One-step synthesis of L- Lactide from Lactic acid using a heterogeneous catalyst

A Thesis

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By

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Certificate

This is to certify that this dissertation entitled “**One step synthesis of L-Lactide from Lactic acid using a heterogeneous catalyst”** towards the partial fulfilment of the BSMS dual degree programme at the Indian Institute of Science Education and Research, Pune represents work carried out by **Rajesh Kumar Meena** at the Praj Matrix, Pune under the supervision of **Dr. Mangesh Kulkarni**, Praj Matrix, Pune, during the academic year 2022-2023.

Student's signature

Date: 30/05/2023

Supervisor's signature

Date: 26/05/2023

Declaration

I hereby declare that the matter embodied in the report entitled "**One step synthesis of L-Lactide from Lactic acid using a heterogeneous catalyst**" is the result of the work carried out by me at the Praj Matrix, Pune, under the supervision of **Dr. Mangesh Kulkarni** and the same has not been submitted elsewhere for any other degree.

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Date: 30/05/2023

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List of Abbreviation

PLA	Poly (Lactic acid)
LA	Lactic acid
ROP	Ring opening polymerization
L2A	Lactic acid dimer
L3A	Lactic acid trimer
HMW	High molecular weight
LMW	Low molecular weight
PLLA	Poly L-Lactic acid
CCA	Chain coupling agent
LT	Lactide
MP	Melting point
HPLC	High pressure liquid chromatography

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Chapter 1.

Introduction

1. Introduction

The long-term approach to reduce the harmful environmental effects of plastic pollution, as illustrated by the marine accumulation of inert microplastics, includes the development of biodegradable plastics (1,2). Bioplastics made from natural plants have recently received much interest from the perspectives of reusability and climate change. Two main factors influencing the hunt for biodegradable and renewable materials are limited availability of fossil fuels and plastic waste in our oceans (3). The most common synthetic bio-based plastic on the market is polylactic acid (PLA), (4) which has many uses. Biomedical and chemical products also frequently use polylactic acid which is regarded as a representative bio-based, biodegradable polymer in packaging, textiles, coatings, and biomedicine (3).

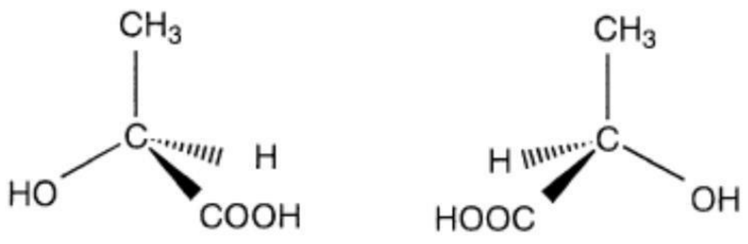
The global PLA market was estimated to be around 360,800 tonnes in 2013 and in 2020 it is predicted to expand by 18.8% to reach over 1.2 million tonnes. The majority of PLA manufactured now is used in packaging for single-use purposes. But the academic community and business sector views demonstrate that PLA can also be used in more robust applications. PLA also has the potential to replace conventional polymers made from fossil fuels with renewable and biodegradable materials, PLA offers intriguing properties that make it appropriate for specialized applications. PLAbased materials are ideally suited for biomedical in vivo applications such as bone fixations, tissue engineering, and drug delivery systems because of their biocompatibility (5). But due to its high manufacturing and feedstock costs, megatonscale PLA production lacks a reliable economic driver despite life-cycle analyses showing that it has a favorable environmental impact (4).

1.1 Lactic Acid (LA)

Lactic acid (LA) is the most commonly active hydroxycarboxylic acid. It was the first time discovered in 1780 by the Swedish chemist Scheele. The production of LA (a naturally occurring organic acid) can be done by chemical synthesis or fermentation. It is found in many foods, especially dairy products. LA is also a primary intermediate metabolite in most organisms, from anaerobic prokaryotes to mammals such as humans. Its main chemical properties are provided in below table. (6)

Table 1. Properties of Lactic acid

Properties		Value
Molecular weight (Da)		90.098
Melting point	(D(-) or L(+))	52.8 - 54°C
	(DL)	16.8 - 33°C
Boiling point DL	(0.5 mmHg)	82°C
	(14 mmHg)	122°C
Dissociation constant (K_a at 25°C)		1.37×10^{-4}
Heat of combustion (H_c)		1361 KJ.mol^{-1}
Specific heat (C_p at 20°C)		190 J.mol^{-1}°C^{-1}



L-Lactic acid **D-Lactic acid**

Figure 1. Isomers of Lactic Acid

Lactic acid exists in two optically active forms (L-Lactic acid and D-Lactic acid), and LLactic acid is more common than other as LA derived from fermentation is 99.5% L isomer. Thermal, mechanical and the biodegradation properties of Lactic acid polymers depend on the concentration of stereoisomers in the initial mixture which are used for the polymerization. Use high purity L or D isomer produces stereo isotropic polymers with properties superior compare to those of polymers which are produced from Lactic acid of meso-isomer purity or less.

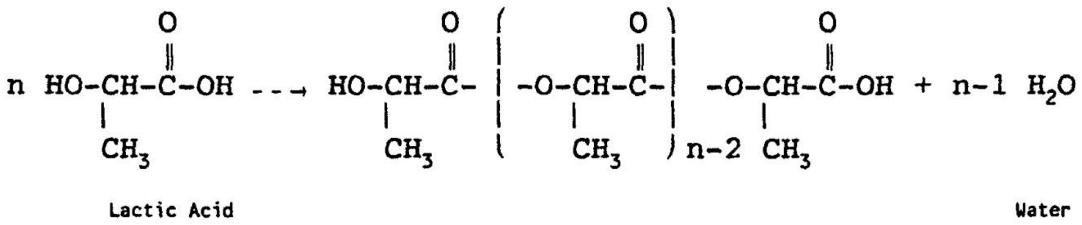
1.2 PLA Synthesis

Currently, renewable sugars are fermented anaerobically to produce aqueous L- Lactic acid (LA), which is the starting point for PLA synthesis. Low molecular weight PLA (LMW) synthesis has been documented since 1932 [7]. It has poor qualities and serves no use in the most of PLA applications. As a result, novel methods for producing a high molecular weight (HMW) polymer, with more commercial and industrial appeal, were discovered. There are generally two process for PLA synthesis.

- Polycondensation process
- Ring opening polymerization of Lactide

1.2.1 Polycondensation Process

As we can see foundation of PLA is LA, and LA is a platform molecule with great potential derived from biomass. Dehydro-polycondensation of LA is a method of making PLA because LA contains both the a-hydroxyl and carboxyl functions (8). Good point of this polymerization is that majority of this polymerization is done without the use of a solvent, but for remove water from the aqueous feedstock and to speed up the condensation process we need high temperatures and vacuum (9). Since water removal in the later phase is difficult due to the growing viscosity of the polymer melt, equilibrium problems are the limiting factor in this kind of polymer synthesis. There are also unintended consequences, like intramolecular transesterifications within polymer chains. Another issue in this polycondensation process in stereo irregularities in the polymer and inferior or undesirable properties racemization [the conversion of L-Lactic acid (LA) into D-Lactic acid during the process [when PLLA is targeted from pure LLA]] (10).



$$n\ HO\text{-}\underset{CH_3}{\underset{|}{CH}}\text{-}\overset{O}{\overset{\|}{C}}\text{-}OH \dashrightarrow HO\text{-}\underset{CH_3}{\underset{|}{CH}}\text{-}\overset{O}{\overset{\|}{C}}\text{-}\left(\text{-}O\text{-}\underset{CH_3}{\underset{|}{CH}}\text{-}\overset{O}{\overset{\|}{C}}\text{-}\right)_{n-2}\text{-}O\text{-}\underset{CH_3}{\underset{|}{CH}}\text{-}\overset{O}{\overset{\|}{C}}\text{-}OH + n-1\ H_2O$$

Figure 2 . PLA polycondensation reaction

Chen et al. were able to synthesize PLA through polycondensation with a molecular weight as high as 130,000 g/mol by continuously lowering the pressure in a controlled way (11). The molecular weight of the polymer can be increased by using a Bronsted acid co-catalyst in liquid polycondensation. Another method for producing PLA via polycondensation is use of a fluid and a soluble (mostly Lewis acid) catalyst, such as $SnCl_2$, Sn(octanoate), and other catalysts such scandium(III) trifluoromethanesulfonate and scandium (III) trifluoromethanesulfonimide [$Sc(OTf)_3$, $Sc(NTf)_3$. Racemization also can be reduced by removing water under milder circumstances, but this has been shown to be solvent and catalyst dependent reaction. A molecular sieve can also be used to separate small fractions of dissolved water in the organic phase, while azeotropic distillation is used to remove water during such reactions. Mostly LA polycondensation reactions show that maximum molecular weight of PLA that can be synthesized by this methos is around 30,000 g/mol (11).

These illustrations show that there are numerous drawbacks of the polycondensation approach to PLA. Additionally, we can see that good quality PLA with a controlled molecular weight, high optical purity, and low polydispersity cannot be obtained through this process.

1.2.2 Ring opening polymerization of Lactide

Current industrial process to synthesis PLA from LA is done with intermediate compound (Lactide). First LA is converted into Lactide then PLA is synthesized by ring opening polymerization of Lactide.

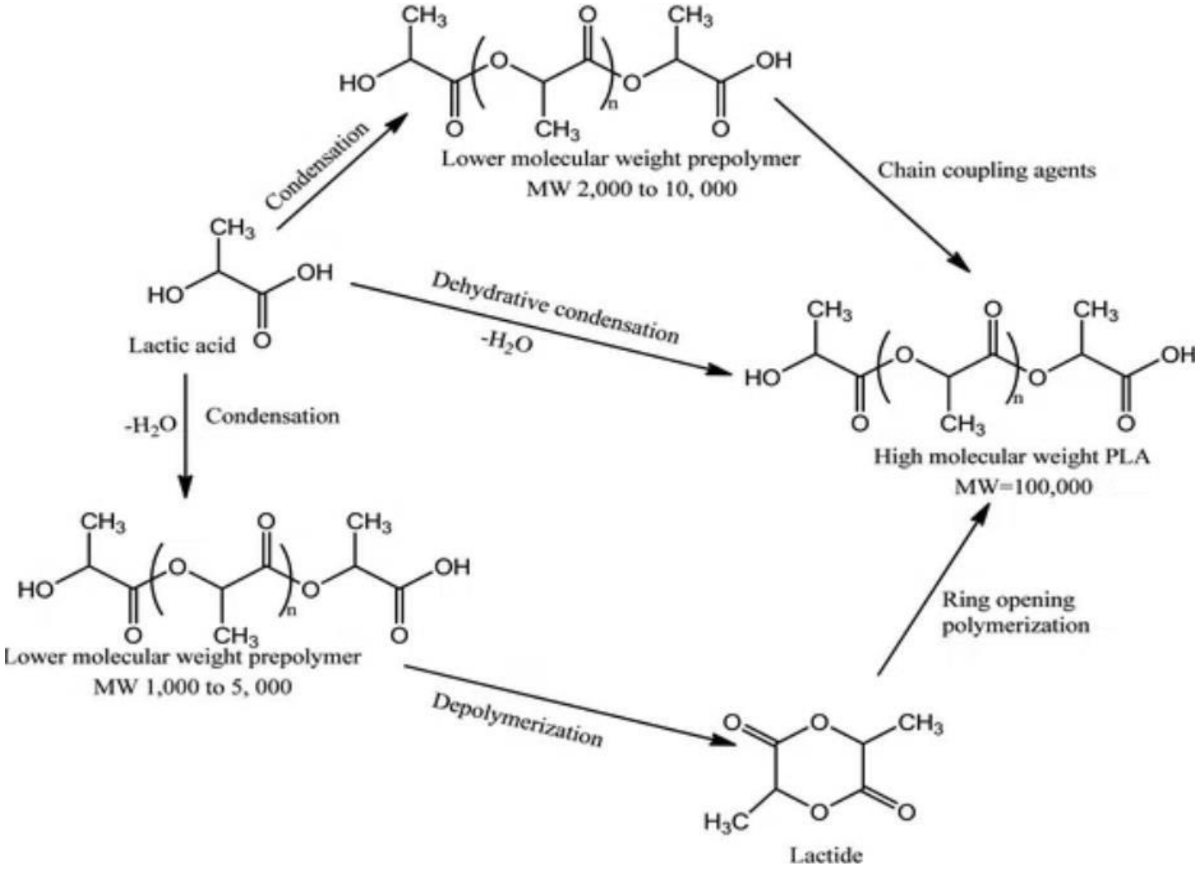


Figure 3. Synthesis method for high molecular weight PLA

And approximately 50% of the total cost of synthesizing PLA, including the cost of the feedstock, is spend on the process of creating LA. Only 20% of the overall cost is attributable to the polymerization step with 30% of the cost of PLA ,spend on making Lactide from LA (11).

1.3 Lactide

Lactide is a cyclic ester which is required for high-molar mass PLA synthesis. Lactide is 3,6-dimethyl-1,4-dioxane-2,5-dione. The LT, a chiral molecule originally generated from Lactic acid, has two stereo centers and two enantiomers, L and D-Lactide (melting point (MP): 97 °C), in addition to its meso-Lactide (MP: 53 °C) and racemic mixture (MP: 125 °C), racemic mixture with an MP of 125 °C. Physical properties of Lactide are shown in table 2 (15).

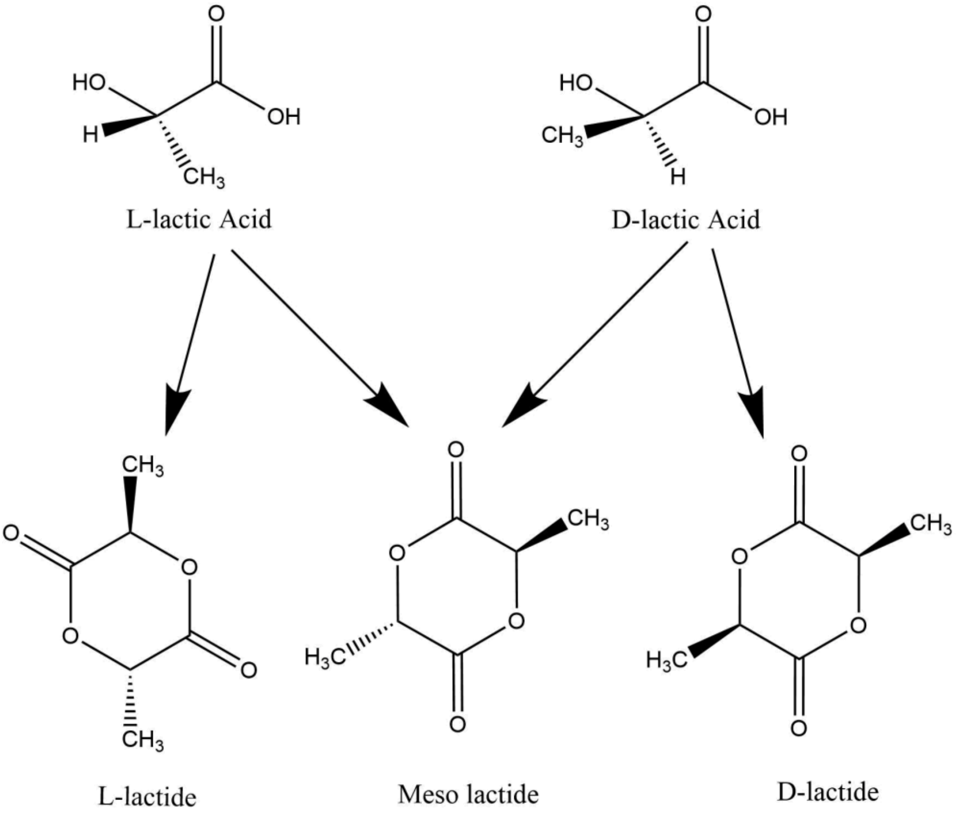


Figure 4. Stereoisomers of Lactide

This product's commercial relevance and rising demand make it very strong. The final polymer's characteristics are determined by the isomerism of the produced Lactide, which is controlled by the Lactic acid optical activity. (15)

Table 2. Properties of Lactide

Physical properties	L-Lactide	D-Lactide	Meso-Lactide
Molecular weight (g/mol)	144.12	144.12	144.12
Optical rotation in degrees	- 260	+ 260	-
Appearance	White crystals	White crystals	-
Melting point (°C)	95-100	95-100	53-54
Boiling point (°C)	255	-	-

1.3.1 Lactide Production

Currently there are generally three methods mentioned in literature for synthesize Lactide from LA.

- Industrial scale process (ROP process)
- Lactide production in gas phase using a solid catalyst bed
- One-step liquid-phase conversion of LA to Lactide

1.3.1.1 Industrial scale process (ROP process)

In present two-stage method for creating Lactide from LA first we have to do polymerization of LA to create oligo-PLA (Mw -3000 Da) through self-catalysis. Then in next step we do depolymerization of oligo-PLA into Lactide through a back-biting mechanism in the presence of a metal catalyst (16). This catalyst could be a salt or an oxide of Tin or Zinc. The first catalyst which was used for backbiting phase was ZnO. Then Sn dust was used in 1959 publication. It turned out to be a better catalyst and produced less racemization. Sn compounds, particularly Stannous octoate and SnO, continue to be the standard examples of the backbiting catalyst and are commonly used in patents and articles due to their high activity and solubility in the polymer mass (11). While Tin (II)-based compounds, such as SnCl2, SnOct2, and others, are considered the most effective catalyst for lactide synthesis.

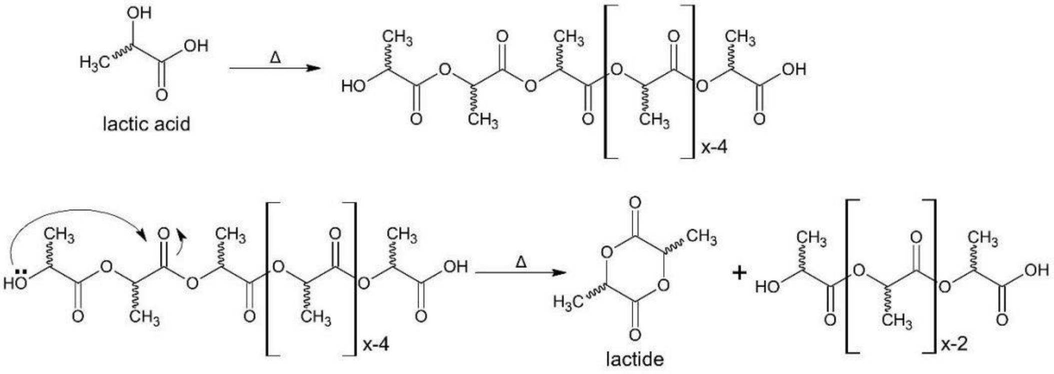


Figure 5. Back bitting reaction

But there were some issues in this process-

- Lactide must be quickly removed from the reaction solution to prevent the thermodynamically preferred reverse reaction.
- Removing water and Lactide from the system becomes challenging because the substrate's viscosity progressively rises as the reaction progresses.
- Therefore, to remove both the water and the Lactide, both stages of Lactide synthesis are carried out for a long time at high temperatures and vacuum.
- These processes need a lot of time and energy because they depend on high temperatures and vacuum.
- Selectivity to L-Lactide is major challenge as there is possibility of formation racemization which produces undesirable D, L-Lactide.
- Oligo-PLA polymerization produces polymeric waste residue.
- Catalyst used in lactide synthesis can’t be reused because it is difficult to separate the catalyst from the waste residue.

In the current industrial process, there are lot of challenges as listed above. Recently a new method for synthesize lactide is reported in which Lactide is directly produced from L-Lactic acid in single step using heterogeneous catalysts.

1.3.1.2 One-step process by heterogeneous catalysts

As there are many issues in two step industrial process so there was urgent need of an alternative process for synthesize of Lactide. Dusselier et al. published a paper in which an aqueous LA solution mixed in toluene or *o*-xylene was converted into Lactide (purity > 98%) with the help of the H-beta zeolite catalyst. The zeolite catalyst was then recycled using calcination (4).

Another paper of Zhang et al. showed that H-beta zeolite can convert high concentrations of LA into Lactide with a 74% yield and a low Si/Al ratio (Si/Al = 15.5). Tin based catalysts are most effective catalysts for the synthesis of Lactide and Polylactic acid (17).

In this process water removal occurs during the ring-closing reaction and Lactide is produced immediately from LA via condensation. In this method reactive distillation concept is used remove water, using a reaction solvent and heterogeneous catalyst. Undesirable meso-lactide isomer also not formed in this process. Exact catalyst activity in this process is yet not known (11).

Difference between reaction mechanism of current industrial process and this one step process in shown in figure 6.

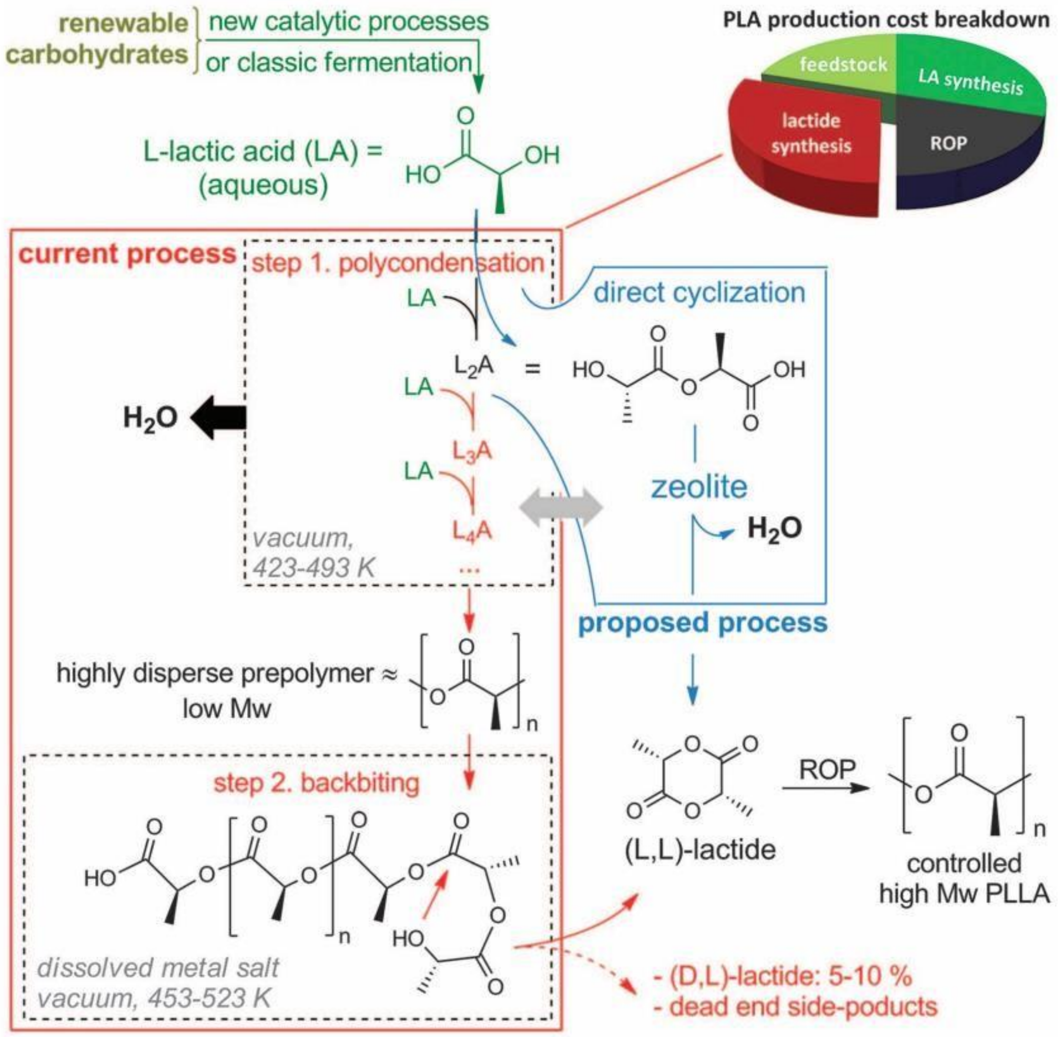


Figure 6. Current back-bitting process (in red box) and one step process (in blue box) (4)

Chemical and reaction pathway is in figure 7 and 8.

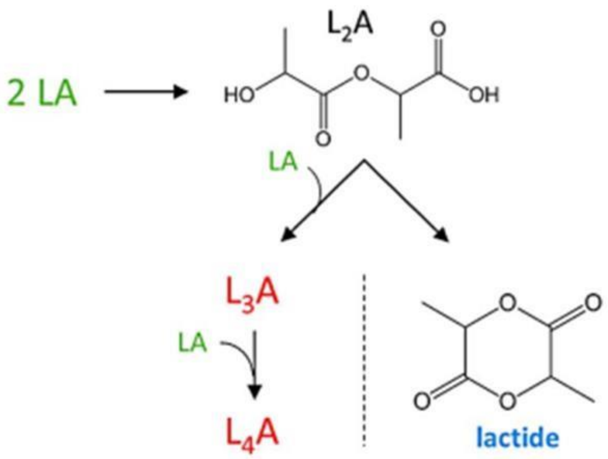


Figure 7. Chemical pathway in one step process (4)

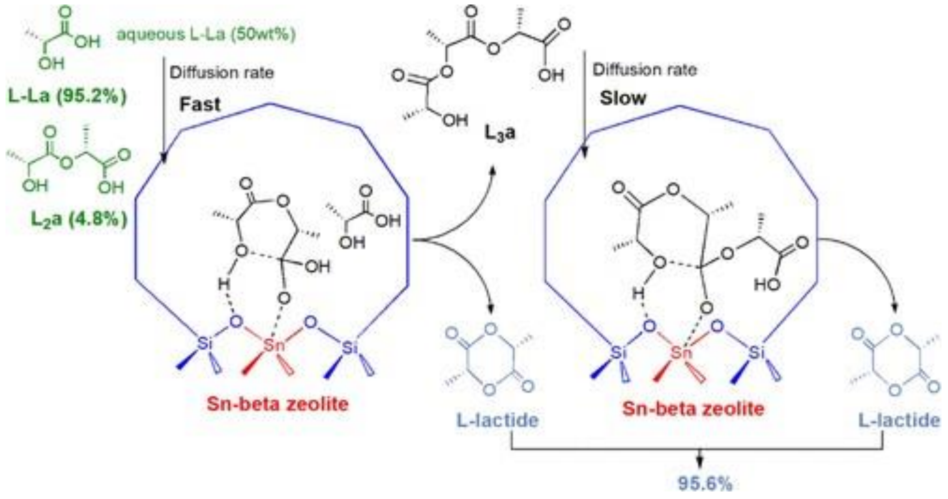


Figure 8. Reaction pathway from L-LA to Lactide reproduced (16)

Reaction pathway L-LA was first converted into a Lactic acid dimer (L_2A) and then formed L-Lactide catalysed by a Sn-beta zeolite, and the average reaction rate in first 20 min increased linearly with increasing Sn content. Importantly, Lactic acid trimers (L_3A) formed during the reaction could also be converted to L-Lactide in the later stage of the reaction, and the diffusion of L_3A to the active site within the Sn-beta zeolite pore is the rate-limiting step (figure 8).

Why this process -

One of the best point of this heterogeneously catalysed process is that catalyst is reusable in this process. Zeolites will go through calcination and displayed no loss of activity or selectivity in both productive and early (kinetic) conditions.

Immediately after complete of reaction a water/solvent liquid-liquid extraction step will done in which short oligomer side products (L_2A, L_3A, L_4A) and unreacted LA are separated from reaction mixture. These separated oligomers can be hydrolysed and recycled.

In next step solvent removal by evaporation will make Lactide to spontaneously crystallise and solvent will be recovered (4,11).

In this process solvent, catalyst, oligomers can be recovered and this method also take less energy and time input compared to traditional methods to produce Lactide.

1.3.1.3 Gas phase synthesis

The "gas-phase synthesis of Lactide," a catalytic process that uses an inert carrier gas stream to evaporate and react LA over a (plug-flow) catalyst bed. SnO and other metal oxides from groups III, IV, V, or VIII are suggested as catalysts, while high-SiO_2content SiO_2-Al_2O_3 materials are also appropriate. Faster response times that subsequently decrease degradation as well as racemization reactions are one of the key advantages of this process. Due to the fact that this gas-phase process runs at atmospheric pressures rather than extremely low pressures, investment costs are predicted to be lower compared to the two-step process. Even though this process has low racemization percentages and extremely high yields (between 70 and 90 percent), the observed volumetric productivities are too low to be taken seriously as a potential alternative method.

1.4 Aim of work

Industrial Lactide synthesis is done by a procedure that uses a lot of energy. A more economically and environmentally advantageous technique is required, as demonstrated by the recent increase in patent filings with various ways for alternative lactide manufacturing processes. The present industrial two-step method's primary drawbacks are racemization, poor selectivity with high energy expenditures.

One step gas phase lactide synthesis process using heterogeneous catalyst has advantages in terms of lower racemization percentages and large yields. However, the volumetric production is relatively poor since the feed is heavily diluted in an inert gas stream. Racemization is avoided mostly by mild conditions and also the characteristics of the catalysts in the most current one-step liquid phase technique, which appears to combine the very best of both by producing high yields and extremely high productivities.

Removal of water and lactide formation take place during the same stage in both the one-step liquid method and gas-phase synthesis. The one-step liquid-phase process appears intriguing in this regard because it requires little energy input. This method can be an alternative to the traditional Lactide production process (Industrial ROP process). Following the literature works introduced previously, it can be concluded that Lactide (LT) production from Lactic acid using a heterogeneous catalyst in liquid phase is a really good process compared to conventional method (15). Reaction temperature, catalyst and solvent represent key parameters in this one step LT production process. Those parameters must be optimized in order to achieve high LT conversion minimizing racemization.

In the present work, main goals are applying this process and screening different parameters and different factors effecting lactide purity and try to get an optimal condition to produce Lactide with good purity. Effect of various parameters such as LA concentration, type of solvent and catalyst type are studied in details.

Chapter 2

Experimental section

2. Materials and Methods

2.1 Materials:

Commercial catalysts (**Zeolite 1, Zeolite 2, Zeolite 3**, **Zeolite 4, Zeolite 5**) were chosen as catalysts for Lactide synthesis. More information about catalysts is in below Table 3. 88% L-Lactic acid was procured from Henan Jindan, China solutions and 50 and 20 wt% Lactic acid were made by dilution. Xylene and Toluene were obtained from

Thermo fisher Scientific India Pvt. Limited and were used as received.

Table 3. Name of catalysts with their composition

Zeolite 1	This catalyst is mixture of Sn and Si
Zeolite 2	This catalyst is mixture of Sn and Cs
Zeolite 3	This catalyst is mixture of K and Zr
Zeolite 4	This catalyst is mixture of K and Sn
Zeolite 5	This catalyst is mixture of K and Sn with different ratio

2.2 Procedure

250 ml round-bottom flask equipped with Dean-Stark apparatus, reflux condenser and magnetic needle bar, L-Lactic acid (6 grams, 88% concentrated), Zeolite 1 catalyst (2 grams), Toluene (120 mL) was charged. The reaction was refluxed for 4 h time.

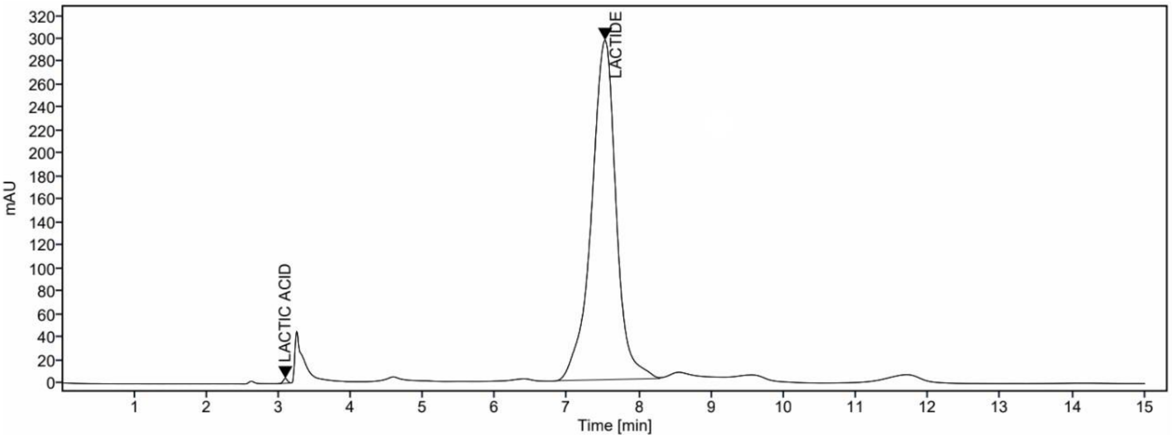
The reaction mixture contains the (solid) catalysts, the reflux solvent, Lactide, Lactic acid and linear oligomers of Lactic acid. After reaction completion reaction mixture was kept for 10 min to cooling. Solid catalyst was removed by filtration and then -washed with acetone for extraction of adsorbed organic species. Reaction mixture was kept in a separating funnel to separate in two phases. Upper layer contains solvent and crude Lactide while lower layer contains oligomers. Both layers were separated and lower layer which contains oligomers was given for analysis after removal of solvent traces. Upper layer which contain solvent and crude Lactide was put on rota equator to evaporate solvent (so it can be reuse) and Lactide was given to analysis. Purity of

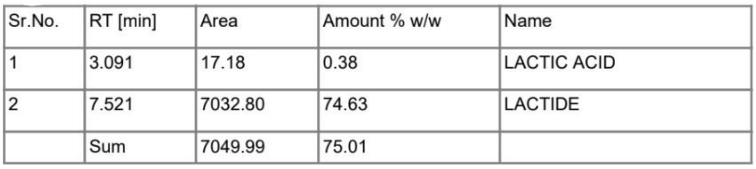
Lactide was measured by HPLC technique. Same procedure was performed for screening of different Lactic acid concentrations (20%, 50%, 88%), different catalysts (**Zeolite 1, Zeolite 2, Zeolite 3, Zeolite 4, Zeolite 5**), different reaction time periods (120min, 180min, and 240 min), different solvents (Toluene, Xylene), different catalyst ratio.

Analytical protocol - Analysis of Lactide sample was performed by HPLC technique.

Column conditions: Flow rate = 1.04ml/min
Column Temperature = 40^{0}C
UV detection wavelength = 210 nm
Injected volume = 20 micro/litre

0.1 gm sample was mixed in 10 ml ACN then this mixture was filtered and injected on HPLC for Lactide analysis.





Sr.No.	RT [min]	Area	Amount % w/w	Name
1	3.091	17.18	0.38	LACTIC ACID
2	7.521	7032.80	74.63	LACTIDE
	Sum	7049.99	75.01	

Figure 9. HPLC graph of Lactide synthesis using Zeolite 1

Peak of Lactic acid was observed at 3 min (retention time) while for Lactide, peak retention time was 7.5 min.

Reaction Setup –

Solvent

Phase Separator

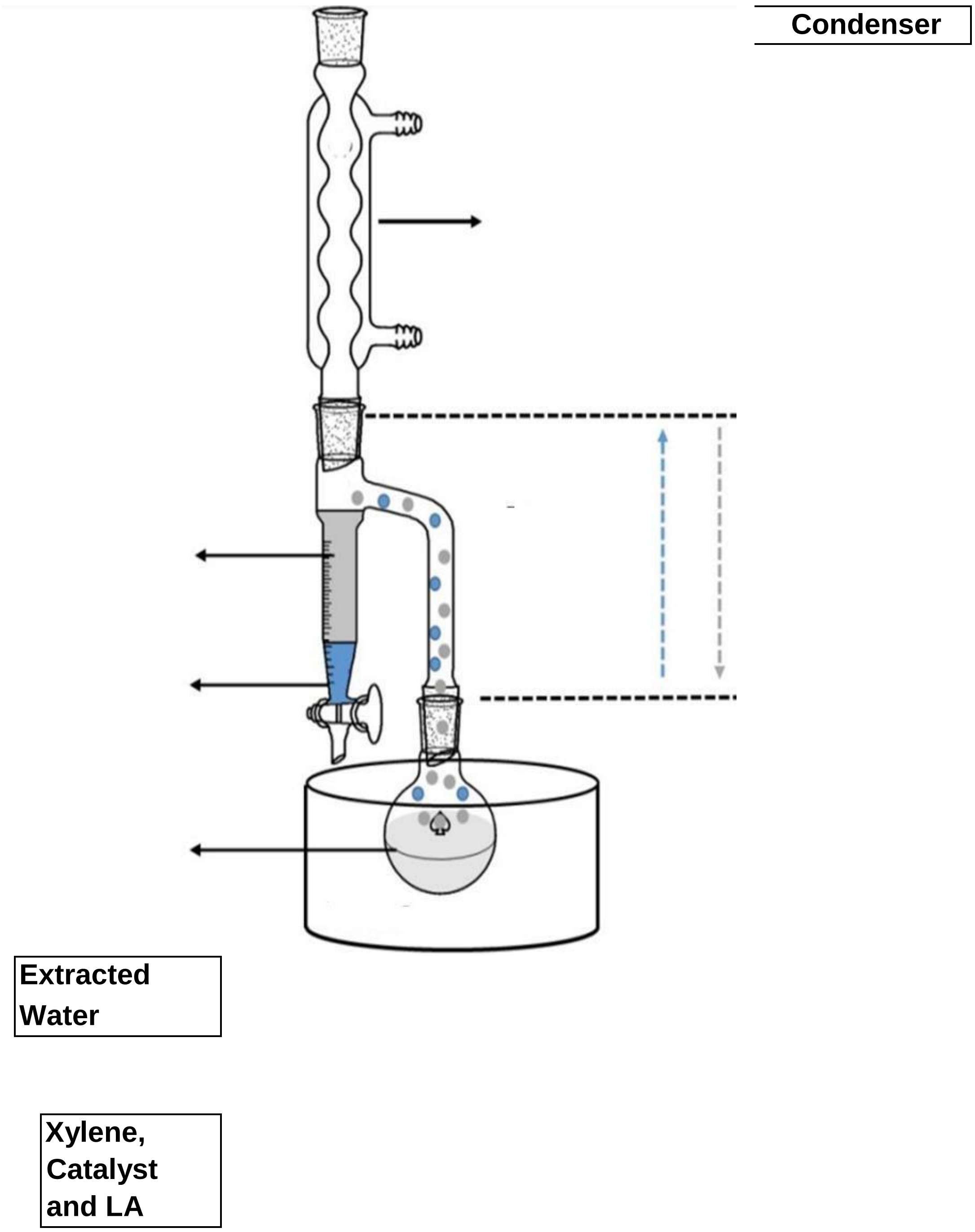


Figure 10. Reaction Setup

2.3 Screening of LA concentration

- Lactic acid concentration (20, 50, 88%) have been screened using Zeolite 1, Zeolite 3 catalysts.

- Lactic acid concentration (50, 88%) have been screened using Zeolite 2 catalyst. Experimental conditions are shown in Table 4.

Table 4. Lactic acid concentration screening

Reaction No.	LA concentration	Catalyst	Catalyst loading	Solvent	Solvent ratio(w/w)	Temp.	Time
	%	Name	(%)	Name		(°C)	(min)
6	88	Zeolite 1	39.64	Xylene	20-25	170	240
5							
3	50						
4							
1	20						
2							
12	88	Zeolite 3	30-40	Toluene	20-25	140	120
11							
9	50						
10							
7	20						
8							
14	88	Zeolite 2	30-40	Xylene	20-25	155	120
13	50						

2.4 Screening of catalyst loading

Four different catalyst concentration (28, 32, 60, 81%) have been screened using Zeolite 2 catalyst. Experimental conditions are shown in Table 5.

Table 5. Screening of catalyst loading

Reaction No.	LA concentration	Catalyst	Catalyst loading	Solvent	Solvent ratio(w/w)	Temp.	Time
	%	Name	(%)	Name		(°C)	(min)
16	50	Zeolite 2	28	Xylene	20-25	155	240

22			32				
26			60				
27			81				
28			81				

2.5 Catalyst Screening

Screening of catalysts was performed under different reaction conditions.

In first set Zeolite 1 and Zeolite 3 catalysts has been screened, while all other conditions kept constant. Experimental conditions are shown in Table 6.

Table 6. Screening of catalyst (Zeolite 1 and Zeolite 3)

Reaction No.	LA concentration	Catalyst	Catalyst loading	Solvent	Solvent ratio(w/w)	Temp.	Time
	%	Name	(%)	Name		(°C)	(min)
19	20	Zeolite 1	40	Xylene	30-35	170	240
18		Zeolite 3					

In second set Zeolite 1, Zeolite 2 and Zeolite 4 catalyst have been screened while all other conditions kept constant. Experimental conditions are shown in Table 7.

Table 7. Screening of catalyst (Zeolite 1, Zeolite 4 and Zeolite 2)

Reaction No.	LA concentration	Catalyst	Catalyst loading	Solvent	Solvent ratio(w/w)	Temp.	Time
	%	Name	(%)	Name		(°C)	(min)
15	20	Zeolite 2	30-40	Xylene	20-25	170	240
16		Zeolite 4					
1		Zeolite 1					
2		Zeolite 1					

In third set Zeolite 2 and Zeolite 5 catalysts has been screened, while all other conditions kept constant. Experimental conditions are shown in Table 8.

Table 8. Screening of catalyst (Zeolite 2 and Zeolite 5)

Reaction No.	LA concentration	Catalyst	Catalyst loading	Solvent	Solvent ratio(w/w)	Temp.	Time
	%	Name	(%)	Name		(°C)	(min)
13	50	Zeolite 2	30-40	Xylene	20-25	155	120
16		Zeolite 2					
17		Zeolite 5					

2.6 Screening of time

Three different reaction time periods (120 min, 180 min, 240 min) have been screened using Zeolite 2 Catalyst. Experimental conditions are shown in Table 9.

Table 9. Time screening using Zeolite 2 catalyst

Reaction No.	LA concentration	Catalyst	Catalyst loading	Solvent	Solvent ratio(w/w)	Temp.	Time
	%	Name	(%)	Name		(°C)	(min)
13	50	Zeolite 2	30-40	Xylene	20-25	155	120
21							180
22							240

Chapter 3

Results and Discussions

3. Results & Analysis

3.1 Effect of LA concentration

Three different Lactic acid concentrations (20%, 50%, 88%) have been screened using Zeolite 1 and Zeolite 3 catalyst keeping all other conditions same. It is observed that

50% concentrated LA gave higher purity of Lactide as compared to 88 and 20% concentrated LA.

There is no significant difference in purity of Lactide obtained from 88% and 50% LA concentration using Zeolite 1 and 3. In order to the confirm this result, Zeolite 2 catalyst have been screened on 88 % and 50% concentrated LA. Zeolite 2 catalyst also showed that 50% LA concentration produced higher purity Lactide.

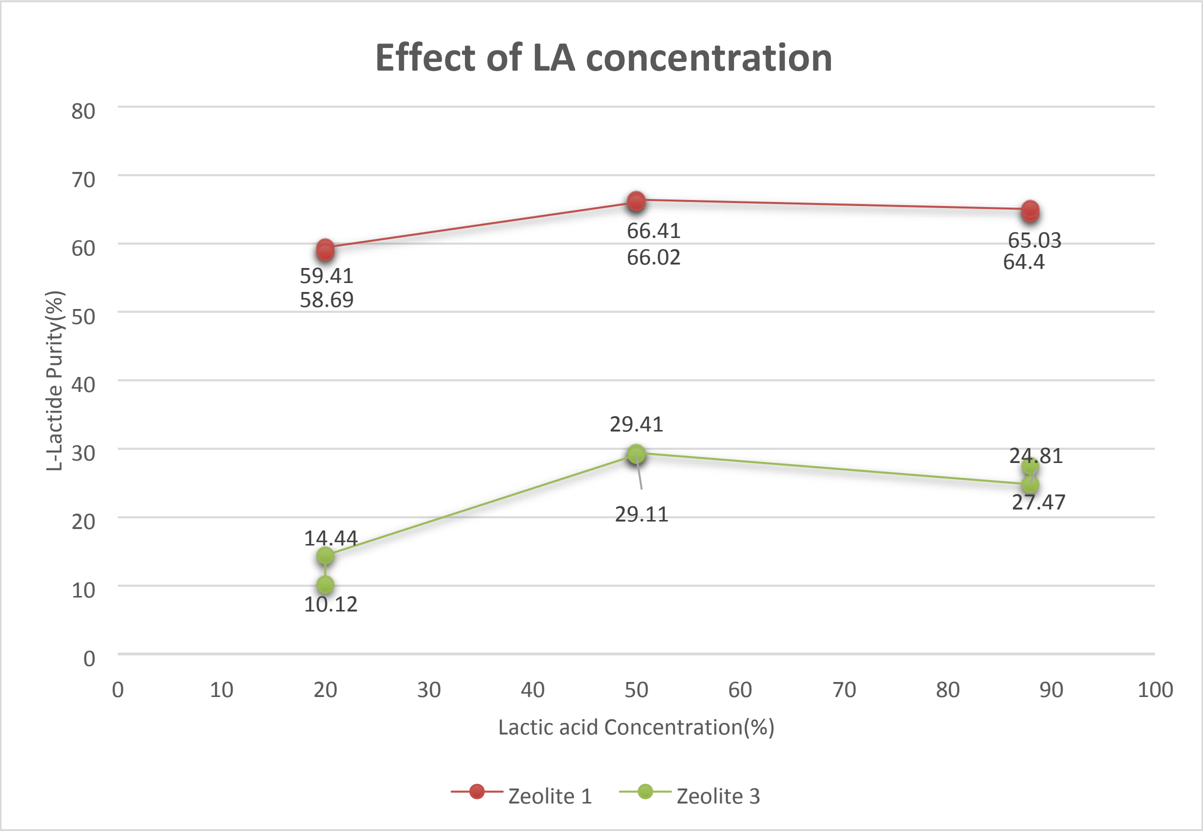


Figure 11. Effect of LA concentration

Conditions: [Zeolite 1 (39.64%), Xylene (1:20-25), Temp 170°C, Time (240 min)]

[Zeolite 3 (30-40%), Toluene (1:20-25), Temp 140°C, Time (120 min)]

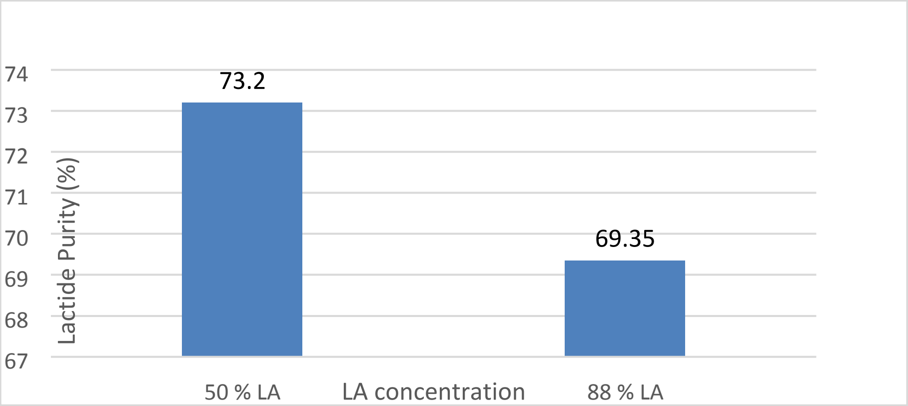


Figure 12. Effect of LA concentration using Zeolite 2 catalyst

Conditions ; [Zeolite 2 (30-40%), Xylene (1:20-25), Temp 155°C, Time (120 min)]

Based on results it can be concluded that, LA concentration preference 50% > 88% > 20% for better Lactide purity. The increase in Lactide purity when increasing Lactic acid concentration from 20% to 50% is likely due to the increased availability of Lactic acid molecules for the reaction. However, increasing the Lactic acid concentration from 50% to 88%, the solubility of the product may decrease. Another reason for this is equilibrated (e.g., commercial) Lactic acid solutions that are highly concentrated contain up to 35 % of oligomers of Lactic acid (mainly dimer, trimer, and tetramer) due to autocatalyzed self-condensation equilibria (4).

Michael Dussiliar et al also found that the optimal Lactic acid concentration for Lactide production using a zeolite catalyst was 50% (4). Another study ‘Controlled synthesis of L-Lactide using zeolite catalysts in a one-step route ‘found that the optimal Lactic acid concentration for Lactide production using Sn-beta zeolite catalyst was 50% (16).

3.2 Catalyst loading effect

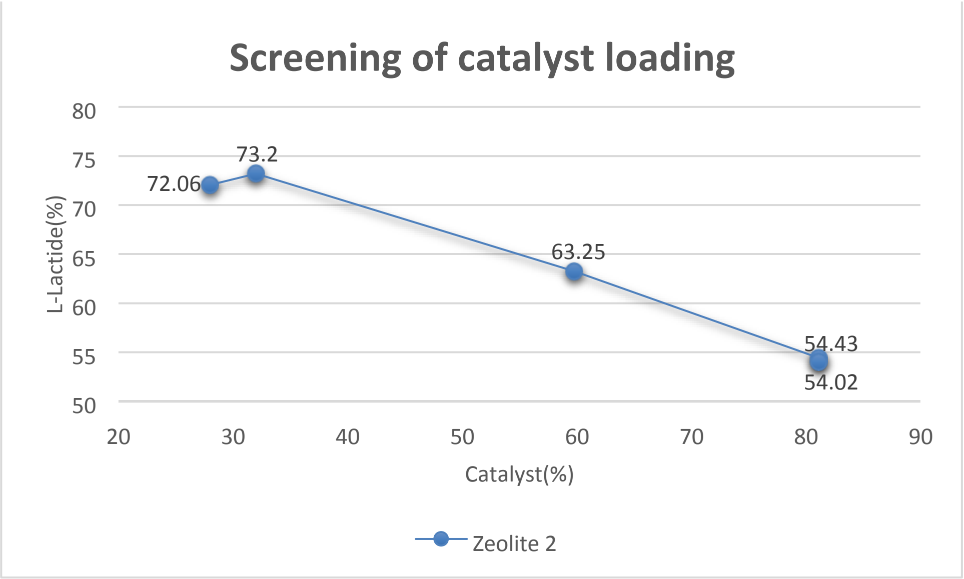


Figure 13. Effect of catalyst loading

Conditions; [50% LA , Zeolite 2, Xylene (1:20-25), Temp 155°C, Time (120 min)]

Four different catalyst loading (28, 32, 60, 81%) have been screened using Zeolite 2 catalyst. Figure 13 shows the effect of zeolite 2 loading on lactide purity. It is clear from the figure that 32% gave higher purity compared to (28, 60, and 80%).

When the catalyst loading increases from 28 to 32%, the number of active sites on the catalyst surface increases. As a result, the reaction rate increases, and more Lactic acid is converted into Lactide. A higher catalyst dose resulted in a faster rate of L3A formation. However, in the stage of L3A conversion to L-lactide, the pathways of L3A diffusion to the active site within the Zeolite pore should increase with increasing catalyst dose. So, L3A should be converted to L- Lactide quickly, which may be the reason why increase catalyst loading from 28 to 32 % resulted in a more Lactide purity. But increase catalyst loading more than 32% results in lower purity Lactide because in later phases of the reaction L3A was not able to fully convert in Lactide because Zeolite 2 catalyst did not get optimal conditions to convert L3A to Lactide(16).

So based on our results we can consider that (30-40%) catalyst loading is optimal catalyst loading for Lactide synthesis. Any excess amount of catalyst used in the reaction resulted in an enhanced rate of racemization and increased impurities.

In the literature ‘Controlled synthesis of L‐Lactide using zeolite catalysts in a onestep route‘ found that the optimal catalyst loading for Lactide synthesis using zeolite catalyst was 30-40% (16).

3.3 Effect of catalyst

First two catalysts Zeolite 1 and Zeolite 3 have been screened by keeping all conditions constant. It can be seen in Figure 14 that Zeolite 1 was giving better Lactide purity compared to Zeolite 3 Catalyst.

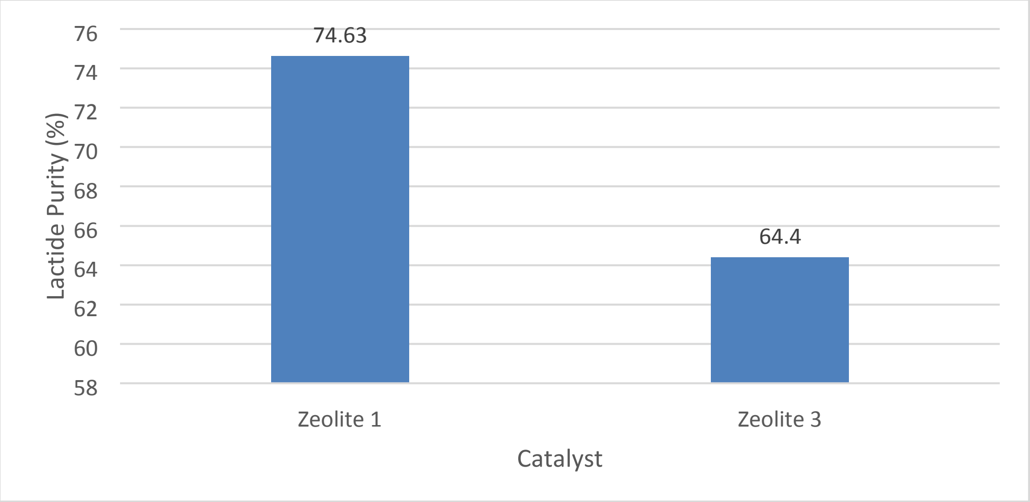


Figure 14. Lactide purity comparison in Zeolite 1 and Zeolite 3

Conditions : [LA(20 % Concentration, Catalyst ratio (40%), Xylene (30-35%), Temperature (170°C), Time (240 min)]

Reasons for this could be that Zeolite 3 has high crystal size compare to zeolite 1. Another reason could be that Zeolite 1 has more Sn content and low Si/Al ratio compare to Zeolite 3.
Performance of Zeolite 1 was then compared with Zeolite 4 and Zeolite 2 under the similar reaction conditions. It was observed that Zeolite 2 was giving higher purity of lactide as compared to Zeolite 4 and 1.

- ✦ Based on results catalyst preference for Lactide synthesis. (Zeolite 4 **<** Zeolite 1 **<** Zeolite 2)

Zeolite 2 has been shown to have even higher lactide purity compared to Zeolite 1 because Zeolite 1 had a highly crystalline structure while Zeolite 2 has slightly lower diffraction intensities than Zeolite 1, because relatively heavy metals (Cs) tend to inhibit the diffraction of the framework atoms due to their large number of electrons (19). Also, lower crystal size of Zeolite 2 results in better Lactide purity because it avoids unwanted side reaction.

Zeolite 4 catalyst give us less lactide purity compare to Zeolite 1 because Zeolite 1 has high bronzed acid site densities than Zeolite 4 which results in more Lactide purity(19).

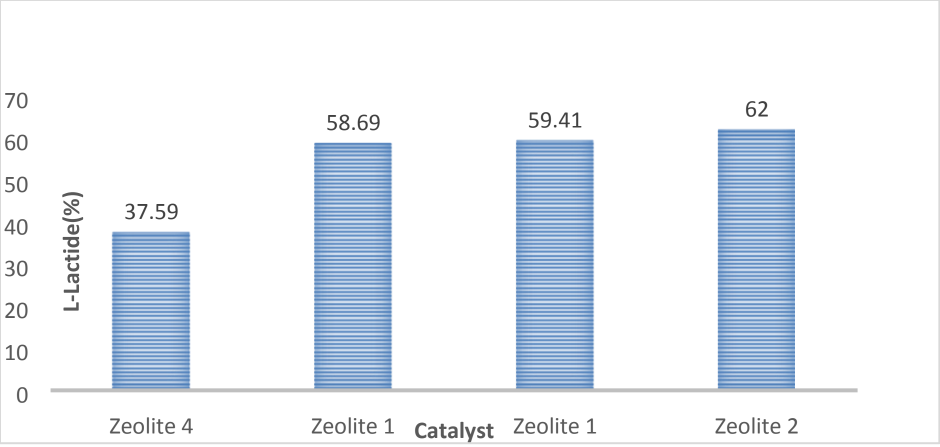


Figure 15. Lactide purity comparison in Zeolite 1, Zeolite 2 and Zeolite 4

Conditions : [LA(20% concentration, Catalyst ratio (30-40%), Xylene (20-25%), Temperature (170°C), Time (240 min)]

Again the performance of Zeolite 2 was compared with Zeolite 3, and Zeolite 5 by keeping all other conditions same. It is observed that Zeolite 5 gives slightly higher purity as compared to Zeolite 2. However, it is better than Zeolite 3. Based on results catalyst preference for Lactide synthesis (Zeolite 3 < Zeolite 2 < Zeolite 5).

Zeolite 5 has been found to have the highest Lactide purity even compare to Zeolite 2. Which can be attributed to the high bronzed acid site densities in zeolite compared to Zeolite 2 catalyst (19). Importantly, not only LA/L_2A but also L_3A existing in the highly concentrated LA could be converted to LT. This is the result of a fast LT production promoted by the increased Brønsted acid site density and its rapid diffusion out of the nanosized crystals avoiding secondary reactions, namely, decyclization and oligomerization (18).

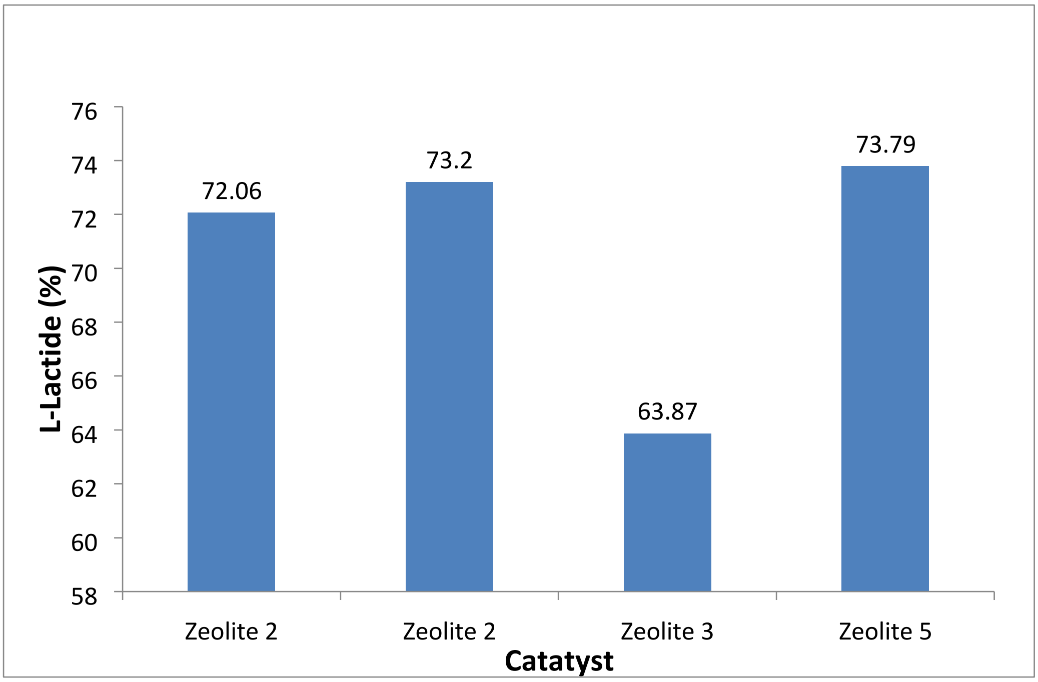


Figure 16. Lactide purity comparison in Zeolite 2, Zeolite 3 and Zeolite 5

Conditions : [LA(50%, Concentration, Catalyst ratio (30-40%), Xylene (20-25%), Temperature (155°C), Time (120 min)]

HPLC graph of Lactide synthesis using Zeolite 2, Zeolite 3 and Zeolite 5 catalysts is shown in Figure 17,18 and 19.

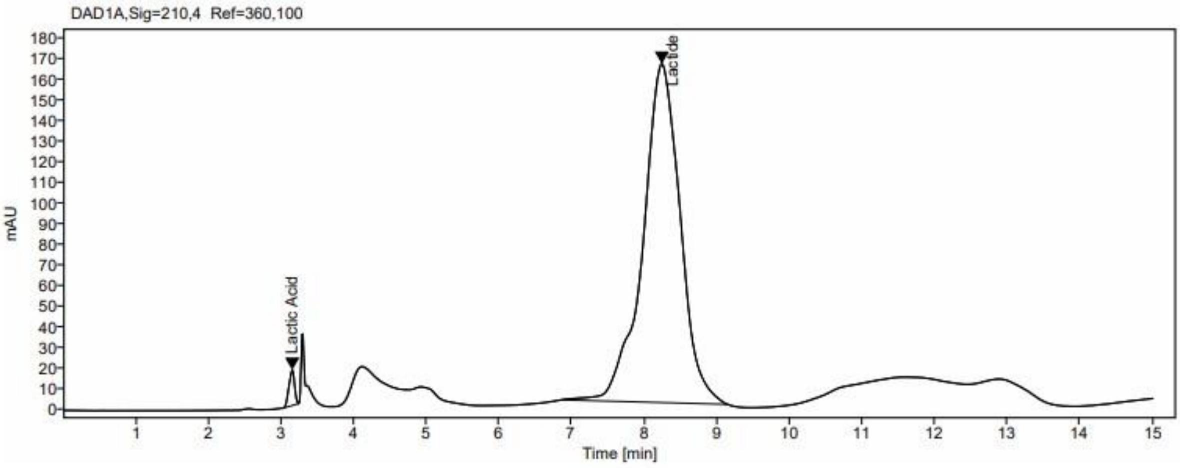
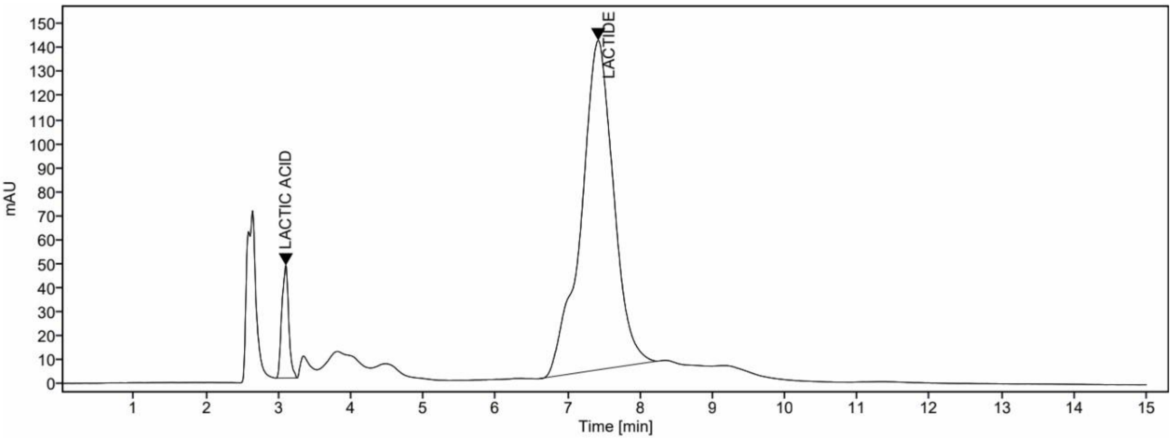


Figure 17. HPLC graph of Lactide synthesis using Zeolite 2 catalyst

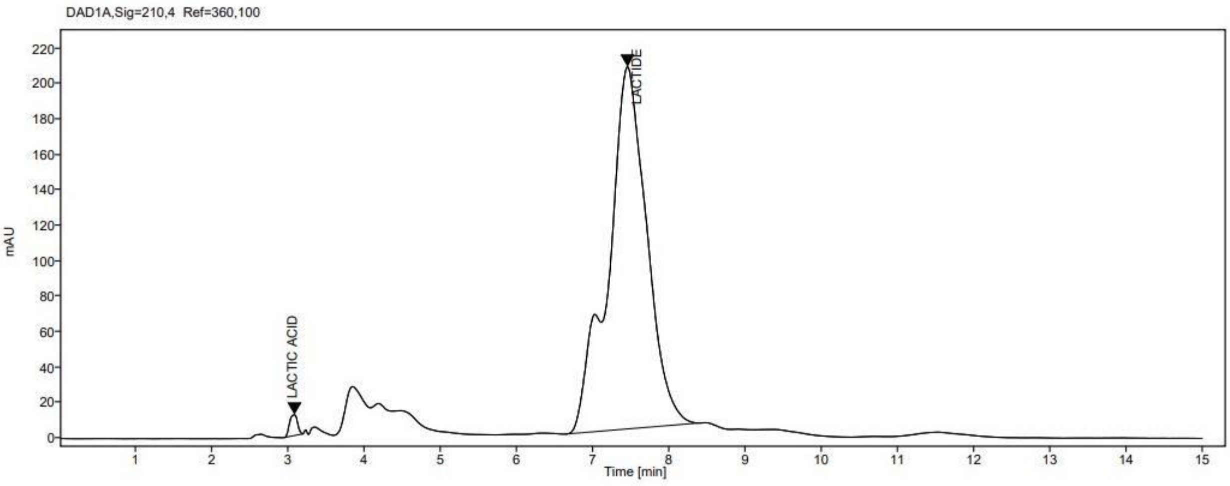
HPLC graph of Lactide synthesis using Zeolite 3 catalyst is shown in Figure 18.



Sr.No.	RT [min]	Area	Amount % w/w	Name
1	3.092	310.11	8.96	LACTIC ACID
2	7.412	4299.30	63.87	LACTIDE
	Sum	4609.40	72.82	

Figure 18. HPLC graph of Lactide synthesis using Zeolite 3 catalyst

HPLC graph of Lactide synthesis using Zeolite 5 catalyst in above conditions is shown in Figure 19.



Sr.No.	RT [min]	Area	Amount % w/w	Name
1	3.073	85.59	1.78	LACTIC ACID
2	7.448	7186.00	73.79	LACTIDE
	Sum	7271.59	75.56	

Figure 19. HPLC graph of Lactide synthesis using Zeolite 5 catalyst

Among all other catalysts Zeolite 5 was found to be optimal, which resulted in the highest purity of Lactide product.

3.4 Effect of time

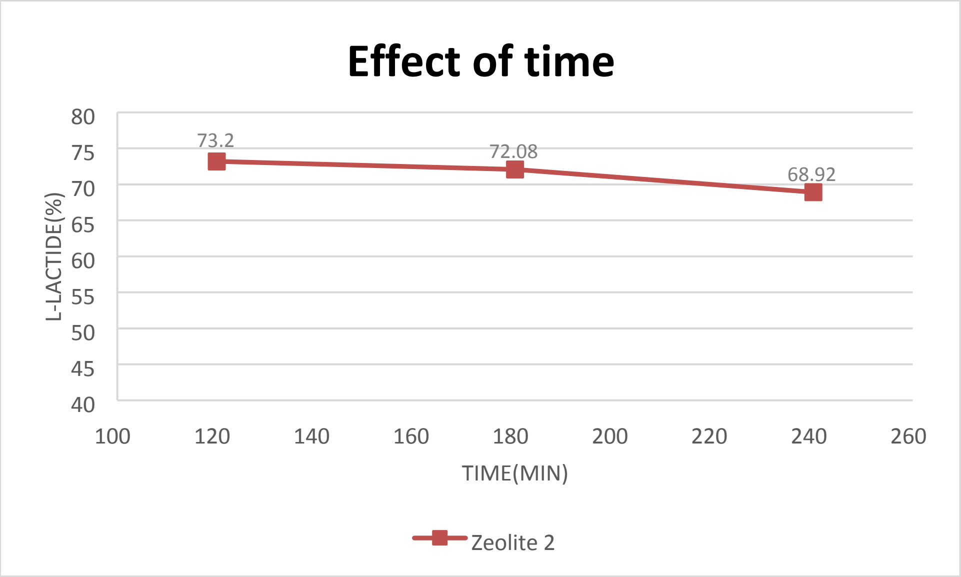


Figure 20. Effect of Time

Conditions ; [50% LA, Zeolite 2 (30-40%), Xylene (1:20-25%), Temp 155°C]

Three-time periods (120 min, 180 min, 240 min) have been screened using Zeolite 2 catalyst, and 120 min gives us the best results in terms of Lactide purity. It has been observed that increasing the reaction time from 120 minutes to 180 minutes and then to 240 minutes decreases the purity of the Lactide product.

According to our results 120 min is optimal timing for lactide purity and increase in time is inversely proportional to Lactide purity.

There could be several reasons -

- During longer reaction times, the Lactide product can undergo further dehydration to form cyclic oligomers or low-molecular-weight linear chains, which can contaminate the final product and reduce its purity.
- Hydrolysis of Lactide back to Lactic acid under prolonged reaction times, especially at high temperatures. This is known as the reverse reaction and can cause a decrease in the overall lactide purity.

- When we put magnetic bid into reaction it was breaking catalyst into small pieces this may lead to the formation of new active sites on the catalyst surface, which could favour secondary reactions or side reactions that reduce the lactide purity. This effect is particularly pronounced for catalysts which structure can change during reaction.

According to our results, reaction time of 120 minutes was found to be optimal, which resulted in the highest purity of Lactide product. A recently published research paper' Controlled Synthesis of L‑Lactide Using Zeolite Catalysts in a One-Step Route' also show that 120 min reaction time is best for lactide synthesis by zeolites (16).

Chapter 4

Conclusion

4. Conclusions

In this project two main goals were identified:

1) Find best catalyst to achieve highest LT purity
2) Find optimal suitable conditions for LT synthesis

Firstly, different concentrations of Lactic Acid (LA) 88%, 50%, and 20% have been screened. 50% LA resulted in the best Lactide purity compared to the other concentrations.

Next, different amounts of catalyst loading (30%, 60%, 80%) have been screened and it can be concluded that a catalyst loading of 30-40% was optimal for better Lactide purity. Different catalysts Zeolite 1, Zeolite 2, Zeolite 3, Zeolite 4 and Zeolite 5 have been screened and through these experiments it was observed that is the Zeolite 5 is most effective catalyst for Lactide synthesis.

To further investigate the Lactide purity, different reaction times have been screened using various catalysts and reaction time of 120 minutes was optimal for Lactide synthesis.

Based on our results we can conclude that purity of Lactide depends on several factors, including the type of catalyst used, reaction time, catalyst loading, and concentration of LA.

Chapter 5

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