation (SSF); separate hydrolysis and fermentation (SHF); simultaneous liquefaction, saccharification and fermentation (SLSF); simultaneous saccharification, fermentation and cofermentation (SSCF), which achieved high substrate conversions and high lactic acid yields.

Wang (2016) used sweet sorghum juice (SSJ) that fermented with *B. coagulans* and *L. rhamnosus* and reflected the highest concentration with 118 g of lactic acid / L which represents a yield of 92.1%. This sweet sorghum juice contained fermentable sugars except for *B. coagulans*. Mixed fermentation at 42 ºC, 24h and pH 5.6 improved the efficiency of open batch type fermentation and in turn overcame the deficiency by using sucrose when *B. coagulans* consumed it on its own thanks to the intervention of *L. rhamnosus* and since the sweet sorghum juice contained said sugar, fermentation between both microorganisms could be carried out. During fermentation, *B. coagulans* converted glucose and fructose (15.5% of total sugar) into L-lactic acid; then *L. rhamnosus* used sucrose and achieved a higher concentration.

The highest yield was achieved by Wang et al. (2019) when using *B. coagulans* capable of fermenting inedible starchy biomass flour with 99.0% yield and a concentration of 68.72 g of lactic acid / L. Carbon sources such as cassava flour and sorghum flour supplemented with mesothermic α-amylase and glucoamylase enzymes were added to said raw material with 69.94% starch.

Among the optimal conditions, the raw material is the mixture of food residues and sweet sorghum juice with *B. coagulans* and *L. rhamnosus* by means of SSF fermentation type Fed-Batch, within a period of 20 - 40 h, at a temperature ranging from 30 to 45 ºC, and a pH between 5 to 7.

The best type of fermentation was Fed Batch using an SSF since it allows a second use of organic waste, requires less energy consumption, presents a low cost and produces a higher production yield (Prieto Lozano, & Torres Rodriguez, 2020).

4.2 Relevant studies on obtaining polylactic acid

The highest yield was evidenced in the study by Yamada, et al. (2014) who used commercial L-lactic acid (85% purity) by microwave heating (MW) with a power of 300 W for 6 h by polycondensation by azeotropic distillation and stannous chloride ($SnCl_2$) as a catalyst at variable concentration, since at 0.1% mol little polymerization was observed, while, with a higher concentration, high values of Mw were evidenced specifically at 1.0% mol and yield of 99% with molecular weights Mw: 46 700 Da; Mn: 9,200 Da. On the other hand, when using conventional heating (CH) at 160 °C, the Mw decreased to 19,600 Da and the yield was maintained. Therefore, it is

necessary to use direct heating with the sample to form a polymer with a well-defined structure (Macías, 2011).

On the other hand, Nagahata (2010) used a commercial lactic acid (90% purity) by direct polycondensation from a mixture of $SnCl_2$ and p-TsOH acid as 0.6% catalyst. After applying microwave radiation for 5h, a 98% yield and a Mw: 9550 Da were obtained. Molecular weights increased as catalyst concentration increased. In comparison, Nagahata (2007), carried out the synthesis from lactic acid 85% purity with the same catalyst and synthesis method (direct polycondensation). Said catalyst showed the highest activity when it was used at 0.6% with 40 W at 200 °C for 30 minutes, obtaining a Mw: 16,000 Da with a yield of 54%. In other words, with a control of temperature and power, the reaction time was reduced from 5 h to 30 min, forming a polymer greater than 10,000 Da.

The appropriate synthesis method is direct polycondensation since a water removal is achieved through a vacuum between 25 - 50 mmHg (Nuñez, 2019). However, it was observed that by the ROP method, Nikolic (2010) achieved the highest molecular weight (Mw = 309940 g/mol; Mn = 112542 g/mol) and the highest yield (99%) was achieved by Yamada, et al. (2014) by azeotropic distillation polycondensation. The microwave type of heating has the advantage of directly heating the sample, accelerating the reaction and reducing the production energy (Sosnik & Gotelli, 2015). The reaction time should range between 15 - 45 min according to the amount of power required, which should range between 100 - 300 W (Jing, 2006), since when irradiated greater than 400 W it generates an inhibition in the polymerization or degradation of PLA (Yamada, 2014).

In addition, the reaction temperature is preferred not to be less than 50 °C, nor greater than 250 °C since it causes deterioration in the formation of the polymer (Vargas, 2002). However, the temperature is controlled from the power, because the equipment stops working when it reaches the programmed power. Finally, the use of a binary catalyst is preferred to improve the catalytic activity, for which the SnCl2 improves remarkably when adding p-TsOH from 0.1% to 0.6%, a concentration considered directly proportional to the molecular weight.

5 Conclusion

The optimal conditions for lactic acid fermentation are: Food residues and sweet sorghum juice, *B. coagulans* and *L. rhamnosus* microorganisms, SSF type Fed Batch fermentation, in a period of 20 - 40 h, at 30 - 45 ºC, and a pH between 5 to 7, while in the synthesis of PLA, a higher yield is obtained when commercial or fermented lactic acid is used between 88 - 90% purity, by direct polycondensation under vacuum between 25 to 50 mmHg using SnCl2 as catalyst / p-TsOH at 0.1 - 0.6% applying microwave heating between 100 - 300 W for 15 - 45 min at 50 - 150 ºC.

6 Recommendation

It is necessary to expand research fields related to the isolation of autochthonous lactic acid bacteria for the development of new lactic acid production processes. In addition, investigate different types of lignocellulosic waste that the country has and that serve as raw materials in the fermentation of lactic acid and subsequent synthesis to PLA, for the production of new materials at lower costs. Likewise, promote new PLA synthesis methodologies that involve microwave heating since, according to the analyzed researches, it has not yet been fully developed despite presenting positive results.

References

1. Achmad, F., Yamane, K., Quan, S., & Kokugan, T. (2009). Sintesis del Ácido poliláctico por policondensación directa al vacio sin catalizadores, solventes e iniciadores. *Chemical Engineering Journal, 151*(1-3), 342-350.
2. Aduana (2019). *Arancel de Importaciones Ingterados del Ecuador*.
3. Alexandri, M., Blanco-Catalá, J., Schneider, R., Turon, X., & Venus, J. (2020). High L (+)-lactic acid productivity in continuous fermentations using bakery waste and lucerne green juice as renewable substrates. *Bioresource Technology, 316*, 123949.
4. Anthony, P. (2016). High molecular weight polylactic acid synthesized by applying different binary catalyst. *Int. J. Chem, Pharm, Sci, 4*(10), 517-521.
5. Bahry, et al. . (2019). *Optimization of lactic acid production using immobilized Lactobacillus Rhamnosus and carob pod waste from the Lebanese food industry*. Journal of Biotechnology, 306(20), 81-88.
6. Bai, Z., Gao, Z., Sun, J., Wu, B., & He, B. (2016). D-Lactic acid production by Sporolactobacillus inulinus YBS1-5 with simultaneous utilization of cottonseed meal and corncob residue. *Bioresource Technology, 207*, 346-352.
7. Bakibaev, A. A., Gazaliev, A. M., Kabieva, S. K., Fedorchenko, V. I., Guba, G. Y., Smetanina, E. I., ... & Gulyaev, R. O. (2015). Polymerization of lactic acid using microwave and conventional heating. *Procedia Chemistry, 15*, 97-102.
8. Brown, et al. (2012). Obtención de Biomateriales derivados de Ácido Láctico empleando métodos no convencionales de síntesis. *Instituto Cubano de Investigaciones de los Derivados de la Caña de Azúcar, 46*(3), 12 – 20.
9. Cao, H. L., Wang, P., & Yuan, W. B. (2009). Microwave-Assisted Synthesis of Poly (L-lactic acid) via Direct Melt Polycondensation Using Solid Super-Acids. *Macromolecular Chemistry and Physics, 210*(23), 2058-2062.
10. Chafran, L. S., Paiva, M. F., França, J. O., Sales, M. J. A., Dias, S. C., & Dias, J. A. (2019). Preparation of PLA blends by polycondensation of D, L-lactic acid using supported 12-tungstophosphoric acid as a heterogeneous catalyst. *Heliyon, 5*(5), e01810.
11. Chen, H., Chen, B., Su, Z., Wang, K., Wang, B., Wang, Y., ... & Qin, P. (2020). Efficient lactic acid production from cassava bagasse by mixed culture of Bacillus coagulans and lactobacillus rhamnosus using stepwise pH controlled simultaneous saccharification and co-fermentation. *Industrial Crops and Products, 146*, 112175.
12. Chen, H., Huo, W., Wang, B., Wang, Y., Wen, H., Cai, D., ... & Qin, P. (2019). L-lactic acid production by simultaneous saccharification and fermentation of dilute ethylediamine pre-treated rice straw. *Industrial Crops and Products, 141*, 111749.

13. De la Torre, I., Acedos, M. G., Ladero, M., & Santos, V. E. (2019). On the use of resting L. delbrueckii spp. delbrueckii cells for D-lactic acid production from orange peel wastes hydrolysates. *Biochemical Engineering Journal*, *145*, 162-169.
14. De la Torre, I., Ladero, M., & Santos, V. E. (2018). Production of D-lactic acid by Lactobacillus delbrueckii ssp. delbrueckii from orange peel waste: techno-economical assessment of nitrogen sources. *Applied microbiology and biotechnology*, *102*(24), 10511-10521.
15. De Oliveira, J. (2016). *Poly (Lactic acid) production by conventional and microwave polymerization of lactic acid produced in submerged fermentation (Doctoral thesis)*. Federal University of Parana.
16. Di Martino, A., Kucharczyk, P., Zednik, J., & Sedlarik, V. (2015). Chitosan grafted low molecular weight polylactic acid for protein encapsulation and burst effect reduction. International journal of pharmaceutics, 496(2), 912–921. Recovered from https://doi.org/10.1016/j.ijpharm.2015.10.017
17. Díaz, A. B., González, C., Marzo, C., Caro, I., & Blandino, A. (2020). Feasibility of exhausted sugar beet pulp as raw material for lactic acid production. *Journal of the Science of Food and Agriculture*, *100*(7), 3036-3045.
18. Dietz, D., Schneider, R., Papendiek, F., & Venus, J. (2016). Leguminose green juice as an efficient nutrient for l (+)-lactic acid production. *Journal of biotechnology*, *236*, 26-34.
19. Dubey, S. P., Abhyankar, H. A., Marchante, V., Brighton, J. L., Bergmann, B., Trinh, G., & David, C. (2017). Microwave energy assisted synthesis of poly lactic acid via continuous reactive extrusion: modelling of reaction kinetics. *RSC advances*, *7*(30), 18529-18538.
20. ECODES. (2019). *El plástico y la salud. El coste oculto de un planeta plástico*. Obtenido de Fundación Ecología y Desarrollo.
21. Estupiñan Duran, H., Parada, D., Laverde, D., Peña B., D., & Vásquez Q., C. (2007). Obtención de ácido poli l-láctico mediante policondensación con catalizador de cinc metálico. *Scientia Et Technica*, *1*(36). Recovered from https://doi.org/10.22517/23447214.4913
22. European Bioplastics European Bioplastics Association (2019). *Capacidad de producción Global de Bioplásticos*.
23. Guba, G., Gusar, A., Bakibayev, A., Tazhbayev, Y., & Minayeva, Y. (2019). Dehydration/polycondensation of lactic acid under microwave irradiation. Bulletin of the Karaganda university. *Chemistry series*, *1*(93), 8-16.
24. Guzman, A., & Arana, L. Síntesis y caracterización del ácido poliláctico (PLA) mediante policondensación asistida por radiación microondas a partir de ácido L-láctico comercial. *Revista Peruana de Química e Ingeniería Química*, *18*(1), 37-44.
25. Hama, S., Mizuno, S., Kihara, M., Tanaka, T., Ogino, C., Noda, H., & Kondo, A. (2015). Production of D-lactic acid from hardwood pulp by mechanical milling followed by simultaneous saccharification and fermentation using metabolically engineered Lactobacillus plantarum. *Bioresource technology*, *187*, 167-172.
26. Huang, W., Cheng, N., Qi, Y., Zhang, T., Jiang, W., Li, H., & Zhang, Q. (2014). Synthesis of high molecular weight poly (L-lactic acid) and poly (D-lactic acid) with improved thermal stability via melt/solid polycondensation catalyzed by biogenic creatinine. *Polymer*, *55*(6), 1491-1496.
27. Jiménez-Bonilla, P., Salas-Arias, J., Esquivel, M., & Vega-Baudrit, J. R. (2014). Optimization of microwave-assisted and conventional heating comparative synthesis of poly (lactic acid) by direct melt polycondensation from agroindustrial banana (musa AAA cavendish) and pineapple (ananas comosus) fermented wastes. *Journal of Polymers and the Environment*, *22*(3), 393-397.

28. Jing, S., Peng, W., Yingmin, Z., & Xiaojuan, M. (2006). Rapid melt polycondensation of L-lactic acid under microwave irradiation. *Macromolecular research*, *14*(6), 659-662.
29. Kasirajan, et al. (2019). Preparación de poli (ácido láctico) a partir de Prosopis juliflora e incorporación de quitosano para aplicaciones de envasado. *Journal of Bioscience and Bioengineering*, *128*(3), 323e331.
30. Kéki, S., Bodnár, I., Borda, J., Deák, G., & Zsuga, M. (2001). Fast Microwave-Mediated Bulk Polycondensation of d, l-Lactic Acid. *Macromolecular Rapid Communications*, *22*(13), 1063-1065.
31. Koekemoer, T. (2018). *Lactic acid production from sugarcane bagasse and harvesting residues* (Doctoral dissertation), Stellenbosch: Stellenbosch University.
32. Kunasundari, B., Naresh, S., & Chu, J. E. (2017, September). *Lactic acid production from xylose by Geobacillus stearothermophilus strain 15*. In AIP Conference Proceedings, 1885(1), 020104. AIP Publishing LLC.
33. Kwan, T. H., Hu, Y., & Lin, C. S. (2016). Valorisation of food waste via fungal hydrolysis and lactic acid fermentation with Lactobacillus casei Shirota. *Bioresource technology*, *217*, 129–136. https://doi.org/10.1016/j.biortech.2016.01.134
34. Labeaga Viteri, Aitziber. (2018). *Polímeros biodegradables. Importancia y potenciales aplicaciones Master Thesis, Universidad Nacional de Educación a Distancia (España)*. Facultad de Ciencias. Departamento de Química Inorgánica e Ingeniería Química.
35. Liu, J., Cai, Y., Liu, L., Zhan, R., Zhao, S., Liang, Y., ... & Hu, G. (2020). Enhanced lactic acid production by Bacillus coagulans through simultaneous saccharification, biodetoxification, and fermentation. *Biofuels, Bioproducts and Biorefining*, *14*(3), 533-543.
36. López-Gómez, J. P., Alexandri, M., Schneider, R., Latorre-Sánchez, M., Lozano, C. C., & Venus, J. (2020). Organic fraction of municipal solid waste for the production of L-lactic acid with high optical purity. *Journal of Cleaner Production*, *247*, 119-165.
37. Lopretti, M. (2017). *Plásticos biodegradables. Una oportunidad de mercado*. Recovered from http://www.ciu.com.uy/innovaportal/file/82560/1/biopolimeros.pdf
38. Macías, R.Y. (2011). *Modificación superficial de mwcnts a partir de la síntesis de nylon-6 asistida por microondas*. Centro de Investigación en Química Aplicada.
39. Medina, J., Cedeno, P., Heras, R., Hernández, J., & Zapata, C. (2018). Mechanical behavior of mixtures of polylactic acid (PLA) with polystyrene (PS). *Revista Ingeniería UC*, *25*(2), 187-188.
40. Montañez, Peña & Estupiñán (2015). Respuesta dieléctrica y bioquímica de un recubrimiento PLA-PGA-HAp-Quitosano-Colágeno sobre Ti6Al4V. de Ingeniare. *Revista chilena de ingeniería*, *24*(2), 215-227.
41. Munilla, M. H., & Carracedo, G. B. (2005). Ácido láctico y poliláctico: Situación actual y tendencias. ICIDCA. *Sobre los Derivados de la Caña de Azúcar*, *39*(1), 49-59.
42. Nagahata, R., Sano, D., Suzuki, H., & Takeuchi, K. (2007). Microwave-Assisted Single-Step Synthesis of Poly (lactic acid) by Direct Polycondensation of Lactic Acid. *Macromolecular rapid communications*, *28*(4), 437-442.
43. Nakamura, T., Nagahata, R., Kunii, K., Soga, H., Sugimoto, S., & Takeuchi, K. (2010). Large-scale polycondensation of lactic acid using microwave batch reactors. *Organic Process Research & Development*, *14*(4), 781-786.
44. Nikolic, L., Ristic, I., Adnadjevic, B., Nikolic, V., Jovanovic, J., & Stankovic, M. (2010). Novel microwave-assisted synthesis of poly(D,L-lactide): the influence of monomer/initiator molar ratio on the product properties. *Sensors (Basel, Switzerland)*, *10*(5), 5063–5073. Recovered from https://doi.org/10.3390/s100505063

45. Nuñez, M. (2019). *Planta de producción de ácido poliláctico (PLA) a partir de ácido láctico*. Universidad de Sevilla, Sevilla, España.
46. Ong, S. A., Ng, Z. J., & Wu, J. C. (2016). Production of high concentration of l-lactic acid from cellobiose by thermophilic Bacillus coagulans WCP10-4. *Applied microbiology and biotechnology*, *100*(14), 6501-6508.
47. Pandey & Aswath (2008). Síntesis de microondas de Poli (Ácido L - Láctico). *Journal of Biomaterials Science*, *20*(1), 33-48.
48. Pleissner, D., Demichelis, F., Mariano, S., Fiore, S., Gutiérrez, I. M. N., Schneider, R., & Venus, J. (2017). Direct production of lactic acid based on simultaneous saccharification and fermentation of mixed restaurant food waste. *Journal of Cleaner Production*, *143*, 615-623.
49. Pleissner, D., Neu, A. K., Mehlmann, K., Schneider, R., Puerta-Quintero, G. I., & Venus, J. (2016). Fermentative lactic acid production from coffee pulp hydrolysate using Bacillus coagulans at laboratory and pilot scales. *Bioresource Technology*, *218*, 167-173.
50. Prieto Lozano, G. A., & Torres Rodriguez, Y. (2020). *Desarrollo de un proceso de fermentación en estado sólido (SSF) para la obtención de proteínas durante la valorización de residuos orgánicos en biorreactores a escala laboratorio*. Universidad Cooperativa de Colombia. Bogotá D.C.
51. Radosavljević, M., Pejin, J., Pribić, M., Kocić-Tanackov, S., Romanić, R., Mladenović, D., Djukić-Vuković, A., & Mojović, L. (2019). Utilization of brewing and malting by-products as carrier and raw materials in l-(+)-lactic acid production and feed application. *Applied microbiology and biotechnology*, *103*(7), 3001–3013. Recovered from https://doi.org/10.1007/s00253-019-09683-5
52. Serna, L., & Albán, F. (2003). Ácido poliláctico (PLA): Propiedades y aplicaciones. *Ingeniería y competitividad*, *5*(1), 16-26.
53. Song, F., & Wu, L. (2011). Synthesis of high molecular weight poly (L-lactic acid) via melt/solid polycondensation: Intensification of dehydration and oligomerization during melt polycondensation. *Journal of applied polymer science*, *120*(5), 2780-2785.
54. Sosnik, A., & Gotelli, G. (2015). *Aplicaciones de la tecnología de radiación de microondas en la síntesis de biomateriales*. Recovered from http://hdl. handle. net/10316.2/36860.
55. Takenaka, M., Kimura, Y., & Ohara, H. (2018). Influence of decomposition temperature of aromatic sulfonic acid catalysts on the molecular weight and thermal stability of poly (L-lactic acid) prepared by melt/solid state polycondenstaion. *Polymer*, *155*, 218-224.
56. Tejada, R. (2015). *Obtención de ácido láctico por fermentación de almidón del Ñame Espino para su uso en la producción de ácido poliláctico.* Universidad Nacional de Colombia, Medellín.
57. Temur Ergan, B., & Bayramoğlu, M. (2018). Poly (l-lactic acid) synthesis using continuous microwave irradiation–simultaneous cooling method. *Chemical Engineering Communications*, *205*(12), 1665-1677.
58. Trakarnpaiboon, S., Srisuk, N., Piyachomkwan, K., Yang, S. T., & Kitpreechavanich, V. (2017). L-Lactic acid production from liquefied cassava starch by thermotolerant Rhizopus microsporus: characterization and optimization. *Process Biochemistry*, *63*, 26-34.
59. Van der Pol, E. C., Eggink, G., & Weusthuis, R. A. (2016). Production of L (+)-lactic acid from acid pretreated sugarcane bagasse using Bacillus coagulans DSM2314 in a simultaneous saccharification and fermentation strategy. *Biotechnology for biofuels*, *9*(1), 1-12.

60. Vargas, S. (2002). *Síntesis y caracterización de polímeros biodegradables preparados a base de ácido láctico*. Universidad de los Andes, Bogotá D.C.
61. Wang, J., Gao, M., Liu, J., Wang, Q., Wang, C., Yin, Z., & Wu, C. (2017). Lactic acid production from Sophora flavescens residues pretreated with sodium hydroxide: Reutilization of the pretreated liquor during fermentation. *Bioresource technology, 241*, 915-921.
62. Wang, Y., Cao, W., Luo, J., Qi, B., & Wan, Y. (2019). One step open fermentation for lactic acid production from inedible starchy biomass by thermophilic Bacillus coagulans IPE22. Bioresource technology, 272, 398-406.
63. Wang, Y., Chen, C., Cai, D., Wang, Z., Qin, P., & Tan, T. (2016). The optimization of L-lactic acid production from sweet sorghum juice by mixed fermentation of Bacillus coagulans and Lactobacillus rhamnosus under unsterile conditions. *Bioresource technology, 218*, 1098-1105.
64. Whulanza, Y., Rahman, S. F., Suyono, E. A., Yohda, M., & Gozan, M. (2018). Use of Candida rugosa lipase as a biocatalyst for L-lactide ring-opening polymerization and polylactic acid production. *Biocatalysis and agricultural biotechnology, 16*, 683-691.
65. Yamada, S., Takasu, A., Takayama, S., & Kawamura, K. (2014). Microwave-assisted solution polycondensation of L-lactic acid using a Dean–Stark apparatus for a non-thermal microwave polymerization effect induced by the electric field. *Polymer Chemistry, 5*(18), 5283-5288.
66. Zaini, N. A. B. M., Chatzifragkou, A., & Charalampopoulos, D. (2019). Microbial production of d-lactic acid from dried distiller's grains with solubles. *Engineering in Life Sciences, 19*(1), 21-30.