

PCL/Fe₃O₄ magnetic electrospun yarn composites as a novel nanomaterial for biomedical applications

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Abstract: Magnetic composite structures were fabricated by embedding iron oxide nanoparticles (Fe₃O₄) into polycaprolactone (PCL) nanofibers through an electrospinning process. The PCL nanofibers incorporating 0.5 and 1 wt. % Fe₃O₄ were electrospun with various yarn and membrane architectures. SEM images of the fabricated fibers revealed diameter increment by raising the Fe₃O₄ proportion. Additionally, elongation at break, in tandem with the ultimate strength of the electrospun PCL yarn was improved by 63 and 67% through embedding 0.5 and 1 wt. % Fe₃O₄, respectively. The saturation magnetization results depended on the number of magnetic nanoparticles loaded in the electrospun fibers, as well as the architectural design of the electrospun fibers. The magnetic response of the fibrous yarns was enhanced by increasing the Fe₃O₄ mass fraction from 0.5 to 1 wt. %. The highest saturation magnetization of 5.38 emu/g was obtained for the electrospun yarn containing 1 wt. % Fe₃O₄, corroborating 13.6 times greater features than that of the fibrous membrane with a similar chemical composition. The obtained results implied that the as-spun fibrous yarn could be a great candidate as a surgical suture with the release capability of bioactive agents under a magnetic field..

Keywords: Electrospinning; Polycaprolactone; Fe₃O₄ nanoparticles; Magnetic yarn; Magnetic properties.

1. INTRODUCTION

Magnetic nanocomposites are assumed as one of the interesting classes of nanostructured materials. The incorporation of inorganic nanoparticles into polymer architectures is considered a common strategy to boost the characteristics of the final products. In this era, magnetic nanoparticles play a crucial role in preparing polymer composites, resulting in considerable improvements in magnetism, conductivity, thermal stability, fatigue resistance, optical properties, sensing ability, and mechanical characteristics (R. Kumar, A. Sudhaik, V.-H. Nguyen, *et al.*, 2023; Y. Kumar *et al.*, 2023). This is mainly due to their fabulous chemistry, compatibility with polymer, and great interfacial adhesion with polymer matrixes (Chen *et al.*, 2022). The magnetism performance of such particulate fillers mostly depends on the particles' average size. It is widely reported that the best magnetism performance could be revealed by the particles finer than 20-30 nm (Chen *et al.*, 2022). Iron oxide (Fe₃O₄) is a well-known mineral magnetite filler, which is abundant in nature. Its chemical stability as well as outstanding conductivity and magnetic properties have promised its

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great capability for use in a wide variety of scientific applications, such as magnetic fluid catalysis, biotechnology, data storage, and many more (Saleh, Parthasarathy, & Irfan, 2019; Unsoy *et al.*, 2015). Moreover, the biocompatibility, non-toxicity, and accessibility of iron oxide nanoparticles have led to the development of their usage in biomedical applications, such as magnetic resonance imaging (MRI), hyperthermia, targeted gene and drug delivery systems, cellular imaging, detoxification of biological fluids, and so on (Nochehdehi, Thomas, Sadri, Afghahi, & Hadavi, 2017; Shan *et al.*, 2016; Zhang *et al.*, 2020).

In recent years, electrospun polymeric nanocomposites have been extensively suggested as potential scaffolds for tissue engineering and biomedical applications (Feng *et al.*, 2023; Kumar & Lim, 2022). Electrospinning is a feasible and versatile procedure for the fabrication of nanoscale fibers. The electrospun fibers could be collected in various forms, including aligned or random fibrous membranes as well as nanofibrous yarns (Jiang, Wang, Liu, Zhang, & Wang, 2021; Joshi & Roy, 2020). The preparation of magnetic nanofibers, with sensitivity to changes in external magnetic fields, has received much interest in the nanotechnology field through providing a wide range of applications, such as DNA separation, targeted drug delivery, tissue engineering, and biosensors (Banitaba, Khademolqorani, *et al.*, 2023; Kumar & Lim, 2022). Magnetic nanofibers have been electrospun by insertion of Fe_3O_4 nanoparticles into various polymer matrixes such as polyphosphazene (Liu *et al.*, 2019), polyimide acid (Luo, Wang, Wang, & Pan, 2016), polyvinyl alcohol (S. Wang *et al.*, 2010), poly (ϵ -caprolactone) (PCL) (Hadjianfar, Semnani, Varshosaz, Mohammadi, & Tehrani, 2021; Yue *et al.*, 2021), gelatin (Cai *et al.*, 2016), and so forth. According to the literature, PCL has been identified as a great candidate for many biomedical applications, resulting from numerous appealing properties, including proper biodegradability and biocompatibility, nontoxicity, tailorable degradation kinetics, and appropriate solubility in common solvents (Cai *et al.*, 2016; Cheng, Jun, Qin, & Lee, 2017; Ou *et al.*, 2020). Hence, it has been widely applied in drug delivery systems, surgical sutures, scaffolds for tissue regeneration, and other long-term degradable implants (Malikmammadov, Tanir, Kiziltay, Hasirci, & Hasirci, 2018; Mochane, Motsoeneng, Sadiku, Mokhena, & Sefadi, 2019).

Numerous researches have focused on evaluating the impact of the nanoparticles' size and

concentration, along with their distribution on the final properties of the synthesized nanocomposites integrated with Fe_3O_4 particles. Besides, fiber orientation has illustrated an effective role in various features of the electrospun nanofibers. So far, however, there has been little discussion regarding the role of the fiber alignment on the magnetic characteristics of the electrospun nanofibers. Correspondingly, magnetic electrospun fibers were prepared in this study by embedding the Fe_3O_4 nanoparticles into PCL nanofibers through the electrospinning procedure. Additionally, PCL/ Fe_3O_4 composite fibers were prepared in two different architectural designs, including highly aligned twisted yarn and random fibrous membrane. Then, morphological, chemical, thermal, stress-strain, and magnetic examinations were attained for the structures and compared.

2. MATERIALS AND METHODS

2.1. Materials

Poly (ϵ -caprolactone) (PCL), with an average molecular weight of 80,000 (g/mol), was purchased from Sigma Aldrich (USA). Polyvinylpyrrolidone (PVP) coated iron oxide nanoparticles (Fe_3O_4) were supplied by Nanosany Company. Chloroform and methanol were obtained from Merck (Germany). All materials were used without further purification.

2.2. Preparation of PCL/ Fe_3O_4 composite fibers

Various concentrations of Fe_3O_4 nanoparticles (0.5, 1, and 1.5 wt. %) were added to the chloroform/methanol solvent mixture (4:1). To approach homogenous dispersion of the nanoparticles, the prepared mixtures were sonicated for 20 min (Cycle: 0.5, Amplitude: 60). Then, PCL polymer was added to the mixture and stirred vigorously for 2 h at 50°C to obtain clear dark brown polymer solutions with a constant concentration of 12 wt. %.

PCL/ Fe_3O_4 composite fibers were electrospun with two different structural designs, including fibrous membrane and twisted yarn. To fabricate the electrospun fibers, prepared electrospinning solutions were loaded into a 1-ml plastic syringe capped with a 22 G stainless steel needle. The syringe fed the polymeric solution with a constant feeding rate of 0.25 ml/h, was controlled using an infusion pump (TOP, Japan). A voltage of 10 kV was applied to fabricate the electrospun fibers. A take-up roller

(3 cm/min) placed on a rotary surface, was utilized to collect the fabricated yarn (See Fig. 1a). A twist level of 6350 TPM was inserted into the generated electrospun yarn through the rotary surface [30]. The fibrous membrane was also formed by using a rotational cylindrical drum located at a constant 15 cm distance from the syringe's tip (See Fig. 1b). Then, the as-spun PCL/Fe₃O₄ twisted yarns and

fibrous membrane were subjected to further considerations. It is worth noting that the solution viscosity is amplified by an increment of the nanoparticle content in the electrospinning solutions, which ties well with the previous research. Therefore, the polymeric solution containing 1.5 wt. % Fe₃O₄ could not be electrospun as a result of its high solution viscosity.

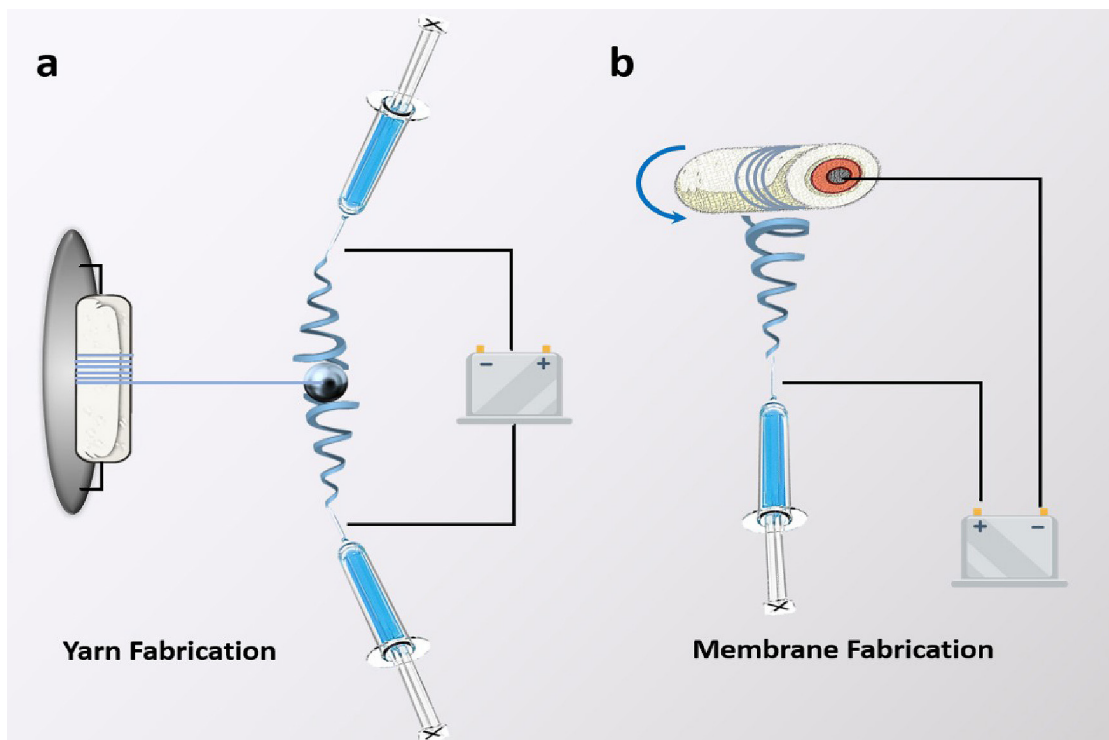


Figure 1. Schematic illustration of the electrospinning apparatus employed for the fabrication of (a) nanofibrous yarn and (b) electrospun membrane.

2.3. Characterizations

Scanning electron microscopy (SEM, PHILIPS XL30) was used to study morphological features of the electrospun fibers, operated at an accelerating voltage of 15 kV. Nanofibrous samples were mounted onto SEM sample holders and sputter-coated with gold. The average diameter of the nanofibers was quantitatively determined through a hundred random measurements of the fibers using image processing software (ImageJ, National Institutes of Health, USA). A Fourier-transform infrared spectrometer (Thermo Nicolet Nexus 670) was utilized to characterize the chemical composition of the fabricated structures. The presence of Fe₃O₄ nanoparticles in the electrospun PCL fibers was studied by using FTIR spectra recorded over the range of

4000-400 cm⁻¹ with 40 scans/min and a resolution of 4 cm⁻¹. FTIR spectra were normalized to the peak intensity at 1730 cm⁻¹ for each composition to compare the prepared samples quantitatively.

The analyses of differential scanning calorimetry (DSC) were conducted using a Mettler TA4000 differential scanning calorimeter in the temperature range from -100 to 100°C with a heating rate of 10°C.min⁻¹ under N₂ atmosphere. Thermal stability of the prepared nanocomposites was characterized via thermogravimetric analysis, performed by a TGA instrument (Mettler Toledo, Switzerland) in the temperature range from 25 to 600°C.

The magnetic properties of the nanofibrous composites with different structures, including twisted yarn and electrospun membrane, were measured using a vibrating sample magnetometer (VSM) (Kavir

VSM, Iran) at ambient temperature. The hysteresis loops of the nanofibers were recorded in a dynamic range of 5×10^{-5} to 500 emu in 10 seconds/point with resolutions of 0.2 and 1 Oe in low and high applied fields, respectively.

The tensile behavior of the electrospun samples was investigated with an Instron 5566 machine equipped with a 50 N load cell. The gauge length was set at 20 mm. In addition, the crosshead speeds of 10 mm/min and 2 mm/min were selected for nanofibrous yarn and electrospun web, respectively. The measurement was repeated 10 times for each sample, and the average value was reported.

3. RESULTS AND DISCUSSION

3.1. Morphological properties

Scanning electron micrographs of the electrospun PCL/Fe₃O₄ yarns containing different concentrations of Fe₃O₄ filler (0.5 and 1 wt. %) and the nanocomposite membrane integrated with 1 wt. % Fe₃O₄ are displayed in Figs. 2a-c. Based on the

obtained SEM images, homogenous and bead-free electrospun fibers were synthesized in all structural designs. This could be assigned to the appropriate condition considered for the electrospinning procedure. Meanwhile, by increasing the nanoparticle content in the electrospun yarn, fibers with irregular surfaces were formed. In addition, agglomeration of the nanoparticles was observed on the electrospun fibers. In the fabricated composite yarn containing 0.5 and 1 wt. % Fe₃O₄, the electrospun fibers showed average diameters of 1073 ± 396 nm and 1768 ± 478 nm, respectively (Fig. 2d). So, increment of the magnetic nanoparticles in the polymeric solution influenced the average diameter of the fabricated nanofibers which is in consistence with the previous studies (Banitaba, Semnani, Heydari-Soureshjani, Rezaei, & Ensafi, 2019). The solution viscosity and conductivity increase as a result of Fe₃O₄ addition into the polymer solution. By increment of the solution viscosity, the elongation rate of the polymer jet reduces due to more entanglement between the polymer chains. Enhancement of the solution conductivity also results in two following

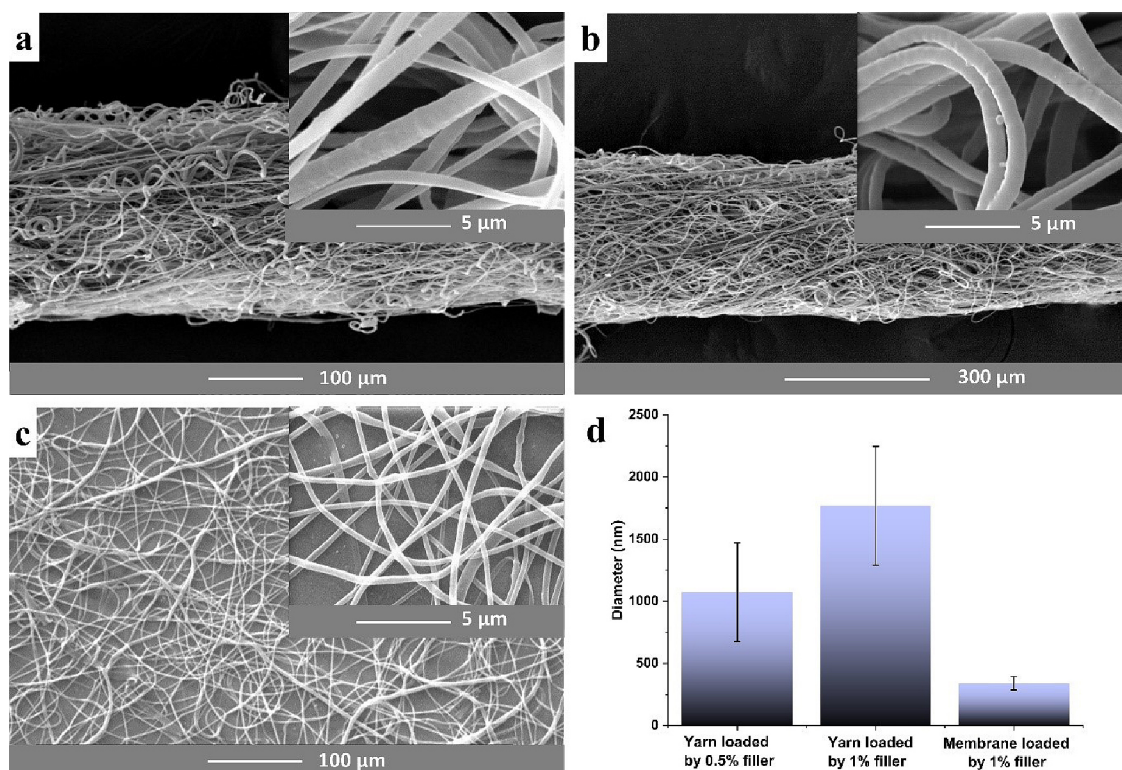


Figure 2. SEM images of the PCL/Fe₃O₄ structures, including (a) nanofibrous yarn containing 0.5 wt. % Fe₃O₄, (b) nanofibrous yarn containing 1 wt. % Fe₃O₄, and (c) electrospun membrane embedded with 1 wt. % Fe₃O₄ and (d) average diameter of the electrospun PCL/Fe₃O₄ fibers in different structural architectures.

effects: increasing the elongation rate and so the formation of the finer fibers, as well as enhancement of the accelerated flow of the polymer solution causing fabrication of the thicker fibers (Banitaba *et al.*, 2019). Thus, it seems that the increment of the average fiber diameter is caused by the interaction of the mentioned effects. Meanwhile, the average diameter of the electrospun fibers was obtained at about 340 ± 55 nm in a PCL membrane structure containing 1 wt. % Fe₃O₄. In fact, the fabricated fibers in the membrane structure were 2.1 and 4.2 times thinner than the PCL electrospun fibers in the yarn structure incorporated with 0.5 and 1 wt. % Fe₃O₄, respectively. The observed significant difference between the average diameters of the electrospun fibers in various structures might result from various electrospinning sets up used for fabrication of the aforementioned nanofibrous structures. It seems that the electrospinning electric field formed in the membrane fabrication setup has more affected the polymeric jet in electrospinning distance compared to that of the yarn fabrication setup (Khademolqorani, Zeinal Hamadani, & Tavanai, 2014).

The average diameter of the fabricated fibrous yarns was obtained at 261 μ m and 486 μ m for Fe₃O₄ contents of 0.5 and 1 wt. %, respectively. Increment of the diameter by 86% for the as-spun yarn containing 1 wt. % Fe₃O₄ could be attributed to the higher diameter of the electrospun fiber and superior tortuosity within the yarn structure. A torsional

stiffness has a direct relation with a diameter and thereby a greater torsion force is required to twist fibers with higher diameter into a yarn body (Meredit, 1954). Herein, the twist level was kept constant to form the electrospun fibrous yarn. Hence, the electrospun fibers with larger diameters represented greater torsional stiffness compared with the ones with finer diameters.

3.2. FTIR characterization

FTIR spectra of PCL/Fe₃O₄ composite fibers containing various fractions of the Fe₃O₄ nanoparticles are represented in Fig. 3a&b. In the pure PCL spectrum (see Fig. 3a), the characteristic peaks at the wavelength of 2929, 2863, 1731, and 1240 cm⁻¹ are attributed to the CH₂ asymmetric, CH₂ symmetric, carbonyl (C=O), asymmetric C–O–C, and C–O stretching vibrations, respectively (Ghasemi-Mobarakeh, Prabhakaran, Morshed, Nasr-Esfahani, & Ramakrishna, 2008; Nasari *et al.*, 2022). By incorporation of the Fe₃O₄ particles into the electrospun fibers, a new peak appeared at a wavenumber of 585 cm⁻¹ corresponding to the Fe–O stretching band. Moreover, by increasing the Fe₃O₄ mass fraction from 0.5 to 1 wt. %, the calculated ratio of the so-called bands (I_{585}/I_{1731}) enhanced from 0.22 to 0.35, which is summarized in Fig. 3b. The observed result confirms more amount of the incorporated Fe₃O₄ nanoparticles in the electrospun fibers.

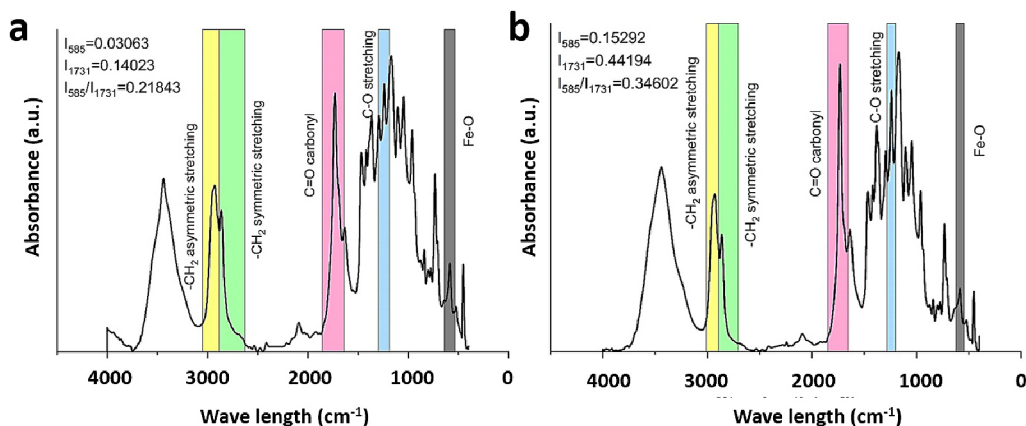


Figure 3. FTIR spectra of the electrospun PCL/Fe₃O₄ fibers, embedded with various Fe₃O₄ mass fractions, including (a) 0.5 wt. % and (b) 1 wt. %.

3.3. Thermal features of the electrospun samples

Differential scanning calorimetric traces of the electrospun membranes, including pure PCL,

PCL/0.5 wt. % Fe₃O₄, and PCL/1 wt. % Fe₃O₄ are shown in Figs. 4a-c, respectively. The crystalline ratio of the prepared membranes was also extracted from the provided data. According to the results, loading the fillers and increasing their ratio in the

electrospun fibers led to a reduction in both melting point onset, as well as the crystalline phases. This could be linked with locating the particulate fillers between the polymer chains of the electrospun fibers, and so reducing their orientation, which is consistent with the previous studies.

The thermal analysis of the fabricated fibers is also represented in Fig. 4d. As can be seen, there are three major loss steps in the obtained curves,

appeared in the temperature ranges from 25-150, 270-380, and 385-460°C, resulting from the water evaporation, degradation of the polymer functional groups, and complete decomposition of the polymer architecture, respectively. Based on the attained data, the onset temperatures were reduced through the addition of filler, which could correspond to the filler aggregation, as well as a reduction in the oriented polymer chains.

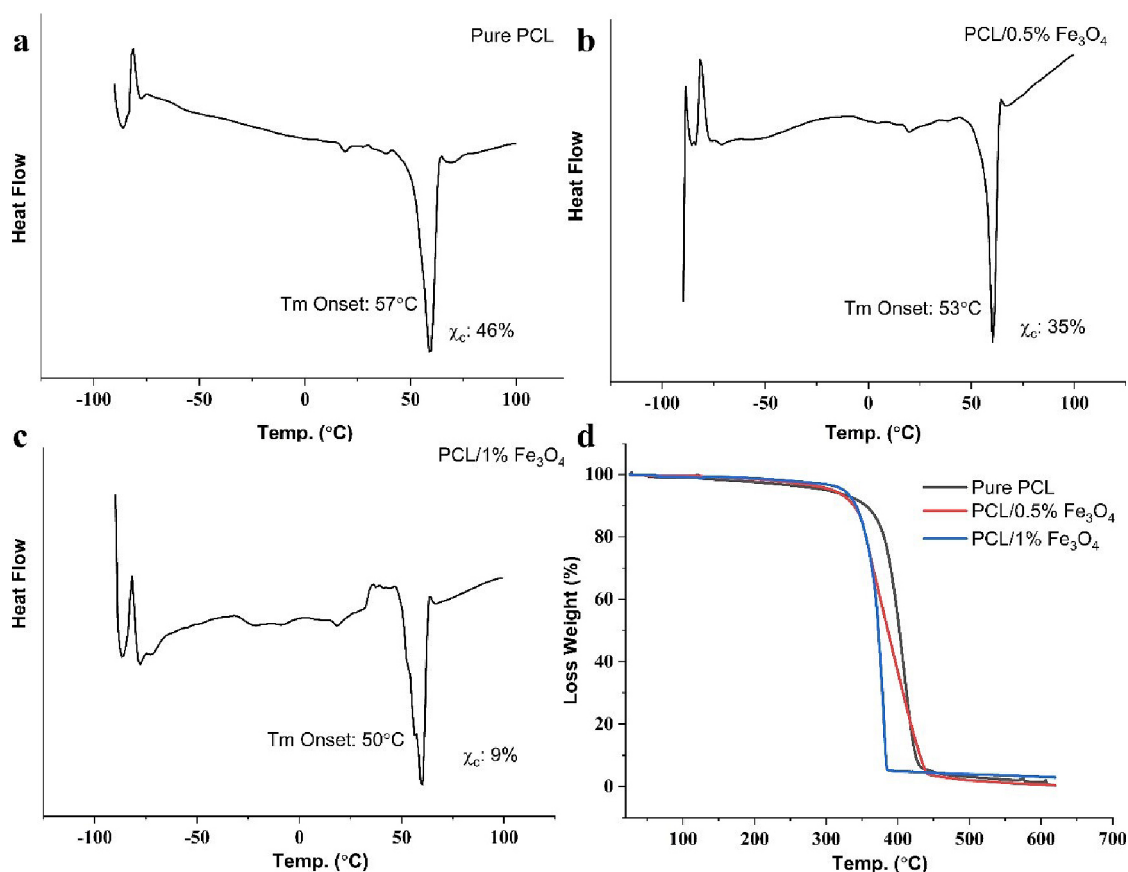


Figure 4. Thermal behavior of the electrospun fibers. (a-c) DSC and (d) TGA traces of the electrospun samples, including pure PCL, PCL/0.5 wt. % Fe₃O₄, and PCL/1 wt. % Fe₃O₄.

3.4. Mechanical behavior of electrospun PCL/Fe₃O₄ yarns and membranes

The incorporation of the fillers into the electrospun fiber structures influences their mechanical characteristics. So, evaluation of the mechanical properties is an essential issue to optimize the filler amount. Fig. 5a displays stress-strain curves of the electrospun PCL/Fe₃O₄ fibers. As can be seen, elongation at break, as well as the mechanical strength, were improved by increment of the filler ratio from 0.5 to 1 wt. %. Since, the elongation at break enhanced from

208 to 340 %. In addition, the mechanical strength raised from 24.14 to 40.28 MPa. The results could be attributed to the higher resistant force induced by the bond strength of filler particles with the applied polymer matrix which ties well with the previous research (Hema & Tamilselvi, 2016; Podsiadlo *et al.*, 2007). Furthermore, electrospun yarn inserted with the high mass fraction of Fe₃O₄ contained fibers with higher diameter and possessed a bulkier structure. From the structural viewpoint, the above features lead to a reduction of the cohesion and frictional forces between the electrospun fibers and

the formation of the electrospun yarn with a loose structure. This can promote the slippage between the fibers resulting in further elongation rate of the as-spun yarn under the applied tensile force. The mechanical properties improvement of the electrospun yarns by incorporation of the Fe₃O₄ nanoparticulate filler could also confirm good dispersion of the nanoparticles within the PCL fibers. Since agglomeration of nanoparticles can lead to stress

concentration points and hence weaker structure of the electrospun yarns. The comparison of mechanical behavior of the electrospun yarn and nanofibrous membrane embedded with the same Fe₃O₄ content is summarized in Fig. 5b. Based on the obtained data, the yarn structure has more capability to undergo tensile loading due to more alignment and cohesion among fibers resulting from twisting of the fibers in this structure.

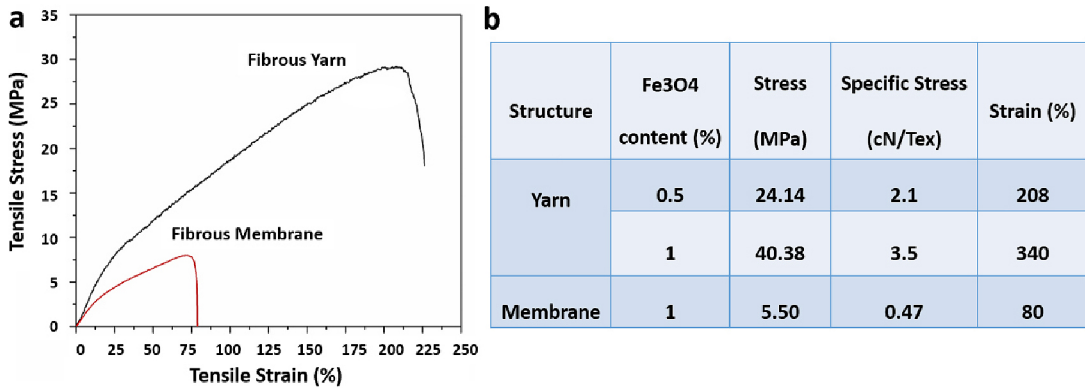


Figure 5. (a) Stress-strain graph curvature of the electrospun PCL/Fe₃O₄ yarn and membrane incorporated with the constant Fe₃O₄ mass fraction of 1 wt. % and (b) Mechanical properties of electrospun PCL/Fe₃O₄ fibers prepared in different formations.

3.5. Magnetic properties of the electrospun PCL/Fe₃O₄ fibers

To characterize the magnetic properties of the electrospun PCL/Fe₃O₄ composite fibers with various structures, M-H hysteresis curves were recorded using VSM at room temperature. Figs. 6a&b exhibit the magnetic features of the electrospun yarn, in tandem with the nanofibrous membrane, respectively. Symmetric hysteresis and saturation magnetization are

observed in the hysteresis curves. The coercive force and remanence of all electrospun fibrous samples were approximately zero which revealed that they were expected to present a superparamagnetic response at room temperature. This behavior may also be due to the small size of magnetic domains inside electrospun PCL/Fe₃O₄ fibers. This means that embedding of Fe₃O₄ nanoparticles with the particle size of 20-30 nm, within the PCL polymer matrix through electrospinning has resulted in no serious aggregation.

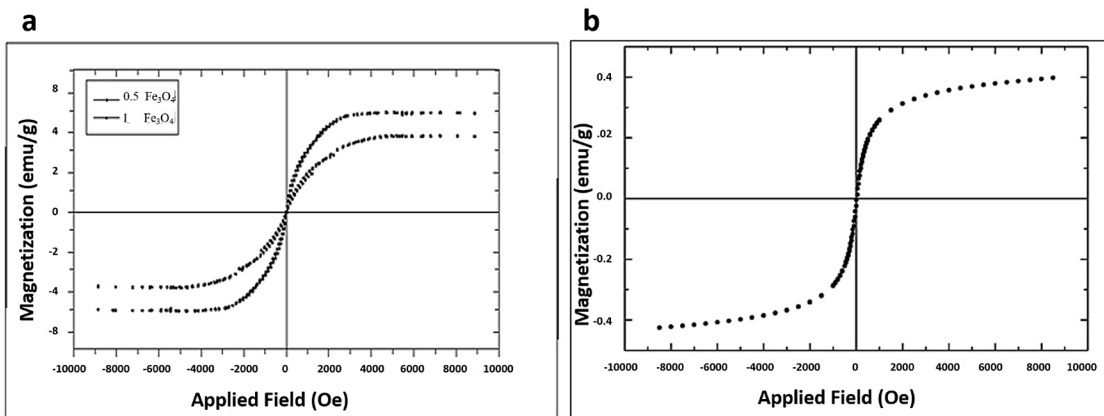


Figure 6. Hysteresis curves of the fabricated PCL/Fe₃O₄ fibers with various structures and Fe₃O₄ mass fractions including (a) nanofibrous yarn and (b) nanofibrous membrane

For electrospun PCL/Fe₃O₄ yarns, the saturation magnetization (Ms) was dependent on the filler ratio inside the composite fibers. So, it resulted in 3.86 and 5.83 emu/g for Fe₃O₄ contents of 0.5% and 1%, respectively. Electrospun yarn embedded with a higher mass fraction of Fe₃O₄ was saturated at the lower applied field. The reduction of the Ms value for the electrospun yarn loaded by Fe₃O₄ low mass fraction was also accompanied by the reduction in the diameter of electrospun PCL/Fe₃O₄ composite fibers. This could be owing to the scale effect such as thermal fluctuation on the surface or magnetically disordered surface formed because of the large specific surface area as well. The Ms values obtained for the electrospun yarns were very low compared with those reported in the previous studies which were in the range of 50.31-70.3 emu/g (G. Wang, Zhao, Li, Wang, & Ma, 2018). Lower obtained values for the electrospun PCL/Fe₃O₄ composite fibers in comparison to the Fe₃O₄ nanoparticles can be assigned to the existence of the nonmagnetic PCL components in the prepared composites, as well as the wide size distribution of the applied Fe₃O₄ nanoparticles in the composite fibers which is in consistence with previous researches. As depicted in Fig. 6, the saturation magnetization of the electrospun membrane yielded 0.397 emu/g at the Fe₃O₄ content of 1%. This value is lower than the magnetization values obtained for the electrospun yarns. This indicates that by decreasing the distance between composite fibers containing magnetic nanoparticles through the twisting process and orientation of them in the yarn structure, it is possible to improve the magnetic properties of electrospun fibrous assemblies.

It is worth noting that the addition of nanoparticulate fillers to a polymer matrix leads to variations in hydrophilicity, cytotoxicity, and overall performance in tissue engineering applications. Regarding the impact of filler presence in the structure, several factors should be considered, including the effect on surface properties, surface energy modification, interfacial bonding and wetting, and polymer matrix characteristics. In fact, if the particles have hydrophilic properties, they might increase the overall hydrophilicity of the composite. Conversely, if the particles have hydrophobic characteristics, they could reduce the composite's hydrophilicity. The addition of particles may also lead to changes in the surface energy of the composite. Surface energy affects the wetting behavior of a material. Hydrophilic surfaces generally have

higher surface energies, whereas hydrophobic surfaces have lower ones. The presence of nanoparticles may modify the surface energy and, consequently, the hydrophilicity of the composite. Nanoparticles can influence the interfacial adhesion between the polymer matrix and any surrounding environment, affecting the overall wetting behavior. Depending on their interaction with the polymer, the particles could enhance or reduce the wetting and hydrophilic properties of the composite. Moreover, certain polymers inherently have hydrophilic or hydrophobic traits, and the presence of fillers may either reinforce or counteract those characteristics. Based on the literature, the incorporation of Fe₃O₄ nanoparticles in the electrospun fibers increases the pores and voids in the structure, enhancing water adsorption (Bagheripour, Moghadassi, & Hosseini, 2017). Rezaei *et al.* (Rezaei, Mirzaei, Taghizadeh, Berenjian, & Ebrahiminezhad, 2021) also declared that the presence of Fe₃O₄ magnetic nanoparticles in the structure of electrospun PCL fibers could enhance the hydrophilicity, leading to enhanced cell attachment and viability. Moreover, the non-cytotoxicity of the electrospun PCL fibers containing magnetic nanoparticles has been widely corroborated (Ge, Asmatulu, Zhu, Zhang, & Yang, 2022; Vieira, Maurmann, Venturini, Pranke, & Bergmann, 2022). Considering the outstanding characteristics of the PCL fibers integrated with magnetic nanoparticulate fillers, the designed structures in the current study have great potential for approaching appropriate biomedical applications.

Overall, electrospinning technology has enabled the fabrication of nanofibrous structures with diverse structural designs and applications, particularly in the field of nanocomposite materials. Despite the fascinating characteristics of the electrospun PCL/Fe₃O₄ nanoparticles, there are still several challenges, which should be considered in future studies. First, achieving uniform dispersion of Fe₃O₄ particles within the PCL nanofibers presents a significant challenge. Agglomeration of nanoparticles can affect the mechanical and magnetic properties, as well as the overall homogeneity of the composite (Banitaba, Semnani, *et al.*, 2023). Second, ensuring strong interfacial bonding between the Fe₃O₄ nanoparticles and the PCL matrix is critical to enhancing mechanical and magnetic properties. Additionally, incorporating Fe₃O₄ into the electrospinning process without adversely affecting the process conditions (e.g., solution viscosity, electrical conductivity) can be complex and

may require optimization (R. Kumar, A. Sudhaik, Sonu, *et al.*, 2023; Sonu *et al.*, 2023). Approaching consistent dispersion of Fe₃O₄ nanoparticles at the nanoscale level is critical to realizing the desired properties and functionality. Furthermore, embedding Fe₃O₄ nanoparticles may increase material and processing costs, necessitating cost-effective production methods and material usage. Correspondingly, strategies for surface modification of Fe₃O₄, optimization of electrospinning parameters, and tailored processing methods need to be explored to address these challenges and realize the full potential of electrospun PCL nanofibers containing Fe₃O₄ in various applications (Banitaba, Ahmed, Norouzi, & Khademolqorani, 2023; Khademolqorani & Banitaba, 2022).

4. CONCLUSIONS

In this study, electrospun magnetic structures were electrospun by incorporation of 0.5 and 1 wt. % Fe₃O₄ magnetic nanoparticles into various electrospun structures of the PCL polymer. Electrospun PCL/Fe₃O₄ fibers showed an irregular surface. In addition, the average fiber diameter increased by an increment of the Fe₃O₄ nanoparticle ratio loaded in the as-spun fibers. FTIR study demonstrated the presence of Fe₃O₄ nanoparticles inside the prepared fibrous composites. The increase of Fe₃O₄ mass fraction from 0.5 to 1 wt. % improved the elongation at break and the ultimate strength of electrospun yarns by 63% and 67%, respectively. Electrospun PCL/Fe₃O₄ composite fibers exhibited superparamagnetic behavior at room temperature. The saturation magnetization showed an interdependent behavior to the number of magnetic nanoparticles inserted into the fibers. The magnetic response of the electrospun yarns was improved from 3.86 emu/g to 5.83 emu/g by increment of the Fe₃O₄ mass fraction. Moreover, the as-spun yarn represented higher saturation magnetization compared with the nanofibrous membrane. Electrospun PCL/Fe₃O₄ magnetic yarns with improved mechanical and magnetic properties could be applicable as surgical sutures with the release capability of bioactive agents under a magnetic field.

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