Investigating the Properties and Hydrolysis Ability of Poly-Lactic Acid/Chitosan Nanocomposites Using Polycaprolactone

Nguyen Thi Thu Trang[1], Nguyen Thuy Chinh[1], Dinh Thi Mai Thanh[1], To Thi Xuan Hang[1], Nguyen Vu Giang[1], Thai Hoang[1, *], Pham Minh Quan[2], Le Duc Giang[3], Nguyen Viet Thai[4], and Geoffrey Lawrence[5]

[1] *Institute for Tropical Technology, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Cau Giay, Ha Noi, Vietnam*
[2] *Institute of Natural Products Chemistry, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Cau Giay, Hanoi, Vietnam*
[3] *Vinh University, 182 Le Duan, Vinh City, Nghe An, Vietnam*
[4] *Faculty of Technical Physical Chemistry, Le Quy Don Technical University, 236 Hoang Quoc Viet, Cau Giay, Hanoi, Vietnam*
[5] *Australian Institute for Bioengineering and Nanotechnology, The University of Queensland, Brisbane 4072, QLD, Australia*

Poly-lactic acid (PLA) has been widely applied in the medical field (in biomedicines such as medical capsules, surgical sutures and suture wounds) owing to its high biodegradability, good biocompatibility and ability to be dissolved in common solvents. Chitosan (CS) is an abundant polysaccharide and a cationic polyelectrolyte present in nature. In this study, the combination of PLA and CS has been used to form PLA/CS nanocomposites having the advantages of both the original components. To enhance the dispersibility and compatibility between PLA and CS in the PLA/CS nanocomposites, polycaprolactone (PCL) is added as a compatibilizer. The Fourier Transform Infrared spectroscopies prove the existence of the interactions of PCL with PLA and CS. A more regular dispersion of CS of 200–400 nm particle size, is observed in the PLA matrix of the PLA/CS nanocomposites containing PCL, through the Field Emission Scanning Electron Microscopy images. The appearance of one glass transition temperature (T_g) value of PLA/CS/PCL nanocomposites occuring between the T_g values of PLA and CS in DSC diagrams confirms the improvement in the compatibility between PLA and CS, due to the presence of PCL. The TGA result shows that PCL plays an important role in enhancing the thermal stability of PLA/CS/PCL nanocomposites. The hydrolysis of PLA/CS/PCL nanocomposites in alkaline and phosphate buffer solutions was investigated. The obtained results show that the PLA/CS/PCL nanocomposites have slower hydrolysis ability than the PLA/CS composites.

Keywords: Poly-Lactic Acid, Chitosan, Polycaprolactone, Glass Transition Temperature, Hydrolysis.

1. INTRODUCTION

Chitosan (CS) is a biodegradable polymer obtained by the deacetylation of chitin, which is present in the shells of insects and marine crustaceans. Chitosan has a number of beneficial properties including biodegradability, bioactivity, non-toxicity, good adhesion and sorption. In spite of these advantageous potentials of CS, both its poor mechanical, processing properties and its insolubility in common organic solvents have delayed its application.[1, 2]

In recent years, biodegradable thermoplastic polymers have attracted attention as biomaterials, particularly for tissue engineering, gene therapy, wound healing and

*Author to whom correspondence should be addressed.

controlled drug delivery.[1] The important polymers used in biomedical applications due to their good mechanical properties, excellent thermal/mechanical properties and superior transparency are poly-lactic acid (PLA), poly-glycolic acid (PLGA), polycaprolactone (PCL), polyhydroxybutyrate (PHB). However, the high crystallinity, strong hydrophobicity and especially the lack of bioactive functions of PLA matrix has often resulted in an uncontrollable biodegradation rate and an undesirable biological response to cells and/or tissues. Therefore, it is promising to combine the bioactive functions of CS with the good mechanical properties of PLA to generate a new kind of biohybrid materials.[2] The earlier reports showed that the compatibility between PLA and CS was limited because of the different structure and hydrophilic property.[3–6] A non-toxic compatibilizer such as PCL, polyethylene oxide (PEO), polyethylene glycol (PEG) was used to improve the compatibility and dispersion between PLA and CS and develop the applications of PLA/CS composites. Rajan et al.[7] investigated the effect of PEG as a compatibilizer in the Rifampicin drug delivery system of CS-PLA-PEG-gelatin nanoparticles. In our previous paper, we studied the effect of PEG on the morphology, thermal property and hydrolysis of PLA/CS composites.[8] The obtained results clearly show that PEG played an important role in increasing the compatibility between PLA and CS. However, using PCL as a compatibilizer for PLA/CS composite and its application in drug delivery has not been investigated yet. Thus in this study, we have focused on investigating the properties and the hydrolysis ability of PLA/CS nanocomposites using PCL. The suitable content of PCL and regression equation for hydrolysis of PLA/CS/PCL nanocomposites have also been presented and discussed in this paper.

2. EXPERIMENTAL SECTION

2.1. Raw Materials

Poly-lactic acid (PLA) was purchased from Nature-Works LLC, USA. Chitosan (CS) and polycaprolactone (PCL) were obtained from Sigma-Aldrich, USA. Chloroform, sodium hydroxide, phosphate buffer solution were of analytical reagent grade and used without further purification.

2.2. Sample Preparation

PLA/CS nanocomposites were prepared by solution method. 400 mg PLA was dissolved in 25 ml chloroform to form a fine solution. CS (at a concentration of 20 wt% in comparison with PLA's weight) was dissolved in acetic acid 1% solution (v/v) at room temperature under magnetic stirring. PCL as a compatibilizer was added to the PLA solution at different ratios (0, 2, 4, 6, 8, 10 wt% of PCL compared to PLA). They are abbreviated as PCL0; PCL2, PCL4, PCL6, PCL8 and PCL10 respectively. The PLA/CS composites were obtained by solvent casting on a

Petri dish, followed by evaporation of the solvent at room temperature for 24 hours and then drying in a vacuum oven at 40 °C for 8 hours.

2.3. Characterization

Fourier transform infrared (FT-IR) spectra of PLA/CS/PCL nanocomposites were recorded on a Nicolet/Nexus 670 spectrometer (USA) at room temperature by 16 scans with 4 cm^{-1} resolution and wave number ranging from 400 to 4000 cm^{-1}. Field emission scanning electron microscopy (FE-SEM) of PLA/CS/PCL nanocomposites coated by platinium was conducted using a S-4800 FE-SEM instrument (Hitachi, Japan). Thermal property study was performed on as DSC-60 thermogravimetric analyzer (Shimadzu Co.) under argon atmosphere from room temperature to 400 °C at a heating rate of 10 °C/min. Determination of weight loss of the samples in phosphate buffer and sodium hydroxide solutions is based on the weight change after hydrolysis by the formula: $m = ((m_b - m_s)/mb) \cdot 100\%$, in which m is loss weight of samples (%), m_b is initial sample weight (g), and m_s is loss weight of samples after hydrolysis (g).

3. RESULTS AND DISCUSSION

3.1. FT-IR Spectra

Figure 1 shows FTIR spectra of pure PLA, CS, PCL0 and PCL6. In the case of CS, the broad band at 3426 cm^{-1} corresponds to the amine and hydroxyl groups, the peak at 2888 cm^{-1} is due to the –CH stretching and the absorption band at 1670 cm^{-1} is due to the carbonyl (C=O) stretching of the secondary amine and the bending vibrations of the N–H is seen at 1581 cm^{-1}. The peaks at 1081 cm^{-1} and 955 cm^{-1} belong to the assigned saccharine structure.[1, 2] Several characteristic bands of PLA are located at 697 cm^{-1} (753 cm^{-1} and 866 cm^{-1} corresponding to aldehyde CH stretching); 1193 cm^{-1} and 1101 cm^{-1} (corresponding to C–O stretch due to alcohols); 1452 cm^{-1} and 1368 cm^{-1} (due to the CH and CH$_3$

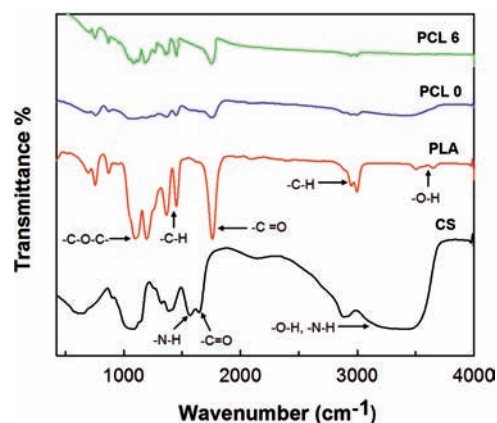**Figure 1.** FTIR spectra of PLA, CS, PCL0 and PCL6.

bend corresponding to alkanes and alkenes); 2945 cm^{-1} (denoting the CH stretch); 2991 cm^{-1} (representing the CH$_3$ stretch); and 3499 cm^{-1} (for the OH stretch).[1,2,7] In comparison to the spectra of PLA and CS, a noticeable amount of change occurs in the FTIR spectra of PCL0 and PCL6 samples. The intensity of the stretching bands gets overlapped and centered near 3426 cm^{-1} for the hydroxyl groups and the amino groups pronouncedly decreases in the PLA. Additionally, the stronger shift (5–20 cm^{-1}) of some peaks characterized carbonyl, amino and hydroxyl groups in the FTIR of PCL6 in comparison with that of PCL0, neat PLA and CS. It is clear that there are interactions such as hydrogen bonding and dipolar interaction among the amino and hydroxyl groups (in CS), carbonyl and hydroxyl groups (in PCL), and carboxyl groups (in PLA) of PLA/CS nanocomposites in the presence of PCL. There is no covalent interaction between PLA and CS chains. The FTIR spectra of PCL2, PCL4, PCL8 and PCL10 are similar to the the FTIR spectra of PCL0 and PCL6 samples. These results were reported after the study on CS/PLA nanoparticles,[2] CS-PLA-PEG-gelatin nanoparticles[7] and PLA/CS/PEG composites.[8]

3.2. Thermal Behavior

DSC thermograms of PLA, CS, PCL0 and PCL6 are shown in Figure 2. The DSC data and the degree of crystallinity (χ_c) of PLA, CS and all the nanocomposites are reported in Table I. The glass transition temperature (T_g) of PLA at 54.7 °C characterizing the semi-crystalline PLA and the polymer melting at 150.5 °C (T_m) is revealed by the thermograms of PLA. The CS shows a T_g of 90.5 °C. By the addition of CS and PCL into PLA, the T_g related peaks become broader and shift towards higher temperature when compared with the T_g of PLA. The PCL0 has two T_g values (55.6 °C and 64.3 °C), implying that the PLA and CS have poor compatibility and miscibility. However, there is an appearance of only one T_g with a significant shift from 2 to 12 °C in comparison with the T_g peak of PLA. The T_g values of PLA/CS/PCL nanocomposites are plotted and tabulated for PCL2, PCL4, PCL6, PCL8
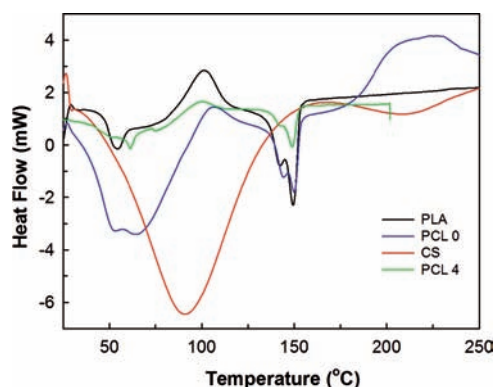
Table I. DSC data and the degree of crystallinity (χ_c) of PLA, CS, PLA/CS and PLA/CS/PCL nanocomposites.

Samples	T_g (°C)	T_m (°C)	ΔH_m (J/g)	χ_c^* (%)
PLA	54.7	150.5	8.5	9.1
CS	90.5	205.3	18.5	–
PCL0	55.6, 64.3	157.3	10.8	11.6
PCL2	56.0	148.1	11.8	12.7
PCL4	61.4	148.9	12.5	13.4
PCL6	56.5	177.9	16.7	17.9
PCL8	57.3	148.9	16.0	17.2
PCL10	66.2	150.7	15.9	17.1

Notes: [*]: $\chi_c(\%) = \Delta H_m \times 100/\Delta H_m^*$ where ΔH_m^* is the heat of fusion for completely crystallized PLA (93.1 J/g).[2] T_g: the glass transition temperature; T_m: the melting temperature; ΔH_m: the enthalpy of melting.

and PCL10 (Fig. 2 and Table I). It is known that the T_g is a complex phenomenon which depends on several factors including intermolecular interactions, steric effects, chain flexibility, molecular weight, branching and cross-linking density.[9] Here due to the presence of CS there are strong interactions between PCL and PLA, CS, leading to the rearrangement of the crystalline structure of PLA. Likewise, melting endothermic peaks of all samples using PCL appears at a higher temperature since CS affects the PLA crystallinity. This also indicates that the polymer phase compatibility took place between the two polymers when using PCL as a compatibilizer.[1,9] The above phenomenon leads to the increase of the degree of crystallinity (χ_c) for all samples using PCL (Table I).

3.3. TGA Analysis

Figure 3 represents the TGA curves of PLA, CS, PLA/CS and PLA/CS/PCL nanocomposites using different PCL content with the temperature ranging from room temperature to 500 °C. CS is degraded by a two-step process. The first step occurring in the range of 90–250 °C corresponds to the loss of absorbed water, surface water and residual acetic acid.[6] The second step is attributed to the decomposition of the saccharide circle, including dehydration in the saccharide structure and the decomposi-
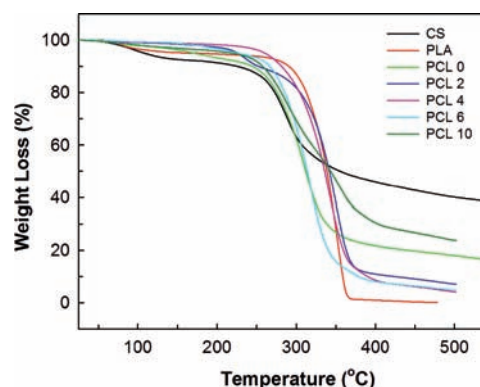

Figure 2. DSC thermograms of PLA, CS, PCL0 and PCL6.

Figure 3. TGA curves of PLA, CS and PLA/CS/PCL nanocomposites.

Table II. TG characterization of PLA, CS and PLA/CS/PCL nanocomposites.

Sample	T_{max} (°C)	Weight loss (%) (°C)				
		250	300	350	400	450
CS	296	12.97	36.99	49.20	54.10	67.30
PLA	352	6.20	13.10	75.70	99.10	99.70
PLA/CS	313	11.19	37.63	73.28	85.78	93.01
PLA/CS/PCL2	350	11.43	19.81	63.18	89.34	91.11
PLA/CS/PCL4	343	5.87	19.63	70.54	91.66	93.97
PLA/CS/PCL6	319	7.90	33.90	84.51	92.11	90.72
PLA/CS/PCL10	330	8.40	27.72	70.93	85.29	87.71

tion of acetyl and di-acetyl in chitin occurring in the temperature range of 250–500 °C, with maximum degradation temperature (T_{max}) at 296 °C.[6, 10, 11] The TGA curves of PLA/CS and PLA/CS/PCL nanocomposites using different PCL content are similar to that of PLA with one value of T_{max} (Table II).[9] The thermal stability of PLA/CS and PLA/CS/PCL nanocomposites is lower than that of PLA, due to low thermal stability of CS. The poor compatibility of PLA and CS is one of major reasons for the low thermal stability of PLA/CS nanocomposite in comparison to all PLA/CS/PCL nanocomposite using different PCL content. It is clear that PCL plays a vital role as a compatibilizer between PLA and CS. Therefore, PLA and CS are better dispersed and combined, significantly improving the thermal stability of the PLA/CS/PCL nanocomposites.[7, 8] This can be proved by lower weight loss of PLA/CS/PCL nanocomposite at different heating temperatures (Table II). Particularly, the PLA/CS/2 wt% of the PCL nanocomposite (PCL2) has the highest T_{max} value and the lowest weight loss in all of the investigated PCLx samples. This shows that CS and PLA are most compatible at 2 wt% of PCL. This is also in line with the results of morphology and DSC analysis as aforementioned.

3.4. FE-SEM Analysis
Figure 4 shows SEM images of PLA/CS/PCL nanocomposites. It is clear that CS particles are dispersed irregularly in the PLA matrix with particle size ranging from about 50 nm to 300 nm. When investigating the increase of PCL content, the PLA and CS are found to be more compatible leading to the phase separation between PLA and CS and the agglomeration of CS particles in the PLA matrix decreases. This is explained by formation of intermolecular interactions between PLA and CS in PLA/CS/PCL nanocomposites as aforementioned.

3.5. Hydrolysis Investigation
The weight loss of PLA, PLA/CS and PLA/CS/PCL nanocomposites is mainly due to the hydrolysis of the PLA by direct influence of water and temperature. Degradation of PLA occurs primarily due to the hydrolysis of the ester links and randomly along the polymer chain in the presence of water.[12, 13]
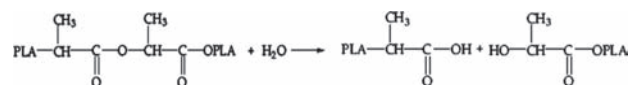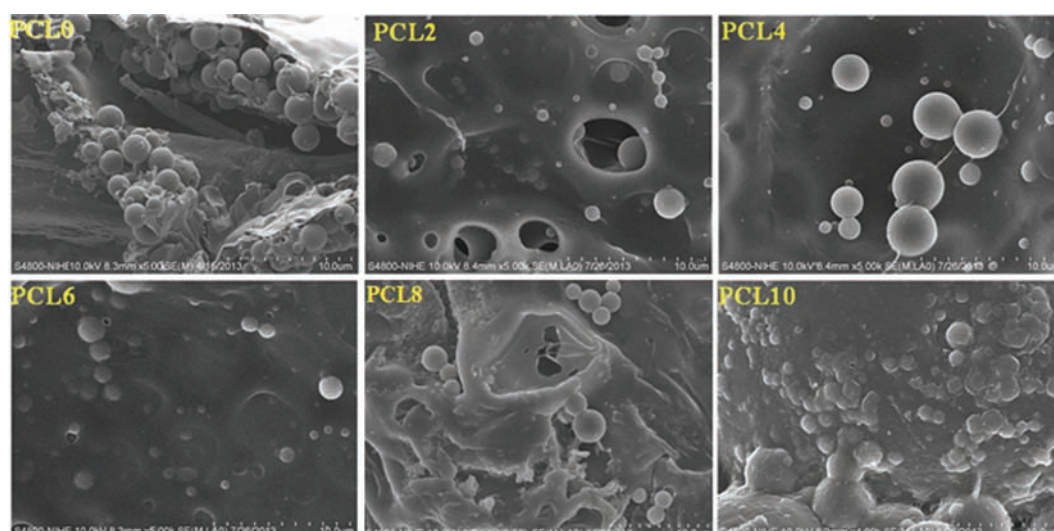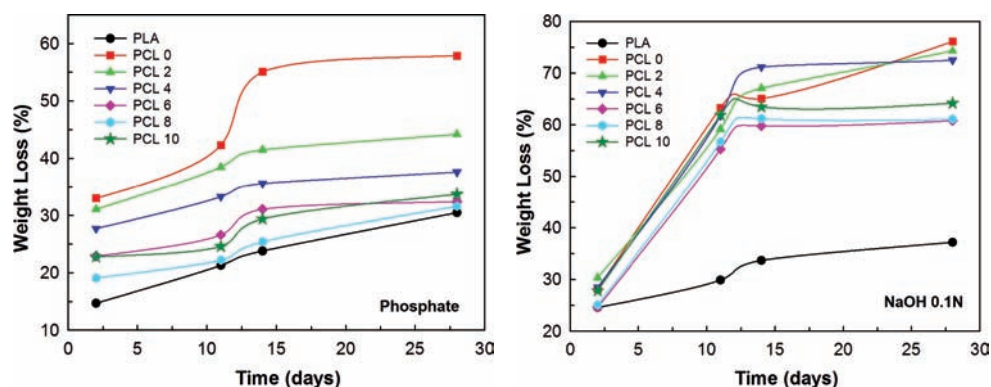

Figure 5 exhibits the loss of weight of PLA from pure PLA, PLA/CS and PLA/CS/PCL nanocomposites versus immersion time in the phosphate buffer of pH = 7.4 and alkaline solution (NaOH 0.1 N). Obviously, the weight loss of nanocomposites in alkaline solution is higher than in phosphate buffer solution, given the same hydrolysis time. This can be explained by OH^-, a strong nucleophilic agent, which attaches to a C atom in the carbonyl groups, causing faster hydrolysis of PLA.[13] It can be clearly seen from the SEM images, that the surface of the nanocomposites was destroyed after 28 days of immersion in the alkaline solution (in Fig. 6).

Figure 4. SEM images of PLA/CS/PCL nanocomposites with different PCL contents.

Figure 5. Weight loss of PLA from PLA, PLA/CS and PLA/CS/PCL nanocomposites versus immersion time in the phosphate buffer (pH = 7.4) and alkaline solution (NaOH 0.1 N).
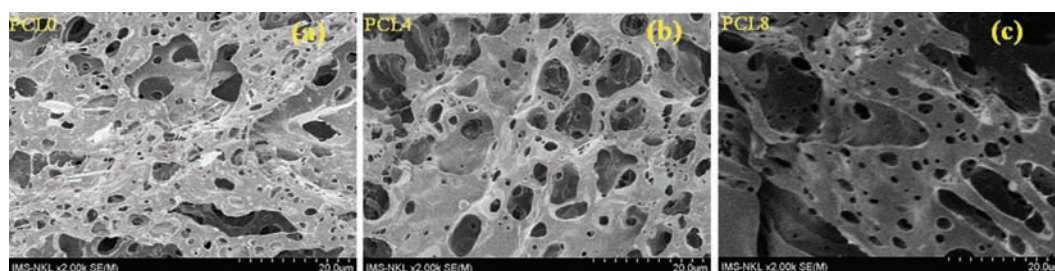
Figure 6. SEM images of PCL0 (a), PCL4 (b) and PCL8 (c) after 28 days of immersion in the alkaline solution.

The regression equations reflecting the relationship between the weight loss of the samples and the hydrolysis time in different solutions, determined according to the obtained data from Figure 4 are presented in Tables III and IV.

Clearly, almost all the obtained equations are suitable quadratic curves, with regression coefficients ranging from 0.892 to 0.999. The highest regression coefficient from the regression equations, reflecting weight loss of PLA from PLA/CS/PCL nanocomposites hydrolyzed in phosphate buffer and alkaline solutions are 0.993 and 0.999, corresponding to the PCL2 and PCL6 samples respectively.

Table III. The regression equation between the weight loss (*Y*-%) of the samples and the hydrolysis time (*X*-days), in phosphate buffer solution.

Sample	Regression equation	R^2
PLA	$y = -0.009x^2 + 0.890x + 12.91$	0.998
PCL0	$y = -0.038x^2 + 2.157x + 28.05$	0.892
PCL2	$y = -0.022x^2 + 1.196x + 28.70$	0.993
PCL4	$y = -0.017x^2 + 0.909x + 25.87$	0.992
PCL6	$y = -0.014x^2 + 0.81x + 21.06$	0.911
PCL8	$y = 0.001x^2 + 0.443x + 18.05$	0.981
	$y = 0.490x + 17.82$	0.981
PCL10	$y = 0.435x + 21.63$	0.914
	$y = -2E - 05x^2 + 0.436x + 21.62$	0.914

Table IV. The regression equation between the weight loss (*Y*-%) of the samples and the hydrolysis time (*X*-days), in alkaline solution.

Sample	Regression equation	R^2
PLA	$y = -0.013x^2 + 0.912x + 22.65$	0.974
PCL0	$y = 18.45\ln(x) + 16.36$	0.991
PCL2	$y = -0.094x^2 + 4.518x + 21.62$	0.998
PCL4	$y = -0.126x^2 + 5.511x + 17.78$	0.997
PCL6	$y = -0.113x^2 + 4.794x + 15.60$	0.999
PCL8	$y = -0.119x^2 + 4.974x + 15.73$	0.998
PCL10	$y = -0.124x^2 + 5.102x + 18.49$	0.989

4. CONCLUSION REMARKS

The FTIR spectra of PLA, CS and PLA/CS/PCL nanocomposites show the existence of interactions between the characterized functional groups in PLA, CS and PCL. The DSC analysis results prove the compatibility between PLA and CS in the presence of PCL as a compatibilizer, leading to an increase in the degree of crystallinity for all PLA/CS/PCL nanocomposites. Thermal stability of PLA/CS/PCL nanocomposites is shown to improve significantly in the presence of PCL. SEM images of the nanocomposite indicates that PCL improves the compatibility between PLA and CS. In the alkaline solution, the nanocomposites have higher weight loss than in the phosphate buffer solution. The most suitable regression equation for the hydrolysis process in the phosphate buffer and the alkaline solutions are 0.993 and 0.999, corresponding to the PCL2 and PCL6 samples respectively.

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