Recent Progress in PLA Nanofiber Manufacturing: Synthesis, Processing Strategies, and Functional Applications

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***Abstract*—Tissue engineering combines life sciences and engineering principles to develop, maintain, or restore damaged human tissue functions. A crucial element is the synthesis of tissue scaffolds using biodegradable electrospun nanofibers, which are implanted in defective tissue areas. Polycaprolactone (PCL) was synthesized via microwave-assisted polycondensation—a rapid and efficient method enabling polycondensation, free and controlled radical Polymerisation, and ring-opening polymerization. Microwave irradiation is increasingly used as a heating source for polymerization in biomedical implant fabrication, including skin, bone, and dental repairs. PCL characterization was conducted using Fourier Transform Infrared Spectroscopy (FT-IR), Scanning Electron Microscopy (SEM), Differential Scanning Calorimetry (DSC), and X-ray Diffraction (XRD). Additionally, polylactic acid (PLA) nanofabrication was performed using electrospinning to create scaffolds for biomedical applications. Scaffolds serve key functions such as enabling cell attachment and migration, delivering and retaining cells and biochemical factors, facilitating nutrient diffusion, and influencing cell behaviour mechanically and biologically. This work provides an overview of tissue engineering fundamentals, novel synthesis technologies, biodegradable polymer properties, and their applications, including melt spinning and electrospinning techniques with SEM-based morphological analysis of PLA scaffolds.**

***Index Terms*—Synthesis, Polymerisation, Electrospinning, Biodegradable, Biocompatible, PLA, PCL, PLGA, FTIR, NMR.**

I. Introduction

Electrospinning has a straightforward setup that allows continuous drawing of fibers directly from molten polymer, eliminating the need for solvents. However, melt spinning cannot produce fibres at the nanoscale, and it is not suitable for polymers like PL that may degrade under electrospinning conditions. During the process, the spinning temperature and the take-up roll speed were maintained at 110°C and 900 rpm, respectively. The fibers were cooled by air before being wound onto the take-up roll.

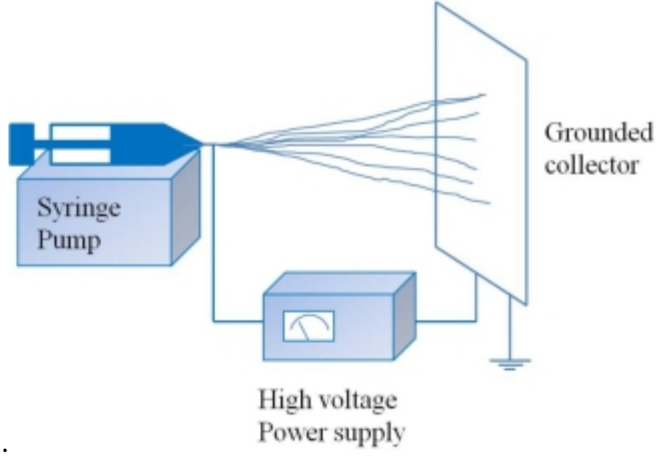

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Figure :1: Electrospinning Setup

Melt electrospinning is an alternative to solution electrospinning, but it usually produces fibers with diameters in the tens-of-microns range. Unlike solution electrospinning, which forms fibers through solvent evaporation, melt electrospinning relies on cooling the polymer jet to create fibers. In recent years, biodegradable polymer is most advanced topic in polymer studies due to its environmental effects and cost-effectiveness. Polycaprolactone is a biodegradable polymer that is currently used in several biomedical applications. It is mainly important due to its mechanical properties, miscibility with many other polymers and due to its biocompatibility. PLA is synthesized by two methods: The polycondensation of hydroxycarboxylic acid and ring-opening polymerization of PLA. We use the ring-opening polymerization method for the synthesis of Polylactic acid by using stannous octoate as a catalyst in a microwave-radiating system.

II. Materials and methods

PLA Synthesis:

Materials: Lactic acid 90% pure was purchased from Loba chemie, used as monomer. 97% pure Glycolic acid was purchased from Sigma Aldrich, as monomer. Stannous Octoate 99% pure was purchased from Sigma Aldrich and used as initiator and catalyst (it acts as both). Stearyl alcohol and Lauryl alcohol (reagent grade) from SD Fine Chemicals Pvt. Ltd used as co-catalyst. Silicon oil used in thermocouple pocket.

Apparatus: Heating mental, Overhead stirrer, stirring rod with Teflon blade, Vacuum setup, Nitrogen balloon, oil tube, thermometer, Temperature sensor, Thermocouple, thermometer pocket, four necked round bottom flask, nitrogen (gas) purging tube, Weigh machine, beakers, conical flask, pipette, water condenser, separating funnel, vacuum adaptor, stand, clamp, rubber bulk, join and bends, connector, stopper, Nitrogen balloon stand (ring clamp), fiber resistance fabric, Petri dish, Funnel, Spatulas, Glass stirring rod, Buchner funnel, wood blocks, rubber tube, etc.,

Fig.1: PLA synthesis setup

Procedure:

Arrange apparatus according to setup. Place mechanical stirrer in central of four neck round bottom flask, and place it in heating mental. Fill balloon with nitrogen gas, purge nitrogen from one neck with the help of gas purging tube via oil tube which help in determining rate of nitrogen gas. Keep RPM speed nearly about 500.Join vacuum through cold trap. Vacuum should apply at interval of time otherwise monomer will also remove with water. Vacuum should start after temperature reaches to 110°C, so it will remove water and since oligomerization is started monomer will not be removed.

Thermocouple place in thermometer pocket which filled with silicon oil. It can be placed in one neck or outside of heating flask but it should touch the heating solution. After arranging the whole setup check the connection before start heating and stirring also check the water inlet and outlet, then start the heating.

Add lactic acid heat for 15 min then add glycolic acid. Lactic acid added before glycolic acid because glycolic acid has higher reactivity compare to lactic acid. Add stannous octoate and/or Stearyl alcohol/ lauryl alcohol (co-initiator) after one hour (after oligomerization), and after this process vacuum is started. To check the progress of rection we determine acid value and/or saponification (sap) value. As reaction proceeds acid value decreases and sap value increases. Also determine acid value of monomer and mixture after adding initiator and/or co-initiator.

III. Synthesis of Solution Polycondensation (Method I)

Figure :2 Experimental set-up for polycondensation reaction

This section outlines the experimental methodologies employed for the polycondensation of lactic acid under various conditions, including solution polymerization, bulk polymerization, and microwave-assisted polymerization. The aim was to optimize polymerization parameters and evaluate the impact on polymer yield and properties Anisole (b.p. 154 ºC) and m-xylene (b.p. 139 ºC), both high boiling point organic solvents, were used as the reaction temperatures for polymerizing lactic acid in solution. The initial aqueous monomer concentration in the solvent mixture was 20% (v/v). The reaction took place in a 2 L borosilicate glass reactor. The first step involved distilling the monomer's aqueous solution over about 8 hours using a Dean-Stark trap to collect the condensed water. Following this, 0.1% mol catalyst was added, and the Dean-Stark trap was replaced with a tube packed with molecular sieves as a drying agent, as shown in Figure 2.1 (6). Polymerization proceeded for up to 70 hours at the solvent's boiling point under a nitrogen atmosphere. Some experiments were done under reduced pressure (0.1 bar), gradually lowering the pressure to reach this set-point. The final polymer was recovered as a white powder by precipitating the solution in an ice bath. Further purification involved dissolving the polymer in chloroform and re-precipitating it in a fourfold volume of ethanol. After drying, the samples were stored in a desiccator for further analysis. The results, including polymer yields around 30%, are presented and discussed.

IV. Vacuum Melt Polycondensation (Method II)

Figure :3 Vacuum dryer

Figure :4 PLA purification

The polycondensation of L-lactic acid was performed under vacuum at high temperature using an oil bath. A volume of 200 mL of L-lactic acid (with 80% purity) was placed in a round-bottom flask fitted with a thermometer, a water-cooled condenser, and a flask to collect the distillate. The system was heated under vacuum with the aid of a water pump and magnetic stirring to facilitate the removal of excess water. Initially, the temperature was maintained at 160 °C, and after two hours of distillation, it was raised to 180 °C. The collected distillate was analyzed by IR spectroscopy to monitor the progress of the polycondensation reaction.

V. Ring Opening Polymerization (Method III)

Experiments were conducted in a 500 mL glass vessel equipped with pressure and temperature control systems, using a mechanical stirrer with a magnetic coupling MRK1/90, connected to a vacuum system through a cold trap, as illustrated in Figure 4.2. Two reflux condensers were set up as shown in Figure 4.2 to remove water by-products and recycle the monomer during polymerization, ensuring yield was not compromised. An initial 200 mL of L-lactic acid aqueous solution was placed in the reaction vessel and reacted overnight under an inert atmosphere at atmospheric pressure, with stirring at 600 rpm. The temperature was maintained at 170 ºC. On average, 79 g of water and 3 g of monomer were collected after this overnight distillation. Subsequently, 0.4 wt % catalyst (relative to the initial monomer weight) was added, the temperature was raised to either 180 ºC or 190 ºC, and the reaction mixture was allowed to heat for one hour before gradually reducing the pressure from atmospheric to 10 mbar over 7 hours. After reaching the target pressure, the system was maintained under these conditions for approximately 4 hours. A significant increase in viscosity was observed during bulk polycondensation of lactic acid, and despite efforts to improve the setup and prevent air leaks, these were not always fully resolved. Many experiments took longer than planned, with some not succeeding. At the end of polymerization, about 130 g of a brownish viscous melt polymer was poured onto a plate and cooled. A small portion was purified by dissolving in chloroform and precipitating in four times the volume of ethanol. After drying, samples were stored in a desiccator for further analysis. On average, about 7% of the polymer samples were lost as low molecular weight oligomers. The outcomes of this method are discussed in detail in Chapters 5 and 6.

VI. Results and Discussion

6.1 Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) Instrument: TA Instruments Q100, Atmosphere: Nitrogen, Heating rate: 10 °C/min. Sample size: ~5 mg. Thermal transitions such as Tg, Tc, Tm, and ΔHm were recorded.

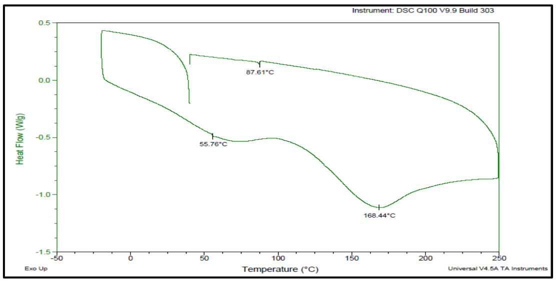


Figure :5 DSC traces from second heating scan of the PLA sample

6.2 Thermogravimetric Analysis

conducted using an SDT Q600 TGA instrument from TA Instruments. Samples were heated 600°C at a rate of 10°C per minute under a nitrogen atmosphere. The degradation temperatures (Td) were determined representing the temperature at the maximum decomposition rate. at 168.44°C. During the cooling phase, a recrystallization temperature of 87.61°C was observed.

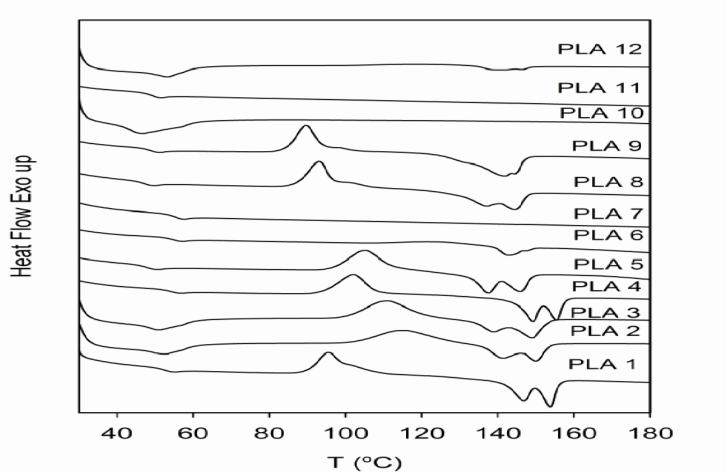


Figure: 6 TGA of PLA sample

6.3 Dynamic Mechanical Thermal Analysis

It is an effective method for studying the viscoelastic behaviour of polymers by applying a sinusoidal load and measuring the resulting deformation across different frequencies and temperatures. In DMTA, the material undergoes forced mechanical vibrations. The storage modulus, E', reflects the polymer's capacity to store energy (elastic behaviour), while the loss modulus, E'', reflects viscous behaviour). This allows for a serves as a measure of the relative contributions of the elastic and viscous components. [4, 5, 15].

A comprehensive characterisation approach was employed to evaluate the resulting PLA polymers. These techniques provide insight into molecular structure, thermal stability, mechanical performance, and stereochemical composition.

The following day, the resulting product was visually inspected, and it was observed that the viscosity has not increased as much as it was expected if the water were totally removed. It was decided to proceed the distillation with a temperature increased to 180 °C, as it should allow further removal of water. The same set-up was used for the reaction. The temperature was gradually increased to 180 °C and after about 2 hours at 180 °C distillation was stopped and the resulting product was left in the closed flask to cool. Distillate was collected and kept for analysis. Resulting prepolymer is pictured in Figure 3. Resulting product was again visually inspected and obvious increase in viscosity was observed. Due to definite increase in viscosity (solidification), assumption was made that water was removed from the lactic acid and resulting product was purified lactic acid with the presence of low molecular weight oligomers. Small amount of product was dissolved in dichloromethane and subjected to analysis by IR together with the distillates from both days.

This temperature increase during the period of the reaction was considered due to increasing viscosity of the reaction mixture, as the theory of sonochemistry would suggest. As it can be observed, addition of catalyst to the reaction accelerated the increase in the temperature, thus also confirming the idea, that Polymerisation was progressing and viscosity was increasing due to rising amount of polymer in the bulk phase. It can be seen, that although the intensity for the spectra are different, same peaks are observed for both samples. By comparing them to the same observed peaks from the authors of [57] it can be expected that in both cases polymerization has occurred and PLA was produced. However, due to different resolution of spectra, it is hard to confirm if the assumption is correct, but it could be assumed that after 8 hours, and by comparison to peaks in Figure 3, the PLA corresponds more to the spectrum of amorphous polymer, while after 4 hours, more distinct peaks in the 1350 cm^{-1} region would suggest a semi-crystalline structure of resulting polymer. This could be potentially explained by the extreme conditions produced by ultrasonic sonochemistry, and the possibility should be considered that after prolonged reaction, destruction of polymer structure occurs, resulting in more amorphous.

6.4 Nuclear Magnetic Resonance

nuclear Magnetic Resonance (NMR) spectroscopy is a key technique used to confirm the chemical structure of PLA (polylactic acid). Typically, ^1H NMR spectra of PLA are recorded using a 500 MHz spectrometer at 25 °C, with deuterated chloroform as the solvent and tetramethyl silane (TMS) as the internal chemical shift reference. The spectra reveal characteristic proton signals corresponding to the PLA's repeating units, allowing verification of its molecular structure and purity.

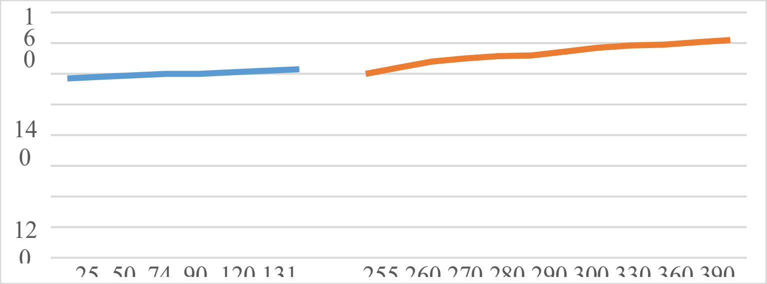


Figure 7: Reactions mixture temperature in C over time, min. blue line corresponds to first 4 hours of reaction, orange line corresponds to following 4 hours with addition of 0.1 % catalyst.

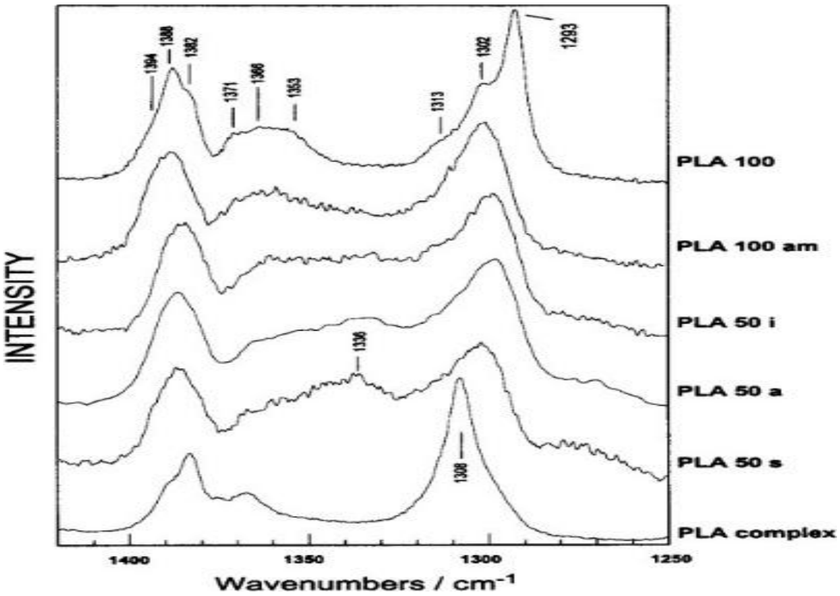


Figure :8 NMR PLA

VII. End-Group Titration

Polyesterification kinetics are typically monitored by tracking the disappearance of carboxyl end groups (COOH) using a standard acid-base titration method. For this, 1 g of polymer sample was dissolved in 20 mL of an ethanol-chloroform mixture (1:1 by volume) and titrated with 0.05 $mol \cdot L^{-1}$ KOH in ethanol. This titration was repeated three times. The concentration of free carboxyl groups, [COOH], is defined as the moles of COOH per gram of polyester. This method was used to evaluate solution polycondensation progress and was found suitable for quantitatively analyzing oligomer end groups but less accurate for polymers with higher molecular weights. Likely, aliphatic ester bonds undergo hydrolysis under the titration conditions, leading to inaccuracies. This limitation might explain why end group quantification is generally not included as a quality parameter in commercial PLA datasheets, unlike other commercial polyesters. Nonetheless, identifying and quantifying end groups is essential for assessing polycondensation kinetics and for any modifications or post-polymerization processes

Morphology of SEM of PLGA Fibers

The morphology of Polylactic acid (PLA) was studied to understand its surface characteristics, structural arrangement, and physical texture, which are important for evaluating its suitability in various applications. Morphological analysis provides insight into particle shape, surface uniformity, porosity, and overall microstructural behaviour of the polymer. micrographs revealed that PCL relatively homogeneous semi-crystalline nature. The polymer matrix appeared continuous, indicating good film-forming ability and uniform distribution of polymer chains [176]

At higher magnification, slight granular features and minor surface irregularities were observed, which may be attributed to the semi-crystalline organization of PLANo major cracks, voids, or phase separation were detected, confirming the structural integrity of the polymer. The presence of a compact morphology suggests strong intermolecular interactions and good cohesion within the material. The observed morphology is consistent with the FT-IR results, where characteristic peaks at 1720 cm^{-1} (C=O stretching), 2940 cm^{-1}, and 2863 cm^{-1} (C–H stretching) confirmed the successful formation of PCL [176,177]. The combination of FT-IR and morphological analysis supports the successful synthesis and structural stability of Polycaprolactone.

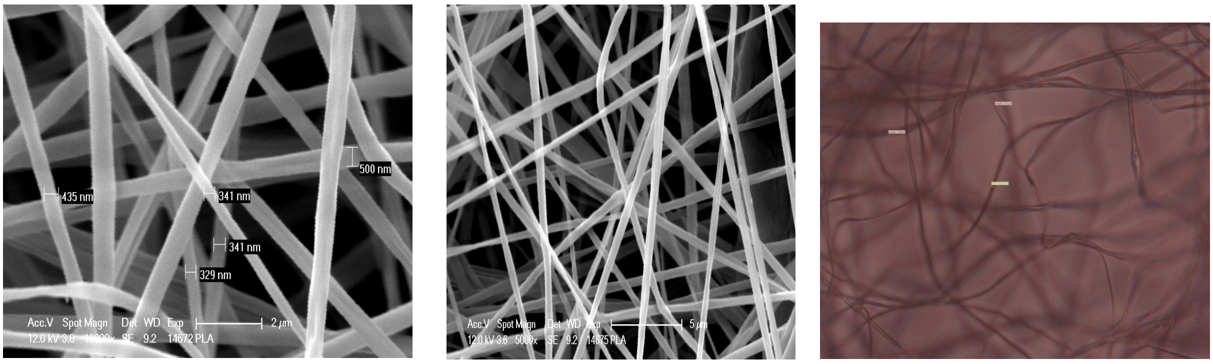


Figure:9 SEM of PLA

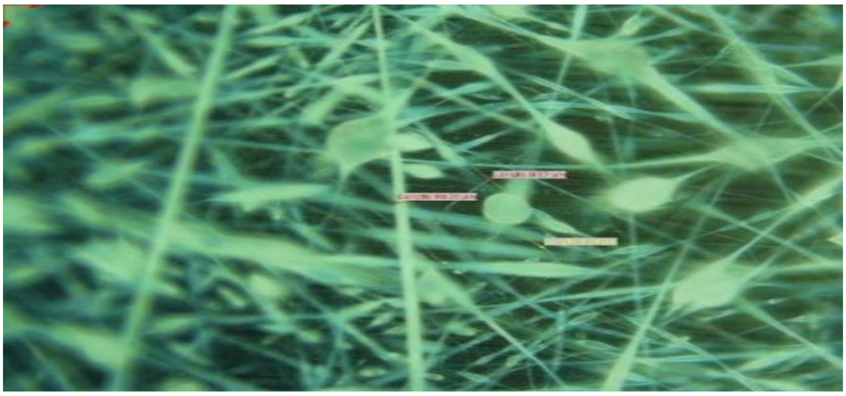


Figure:10 PLA nanofibers by using the electrospinning technique for 5% confocal images and scanning electron microscopy images fiber diameter noted in the range of 21 µm. to 27 µm,

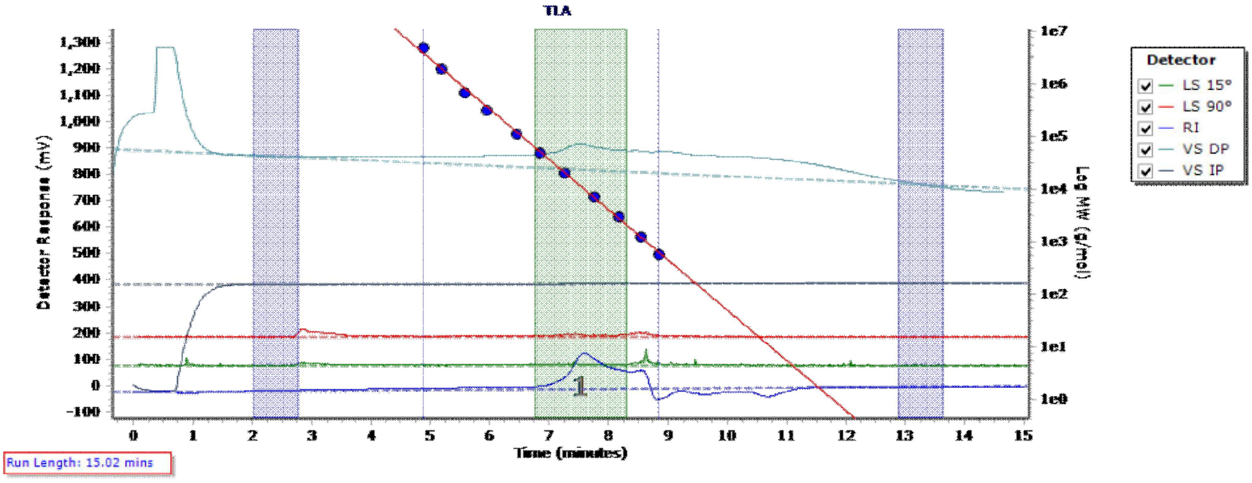
Scanning Electron Microscopy (SEM) for PLASEM image of a randomly oriented 15% PCL nanofiber deposition. Electrospun 15% PLA nanofiber diameter was 220 to 445 nm. Scale bar = 1000x Polycaprolactone (PLA) nanofibers by using the electrospinning technique for 15, 20% confocal images and scanning electrospinning

Table 3.4 Gel Permission Chromatography

No.	**Temperature (°C)**	**Reaction time (min)**	**Watts (W)**	**Catalyst concentration (g)**	**Mnc**	**Mnw**	**PDI**
1	120	20	300	0.01	9020	18905	2.09
2	150	20	300	0.01	10565	27493	2.602
3	190	20	300	0.01	10974	31829	2.9
4	200	20	300	0.01	12878	26816	2.80

Figure :11 a) GPC flow curve of PLGA 60:40

The polymer’s molecular weight was measured by gel permeation chromatography (GPC). Before analysis, samples were dissolved in chloroform at concentrations of 5–10 mg/mL and filtered using 0.22 µm filters. GPC was conducted with a mixed column and chloroform as the mobile phase. Detection was done with a refractive index detector, and molecular weights were determined using polystyrene standards via the universal calibration method. For PLGA 16918 number average molecular weight was observed



VIII. Conclusion

(PLA) using both microwave-assisted and conventional heating methods through bulk polycondensation of L-lactic acid. The experimental setup, designed with controlled temperature, pressure, and continuous removal of water by-product, enabled efficient polymerization while improving monomer recycling and overall reaction yield.

The use of a catalyst and stepwise temperature and vacuum control significantly promoted polymer growth, although viscosity increase during the reaction indicated the formation of high molecular weight PLA. However, challenges such as air leakage and long reaction times affected process consistency in some experiments.

Thermal analysis revealed key properties of the synthesised PLA, with a glass transition temperature (Tg) of approximately 55.76 °C, a melting temperature (Tm) of 168.44 °C, and a recrystallisation temperature of 87.61 °C during cooling. Thermogravimetric analysis further confirmed its thermal stability and decomposition behaviour.

Overall, the study highlights that both heating methods can be used for PLA synthesis, but process optimization is essential to achieve consistent high-quality polymer. The results also confirm that the produced PLA exhibits desirable thermal properties suitable.

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