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Effect of Different Solvent Systems on Fiber Morphology and Property of Electrospun PCL Nano Fibers

Farklı Çözücü Sistemlerinin Elektrik Alan Lif Çekim Yöntemi ile Üretilmiş PCL Nano Liflerin Lif Morfolojisi ve Özelliklerine Etkisi

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EFFECT OF DIFFERENT SOLVENT SYSTEMS ON FIBER MORPHOLOGY AND PROPERTY OF ELECTROSPUN PCL NANO FIBERS

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Abstract: Polycaprolactone (PCL) is biocompatible aliphatic polyester with many possible applications in the medical field. Porous electrospun Polycaprolactone (PCL) fibers were produced through a non-solvent induced phase separation mechanism, using binary solvent systems with different properties. The effect of single and binary solvent systems on the fiber size and surface morphology were investigated. Dichloromethane (DCM) was used as a good solvent in mixtures with a poor solvent, dimethyl sulfoxide (DMSO), in order generate to pores on the fiber surface. The effect of polymer concentrations (12%, 14% and 16%) w/v and solvents ratios (9:1, 7:3 and 5:5) v/v were investigated on nanofiber formation. During electrospun fiber production, the flow rate was 0.12mL/h, the distance between needle and collector was 15cm and the applied voltage was 12kV. SEM micrographs showed successfull production of PCL nanofibers with different solvents. With increasing the polymer concentration and changing the ratio of the solvents porous PCL electrospun nanofiber was produced. In binary solvent systems 16% PCL polymers and (7:3) % solvents ratio solution make even, beads free, smooth and porous PCL electrospun fiber. Combining the inherent properties of the PCL matrix with the characteristic of nanofibrous mats, result in promising materials that can be suitable for different applications, including biomedical applications. The advantages of nanofibrous structures include large surface area, small diameter of pores and high porosity, which make them of great interest in different applications. Porous electrospun fiber is better for cell development.

Keyword: Polycaprolactone (PCL), Electrospinning, Nanofibers, Porous fibers

FARKLI ÇÖZÜCÜ SİSTEMLERİNİN ELEKTRİK ALAN LİF ÇEKİM YÖNTEMİ İLE ÜRETİLMİŞ PCL NANO LİFLERİN LİF MORFOLOJİSİ VE ÖZELLİKLERİNE ETKİSİ

Öz: Polikaprolakton (PCL) tıbbi alanda olası birçok uygulaması bulunan biyouyumlu alifatik bir poliesterdir. Bu çalışmada farklı özelliklere sahip ikili çözücü sistemleri kullanılarak, çözücü kaynaklı olmayan faz ayırma mekanizması yolu ile elektrik alan lif çekimi yönteminde gözenekli PCL lifleri üretilmiştir. Tekli ve ikili çözücü sistemlerinin lif boyutu ve yüzey morfolojisi üzerindeki etkisi araştırılmıştır. Diklorometan (DCM), lif yüzeyinde gözenekler oluşturmak için zayıf bir çözücü olan dimetil sülfoksit (DMSO) ile karışımlarda iyi bir çözücü olarak kullanılmıştır. Nano lif oluşumuna polimer konsantrasyonlarının (%12, %14 ve %16) w/v ve çözücü oranlarının (9:1, 7:3 ve 5:5) v/v etkisi araştırılmıştır. Elektrik alan ile lif çekimimde akış hızı 0,12mL/h, iğne ile kolektör arasındaki mesafe 15cm ve uygulanan voltaj 12kV olarak seçilmiştir. SEM fotoğrafları, farklı çözücüler ile PCL nanoliflerinin başarılı bir şekilde üretildiğini göstermiştir. Polimer konsantrasyonunun arttırılması ve çözücü oranlarının değiştirilmesi ile gözenekli PCL nanolifler üretilmiştir. İkili çözücü sistemlerinde %16 PCL polimerleri ve (7:3) % çözücü oranlı çözelti ile düzgün, boncuksuz, pürüzsüz ve gözenekli PCL lifler üretilebilmiştir. PCL matrisinin kendine has özelliklerini nano lifli matların karakteristiğiyle birleştirmek, biyomedikal uygulamalar dahil olmak üzere farklı uygulamalar için uygun olabilecek umut verici malzemelerin üretimi

ile sonuçlanmıştır.Nanolifli yapıların geniş yüzey alanı, küçük gözenek çapı ve yüksek gözeneklilik gibi özellikleri içeren avantajları bu lifleri farklı uygulamalarda ilgi odağı haline getirmektedir. Elektrik alan lif çekimi ile üretilmiş gözenekli lifler hücre geliştirme için daha iyi bir alternatifdir.

Anahtar Kelimeler : Polikaprolakton (PCL), Elektrik alan ile lif çekimi, nanolifler, gözenekli lifler

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1. INTRODUCTION

Natural and synthetic biodegradable polymers are consumed widely for biomedical purposes, their field of interests comprises, tissue engineering, drug delivery, regenerative medicines etc. Polymers such as Polyesters (aliphatic Polyesters) such as Polycaprolactone (PCL), poly (glycolic acid) (PGA), poly (lactic acid) (PLA), poly (trimethylene carbonate) (PTMC) have gained importance in biomaterials as of their biodegradable behaviors. Various factors such as chain length, molecular weight, degree of crystallinity, branching and the introductory system of these polyester affects their biodegradation rate. All these factors effecting biodegradability of such polyesters are tailored through polymerization techniques, polymeric reactions condition, initial reactants (monomers) and the final obtained end polymers. Subjecting to these different conditions the end polymers result in various enhanced characteristics like Tg and Tm values (glass transition and melting temperatures, respectively), solubility, stiffness and extensibility etc.

Polycaprolactone (PCL) is an aliphatic polyester produced via ring-opening polymerization (polymerization of ε-caprolactone monomers, that can proceed either via anionic, cationic, coordination or radical polymerization routes) technique has non-hazardous nature [1] (Figure1). Different methodologies have been found in literature for caprolactones, polymerizations (anionic, cationic, ring-opening mechanism) besides usage of catalyst like stannous octoate [2, 3] and aluminum alkoxides [4]. Those reactions were subjected to various reactions conditions including polymerization, time, temperature, catalyst (types and concentration) and different ratios of monomer to solvent. Changing one variable results in difference of molecular weight and polydispersity indices (PDI) that directly effects the mechanical as well biodegradable behavior of the PCL [5]. In solvents such as benzene (C_6H_6), carbon tetrachloride, chloroform, cyclohexanone, dichloromethane, toluene, 2-nitropropane, PCL has high solubility while it has lower solubility in acetone, acetonitrile, 2-butanone, dimethylformamide, ethyl acetate, and it has no affinity for dissolution in water, ethyl alcohol, diethyl ether and petroleum ether [2, 3, 6-11]. PCL emits semi crystalline nature at room as well human body normal temperature. Melting temperature (Tm) and glass transition temperature (Tg) of PCL is 60℃ and -60℃ respectively [12-15]. The amorphous regions of PCL are found to be in rubbery conditions at an amorphous temperature that provides PCL polymer chains free movement in body and hence its capacity of permeability for body metabolites enhances once replaced in body. In scaffolds preparations degradation behavior is the most important fact of consideration in tissue engineering applications of biomaterials, it is maintained in such a way that tissues generations rate is the same as the degradation rate of biomaterial used. Tissue growth rate is highly affected by it, if in any case, the biodegradation rate is slower or higher from it will hinder the connections of scaffolds and tissue as well resulting in delayed healing process [16].

PCL has a more stable nature because of less frequent ester linkages per monomer which results (when used as biomaterial) in longer degradation time via enzymatic hydrolysis in vivo. Normally the degradation of PCL takes place in time period of 2 to 3 years once used in biological medium of variable interstitial fluid [17-20]. Lipase enzymes (that is found in interstitial fluid) helps in its enzymatic degradation, by breaking the ester linkages of PCL [15, 21, 22]. PH of the medium (alkaline conditions speeds up its degradation compare to acidic) effect the degradation of PCL [23]. Degradation in presence of lipase occurs in the formation of 6-hydroxycaproic acid that is released in body fluid which is further undertaken by cells and results in 2-βoxidations to form 3-acetyl CoA molecules, which further metabolizes in the citric acid cycle and is disposed via urinary rout by filtration in renal tubules without any accumulation in body [17, 24].

Though biocompatibility of PCL is low its rubbery nature, adjustable biodegradability and easiness in blending it have been widely used in supporting devices mainly in hard tissues, scaffolds material, surgical sutures also in drug delivery on micro and nanoscale [2, 3, 18]. The surface roughness and hydrophilic nature of PCL tailored in it makes it suitable for tissue's interfacial characteristics [25, 26]. Food and Drug Administration (FDA) has approved a wide range of devices blended of PCL for human usage such as "Monocryl" sutures that are prepared by copolymerizing glycolides and ε-caprolactone in form of monofilament absorbable surgical suture (trademarked by Ethicon), "Capron or PCL in form of rods used in birth control process has been used for secretion of progestin

hormones. In the drug delivery field, it is used by name of "SynBiosys" in form of spheres that are composed of multi-block copolymers of ε-caprolactone lactide and ethyl glycol has been approved by FDA in biomedicines [6, 27]. Usually, a liquid substance that can dissolve one or more substance is said to be a solvent. Rather all liquid substances cannot be said a solvent or good solvent. Every specific solvent induces some properties in the end product. Solvents are selected as per the degree of polymerizations of the polymers subjected to the experimental work. The selection of a good solvent indicates improving the final product characteristics. Non-solvent has either no capability of dissolving the polymer or it can partially dissolve it.

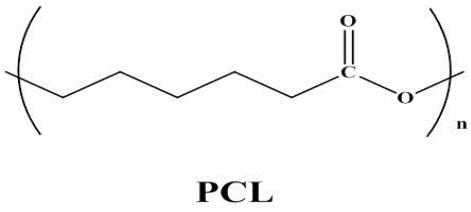

Figure 1. PCL polymer chemical structure

Polycaprolactone (PCL), synthetic polyester largely used in biomaterials, is fully biodegradable, at 60℃ and above once composted on in large-scaled usage. Biodegradation of PCL occurs through bacteria and fungi that produce special enzymes. During the degradation stages firstly it undergoes hydrolysis reaction, during which it is converted to water-soluble compounds with lactic acid formation. Rapid metabolic activities help the conversion of these compounds and lactic acid to water, carbon dioxide, and other biomasses in the presence of micro-organisms once it is hydrolyzed. Below the temperature of 60℃ (as itove once composted on in large-scaled usage. Biodegradation of PCL occurs through bacteria and fungi that produce special enzymes. During the degradation stages firstly it undergoes hydrolysis reaction, during which60℃ [28, 29].

Due to quick reduction ability and prolonged degradation behavior in water (like up to 3 or 4 years), it compels the researchers to use PCL investigations in the biological materials capable of target careful cell response by controlled intracellular ways of resorption. The hydrophobic, Simi crystalline and high solubility at room temperature (of PCL), with the easiness of process ability as of low melting point and extraordinary blending compatibility stimulated researchers to study its behavior in biomaterials [30]. In fact, besides its born biocompatibility and biodegradability usage of PCL has been studied for drug delivery with blends of polymers and copolymers. Furthermore, the penetrability for a wide range of drugs capable of constant drug distribution in a matrix with long release assurance up to several months via degradation behavior keeps it promising in the drug delivery field. As of slow degradation, it has been widely used as long-term implants and preparation of scaffolds for repairing the defective tissues in the human body as of its 3D cell culture supports the tissue engineering process for healing [31]. As Food and Drug Administration, USA (FDA) and European Community (CE) have certified the usage of PCL for biomaterials especially in drug delivery channels as well medical devices, surprising it has been commercialized to clinical studies too. In the recent era, green biomaterials included PCL for its usage in a variety of applications. Preferable viscoelastic and rheological characteristics in contrast to many other aliphatic polyester's family members consume its larger-scale manufacturing in a variety of biodegradable devices. Mechanical behavior of the PCL makes it promising material in tissue engineering areas like wound dressing, dental implants, and contraceptive as well in non-medical areas including environment protection, food technology and packaging. Many biopolymers in the blended form with PCL have gained more attractions as of its bio-friendly nature, it is featured in controlled and ease of shaping material in the tissue engineering field [32]. Functional groups in many cases are used to modify the structural morphology and behaviors like hydrophilicity, adhesiveness, and tailored biocompatibility for favorable response in cell culture. PCL can be formulated by self-assembled in hydrogel (3D) form, by using copolymerization technique which induces amphiphilic nature thus contributing the encapsulation nature to make it suitable for biomedicines and molecules [33].

In recent times bio-based plastics are gaining more attention from researchers. The market place reflects the rapid growth and development of these entities. Since 2007 the worldwide capacity of bio-based plastics has been increased from 0.36 million metric tons to 3.45 million metric tons in the current era of 2020 [34].PCL growth can be compared to the increasing number of publications recently on its importance in new bio-composites which is increasing day by day [35, 36]. Crude oil is the raw source of the production of PCL. It has benefits over other polymers in terms of biocompatibility, flexible nature and thermoplasticity. As per the 2015 global bioresorbable polymers market analysis forecasting in terms of usage of synthetic polymers, the market size was estimated to 298 tons. As per the increased demands in medical applications, it has been coupled with biocompatibility and cost-effectiveness of the items. Bioresorbable polymers have benefits as of their complete biodegradability in the human body that saves the body in temporary transplants that requires a second surgery and lessen the post-surgery risk without any subjective threat to the body. Drug delivery and orthopedics applications of bioresorbable polymers have flourished the globe in North America's polymers industry. The U.S is the center point of research and development for the medical sector that refers to the increasing demands of bioresorbable polymers [37, 38].

Recently product demand has grown significantly as of healthcare awareness. Product growth has been driven by the up-gradation of the health sector from the government's side. Compare to conventional polymer bioresorbable polymers has higher costs because of the use of sophisticated technology

which remained a barrier in product growth. Bone tissue engineering is served widely by biomedical polymer Polycaprolactone (PCL). Its biocompatible nature, high mechanical strength (that is a need in tissue engineering) and comparatively low cost to other polymers have increased its demand. By the year 2025, its net worth is estimated to exceed USD 88 million [39, 40].

PCL is synthetic polyester, which has greater attraction and interest to the researcher in recent decades, due to its biodegradability and suitability in the biomedical application. It has a large application in various sectors including pharmaceutical, drug delivery system, wound bandage healing application, filtration of water and air, tissue engineering, packaging and some other relevant applications.

This study aims to investigate the fiber morphology and property of PCL electrospun nanofiber via different solvent systems. According to the plan of this study dichloromethane (DCM) is the core solvent and it was selected due to its comparatively low boiling point. Dimethyl sulfoxide (DMSO) was selected as a non-solvent based on its high dielectric constant, which is essential for fiber formation and its miscibility with all the good solvents and its high boiling point.

1.1 Literature review

Non-solvent induced phase separations technique was used to fabricate porous electrospun poly (e-caprolactone) (PCL) fibers, by using binary solvent systems with various characteristics. *Konstantinos Alexandros G. Katsogianni* generated pores on the surface of PCL fiber by using chloroform (CF), dichloromethane (DCM), tetrahydrofuran (THF) and formic acid (FA) as suitable solvents (good solvents) in combination with poor solvent dimethyl sulfoxide (DMSO). During the process, chloroform was selected as a bead free and porous productive solvent on PCL fiber surface morphology [41].

PCL was dissolved in chloroform and ethanol solvent system by varying percentage ratios of the solvents. By the addition of the acetic acid and formic acid in the solvent system separately, electrospun of the solution was done to get fibrous webs. *Ipek Y Enis* concluded from his work that increasing the polymer concentration affects the diameter directly, leading to a larger average porous surface, and by addition of the formic acid and acetic acid in the solvent system bring reduction of fiber from micro to nano level. These nanofibrous PCL can be used in vascular grafts [42].

Xiaohong Qin and Dequn Wu's research proved that smooth PCL nanofibers with similar morphologies were fabricated by electrospinning when NMP and AC were used as solvent system. At the same time when PCL was electrospun in DCM and CF solvent system, holes were found on fiber morphology because of the evaporation of solvents. With low viscous in the CA solvent, the electrospinning was preferable [43].

Yazhou Wang successfully fabricated nano/micro scale porous fibers by electrospinning process in a polymer solution of suspended sodium chloride salt particles, later on after the electrospinning leaching process was applied to remove the salt from fibers morphology. Salt was found to be effective for porous structure and its distributions on resulting fibers. Sodium chloride is friendly agent that helped in creating porous morphology of electrospun fibers that can serve biomedical applications like drug delivery and tissue engineering [44].

Thi-Hiep Nguyen fabricated porous poly (ε "-caprolactone) (PCL) fiber-based fibrous scaffold via the electrospinning process by using dimethyl chloride and acetone in a simple ratio. Porous fibers (PCL-DCM), porous (PCL-DCM/Ace) and CaP coating on PCL/DCM-Ace were tested in SBF solution, results proved that PCL fiber-based scaffold has greater impact on cell interaction, growth also proliferation *in-vivo* by immersing in simulated body fluid (PCL-DCM/Ace-12). Further, they proved that PCL-DCM/Ace-12 scaffolds have a high speedy tendency of bone formation in tissue engineering [45].

Kulpreechanan studied the impact of solution concentration on fiber size in exponential way of PCL via electrospinning, by using (DCM)/dimethylformamide (DMF) in 1:1 volumetric mixing ratio, and (5-30 %w/v), applied voltage (10-25 kV), solution flow rate (0.1-2.0 mL/h) with collecting distance of (10, 20 cm) the process parameters. Fibers obtained in such conditions were of 10s nm-2.6 μm having bead or smooth morphologies. He further proved that voltage and collecting distance has minimal impact on the size of fibers [46].

Murat Simsek investigated surface morphology of PCL by dissolving it in various (acetone/dimethylformamide (DMF), tetrahydrofuran (THF)/DMF, dichloromethane (DCM)/DMF, chloroform (CF)/DMF, acetone/dimethyl sulfoxide (DMSO), THF/DMSO, DCM/DMSO, CF/DMSO) solvent/non-solvent systems (fixed ratio of 80/20 v/v). Results of electrospun fibers revealed that surface texture varies with a porous structure, and surface roughness at relative humidity of 60-90% as well room temperature. Those with porous morphologies can have the potential to be used in filtration technology as well biomaterials [47].

Hyung Hwan Kim and Min Jin Kim investigated PCL's electrospinning by using formic acid, dichloromethane/ dimethylformamide (DMF), chloroform/DMF, and dichloroethane solvent systems, and concluded that average solvent concentration controls electrospun fiber mat diameter. Various fibrous sizes of (0.1, 0.8, 1.9, and 3.4 μm) were fabricated and characterized, which subsequently revealed that the diameter of the fiber has great impact on the surface roughness as well mechanical properties of PCL mat. Further, they concluded that mat can have a desirable use in biomaterials for tissue engineering purposes [2]. Different applications are presented in (figure-2).

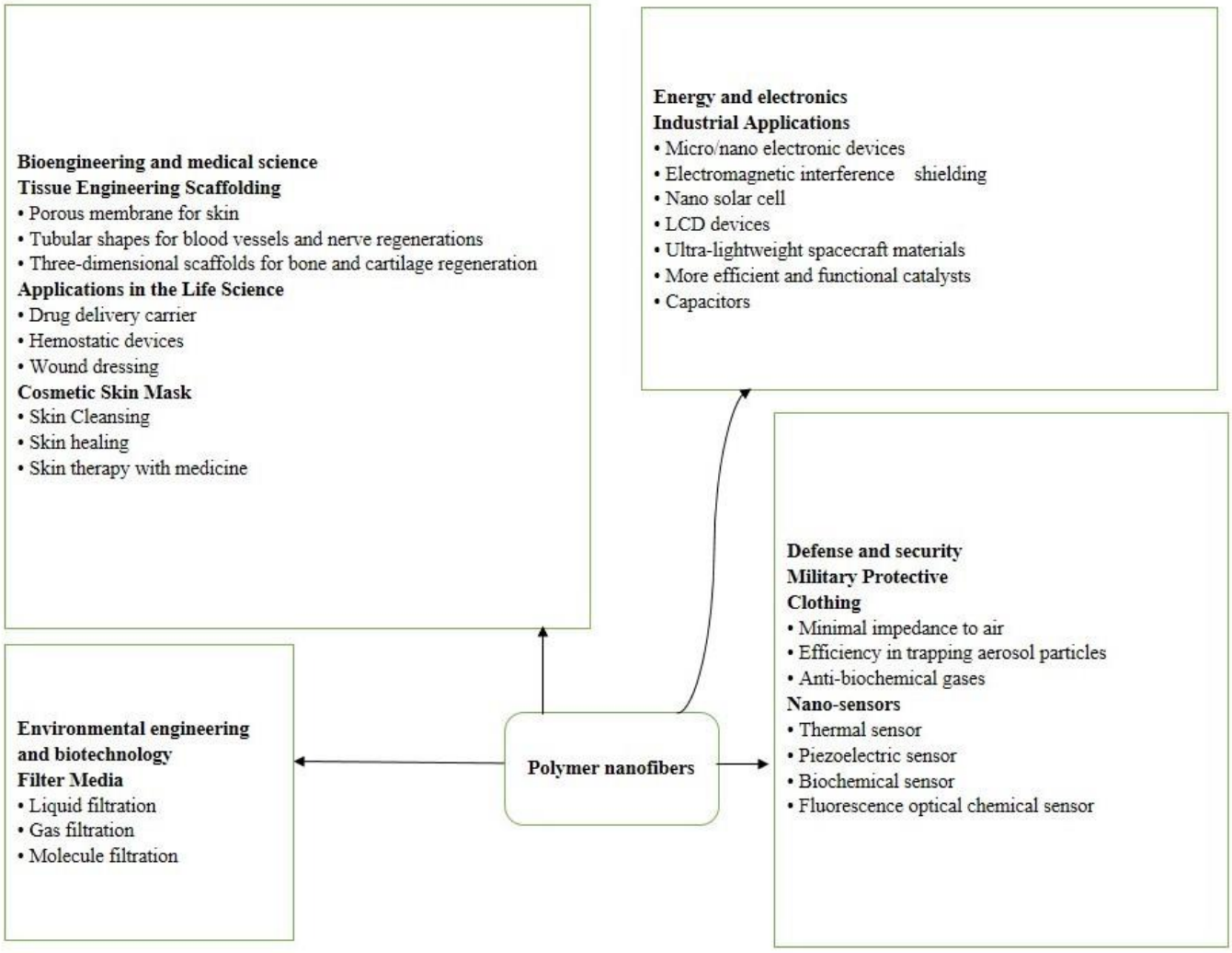

Figure 2. Potential applications of electrospun nanofibers

2. MATERIALS AND METHODS

2.1 Materials

Polycaprolactone (PCL) was purchased from Shanghai, China. Dichloromethane (DCM) and Dimethyl sulfoxide (DMSO) were purchased from Shanghai China. According to the designs of the experiment 12%, 14% and 16% (w/v) PCL polymer use respectively in both single and binary solvent systems where DCM was the core solvent. DCM was used as a good solvent in a single solvent system and binary solvent system DCM use as the main solvent and DMSO used as a co-solvent. The ration of binary solvent system solvents is respectively 9:1, 7:3 and 5:5 percent (v/v). A 20 ml plastic syringe (Jiangyin medical device Co., Ltd) and a stainless steel blunt tip needle with a diameter of 13mm & 20 G were purchased from DAJIUN, China. Those provided the well-dissolved polymer solution to the receiver through the needle. To collect the polymer fiber a flatbed frame was wrap with aluminum foil which was called a flatbed collector.

2.1.1 Chemicals (Solvents) used in the experiment

Dichloromethane (DCM) was used as a core solvent and dimethyl sulfoxide (DMSO) was used as a non-solvent for PCL polymer. Combined with DCM and DMSO solvent were used to investigating electrospun nanofiber morphology.

2.1.2 Preparation of Polycaprolactone (PCL) Solutions

Two different solvents used this research work to dissolve the PCL polymer. Between two different solvents dichloromethane (DCM) was used as the main solvent. Single and binary both solvent system was used to prepare the polymeric solution. For single solvent system DCM was used with (12%, 14% and 16%) PCL polymer individually and in binary solvent system

(DCM/DMSO) solvents (v/v) ratio were use with (12%, 14% and 16%) PCL polymer respectively.

For preparing the solution, the required pre-weight amount of polymer was placed in a conical flask with the desired solvent. A magnetic stirrer machine was used to dissolve the polymer. All solutions prepared at room temperature (20-25℃) for 1.5-4 hours until the polymers were completely dissolved in the solvent. In the binary solvent system, first ratio was used 9:1 to find out the best result and the further solvent ratio was 7:3 and 5:5 respectively. The data presented in Table 1.

2.2 Methods

2.2.1 Electrospinning process

To perform the experiment a horizontal layer electrospinning setup was used. This device consists with four-part: high voltage supplier (DW-N5034ACCD, Tianjin, China), injective pump (KD Scientific, USA) and syringe with a needle (inner diameter of 13mm) and flatbed collector (Length and width 6×6 cm). To experiment, a 20 ml plastic syringe (Jiangyin medical device Co., Ltd.) was filled with a polymer solution and connected to a metallic needle (inner diameter 13mm, 20G). An injective pump (KD Scientific, USA) placed a side of the chamber was used to control the flow rate. To eliminate solvent vapors, a ventilation system is connected to the chamber.

The distance between needle tips to the collector was 15cm and the flow rate of the injecting pump was 0.12 ml/h. 12kV power supply was applied during the electrospinning process. The flatbed collector with rapped aluminum foil and its distance was 15 cm from the needle tip. In the horizontal layout of the electrospinning process, the collector was usually placed in a vertical position in front of the needle. The positive electrode of voltage was connected to the metallic needle and the negative one was connected with the collector. The electrospinning experiments were performed at room temperature between 20-25℃ with relative humidity around 45%. A total of twelve samples were prepared to investigate [3.1 (a-c), 3.2 (a-i)]. The time duration for each sample are presented in Table 2.

Table 1. General calculation for the proportion of solvents and polymer in 10ml solutions

Concentration %	Polymer name	Mass of polymer (gm)	Ratio of the solvents	Volume of solvent (ml)	
				DCM	DMSO
12	PCL	12	10	9.88	N/A
	PCL	12	9:1	8.89	0.98
	PCL	12	7:3	6.92	2.96
	PCL	12	5:5	4.94	4.94
14	PCL	14	10	9.86	N/A
	PCL	14	9:1	8.87	0.99
	PCL	14	7:3	6.90	2.96
	PCL	14	5:5	4.93	4.93
16	PCL	16	10	9.84	N/A
	PCL	16	9:1	8.56	0.98
	PCL	16	7:3	6.88	2.95
	PCL	16	5:5	4.92	4.92

Table 2. Duration of Electro spinning

Sample No	Duration of Electro spinning (min)
3.1 (a)	30
3.1 (b)	32
3.1 (c)	34
3.2 (a)	33
3.2 (b)	37
3.2 (c)	40
3.2 (d)	43
3.2 (e)	42
3.2 (f)	45
3.2 (g)	45
3.2 (h)	40
3.2 (i)	42

2.3 Characterization of electrospun fibers

2.3.1 Scanning electron microscopy (SEM)

The morphology of electrospun fibers was observed by scanning electron microscopy (SEM, JSM-7800F, JEOL, Japan) using an accelerating voltage of 5.0 kV. Before observation, the nanofibers collected on the aluminum foil were coated using a gold/palladium sputter coater for 120 seconds to create the conductive surface. The diameter of PCL nanofibers and pores was measured by image software (Nano Measurer 1.2 version). At least 150 diameters were a measure to determine the mean diameter. The measurements were carried out twenty times for each sample. In addition, the pores were assumed circular in each measurement.

2.3.2 Tensile strength test

The mechanical behavior of electrospun fibrous mats was tested with the Instron 5566 machine (Norwood, MA, USA). According to the testing standard ASTM D3822-07, the tensile test samples were cut in a dimension at 3 cm × 0.5 cm (Length × Width) to perform the test. The drawing rate was set 15mm/ minute at 25±1℃, 65±5% relative humidity. The tests were carried out seven times for each sample. The test samples are cured at the temperature 30±5℃ and 95±5% relative humidity during tenacity test. All testing samples are taken from the center of the mat.

2.3.3 Fourier Transform Infrared Ray (FTIR)

To identify the bond arrangement of the PCL granules with DCM and DCM/DMSO solvent, FTIR spectra were investigated with the Bruker spectrometer (VERTEX-70). It was equipped with a liquid-nitrogen-cooled MCT detector. The spectra were recorded from 3600-600 cm^{-1}. The number of scanning was 40 times and the resolution power was 4 cm^{-1}.

2.3.4 X-Ray Diffraction (XRD) analysis

XRD patterns of commercial PCL polymer, commercial DCM and DCM/DMSO solvents were recorded by using Ultima IV X-Ray Diffractometer (X'Pre-pro MPD, Holland) and Cu Kα (λ=1.5418 Angstrom). For all samples, Bragg angle (2θ) 5° to 50° were scanned.

2.3.5 WCA (Water contract angle)

The contact angle is one of the common ways to measure the wettability of a surface or material. Wetting refers to the study of how a liquid deposited on a solid (or liquid) substrate spreads out or the ability of liquids to form boundary surfaces with solid states. The wetting ability is determined by measuring the contact angle, which the liquid forms in contact with the solids or liquids [2].

The solid-liquid contact angle can be defined from the equilibrium of surface forces in the three phases intersecting point according to Figure 3. The contact angle is then (Young's equation)[48]:

$$COS\theta = (\gamma_{SV} - \gamma_{SL})/\gamma_{LV} \quad (1)$$

Where θ is the contact angle, γ_{LV} is the surface tension (or free energy) of the liquid in equilibrium with vapor, γ_{SV} the surface tension (or free energy) of the solid surface in equilibrium with vapor and γ_{SL} the solid-liquid interfacial tension.

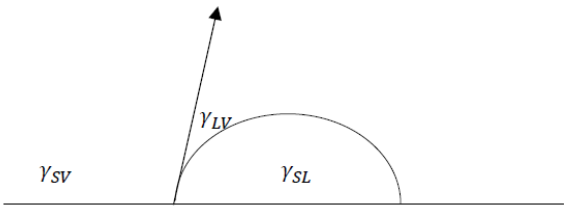

Figure 3. Schematic representation of the contact angle equilibrium [48].

Contact angle measurements were applied to measure solid surface wettability where the angle showed a liquid contact with three-phases of matter including solid, liquid, and gas intersection. However, in practice a dynamic phenomenon of contact angle hysteresis is often observed, ranging from the advancing (maximal) contact angle to the receding (minimal) contact angle. In the case of complete wetting (spreading), the contact angle is 0°. Between 0° and 90°, the solid is wettable and above 90° it is not wettable. In these studies, we use OCA15EC optical contact angle machine which is followed the optical method. For this test, we cut 4 different samples (5cm×3cm) and pasted them on a glass slide to measure the water contact angle. Each sample had various fiber diameters and different surface morphology. A clean fiber mat surface was ensured as well adjust the camera focal length, settings and droplet volume of 0.3 ml. Three measurements were taken at different locations of each same mat, and the average value was obtained. Then the data was collected from the computer.

3. RESULTS AND DISCUSSION

In the electrospinning section of the solvent and use of the solvent systems (single and binary) to make the polymeric solution is one of the main factors influencing electrospun fiber morphology and properties. Though different solvents may be used to dissolve a polymer, as a result, electrospun nanofiber will present different fiber morphology. During electrospinning high voltage is applied to generate an electric field and therefore the polymeric solutions are stretched due to the repulsion of the charges present on the jet surface. The solutions with higher conductivity carry more charges consequently they are more susceptible to the electric field. Therefore, the mass throughout of the solution from a spinneret increase.

Single and binary solvent systems were used to dissolve the PCL polymer. The reason was to use different solvent systems to investigate the electrospun fiber morphology and properties. A polymeric concentration (12%, 14% and 16%) w/v was chosen and the process parameter kept constant voltage of 12 kV, flow

rate 0.12 mL/h, the distance between needle and collector 15cm. The selection of different parameters are based on the single and binary solvent system. The chosen parameters provide the best output than others. DCM was chosen as a single solvent system and DCM/DMSO chosen as a binary solvent system. PCL was dissolved into the above-mentioned solvent system and perform electrospinning to produce electrospun nanofibers.

3.1 Effect of the single solvent system

In this study, only DCM was chosen as a single solvent system because of its good solubility parameter. 12%, 14% and 16% PCL were dissolved into DCM and electrospinning was performed. As a good solvent DCM shows relatively high electrospinning capability with an average diameter of 1.40-3.01 µm for PCL. The increase of polymer percentages affected the fiber properties.

SEM image showed that smooth and beads free fiber were produced and there was no pore on the fiber surface but had some junction on the fiber (Figure 4: a, c). PCL is a hydrophobic polymer that does not dissolve in water, and DCM is high volatile solvents poorly miscible with water. The increase of the polymer percentages averages fiber diameter increased. Table 3 were shown the average diameter fibers distribution.

3.2 Effect of the binary solvent system

The binary solvent system was prepared by DCM and DMSO volume by volume different ratio (9:1, 7:3, 5:5) with 12%, 14% and 16% PCL polymer. All the ratio produced smooth and beads free nanofibers mats. The binary system showed that the addition of DMSO to the solvent enables to production nanofiber with pores in some ratio of the solvents. Pores percentage was increased with the increase of DMSO percentage in the solvent. The electrospinning parameter was the same as the user of a single solvent system electrospinning of the PCL solution.

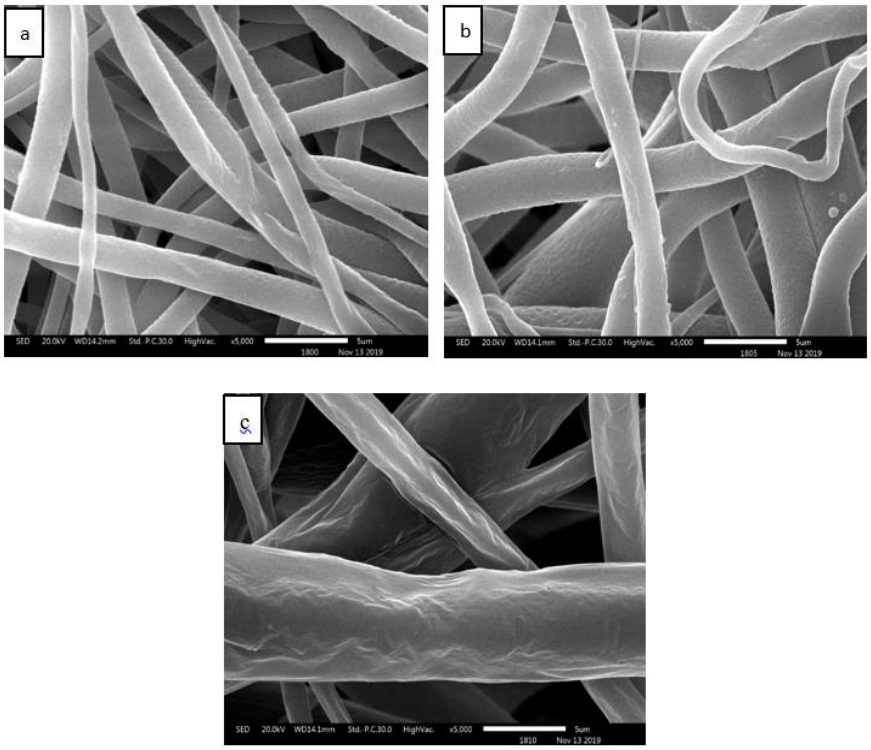

Figure 4. SEM pictures of the nanofibers production by a single solvent system. (a) 12% PCL/DCM w/v (b) 14% PCL/DCM w/v and (c) 16% PCL/DCM w/v.

Table 3. Single solvent system average fibers and pores diameter

Sample No	PCL	Single system		SEM	
				Fiber avg. dimeter	Fiber avg. pore diameter
3.1 (a)	12%	Single	DCM	1.40 µm	N/A
3.1 (b)	14%	Single	DCM	1.79 µm	N/A
3.1 (c)	16%	Single	DCM	3.01 µm	N/A

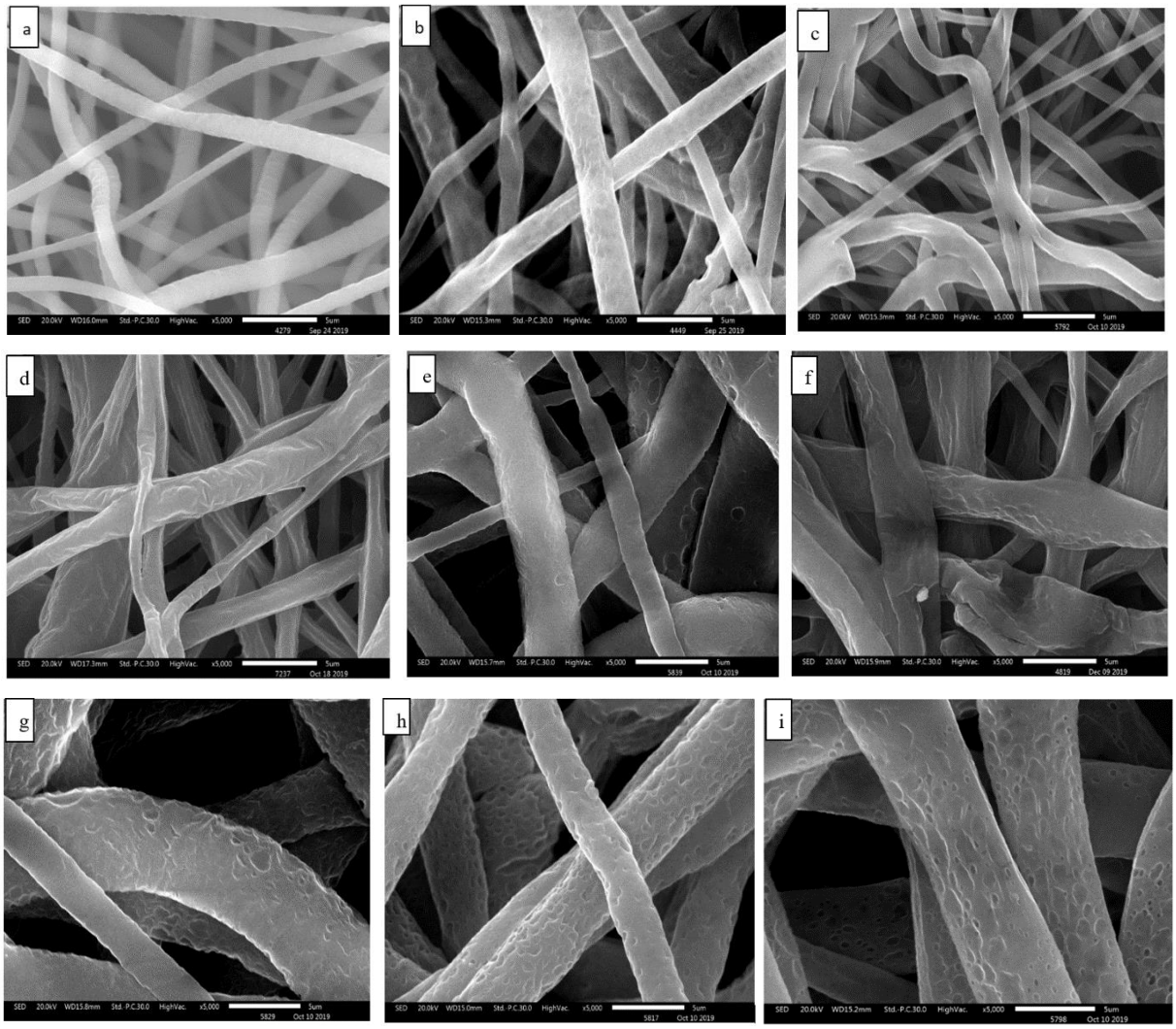

Figure 5. SEM pictures of the nanofibers production by the binary solvent system. 12%PCL/DCM: DMSO (a) 9:1 v/v (b) 7:3 v/v (c) 5:5 v/v, 14%PCL/DCM: DMSO (d) 9:1 v/v (e) 7:3 v/v (f) 5:5 v/v and16%PCL/DCM: DMSO (g) 9:1 v/v (h) 7:3 v/v (i) 5:5 v/v.

The formation of a pore mechanism may be explained in two ways one is phase separation and another is breath figures. Thermodynamic instability is the driving force in the phase separation process. During electro spinning process penetration of a non- solvent in the jet (vapor induced phase separation) could induce phase separation or temperature decrease of the electrospun jet surface between the needle and the collector (thermally induced phase separation). On the other hand, breath figures are formed when the reduction of temperature due to rapid evaporation of the solvent leads to condensation of the water vapor from the environment to the jet surface in this work both mechanisms may explain the formation of pores using PCL solution binary solvent system. In table 4 shown produced electrospun samples average fiber diameter and pore size. SEM figure 5 (a, c and d) had no hole on the fiber surface but smooth electrospun fibers were produced. Some fiber junctions were identified in figure 5 (c, d and f). On the other hand, in figure 5 (b, e, g, h and i) SEM image shown smooth electrospun fibers with hole. Above all the sample (Figure 5: h) 16%PCL/DCM: DMSO (7:3) v/v ratio sample had good pore and smaller fiber diameter compare to other pore fiber samples. The pores of fibers are produced within itself. This indicates that the fibers have good porosity with smaller diameter.

3.3 Mechanical strength performance

3.3.1 Effect of the single solvent system

A nonlinear curve was obtained for the single solvent system PCL electrospun nanofiber. Tensile strength, strain at break and nanofibers average diameter were a measure to identify the effect of mechanical strength performance.

The increase of PCL polymer concentration in the solution, the electrospun nanofiber average diameter are also increased. Nanofiber average diameter was 1.40 μm, 1.79 μm and 3.01 μm

for (12, 24 and 16) % PCL/DCM respectively. As shown in Table 5, electrospun PCL nanofiber had 0.68-1.49 MPa ultimate tensile strength and 65.54- 217.75 % strain at break for the samples. It indicates that breaking strain and tensile strength decreased with a fiber size increment. Different polymer percent's in a single solvent system had an impact on produced nanofiber and solvent properties. Figure 6 demonstrates that 12% PCL/DCM nanofiber with lower fiber diameter shown higher mechanical strength compare to 16% PCL/DCM because it had some fiber junctions and entanglement.

3.3.2 Effect of the binary solvent system

Nanofiber tensile test was carried out to investigate the mechanical characterization in a binary solvent system. Produced porous and non-porous nanofiber diameter, pore size, polymer concentration and solvent ratio affected nanofiber mechanical properties.

Table 4. Binary solvent system average fibers and pores diameter

Sample No	PCL	Single system			SEM	
					Fiber avg. dimeter	Fiber avg. pore diameter
3.2 (a)	12%	Binary	DCM:DMSO	9:1	1.08 µm	N/A
3.2 (b)				7:3	1.97 µm	1.00 µm
3.2 (c)				5:5	0.91 µm	N/A
3.2 (d)	14%	Binary	DCM:DMSO	9:1	1.68 µm	N/A
3.2 (e)				7:3	2.70 µm	0.84 µm
3.2 (f)				5:5	2.54 µm	N/A
3.2 (g)	16%	Binary	DCM:DMSO	9:1	4.51 µm	0.84 µm
3.2 (h)				7:3	3.93 µm	0.51 µm
3.2 (i)				5:5	5.24 µm	0.85 µm

Table 5. Mechanical properties of electrospun PCL nanofiber in a single solvent system

Sample No	Material	Tensile strength (MPa)	Standard Deviation (Tensile strength)	Deformation (Strain %)	Standard Deviation (Strain)
3.1 (a)	12% PCL/DCM	1.49	0.02	217.75	1.12
3.1 (b)	14% PCL/DCM	0.84	0.05	118.38	0.45
3.1 (c)	16% PCL/DCM	0.68	0.05	65.54	0.23

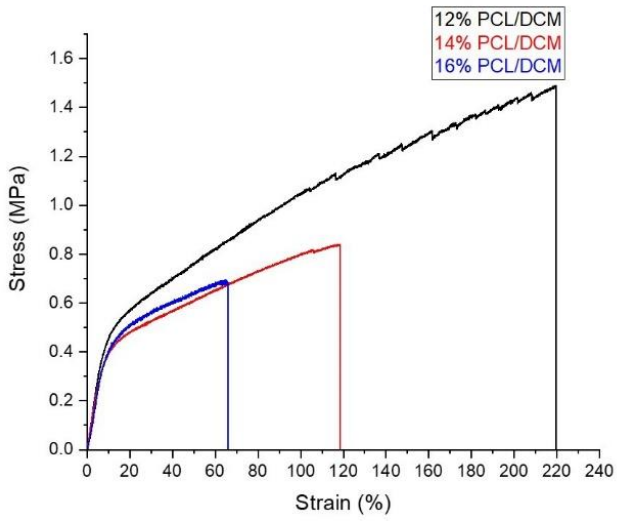

Figure 6. Stress-strain curve of PCL electrospun nanofibers in a single solvent system

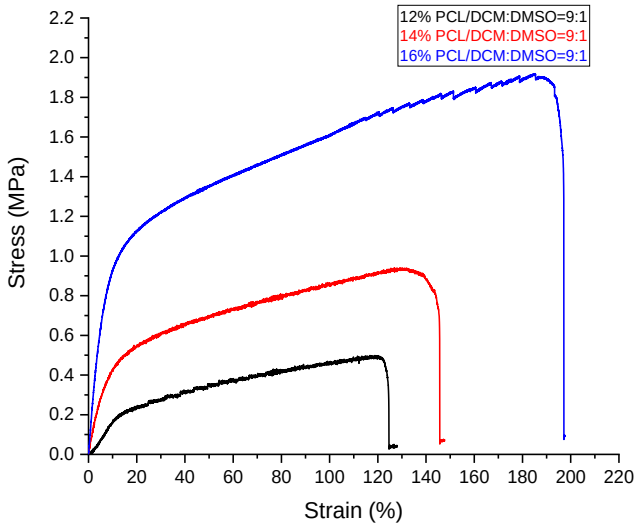

Figure 7. Stress-strain curve of PCL electrospun nanofibers in a binary solvent system

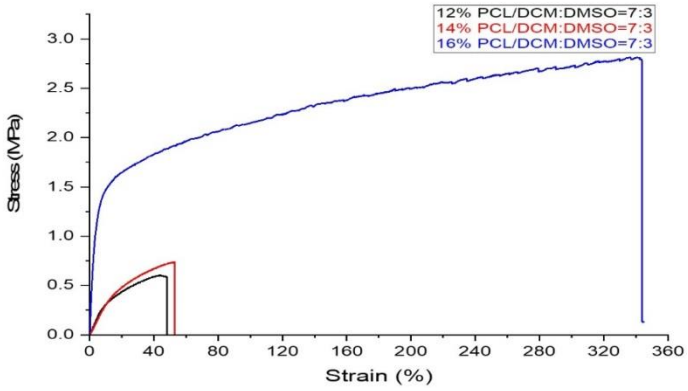

Figure 8. Stress-strain curve of PCL electrospun nanofibers in a binary solvent system

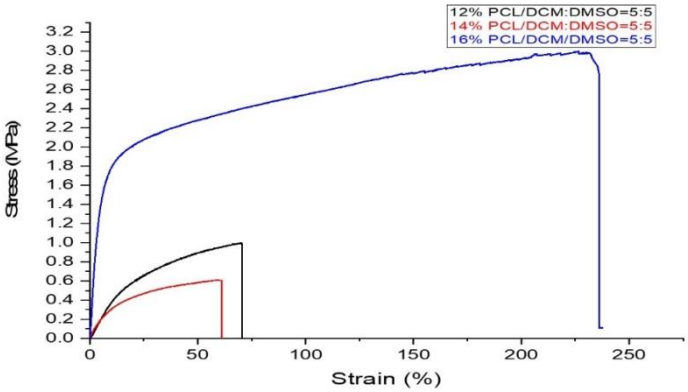

Figure 9. Stress-strain curve of PCL electrospun nanofibers in a binary solvent system

Different percent of PCL polymer used to produce electrospun nanofibers with different solvent ratios. Figure 7-9 demonstrate that 16%PCL/DCM: DMSO solutions all the ratio provide better elasticity properties compare to other percent polymer and solvent ratio. According to figures 7 and 8 increased the polymer percentage breaking strain and tensile strength were also increased because of adding DMSO in the solvent. Table 6 shows the mechanical properties of a binary solvent system for all samples. But in figure 8 14%PCL/DCM: DMSO (5:5) v/v sample was shown different results. Increase of polymer percentage its strength was decrease because figure 5 (f) SEM image showed that the electrospun nanofiber had some damages. Above all the binary solvent system sample 16% polymer all ratio sample provide higher mechanical strength with pore surface.

After analyzing SEM and mechanical properties data 16% PCL all single and binary solvent system sample was taken for others investigation.

3.4 Electrical conductivity and viscosity:

The different polymer solution was subjected to measure the electrical conductivity and viscosity. The data presented in Table 7 and 8. It demonstrated that with the increase of materials percentage both values are increased. The maximum range of electrical conductivity achieved in the 16% PCL of binary solvent system.

Table 6. Mechanical properties of electrospun PCL nanofiber in a binary solvent system

Material	12% PCL/DCM: DMSO			14% PCL/DCM:DMSO			16% PCL/DCM:DMSO		
Sample No	3.2 (a)	3.2 (b)	3.2 (c)	3.2 (d)	3.2 (e)	3.2 (f)	3.2 (g)	3.2 (h)	3.2 (i)
Solvent Ratio	9:1	7:3	5:5	9:1	7:3	5:5	9:1	7:3	5:5
Tensile strength (MPa)	0.5	0.59	1.00	0.77	0.74	0.61	1.89	2.82	2.80
Standard deviation (Tensile strength)	0.04	0.03	0.31	0.03	0.03	0.04	0.43	0.47	0.34
Strain %	120.61	47.02	70.00	145.45	52.91	61.11	191.00	344.00	235.00
Standard deviation (Strain %)	1.50	1.21	1.23	1.48	1.32	0.98	1.79	2.11	1.67

Table 7. Electrical conductivity and viscosity of electrospun PCL nanofiber in a single solvent system

Sample No	Material	Viscosity (cP)	Electrical Conductivity (µS/cm)
3.1 (a)	12% PCL/DCM	350	4020
3.2 (b)	14% PCL/DCM	420	4180
3.3 (c)	16% PCL/DCM	540	4230

Table 8. Electrical conductivity and viscosity of electrospun PCL nanofiber in a binary solvent system

Material	12% PCL/DCM: DMSO			14% PCL/DCM:DMSO			16% PCL/DCM:DMSO		
Solvent Ratio	9:1	7:3	5:5	9:1	7:3	5:5	9:1	7:3	5:5
Sample No	3.2 (a)	3.2(b)	3.2 ©	3.2 (d)	3.2 (e)	3.2 (f)	3.2 (g)	3.2 (h)	3.2 (i)
Viscosity (cP)	460	450	480	580	620	650	820	930	900
Electrical Conductivity (µS/cm)	4170	4210	4200	4190	4250	4220	4350	4380	4350

3.5 Fourier Transform Infrared Ray (FTIR):

FT-IR spectra were conducted to identify the effect of the single and binary solvent system of PCL electrospun fibers. The FTIR spectra of PCL electrospun fiber are given below (figure 10). The infrared variations and assignments of PCL electrospun fiber FTIR spectra range indicated 2900 to 3000 cm^{-1} C-H_2 asymmetric stretching, 2800 to 2900 cm^{-1} C-H_2 symmetric stretching, 1700 to 1760 cm^{-1} C=O stretching, 1150 to 1200 cm^{-1} O-C-O stretching and 1000 to 1100 cm^{-1} C-C stretching. A very strong carbonyl group bond stretching at 1720 cm^{-1} and C–H stretching at 2860 and 2940 cm^{-1} were detected in the PCL electrrospun nanofibers [43, 49]. There was no difference found among single and binary solvent systems with their ratios of PCL electrospun fibers.

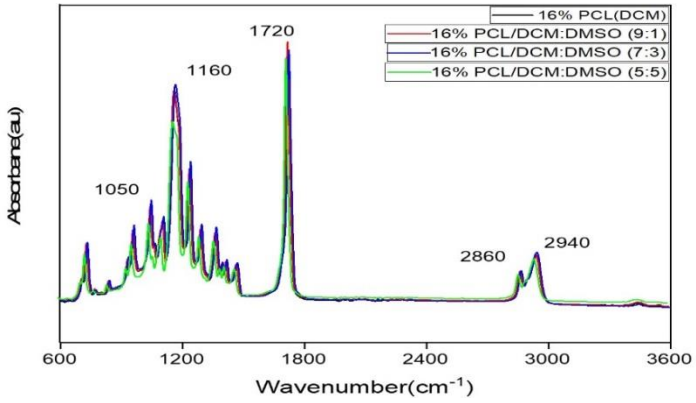

Figure 10. FTIR spectra of PCL electrospun fiber in a single and binary solvent system

3.6 X-Ray Diffraction (XRD) analysis:

The XRD technique was used to identify, characterize and calculate the crystalline value. The effect of electrospinning, as compared to different solvent system, on the structure of PCL is illustrated by the x-ray diffraction patterns shown in Figure 11. There was no tendency in the overall degree of crystallinity of the polymer produced by electrospinning or different solvent system. There are two distinct peaks observed at $2\theta = 21.4°$ and $2\theta = 23.7°$, which are indexed to the (110) and (200) planes, respectively, of an orthorhombic crystalline structure of PCL [49, 50]. The intensities of the peak change with the change of solvent ratios which is shown in the different plane of that orientations. The effect of the single and binary solvent system with different ratios of the binary also observed for electrospinning on the structure of the resulting nanofibers, but again there is no measured values in the degree of crystallinity. Some slight shifting of the peaks was observed. We believe that this may be due to differences in x-ray transparency of the specimens since each specimen was different about the fraction of the total specimen area covered by fibers.

3.7 WCA

Hydrophilicity and hydrophobicity of the nanofibers were analyzed by the optical contact angle machine (OCA15EC). As surficial properties such as the morphology of surface, hydrophilic nature impacts on the cell adhesion during the biological usage. The contact angle measurement of the PCL mats was related to the average diameter and porous surface of the nanofibers.

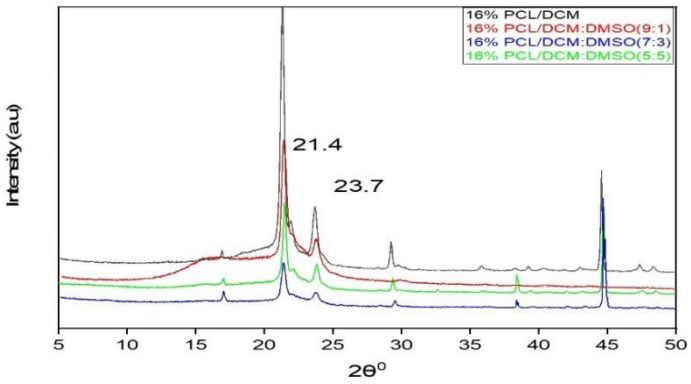

Figure 11. XRD curved of 16% PCL w/v with DCM and DCM/DMSO (9:1, 7:3 and 5:5) v/v ratio

Tables 3 and 4 explain the pore size and fiber diameter, which correlates to the water contact angle measurements of the nanofiber PCL fiber mats. In figure 12 shown a 16%PCL/DCM single solvent system and 16%DCM/DMSO (9:1, 7:3 and 5:5) binary solvent system volume by volume ratios contract angle 128.11°, 121.81°, 120.64° and 119.59° respectively. All the observations reveal the hydrophobic nature of the mats. With the increased porous morphology, the contact angle was found to be smaller. Also when the fiber diameter was observed to be larger the water contact angle measurements were found to be smaller, above 90° which implicit hydrophobic nature. With an increasing percentage of the DMSO in the electrospinning solution, the nanofibers mat collected showed a decrease in water contact angle, indicating the decreased in hydrophobicity.

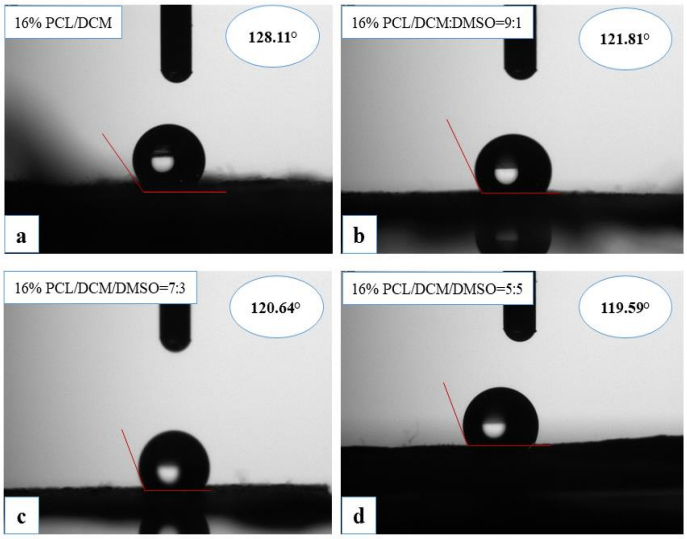

Figure 12. Water contact angle value of PCL nanofibers

4. CONCLUSION

In this research work, polymeric solution electrospinning was used to produce porous PCL nanofiber and different solvent systems use to investigate the nanofibrous mat morphology and properties. In the first step, the effect of single solvent with different percent PCL polymer and in the second step the effect of binary solvent system volume by volume ratios with different percent PCL polymer morphology was investigated. SEM analysis was performed on the produced electrospun samples and the results have shown that between all the sample binary solvent systems dichloromethane (DCM)/ dimethyl sulfoxide (DMSO) can produce porous PCL nanofiber in bulk range, although some defects were detected. The thinnest defect-free porous nanofibers distribution was produced in 16%PCL/DCM: DMSO (7:3) solvents v/v ratio.

The solution concentration has a significant effect on fiber morphology. In a single solvent system increasing polymer concentration fiber average diameter was an increase but the tensile strength decrease. When we observed a binary solvent system, the increase of polymer percentage in the solution pore surface was created on the fiber surface. The addition of DMSO help to create a pore surface on the nanofiber mat. Some samples of binary solvent systems shown good mechanical strength with pores on the fiber surface. 16% PCL/DCM: DMSO (7:3) solvents v/v ratio shown 2.82 MPa maximum tensile strength and 344% strain (deformation). The average pore size of the sample was 0.51µm with more even pore size compared to other samples.

FTI'R and X-RD tests were performed to identify the sample geometrical properties. FTI'R spectra were performed to ensure any unknown substance existing on the sample or not. X-RD test help to determine there was any chance of crystallinity in the polymer of produced samples. There were no changes found by the use of single and binary solvent systems with different percentages of PCL polymer.

So far the selection of green solvent is still challenged for electrospinning, most of the synthetic polymer including PCL, PLA and PLGA have been dissolved in chlorinated and toxic solvents. The methodology proposed in this study is to develop porous electrospun PCL nanofiber morphology and properties. The three factors should be kept in mind: polymer concentration, solvent systems and solvents ratio. Such nanoporous, non-woven structures may be very useful in numerous applications including tissue engineering, drug delivery, medical textiles, and membrane separation. Electrospinning can, therefore, be used to produce novel material structures with dramatic improvement in properties. This study provides the information regarding different solvent system for producing PCL nanofibers. The changing parameters with different results reveals the fibers morphology and properties of elcetrospinning PCL nanofibers.

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CONFLICT OF INTEREST

There is no conflict of interest in this paper.

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