

In Vitro Degradation of Dry-Jet-Wet Spun Poly(lactic acid) Monofilament and Knitted Scaffold

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ABSTRACT: *In vitro* degradation behavior of dry-jet-wet spun poly(lactic acid) (PLA) monofilament and knitted scaffold were studied at three different pH i.e., at 4.6, 7.4, and 8.0 at 37°C for 20 weeks. Characterization of PLA by intrinsic viscosity, thermal properties, and scanning electron microscopy (SEM) was carried out. It is observed that the pH of the medium has significant role on degradation behavior of PLA. The degradation at pH 4.6 is observed to be maximum, which is confirmed by the drop of 52% in intrinsic viscosity. The degradation

process has effect on the hydrophobicity of the PLA. The decrease in contact angle from 73° to 48° indicates that the PLA surface tends to become more hydrophilic as the degradation proceeds. The SEM analysis showed that with the degradation, surface deterioration takes place. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 103: 2006–2012, 2007

Key words: poly(lactic acid); surface degradation; scaffold; knitting

INTRODUCTION

A new era of polyesters based on lactic acid and glycolic acid has generated dramatic interest among the polymer engineers during the last one decade. Polylactide and poly(lactide-co-glycolide) are known to undergo degradation in the physiological environment and to yield normal metabolites of low toxicity. Their degradation occurs with the simple hydrolysis of the ester bonds in an aqueous environment and the degradation products (carbon dioxide and water) are metabolized by the organism.¹ Owing to their nature of biodegradability and biocompatibility, these polymers are now being used clinically in human therapy, such as sutures, bone fractures fixation devices and sustained release drug delivery systems.^{2–12} Application of these polymers in tissue engineering in various forms like foams, films, nonwovens, and knitted fabric material is at exploring stage.^{13–16} In addition to the biodegradability and biocompatibility, the physical, chemical, mechanical, and degradative properties of these materials can be engineered to simulate specific application.

The degradation behavior of a scaffold has crucial impact on the long term performance of a tissue-engineered cell/polymer construct.⁶ The degradation kinetics may affect a range of processes, such as cell

growth, tissue regeneration, and host response. PLA molecular weight, crystallinity, environmental conditions are important factors affecting the rate of degradation and becomes important criterion for determining final applications.

Ideal materials for implantation should have enough initial mechanical properties for few weeks after implantation. Once the healing starts, the mechanical stability should gradually decrease as the tissue regeneration progresses, leading to a gradual transfer of load to the new tissues. Metals can not meet these demands, but polymers of the poly(α -hydroxyl acids) such as poly(lactic acid) are beginning to do so.¹ Various research groups reported the *in vivo* and *in vitro* degradation behavior of PLA and its copolymers in different forms.^{6,17–30} In the present work, the effect of pH of solution on degradation behavior on the dry-jet-wet spun PLA monofilament and its knitted fabric were studied. The PLA knitted fabric is proposed as the scaffolding material for the urinary bladder tissues. The urine pH varies from 4.6 to 8.0. So the *in vitro* degradation study was carried out at three different pH i.e., at 4.6, 7.4, and 8.0 to simulate with the body fluid.

EXPERIMENTAL

Development of PLA monofilament and knitted fabric

Poly(L-lactic acid) (PLA) was received from Polymer laboratory, University of Uppsala, Sweden. The

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intrinsic viscosity of PLA is 3.32 dL/g. The monofilament of PLA is developed by employing the dry-jet-wet spinning method as described elsewhere in detailed using solvent and nonsolvent system.^{31,32} The as spun PLA monofilament was further subjected to postspinning operations to achieve the desired properties. The knitting was carried out on Krenzel, Switzerland, weft knitting machine to produce the knitted scaffold.

In vitro PLA degradation studies

The *in vitro* degradation study of PLA monofilament and knitted fabric were carried out at three different pH i.e., at 4.6 (Citrate buffer solution), 7.4 (Ringer buffer solution), and 8.0 (Phosphate buffer solution). The preweighted monofilament and fabric were immersed in 30 mL of solution in culture tubes. These tubes were placed in the water bath at constant temperature of 37°C. The degradation study was carried out for 3 days, 1 week, 2 weeks, 4 weeks, 8 weeks, 12 weeks, 16 weeks, and 20 weeks. After a certain period of degradation, samples were taken out and washed with distilled water repeatedly and dried in vacuum oven at 40°C for 8 h.

Intrinsic viscosity

The intrinsic viscosity was measured by using an Ubbelohde viscometer (capillary diameter = 0.5 mm) at 20°C. The chloroform was used as solvent and the five different concentrations were studied for each sample. The intrinsic viscosity is then determined by plotting the data as described in literature.

Thermal analysis

Differential scanning calorimetry (DSC) studies were performed on Perkin–Elmer DSC-7 system. Vacuum dried samples were loaded and the thermograms were run in the temperature range of 50–200°C under nitrogen atmosphere at a heating rate of 10°C/min. The heat of fusion (ΔH_f) values were obtained from the area under the melting thermograms. The crystallinity was obtained by the following expression³³:

$$\text{Crystallinity (\%)} = \frac{\Delta H_f}{\Delta H_{f(\text{crys})}} \times 100$$

where, ΔH_f is the heat of fusion of the sample and $\Delta H_{f(\text{crys})}$ is the heat of fusion of 100% crystalline PLA and was taken as 93.7 J/g.

Thermogravimetric analysis (TGA) was carried out using Perkin–Elmer TGA-7. The tests were carried out in nitrogen atmosphere for the temperature range of 50–500°C with the heating rate 10°C/min. The initial decomposition temperature (IDT) was

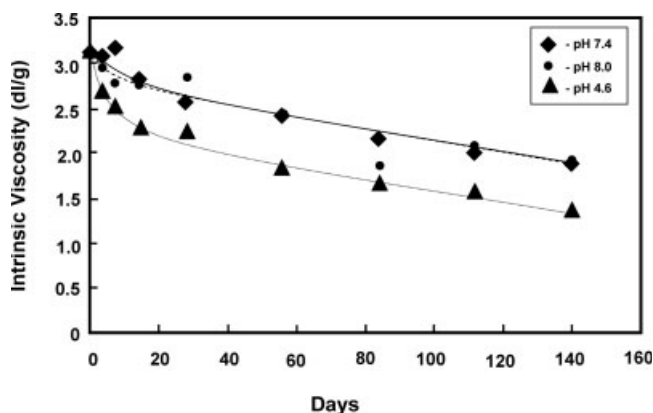


Figure 1 Variation of intrinsic viscosity with the degradation time at different pH.

determined from the slopes of the thermograms where degradation is initiated.

Scanning electron microscopy (SEM)

The surface characteristics of fibers were studied using LEO 435 VP (Leica-Oxford Link-Isis) SEM, after coating them with gold.

Contact angle measurement

The dynamic contact angle of PLA monofilament with distilled water was measured by a digital contact angle measurement system DCAT-11 from DATAPHYSICS, Germany.

RESULTS AND DISCUSSION

The hydrolysis of ester linkage in the main chain causes the degradation of PLA. In this study, the *in vitro* degradation of PLA monofilament and knitted scaffold was carried out at three different pH conditions of 4.6, 7.4, and 8.0. The changes in intrinsic viscosity of PLA following the *in vitro* degradation are shown in Figure 1. The results showed that the intrinsic viscosity of PLA decreases gradually along the degradation period irrespective of the pH and the medium. After 20 weeks of degradation, the intrinsic viscosity dropped from 3.11 dL/g to 1.48, 1.88 and 1.9 dL/g for the pH 4.6, 7.4, and 8.0 respectively. The severe degradation observed in case of pH 4.6 as compared to the normal and weak basic conditions. It means that the hydronium ions have significant catalytic effects on the hydrolysis of PLA. The similar behavior was observed by Tsuji and Ikarashi²⁸ There is catalytic effect of pH on degradation process. As the pH deviates from neutral pH, the change in the reaction rate may be accelerated due to catalytic effect.³⁴ It was reported that the rate

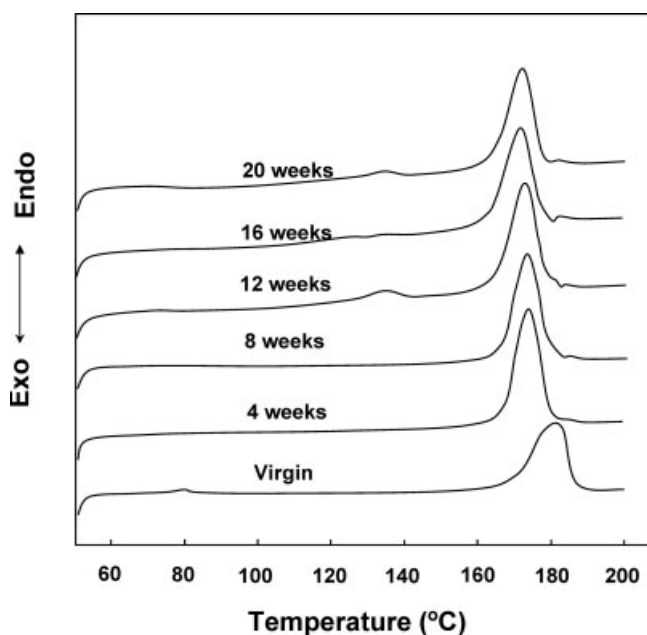


Figure 2 DSC thermograms of the PLA degraded for various time periods at 4.6 pH.

of hydrolysis increases with an increase in pH deviation from 7. *In vivo* degradation of PLA also showed the decrease in intrinsic viscosity as the degradation proceeds.^{17,20}

The thermal behavior of the PLA for different degradation periods was studied by DSC and TGA analysis. The DSC thermograms are shown in Figures 2–4. The thermograms exhibited no recrystallization peaks

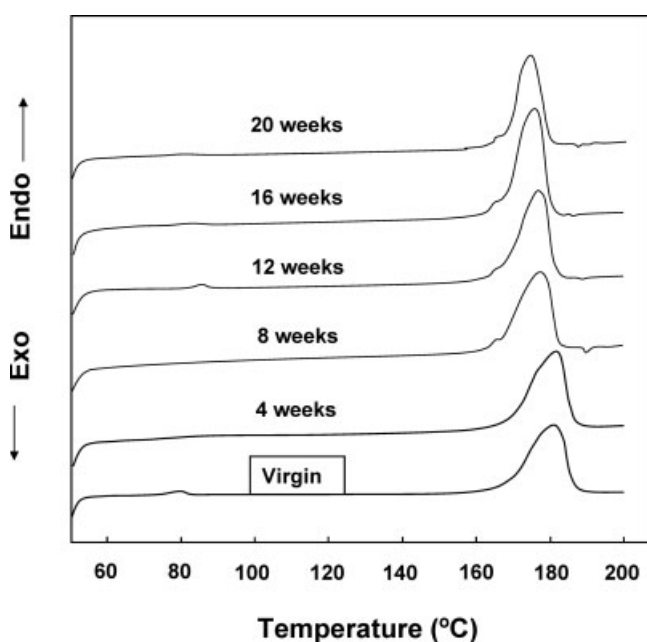


Figure 3 DSC thermograms of the PLA degraded for various time periods at 7.4 pH.

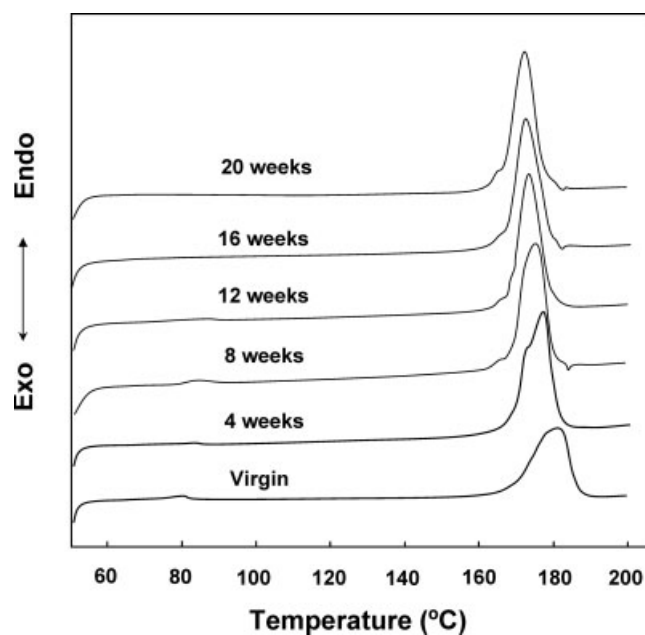


Figure 4 DSC thermograms of the PLA degraded for various time periods at 8.0 pH.

because the PLA apparently had high crystallinities. The data of crystallinity was shown in Figure 5. It is observed that the crystallinity of the PLA increases as the degradation period increases for all the pH. The increase in the crystallinity is higher as pH deviates from pH 7.4. At pH 7.4 the increase in crystallinity was 5.3% whereas at pH 8.0 and 4.6, the increase in crystallinity is 18.8 and 21.9%, respectively, after the 140 days of degradation.

The increase in the crystallinity during the degradation can be explained with two mechanisms. It may be the result of rearrangement of shorter molecular chains generated by the degradation process itself, along with the consequent formation of new crystals. Or it may be due to the degradation of the

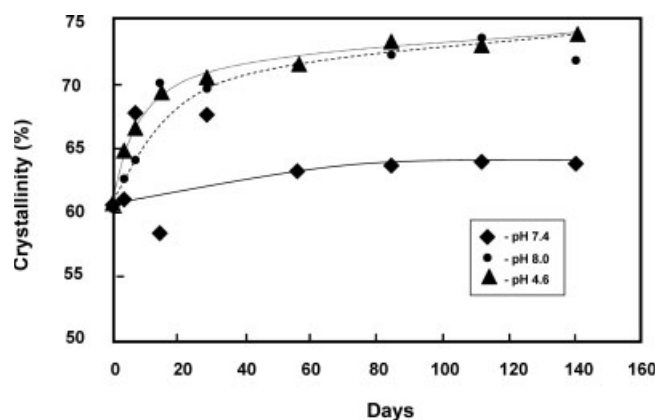


Figure 5 Variation of crystallinity with the degradation time at different pH.

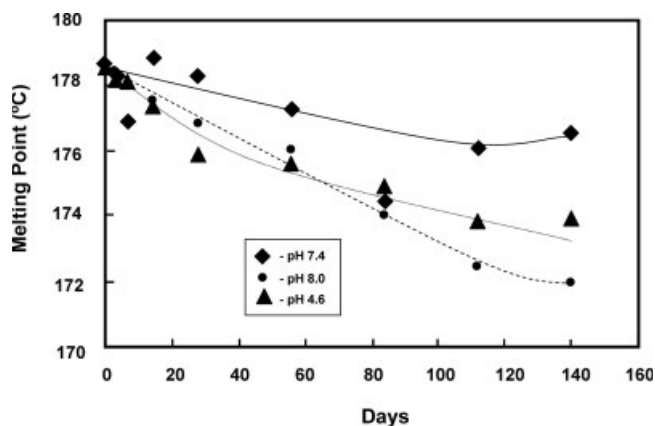


Figure 6 Variation of the melting point of PLA with degradation time at different pH.

amorphous part of the polymer merely results in a larger percentage of crystalline phase being left behind.¹ The arrangement of macromolecules in amorphous region of semicrystalline polymers is more irregular and less compact as compared to that of crystalline region. These macromolecules in amorphous region are more susceptible for initial hydrolysis. As the hydrolysis proceeds in this region, the mobility of macromolecules increases as the overall entanglement decreases, which results in the rearrangement of molecular chains and the apparent crystallinity observed to be increased. The same observation was reported by various researchers.^{6,20,23,29,30}

Figure 6 represents melting point of PLA with respect to degradation time for all three pH determined by DCS analysis. It was observed that as the degradation proceeds, the melting point decreases.

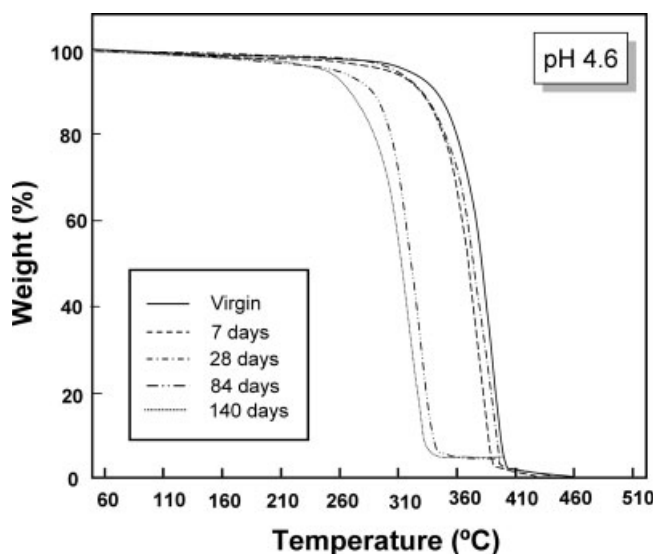


Figure 7 TGA analysis of the PLA degraded for various periods at 4.6 pH.

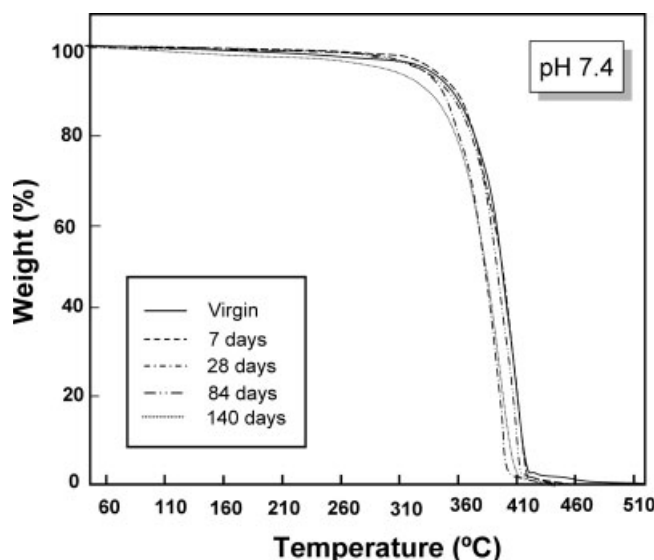


Figure 8 TGA analysis of the PLA degraded for various periods at 7.4 pH.

For pH 7.4, Yuan et al.²³ reported the same trend for low molecular weight PLA and the reverse trend for high molecular weight PLA. Tsuji and Ikarashi²⁸ observed rise in melting temperature with the degradation time for same pH. It may be due to the fact that the crystalline thickness decreases by the hydrolysis. The observations for higher and lower pH are similar to the trend observed in the present work. It confirms that the hydronium and hydroxide ions have significant catalytic effects on hydrolysis of PLA with respect to the crystallinity.

The thermogravimetric analysis of PLA is shown in Figures 7–8. It is observed that the IDT progressively decreases initially as the degradation proceeds and tends to stabilize beyond 8 weeks of degradation (Table I). However, at pH 4.6, the IDT continues to decrease even up to 20 weeks of degradation. It confirms the fact that the fragments with shorter chain length degrade at a relatively lower temperature. As the degradation proceeds, the fraction of these short

TABLE I
Initial Degradation Temperature (IDT) Derived from TGA Analysis

Days	Initial degradation temperature (°C)		
	pH 7.4	pH 8.0	pH 4.6
0	364	364	364
3	360	350	366
7	338	352	358
14	344	356	356
28	328	364	356
56	334	346	360
84	342	346	308
112	348	344	306
140	348	348	295

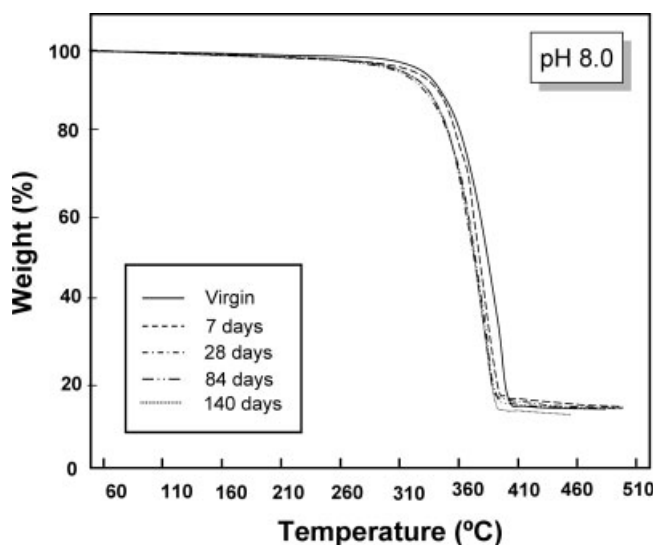


Figure 9 TGA analysis of the PLA degraded for various periods at 8.0 pH.

length macromolecules increases, which causes the decrease in the IDT. The degradation at pH 4.6 shows a drastic loss in IDT of PLA. This is in line with our observations that the acidic environment of pH 4.6 is highly drastic as compared to a pH of 8 and leads to much shorter chains thereby decreasing the IDT significantly.

Surface characteristic of the PLA changes with degradation process. PLA is a relatively hydrophobic polymeric material. The surface behavior of PLA was characterized using Tensiometer by measuring the contact angle with respect to water. The contact angle tends to reduce as the degradation temperature increases and subsequently stays constant beyond the degradation period of 50 h. It is observed that the contact angle value for normal PLA is 73° and with increase in degradation time, contact angle

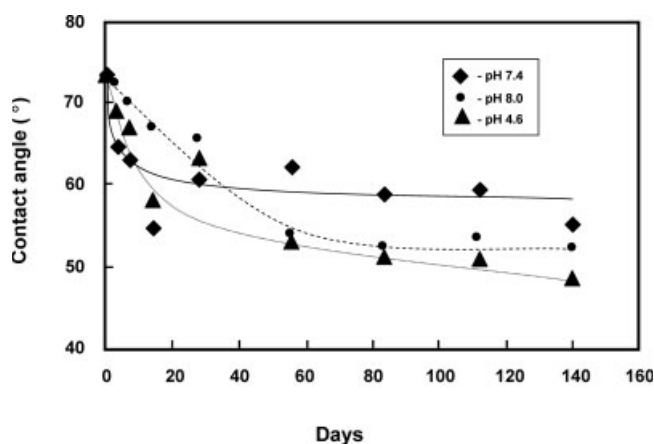


Figure 10 Contact angle variation with the degradation time at different pH.

value decreases, which shows that the PLA has become less hydrophobic as it degrades. It is observed that the contact angle is 55° and 52° for the

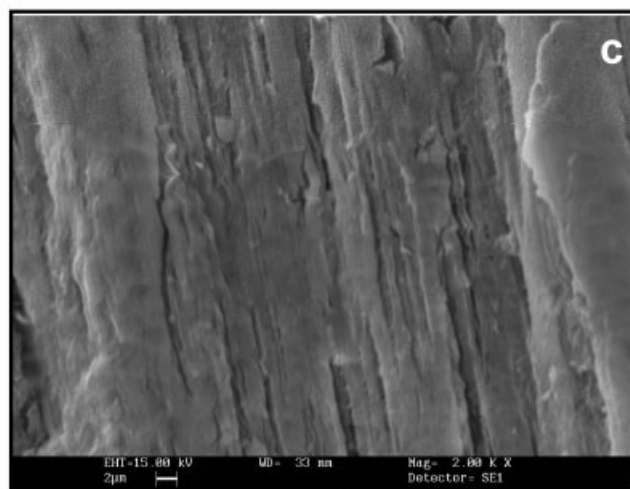
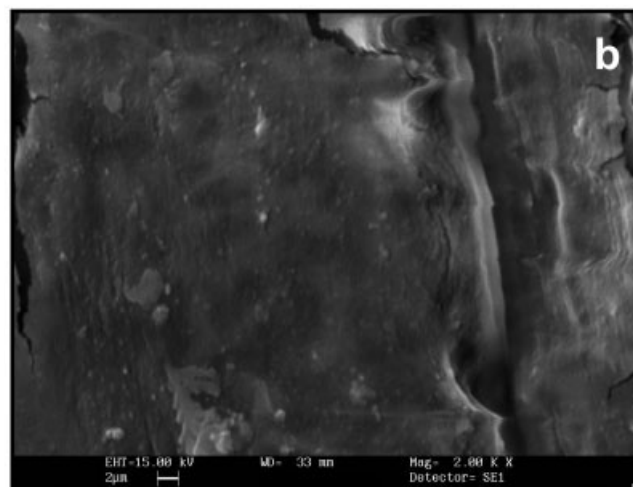
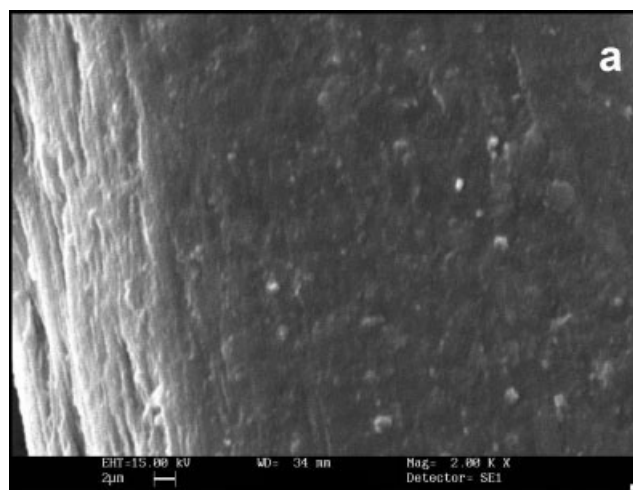


Figure 11 SEM of PLA fibers degraded at pH 4.6 pH. (a) control PLA sample; (b) degradation time 8 weeks; (c) degradation time 20 weeks.

samples degraded at pH 7.4, and 8.0 for the time period of 20 weeks. For the same sample, which degraded at pH 4.6, the contact angle observed to be slightly lower that is 48° (Fig. 6). It again confirms the faster degradation of PLA at a lower pH. Since the contact angle is related to the surface functionality and polarity, it may be proposed that the polar functional groups such as carboxyl and hydroxyl groups are created by the ester linkage hydrolysis on the surface. The concentration of these groups increases as the degradation period increases. This introduces hydrophilicity on its surface and reduces the contact angle.

The morphology of the PLA fiber was studied by SEM. The SEM micrographs of the PLA fibers before degradation and degradation after 20 weeks at different pH are shown in the Figures 7–13. From the picture of the PLA fiber before degradation (Fig. 8 control), this fiber did not show any obvious defects on its surfaces. After 8 weeks of degradation, the

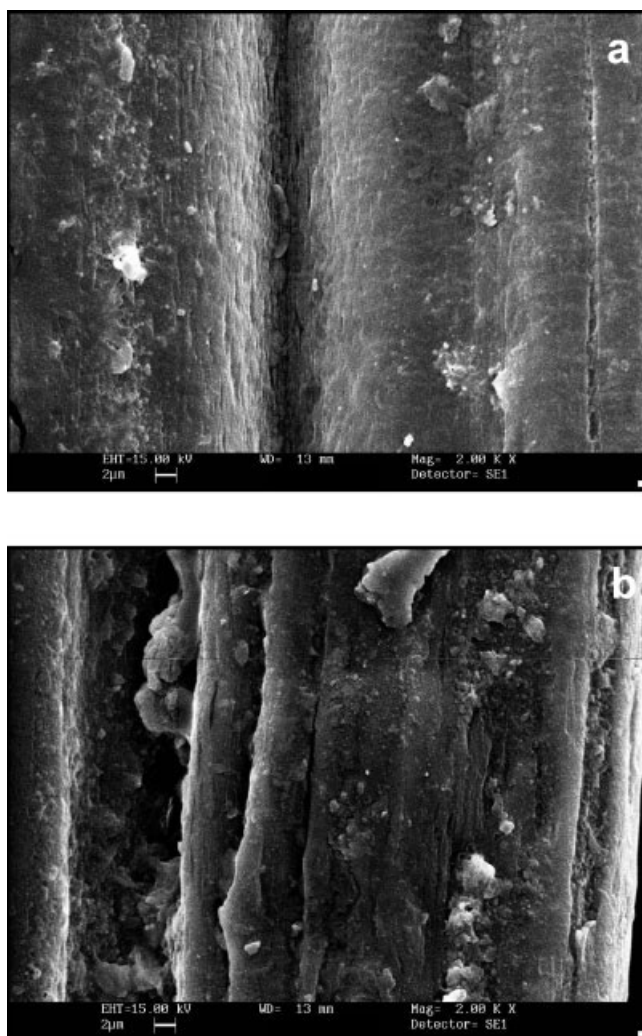


Figure 12 SEM of PLA fibers degraded at pH 7.4. (a) degradation time 8 weeks; (b) degradation time 20 weeks.

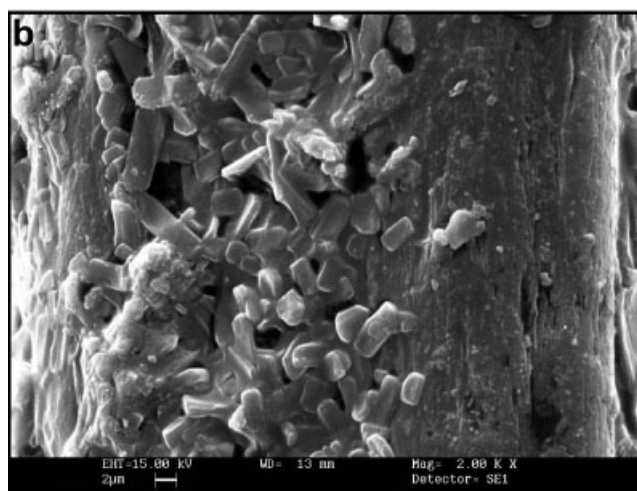
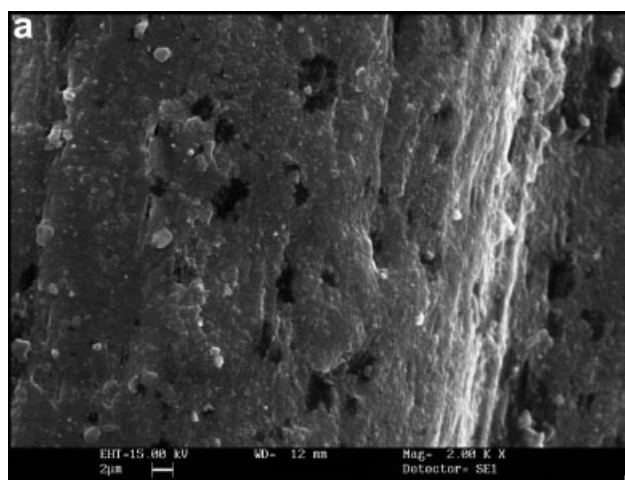


Figure 13 SEM of PLA fibers degraded at 8.0 pH. (a) degradation time 8 weeks; (b) degradation time 20 weeks.

surface shows roughness (Figs. 7a, 8a, 9a). However after 20 weeks of degradation, fiber surfaces deteriorated as seen in the pictures (Figs. 7b, 8b, 9b). The severity of degradation is a maximum in case of the fiber degraded at pH 4.6 as observed. At lower pH, faster degradation of PLA is observed due to heterogeneous erosion of PLA through autocatalysis. The generated monomers, which are carboxylic acids accelerate polymer degradation by lowering pH.³² Some segments of PLA in the amorphous regions get hydrolyzed and removed by the medium. It also gives the catalytic effect to the degradation process as the more area gets exposed to the medium.

CONCLUSIONS

The *in vitro* degradation of PLA fiber spun by dry-jet-wet technique and its knitted scaffold is characterized by various techniques. It is observed that pH of the medium has significant effect on the degrada-

tion behavior of the PLA. The intrinsic viscosity of the polymer drops drastically at pH 4.6 compared to higher pH values. There is an apparent increase in the crystallinity of PLA as the degradation proceeds. The surface hydrophilicity of PLA increases with the increase in the degradation time as reflected from the contact angle.

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