Research Article

Evaluation resistance levels of the PCL/Gt nanofiber mats during exposure to PAHs for use in the occupational setting

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Abstract
Polycyclic aromatic hydrocarbons (PAHs) are present in the environment as well as in occupational settings. Occupational exposure of workers to PAHs has been associated with an increased risk of developing skin injuries, and therefore, it is very important to limit skin exposure to PAHs. The past few decades have been seen a growing trend toward the use of the electrospinning technique in various applications. It provides an effective means of producing nanofibers with desirable properties. Polycaprolactone (PCL)/gelatin (Gt) nanofibers were successfully prepared by electrospinning. Electrospun PCL/Gt composites were analyzed by scanning electron microscope. The degradation behaviors of nanofibers were examined in both phosphate buffered saline and naphthalene at two different temperatures for 14 days. The highest degradation rate was observed for all nanofibers during the first week. The high content PCL nanofibers degraded at a slightly faster rate than the high content Gt nanofibers. It seems that PCL/Gt nanofiber mats could use for skin care materials during exposure to PAHs.

Keywords Polycyclic aromatic hydrocarbons · Nanofiber · Degradation · Electrospinning · PCL · Gelatin

1 Introduction

Polycyclic aromatic hydrocarbons (PAHs) are comprised of at least two benzene rings, such as benzo(a) pyrene, naphthalene, and anthracene [1]. PAHs are carcinogenic agents that can come into contact with humans, both in the environment and particularly in some industrial workplaces [2, 3]. Dermal exposure to PAHs can be important in some occupational environments due to contact with contaminated surfaces such as clothing and tools [4, 5]. Several studies have shown that dermal exposure might have much greater health effects than inhalation exposure [6, 7]. Naphthalene, the simplest PAH, is widely used in some production processes such as plasticizers, resins, insecticides, and surfactants [8–10]. Naphthalene exposure causes adverse health effects such as carcinogenicity, cataracts, laryngeal tumors, and hemolytic anemia in children [9, 10]. Naphthalene has been classified as a possible human carcinogen by various agencies including the International Agency for Research on Cancer (IARC), Environmental Protection Agency (EPA), German Research Foundation (DFG), and National Toxicology Program (NTP) [10–14]. The absorption of naphthalene across the skin is fast. This is due to its hydrophobicity and small molecular weight. Exposure to naphthalene has been shown to cause P450 enzymes to metabolize naphthalene into reactive electrophilic molecules in the skin [9]. Several studies have demonstrated that the skin can metabolize naphthalene into a number of metabolites (naphthyl-keratin adducts) [9–16]. Thus, determining how to protect the skin from PAHs is important. The use of skin barriers such as creams, gels, and clothing in the workplace can help prevent the dermal absorption of PAHs

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and can also help prevent or reduce the development of skin injuries such as dermatitis and cancer [17, 18]. Due to the unique properties of nanofiber mats such as their large surface area and high porosity, they have been proposed for use in skin care applications in the workplaces in order to prevent injury [19].

Electrospinning is an efficient, inexpensive, and simple technique for the fabrication of nanofiber mats for various purposes [20–22]. This technique can be used to develop materials for use in filtration, protection, electrical and optical applications, sensors, chemical and biologically resistant clothing, and others [23–26]. The morphology of nanofibers is strongly influenced by the parameters of electrospinning such as solution parameters, processing parameters, and ambient parameters [27, 28]. Some studies have been carried out on polymer combinations, in particular, a blend of natural and synthetic polymers, for improving their biological and physicochemical features [28, 29]. Polycaprolactone (PCL) is a synthetic polymer that has a low cost, high mechanical strength and good biocompatibility [30, 31], but a disadvantage of nanofibers made from synthetic polymers such as PCL is their low hydrophilicity and lack of surface cell-recognition sites that lead to low-affinity interactions between cells and PCL fibers [32]. Gelatin (Gt) is a biopolymer that has good biocompatibility, biodegradability, and commercial availability [31, 33]. One limitation of Gt is its weak mechanical properties [32]. Therefore, it seems possible that Gt can be combined with PCL to enhance their processability and desirable traits [34, 35]. Traditionally, common solvents used in electrospinning PCL/Gt were perfluorinated alcohols such as 1.1.1, 3, 3, 3-hexafluoro-2-propanol (HFIP) and 2, 2, 2-trifluoroethanol (TFE), but these solvents are expensive, very toxic, and corrosive. The vapors of these solvents can cause injuries such as eye damage and serious respiratory system problems [30, 31, 35, 36]. Therefore, cheaper and less toxic solvents need to be used to prepare PCL/Gt solutions [29, 30, 32].

The aim of this study was to investigate the characteristics of electrospun PCL/Gt nanofiber mats, such as the morphology of the PCL/Gt nanofibers, degradation of the electrospun nanofiber mats in phosphate buffered saline (PBS), and the stability and resistance levels of the PCL/Gt nanofiber mats for use as skin care materials during exposure to PAHs and their stability at high ambient temperatures in occupational settings.

2 Materials and methods

2.1 Materials

PCL (Mw = 80,000 g/mol) and gelatin, from porcine skin type A (Gel Strength _300 g Bloom), were purchased from Sigma-Aldrich along with glacial acetic acid, formic acid, naphthalene, and PBS.

2.2 Solutions preparation

A separate solution was prepared from PCL and gelatin (15% w/w) in glacial acetic acid/formic acid mixed in a 9:1 ratio (AA/FA) for 4 h at room temperature. Following this, PCL and gelatin were mixed at nine different weight ratios (90:10, 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, 20:80, and 10:90) for 20 h at room temperature on a magnetic stirrer prior to electrospinning [30, 36]. The electrospinning process was started about 15–30 min after the preparation was completed.

2.3 Electrospinning process

For the electrospinning process, the polymer solutions were loaded into a 2 ml plastic syringe fitted with a 23G needle. The polymer solution was controlled by a syringe pump. In order to understand the effects of different parameters (voltage, flow rate, distance, and different weight ratios) on morphology nanofibers and electrospinning behavior, a series of experiments were performed. The flow rate of the solution was 0.6–2 ml/h. The distance between the needle tip and collector was 10–20 cm and a high voltage in the range of 8–25 kV was applied. Nanofibers were collected on a flat piece of aluminum foil measuring 12 × 8 cm [30, 36].

2.4 Degradation procedure

All of the samples of the nanofibers were cut into 1 cm^2 pieces and then each piece of the mat was immersed in phosphate buffered saline (PBS, pH 7.4) and incubated at 37 °C or 50 °C for 2 weeks (0, 7, and 14 days). The higher temperature (50 °C) was used to determine whether the nanofiber mats could be resistant to high ambient temperatures in occupational settings.

The nanofiber mats were removed from the PBS at the indicated time intervals, washed with de-ionized water, dried at room temperature for 24 h, and then weighed. Weight loss percentages were calculated as follows:

$$weight\ loss\,(\%) = (W_O - W_t/W_o) \times 100 \quad (1)$$

where W_O is the initial weight of the nanofiber mats before immersing them in PBS and W_t is the residual weight at each time interval [29, 34, 36, 37].

For the purpose of analysis of their properties of stability and degradation behaviors after exposure to PAHs, the nanofiber mats were immersed in two concentrations of naphthalene (500 or 1200 nmol) at 37 °C and 50 °C for

2 weeks and analyzed as described for the PBS experiments [8].

2.5 Characterization of the composite nanofibers mat

The morphology of the electrospun nanofibers was determined by SEM (DSM-960A Model, ZEISS, Germany) at an accelerating voltage of 20 kV. Before SEM analysis, small pieces of the PCL/gelatin nanofiber mats were coated with gold. Using Image J software, the diameters of the 35 different nanofibers were determined.

2.6 Statistical analysis

All data were derived from triplicate samples. All results are reported in mean and standard deviation. The normality of the data was tested with the Kolmogorov–Smirnov method. Statistical analysis was performed using one-way analysis of variance (ANOVA) and Pearson's product-moment correlation test with SPSS-24 software (SPSS, Inc., Chicago, IL, USA). One-way ANOVA was used to compare the degradation behavior of the nanofibers in PBS and naphthalene in two concentrations and at two temperatures.

3 Results

3.1 Fabrication of PCL/Gt nanofibers

Composite PCL/Gt mats with various weight ratios were prepared using the electrospun technique depicted above. Electrospinning parameters such as weigh ratio polymeric solution, applied voltage, needle to collector distance, and so on have significant influence on the nanofibers structure. The optimized processing electrospinning were used to prepare. The results obtained from the optimization of the electrospinning process parameters used for fabrication of the PCL/Gt nanofibers are presented in Table 1.

Table 1 Electrospinning process parameters used for fabrication of PCL/Gt nanofibers

Solution (PCL/Gt)	Flow rate (ml/h)	Voltage (kV)	Distance (cm)
90:10	0.6	10	15
80:20	0.6	12	15
70:30	0.6	12	15
60:40	0.6	12	15
50:50	0.6	10	15
40:60	0.6	12	15
30:70	0.6	12	15
20:80	0.6	12	15
10:90	0.6	10	15

3.2 Morphology of PCL/Gt nanofiber mats

The nanofiber mats composed of PCL and Gt, made by the electrospinning method, used a cost-effective solvent mixture. Figure 1 presents the nanofibrous morphology under SEM by the different volume ratios of PCL/Gt. SEM images revealed the morphological differences among nanofiber mats. The image analysis shows that a uniform structure, smooth surface with non-bead morphology was observed for all types of fibrous mats.

The average fiber diameter of the nanofibers is shown in Table 2. The results of fiber diameter shown in Fig. 1 and Table 2 indicated that with increasing of gelatin content in PCL/Gt blend, the fiber diameter decreased.

3.3 Degradation behavior of PCL/Gt nanofiber mats

In vitro degradation of electrospun fibrous mats was evaluated by immersing them in PBS solution and naphthalene at two temperatures for 14 days. The weight loss of the PCL/Gt nanofibers are shown in Figs. 2a, b, 3a, b and 4a, b.

The results of this study indicate that no difference (P value > 0.05) was found in the degradation behavior of the PCL/Gt nanofibers mats between PBS and naphthalene at either temperature (37 °C and 50 °C) on day 7 and day 14. There was a significant positive correlation between a high gelatin content and more degradation in PBS ($r = 0.988$, $r = 0.981$, respectively, P value < 0.001) and naphthalene at 500 nmol ($r = 0.953$, $r = 0.966$, P value < 0.001) and 1200 nmol ($r = 0.984$, $r = 0.944$, P value < 0.001), at either temperature (37 °C and 50 °C, respectively). The hydrophilicity of PCL/Gt nanofiber mats increased with increasing gelatin content and therefore by increasing gelatin content the biodegrability of PCL/Gt nanofiber mats increased in PBS and naphthalene during a 14-days period.

4 Discussion

Natural, synthetic, or a combination of these polymers can be used for fabricating nanofibrous mats for personal skin care, tissue regeneration, and other uses [34]. For producing non-bead PCL/Gt nanofibers, several parameters such as the solvent, voltage, needle to collector distance, and flow rate were varied to optimize the electrospinning process conditions (Table 1). Composite PCL/Gt mats with various weight ratios were successfully made from an acetic acid/formic acid solvent system. The emulsive structure was formed by mixing the PCL and gelatin in AA/FA solvent. A suitable process

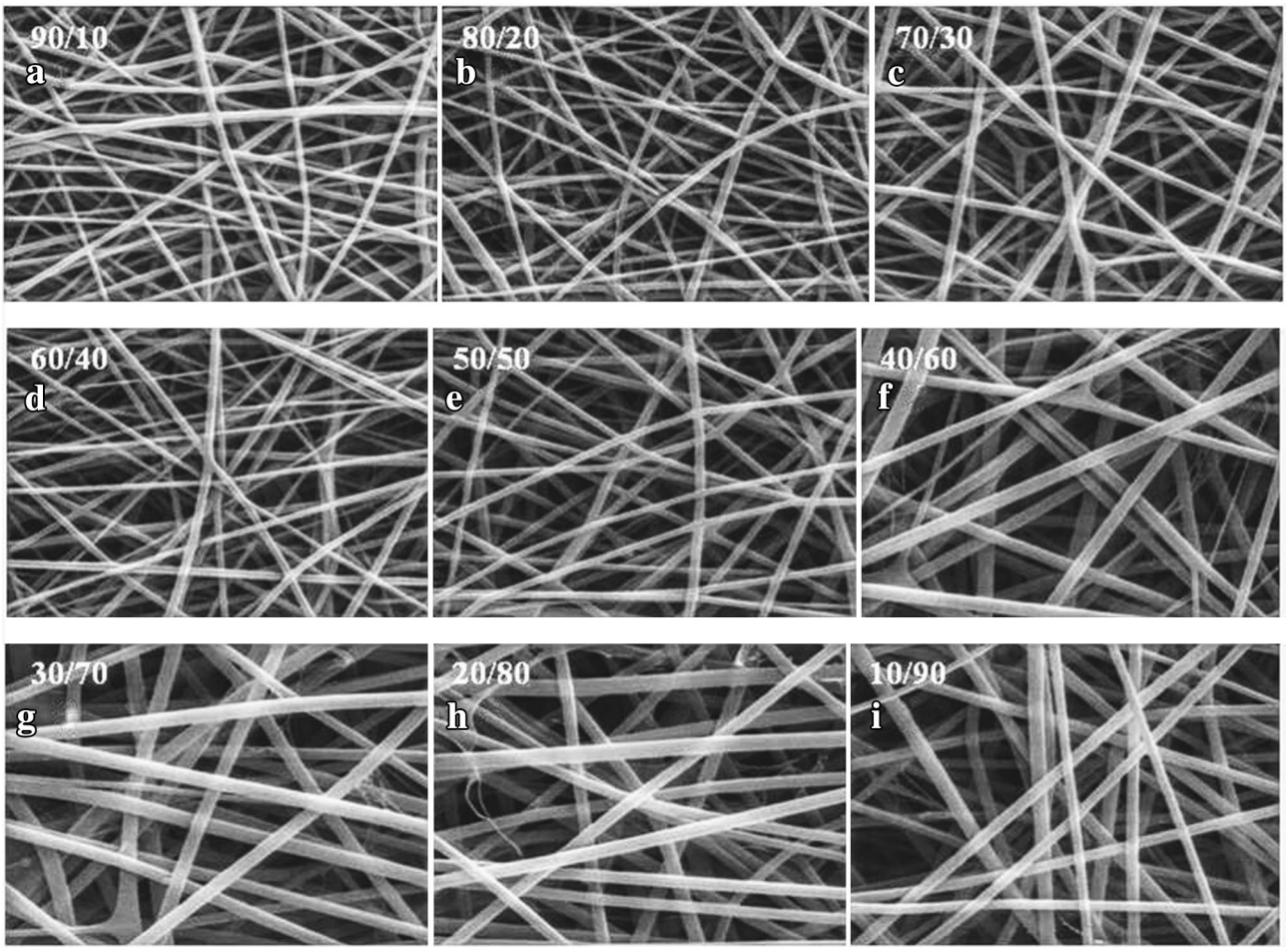

Fig. 1 SEM morphology nanofibrous by the different weight ratio of PCL/Gt: **a** (90:10), **b** (80:20), **c** (70:30), **d** (60:40), **e** (50:50), **f** (40:60), **g** (70:30), **h** (20:80), **i** (10:90)

Table 2 The average fiber diameter of PCL/Gt nanofiber

Ratio(v/v) of PCL/Gt	Average fiber diameter (nm)	Fiber morphology
90:10	37.87 ± 217	Non-bead
80;20	27.84 ± 219	Non-bead
70:30	249 ± 35.55	Non-bead
60:40	271 ± 70	Non-bead
50:50	298 ± 41.29	Non-bead
40:60	191.15 ± 431	Non-bead
30:70	131.15 ± 520	Non-bead
20:80	122 ± 532	Non-bead
10:90	95.5 ± 568	Non-bead

for producing a 15% wt of PCL/Gt nanofiber was a flow rate of 0.6 ml/h, distance 15 cm, and a voltage between 10 and 12 kV. Non-bead fiber morphology was obtained from different ratios of PCL/Gt. The fiber diameter increased gradually from 217 nm to 568 nm upon increasing the content of gelatin. Denis et al. (2015) showed that when using AA/FA as a solvent, PCL/Gt has a good stability in the concentration of 15% w/w and the desire settings for electrospinning was at a voltage range between 8 and 12 kV, where the distance between the syringe needle tip and collector was 15 cm, the flow rate was 0.6 ml/h, and an inner diameter of 0.34 mm was used [30]. In another study, the electrospinning of PCL/Gt was performed with acetic acid, ethyl acetate, and water as a spinning solvent. The optimum concentration of PCL/Gt was 16% w/w. The flow rate of the polymer solution was 1 ml/h, the voltage was 10 kV, and the distance between the needle tip and the collector was 10 cm [29]. Analysis of the fiber diameter showed that a higher PCL content produced a smaller fiber diameter and the average fiber diameter was increased gradually by increasing the gelatin content. A possible explanation for this finding may be the presence of an emulsion, which can be stronger at higher Gt contents. These results are consistent with the data obtained in Denis et al.'s study [30].

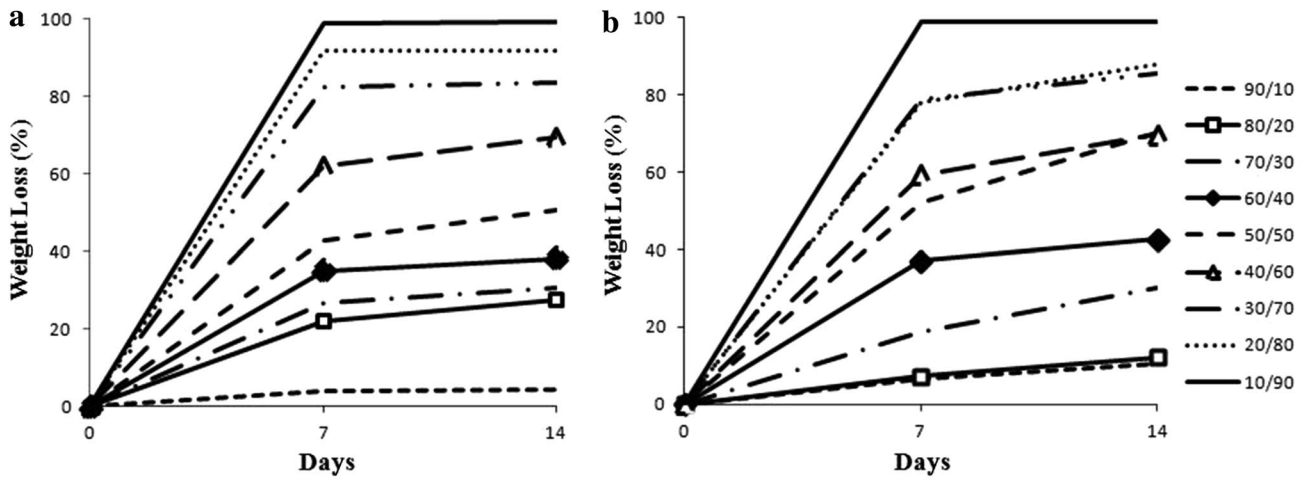

Fig. 2 The percentages of weight loss of PCL/Gt nanofibers in PBS solution at **a** 37 °C, **b**: 50 °C

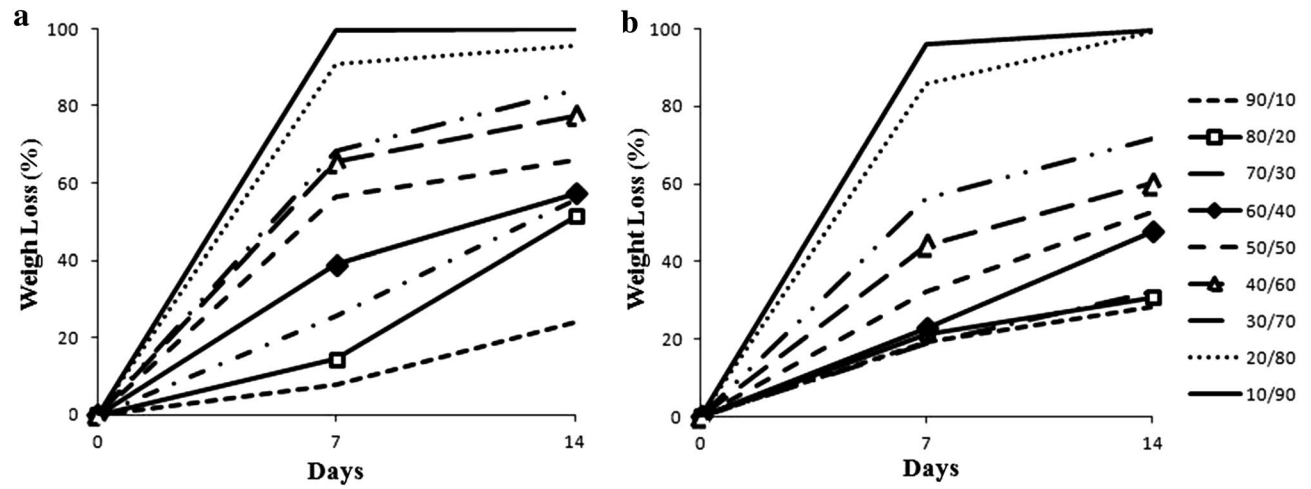

Fig. 3 The percentages of weight loss of PCL/Gt nanofibers in naphthalene (500 nmol) at **a**: 37 °C, **b** 50 °C

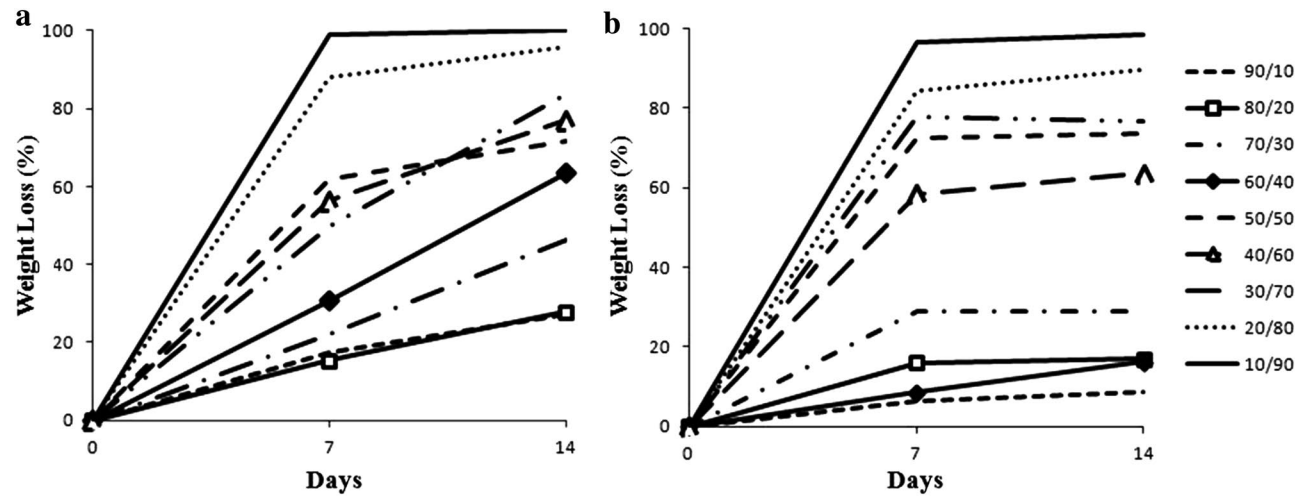

Fig. 4 The percentages of weight loss of PCL/Gt nanofibers in naphthalene (1200 nmol) at **a** 37 °C, **b** 50 °C

Experimental findings of the degradation behavior indicate that weight loss for all PCL/Gt nanofibers mats occurred during the 2 weeks of incubation in PBS and naphthalene at both temperatures, 37 °C and 50 °C. The degradation rate of the PCL/Gt nanofiber mats was faster during the first week of the incubation period and then decreased slowly. It seems possible that these results were due to surface erosion being much faster than the subsequent bulk erosion of the inner part of material during the first week [36]. This result is consistent with previous findings [36, 38]. After 2 weeks in PBS and naphthalene, the PCL/Gt nanofiber mats containing 10–40% gelatin kept their structural integrity while the percentage of weight loss for the 80 and 90% (v/v) gelatin containing composite mats were more than 90% in both solutions (PBS and naphthalene) after 7 days. The hydrophilicity of the PCL/Gt nanofiber mats as a substrate due to the increasing Gt content were improved although their mechanical and structure properties decreased [34]. The presence of amide groups in the gelatin results in the formation of hydrogen bonds with water molecules and thus gelatin is easily dissolved. Gelatin is an amorphous polymer whereas PCL is a crystalline polymer. Thus, nanofiber mats in the amorphous region are more rapidly degraded than nanofiber mats in the crystalline region [31, 34, 39]. There was a significant correlation between a higher gelatin content and more degradation in PBS and naphthalene (P value < 0.001). Dulnik et al. (2016) reported degradation behavior of mats with PCL to gelatin weight content ratios of 90:10, 80:20, and 70:30, and showed that after 90 days of incubation in PBS at 37 °C, there was no significant reduction in molecular degradation of PCL and the degradation speed of the nanofiber mats was very fast during the first day [36]. In the current study, no difference was found in the degradation behavior of PCL/Gt nanofiber mats between PBS and naphthalene (P value > 0.05).

This study produced results that corroborate the findings of a great deal of the previous work in this field [29, 31, 37]. Overall, this study strengthens the idea that PCL/Gt nanofiber mats can be used to produce skin care products for the protection of the health of workers against PAHs. Further experimental investigations are needed to assess the biological properties in vitro of these electrospun nanofiber mats.

5 Conclusions

Advance in nanotechnology and nanofiber production allow the design of electrospinning nanofibers, which have the potential to become the good candidate for numerous applications. Small pore size, high porosities, low basis weight, and high surface area to volume make them ideal candidates for versatile usage in skin care applications. Therefore, nanofibers can be introduced as a better alternatives for skin protection against oxidative stress in occupational settings for worker's healthcare. In this study, PCL/Gt nanofiber was successfully prepared by an electrospinning process using an excellent, economic, and less toxic solvent system. PCL/Gt blends in AA/FA showed an emulsion structure but were stable during the electrospinning of the polymer solution. The results of this study indicate that the concentration of gelatin can influence the degradation behavior of PCL/Gt nanofibers. Nanofiber mats made with a high content of PCL degraded very slowly compared with a higher content of gelatin in PBS and naphthalene solutions. Overall, these results indicate that PCL/Gt nanofibrous mats could have promising application potential for skin care materials in exposure to PAHs. So, it seems that electrospinning nanofibers will continue to attract attention in occupational settings for keeping worker's health in many subsequent years.

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Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest.

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