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Controlling electron movement with magnetic field in electrospinning method

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ABSTRACT

Electrospinning is one of the simple and effective production methods to produce fiber structures from various polymers whose diameters can vary from nano to micro scale. One of the biggest problems encountered in the production of fiber mats by the electrospinning method is that the electrical field dispersed due to instabilities prevents the production of homogeneous material. Although the fibers produced by the currently used electrospinning method tend to be pulled out of the collector plate due to instability, this causes both material loss and the inability to produce fiber mats with the desired properties. In this study, electrons focused on the collector plate by using a magnetic field. Neodymium magnets of different shapes, sizes and thicknesses were used to investigate the change in magnetic field strength. It was observed that the use of neodymium magnets in the electrospinning device enabled more homogeneous fiber formation and more focused production without material loss. Thus, it has been determined that the fact that there is no need for extra energy consumption by using permanent magnets and that the system placed to obtain the magnetic field is not on the production line, controls the instability and makes fiber production with the electrospinning device more cost-effective and more applicable.

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1. INTRODUCTION

Electrospinning, a method that employs an electrically-charged jet of a polymer solution/melts to produce fibers, has garnered significant interest. The electrospinning method enables the creation of polymeric surfaces composed of fibers ranging from a few microns to less than 100 nm in diameter. The properties of the resulting fibers are strongly affected by parameters such as solution features (concentration, viscosity, surface tension, etc.), processing variables (voltage, solution injection rate, distance between the syringe needle and the collector, etc.), the spinning system (nozzle type, diameter, etc.), and external environmental conditions (temperature, humidity, etc.). Electrospun fibers are unique in their properties, including large specific surface areas, excellent mechanical properties, diverse compositions, etc., and have therefore found increasing applications in areas such as energy storage, filtration, textiles, medical and pharmaceutical products, and others [1-4].

The electrospinning method is used to produce nanomaterials using an electrostatic field that utilizes the path of an electrically charged nanofluid starting from the surface of a polymer solution [5]. A voltage difference of kV is created between a syringe needle and a collector in this method, which is used to accelerate or stop the nanofluid. An electric charge is induced on the surface of a polymeric droplet due to the strong external electric field between the syringe needle and the collector, causing the originally hemispherical surface of the polymeric droplet at the mouth of the syringe needle to gradually elongate into a conical shape known as a Taylor cone [6]. Determining the size and density of nanomaterials produced using the electrospinning method can be extremely difficult because the shape of the Taylor cone can affect these parameters [6].

One of the biggest problems encountered in the production of fiber mats with the electrospinning method, the theory of which is described above, is that the electrical field dispersed due to instabilities prevents the production of homogeneous and efficient fiber material. In addition, since material loss occurs due to instabilities during production, it also causes more material and energy consumption to produce fiber mats with the desired properties. When the studies in the literature are analysed, it has been determined that various studies have been performed to examine the effect of magnetic fields on fiber production in the electrospinning method. Liu et al. obtained nanofibers from poly (vinyl pyrrolidone) (PVP) and poly (D, L-lactic-co-glycolic acid) (PLGA) polymers using the magnetic field assisted electrospinning (MFAES) method [7]. In the MFAES processing,

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two bar magnets (2.5×2.5×15 cm, Rochester Magnet Co., Part No.: RMC5B-522, non-conductive) of conventional configuration were used in the collector environment [7]. Thick insulation boards are placed between the magnets and the aluminium foil, which is the collector, to make sure that there is no direct contact between them. The optimum distance between the two magnets was kept in the range of 0.5-4 cm. Fibers manufactured using the MFAES method are significantly more uniform than fieldless ones, and have much less, if any, splitting [7]. In their study by Pokorny et al. Helmholtz coils were used as a source of variable magnetic field and its effect on the electrospinning process was investigated [8]. A 12 wt. % aqueous solution of poly(vinyl alcohol) (PVA) was used as the non-magnetic material for spinning. As a result of the study, it was observed that the intensity of the magnetic field did not affect the diameter of the nanofibrous layer. It was determined that the important difference was in the diameters of the nanofibrous layers for different high-voltage polarities [8]. Bagheri et al. examined the influence of electrical and magnetic fields on producing more efficient nanofibers by electrospinning method [9]. Within the scope of the study, polyamide nanofibers were prepared with the traditional approach and under subsidiary electric and magnetic fields. A helical-shaped subsidiary electrode made of copper tube was used as a subsidiary electrode. For the magnetic field, two permanent magnets are inserted into the parallel position of the main negative aluminium collector. Besides, magnetic ionic liquid (MIL) was added to the polymeric solution to induce sufficient magnetic susceptibility. Scanning electron microscope (SEM) images discovered that the application of subsidiary electric and magnetic fields resulted in aligned nanofibers with average diameters of 200 nm and 90 nm, respectively, while the average diameter for traditional electrospun nonwoven nanofibers was 500 nm. In addition, the study showed that increasing the aspect ratio of electrospun nanofibers due to the decline in diameter increased extraction performance [9]. Xu et al. carried out a magnetic field relieved setup design to produce nanofibers with controlled fibre diameter and deposition zone by alteration of the magnetic/electric field [10]. The diameter and deposition area of the prepared nanofibers were controlled with an additional helical tube that could provide an external electric-magnetic field. The obtained results show that the accuracy of the electric-magnetic field can control the validity of placement through the electrospinning method. In addition, it has been determined that the charged particles point to the N and S poles at the magnetic moment position and distort and rotate in one direction [10]. In addition to all the results, it has been observed that the magnetic field can affect the charged jet at a proper distance so that the jet changes the initial electric magnetic field and guides the spinning point in a field spinning operation in a system.

In the literature, it is seen that magnetic ionic liquid, Helmholtz coils, helical tubes or permanent magnets are used to investigate the effect of magnetic field on fiber production. Active systems used in the production of the magnetic field need external energy. The electricity consumption of the electrospinning device, which is currently operating at high voltages, is quite high. Integrating a system that needs additional energy consumption means a significant increase in production costs. When the same studies are examined, it is seen that the magnetic field generating systems are placed between the needle tip and collector plate to deflect the electric field. Adding additional systems to the fiber production path has the potential to be a major obstacle to the industrialization of the electrospin device.

This study, it is aimed to focus the electron movement on the collector plate instead of deflecting it by using a magnetic field. Neodymium magnets that provide a constant magnetic field are placed behind the collector plate, aiming to focus the fibers produced on the collector plate without the need for an extra system on the production line.

2. THE THEORETICAL AND MATHEMATICAL BACKGROUND

The electrospin method consists of three main parts as seen in Figure 1.

1. High voltage source,
2. Feeding unit (syringe, metal needle etc.),
3. Collector (conductor plate, rotary cylinder, etc.) [11].

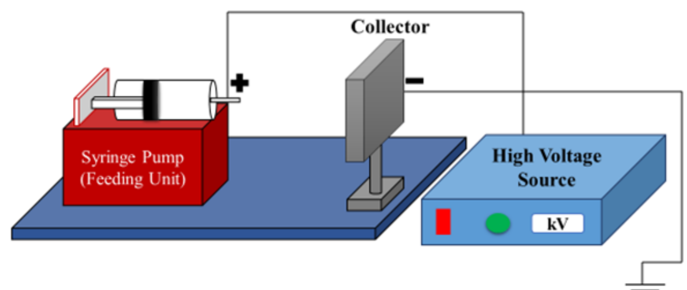


Fig. 1. Simple schematic representation of the electrospinning method.

There is an automatic pump located at the back of the syringe to ensure that the polymer solution is fed slowly and controlled during the electrospinning process. The automatic pump is adjusted to deliver the polymer solution in the syringe at the desired speed. An electric field is created with the electric current given to the polymer solution and an electrical charge occurs on the surface of the solution. The polymer drop exists in a spherical shape due to the forces exerted by the surface tension up to a critical voltage value. When the applied potential difference reaches a threshold value, the electrostatic forces are equalized to the surface tension forces. At this point, the polymer drop changes shape, forming a conical shape. This shape is called the 'Taylor cone'. After some increase in the electric field, the surface tension cannot balance any more electrostatic force and a thin charged jet is launched from the Taylor cone. The polymer jet splits into very fine fibers and falls on a metal plate [12, 13].

There are certain stages of the electrospinning method. These stages can be listed as follows:

1. Droplet formation: In the first stage of the electrospinning method, the molten or solution-formed liquid polymer is fed from the needle tip to the drafting zone at very low speeds. A droplet forms at the tip of the needle and the droplet falls with the effect of gravity. This droplet is under the influence of two forces. Surface tension of the liquid, and gravitational force. If no voltage is applied, this liquid droplet will fall off after a certain time. With the increase in voltage, the droplet grows.

2. Taylor cone formation: The solution droplet suspended at the needle tip is spherical up to a critical voltage value with the effect of surface tension forces. Although the applied voltage arrives at a critical value, the electrostatic forces are equalized to the surface tension forces. At this point, the polymer drop changes shape and takes the form of a cone. This cone is called a Taylor cone [14-15].

3. Jet formation: After the Taylor cone is formed, after a slight increase in the electric field, the surface tension cannot balance any more electrostatic force and a charged thin jet is thrown from the Taylor cone.

4. Elongation of the jet in the steady region: As soon as the voltage applied to the polymer solution exceeds the critical voltage value, the jet initiation occurs suddenly. Beginning from the Taylor cone, the jet accelerates and follows a linear path for a while. Consequently, the diameter of the jet becomes smaller rapidly due to the elongation of the jet and the evaporation of the solvent. With the thinning of the jet, the surface charge per unit area of the jet decreases, while the surface area per unit mass increases.

5. Formation of unstable region (Whipping instability): Some instabilities occur at this stage. After some distance, the jet ejected from the cone continues to elongate rapidly towards the collector with some bending instability due to the repulsive electrostatic forces caused by the charges inside the jet. Then, due to bending instability, the jet can split into many other jets. Due to the simultaneous elongation of the jet, the fiber diameter decreases, and the surface area increases with the evaporation of the solvent. This condition, known as asymmetrical or whipping instability, has been shown to reduce jet diameter [16].

6. Solidification of the jet in the form of fiber: While the polymer jet moves in the unstable region, the amount of mass increases with the increase of the jet area and the solvent in the solution evaporates. In this step, the jet continues on its way by forming rapid bends or splitting into fine jets, reaching the collector.

The mathematical model of electrospinning is predicated on the approach proposed by [5, 17]. Fick's first law is used to describe the transfer of solvent mass between a fluid and the surrounding gaseous medium as in Equation (1). Where *m*: mass, *d*: diameter, *l*: length, *i*: position, h_m: mass transfer coefficient, *ρ*: polymer solution density, $C_{s,eq}$: concentration of solution at test temperature, $C_{s,\infty}$: concentration of solution at evaporation temperature.

$$\frac{dm_{si,i+1}}{dt} = h_m \pi \, d_{i,i+1} \, l_{i,i+1} \, \rho \, (C_{s,eq} - C_{s,\infty})) \tag{1}$$

The viscoelastic behaviour of a polymer solution was modelled in this study using the nonlinear Maxwell rheological model, which consists of a non-linear spring called the Hooke element, connected in series with a non-linear viscous damper as in Equation (2). Where *σ:* stress, ℵ*:* viscosity, *τ:* strain time, *r:* diameter vector, *v:* velocity vector.

$$\frac{d\sigma_{i,i+1}}{dt} = \frac{\aleph_{i,i+1}}{\tau_{,i+1}} \frac{(r_i - r_{i+1})(v_i - v_{i+1})}{l^2{}_{i,i+1}} - \frac{\sigma_{i,i+1}}{\tau_{i,i+1}} \tag{2}$$

A scalar function is used to describe the electrostatic potential outside of a polymeric droplet as in Equation (3). Where *φ*: electrostatic potential of the polymer drop, q_p*:* charge density, ε_0*:* relative permeability of air, ε_r*:* relative permeability of the substance, *Q:* charge, r_i*:* instantaneous diameter, *r′:* maximum diameter.

$$\varphi = \frac{q_p r^3}{3\varepsilon_0 \varepsilon_r} \frac{1}{|r_i|} - \frac{Q}{4\pi\varepsilon_0\varepsilon_r} \frac{1}{|r_i - r'|} \tag{3}$$

The difference in electric potentials between the anode and cathode is responsible for the strength of the electric field's electrostatic force, which is defined by Equation (4) acting on the fluid's mass point. Where F_{Ei}*:* electrical force, *q:* charge, *E:* electric field strength.

$$F_{Ei} = q_i E_i \tag{4}$$

Lorentz force equation proves that the electrical force is affected by the magnetic field as in Equation (5). Where *q:* load, *V:* velocity, *B:* magnetic field*).*

$$F_{Ei} = qVB \tag{5}$$

In this study, it has tried to manipulate the electric field in electrospinning by using a magnetic field to create high-quality nanofibers.

3. EXPERIMENTAL

In the electrospinning method, the fibers are formed as a result of a high voltage applied to the needle tip (anode) and an electron beam flowing in the gap towards the collecting plate (cathode) and an electrical field is created by this. A magnetic field is perpendicular to this field must be applied to direct this electric field that provides the formation of fibers. For this purpose, the constant magnetic field source (magnets) is placed at a distance appropriate to the electric field according to the deflection direction. It has been investigated whether the desired deviation in the electrical field is caused by the distance change. In this study, as shown in Figure 2 neodymium (Nd) magnets have been used to create the magnetic field used as a manipulator.

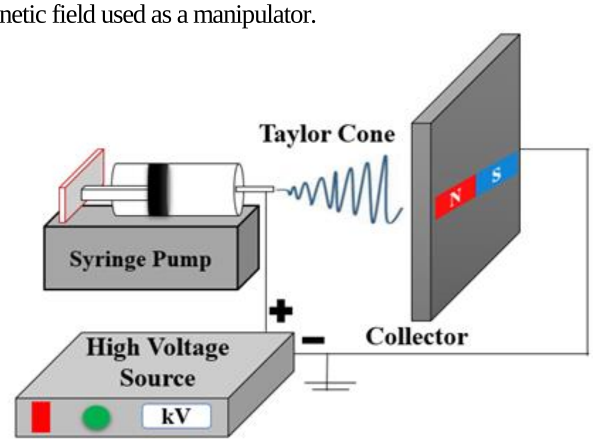


Fig. 2. Schematic illustration of electrospinning set up with *Nd* magnets.

The study was first started by using neodymium magnets with a length: of 15mm, width: of 15mm, and thickness: of 2mm. Nanofiber production conditions were kept as standard to observe the effects of magnets. Polyacrylonitrile (PAN), the most commonly used polymer, was used for nanofiber production [18, 19]. While determining the production conditions, optimum conditions for PAN nanofibers determined by the previous study were taken into consideration [20]. In all trials, 20 kV voltage was applied to 8% wt PAN solution, 0.5 mL/hour feed rate was used and the distance between needle tip and collector was kept as 12 cm. Aluminum foil on a 25 cm x 30 cm metal plate was used as a collector. Production was carried out for two hours in all trials.

In the first part, all other conditions were kept constant so that only the effect of magnets on electron movement could be observed. Dimensions and properties of *Nd* magnets are given in Table 1. The second part aims to determine the optimum production conditions of the device to be developed by changing magnets with different properties, different types of collectors and the distance between the needle tip and collector. Characteristics of the second part trials are given in Table 2.

Table 1. Dimensions and properties of *Nd* magnets

Typs	*Length(mm)*	*Width (mm)*	*Thickness(mm)*
Square	15	15	2
Rectangle	40	20	5
Types	*Diameter(mm)*	*Hole diameter*	*Thickness(mm)*
Circle	40	10/5.5	5
	30	10	5

Table 2 Characteristics of second part trials

Collector plate	*Needle tip-to-collector distance (cm)*
Metal/	8
Cardboard	12
	16

Thus, the relationship of the magnetic field strength created by the magnets with the collector material and distance was observed.

4. RESULTS

4.1. First Part Results

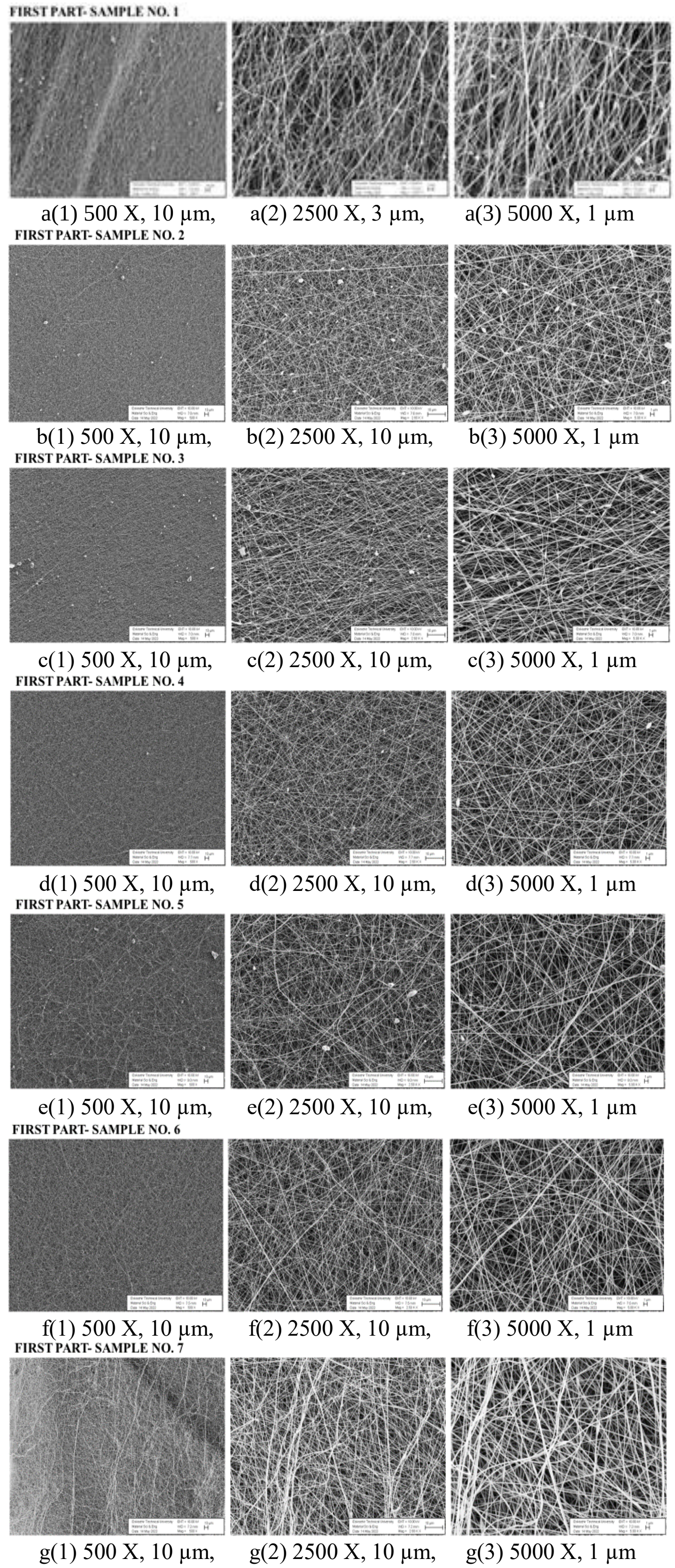
The magnet conditions and production dimensions of all trials carried out in the first part are given in Table 3. All trial conditions are given in Appendix Part. As the production dimensions, the height and width of the shape obtained on the metal were measured. Thus, it was investigated whether the deposition of fibers on the metal plate was controlled or not.

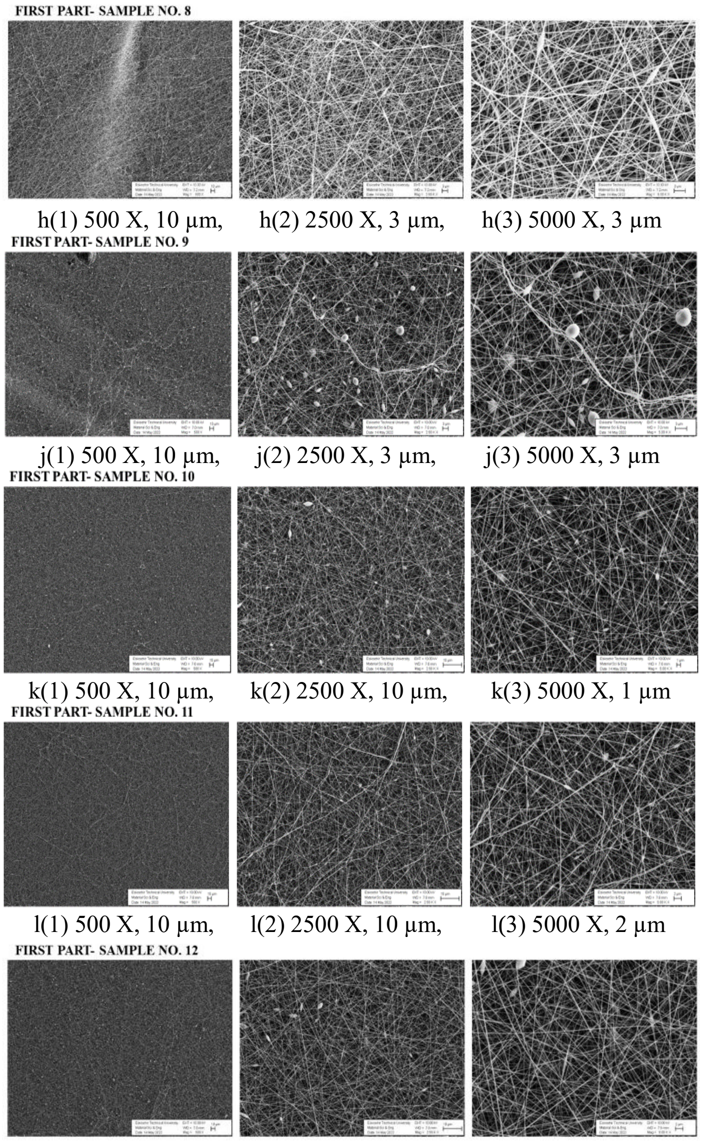
Table 3. The first part is production dimensions.

Sample no	*Distance (cm)*	*Height (cm)*	*Width (cm)*
1.1	12	16	13.5
1.2	12	21	16
1.3	12	14.5	12.5
1.4	12	13.5	11.5
1.5	12	14	12
1.6	12	11.5	11
1.7	12	12.5	9
1.8	12	12.5	10
1.9	12	13	10.5
1.10	12	18.5	15.5
1.11	12	18	15.5
1.12	12	14	11

SEM images were taken to observe the effect of magnets on fiber properties in Figure 3 a(1, 2, 3) to m(1, 2, 3). SEM images were used to examine the morphological properties of the produced nanofibers. It has been observed that the surfaces of nanofibers produced without using magnets are rougher and their distribution is more dispersed. Additionally, a sparser fiber collection due to material loss can be seen in the images.

According to the magnetic field strength provided by the magnets used, both smoother fiber surfaces and homogeneous fiber distribution were obtained. In addition, a denser fiber collection is observed since there is no material loss due to the focus provided by the magnets. SEM images were taken into consideration for the magnet combination and magnetic field strength to be used.





FIRST PART- SAMPLE NO. 8

h(1) 500 X, 10 µm, h(2) 2500 X, 3 µm, h(3) 5000 X, 3 µm

FIRST PART- SAMPLE NO. 9

j(1) 500 X, 10 µm, j(2) 2500 X, 3 µm, j(3) 5000 X, 3 µm

FIRST PART- SAMPLE NO. 10

k(1) 500 X, 10 µm, k(2) 2500 X, 10 µm, k(3) 5000 X, 1 µm

FIRST PART- SAMPLE NO. 11

l(1) 500 X, 10 µm, l(2) 2500 X, 10 µm, l(3) 5000 X, 2 µm

FIRST PART- SAMPLE NO. 12

m(1) 500 X, 10 µm, m(2) 2500 X, 10 µm, m(3) 5000 X, 2 µm

Fig. 3. SEM images of the first part productions at 500 X (1), 2500 X (2) and 5000 X (3) magnifications, respectively for 12 samples.

The results of the first part can be summarized as follows:

- It was observed that nanofibers produced using magnets were denser and more homogeneous compared to the production without magnets.
- When the magnet coefficient was increased to three, it was observed that the fibers were smoother and more homogeneous.
- It was observed that changing the location of the magnets behind the metal plate did not cause a significant change in the fiber structure.
- It was observed that the presence of magnets on the front or back surface of the metal plate did not cause a significant change in the fiber structure.
- It has been observed that one of the magnet directions causes focusing and the other side causes dispersion.

4.2. Second Part Results

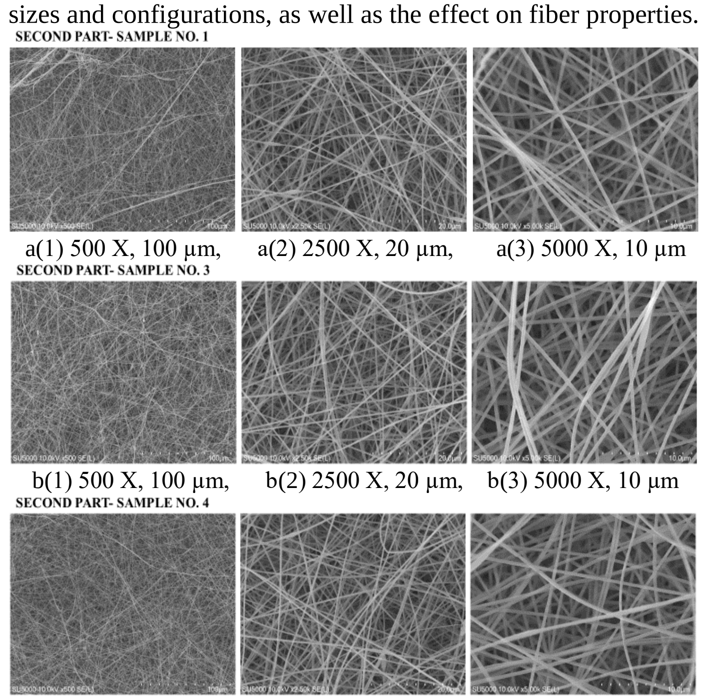
After the completion of the first part, in line with the results obtained, Fiber production characteristics were investigated by using *Nd* magnets as length: 40 mm, width: 20 mm, thickness: 5 mm, diameter: 40 mm, hole diameter: 10/5.5 mm, thickness 5 mm and diameter: 30 mm, hole diameter:10 mm, thickness 5 mm.

In this part, the effects of parameters such as different collector properties, the change in distance between the needle tip and collector, and the magnet position on the fiber properties were observed. The distance part given in Table 4 shows the distance between the needle tip and the collector.

Table 4. The second part production dimensions.

Sample no	*Distance (cm)*	*Height (cm)*	*Width (cm)*
2.1	12	13	9.5
2.2	12	13	10
2.3	12	12	8.5
2.4	12	12.5	9.5
2.5	12	12	9.5
2.6	12	11	9.5
2.7	12	10.5	9.5
2.8	12	14.5	10
2.9	8	8	7
2.10	8	8.5	7
2.11	16	21	13
2.12	16	21	14
2.13	16	17	13
2.14	16	17	13
2.15	16	18	14
2.16	12	10.5	9
2.17	8	6	5.5
2.18	12	11	9
2.19	8	7.5	6.5

SEM images in Figure 4 (a) to (k) were taken to investigate the effect of manufacturing dimensions of magnets in different sizes and configurations, as well as the effect on fiber properties.



SECOND PART- SAMPLE NO. 1

a(1) 500 X, 100 µm, a(2) 2500 X, 20 µm, a(3) 5000 X, 10 µm

SECOND PART- SAMPLE NO. 3

b(1) 500 X, 100 µm, b(2) 2500 X, 20 µm, b(3) 5000 X, 10 µm

SECOND PART- SAMPLE NO. 4

c(1) 500 X, 100 µm, c(2) 2500 X, 20 µm, c(3) 5000 X, 10 µm

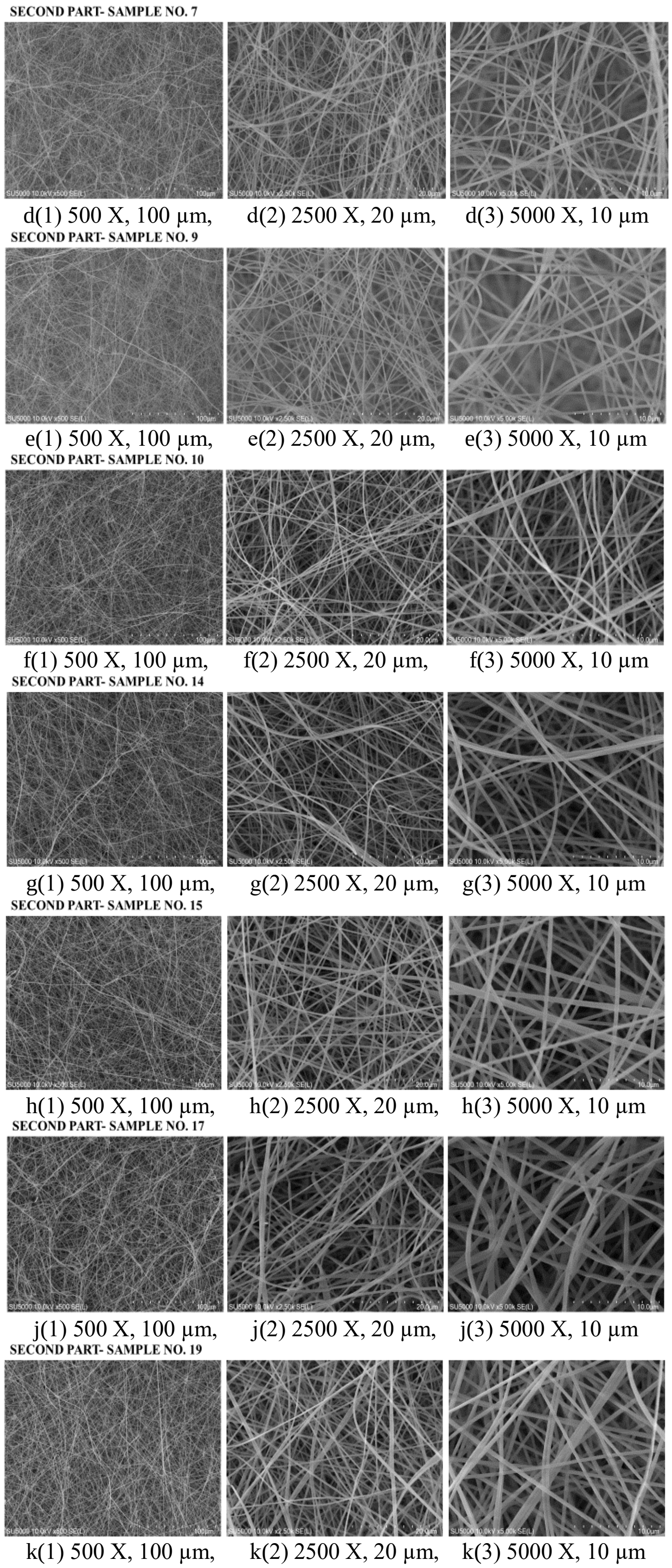


Fig. 4. SEM images of the second part productions at 500 X (1), 2500 X (2) and 5000 X (3) magnifications, respectively for 10 samples.

In Table 5, the effect of magnets in different shapes and configurations on the production dimensions by changing the distance between the needle tip and collector is given comparatively. At 12 cm, which is the optimum condition for PAN fibers, the production size did not change with the strength of the magnets. It was also observed that as the magnet power increased at closer and farther distances, the dispersion decreased and the focusing increased.

Table 5. Effect of magnets of different strengths on production dimensions with distance.

Sample no	*8 cm*		*12 cm*		*16 cm*	
	Height(cm)	*Width(cm)*	*Height(cm)*	*Width(cm)*	*Height (cm)*	*Width (cm)*
3.1	8	7	16	13.5	27	15
3.2	8.5	7	10.5	9.5	21	13
3.3	7.5	6.5	11	9	17	13
3.4	6	5.5	10.5	9	18	14

In the first part, it was found that the magnet direction affects the focusing. In the direction of the measurements, it was observed that if the *S* pole of the magnets is towards the collector, there is focus, and if the *N* pole is towards the collector, dispersion occurs.

Table 6. Effect of magnet direction on production dimensions.

Sample no	*S pole towards the collector*		*N pole towards the collector*	
	Height (cm)	*Width(cm)*	*Height (cm)*	*Width (cm)*
4.1	14.5	12.5	21	16
4.2	13	10.5	18.5	15.5
4.3	12	8.5	13	10
4.4	10.5	9.5	14.5	10

5. CONCLUSION

In this study, neodymium magnets were used to control electron movement with a magnetic field in the electrospin method. Nanofiber production conditions were kept as standard to observe the effects of magnets. Polyacrylonitrile (PAN), the most commonly used polymer, was used for nanofiber production. While determining the production conditions, optimum conditions for PAN nanofibers were taken into consideration. The results of the electric field modelling studies can be summarized as follows:

It has been observed that the use of magnets prevents the produced fibers from spreading to the entire device, allowing focus only on the collector plate.

From the magnet directions, it has been observed that the *S* pole towards the needle tip causes focusing, and the *N* pole towards the needle tip causes dispersion. The *S* and *N* fields are opposite to each other and the *S* direction is inward while the *N* direction is outward. During nanofiber production, focusing was achieved when the *S* direction was towards the needle tip, while dispersion was observed when the N direction was towards the needle tip. This situation occurred because of the distribution of magnetic fields.

Compared to the production without magnets, it has been observed that nanofibers produced using magnets are more dense and homogeneous.

It has been observed that the presence of magnets on the front or back surface of the metal plate does not cause a significant change in the fiber structure.

At 12 cm, which is the optimum condition for PAN fibers, the production size does not change with the strength of the magnets, while it is observed that the dispersion decreases and the focusing increases as the magnet power increases at closer and farther distances.

When the distance between the needle tip and collector is 8 cm and the magnet power is increased, it has been observed that the nanofiber diameters increase from 250 nm to 450 nm on average.

Also, unlike the studies in the literature, the aim is not to deflect the electron movement but to focus it on the collector plate. The fibers can be focused on the collector plate by placing neodymium magnets that provide a constant magnetic field behind the collector plate.

Consequently, the proposed electrospin device is more cost-effective and more applicable because of no need for extra energy consumption for the magnetic fields.

Appendix

Table A3. First part trial conditions.

No	*Magnet shape*
1.1	Without magnet
1.2	5x5 square, single-layer magnet
1.3	5x5 square, single layer magnet, direction changed
1.4	5x5 square, 2 layers magnet
1.5	5x5 square, 3 layers magnet
1.6	7x7 frame, 3 layers of magnets, right in the middle of the collector
1.7	7x7 frame, 3 layers of magnets, on the right side of the collector
1.8	7x7 frame, 3 layers of magnets, on the left side of the collector
1.9	3x3 frame, 5 layers of magnets, right in the middle of the collector
1.10	3x3 frame, 5 layers of magnets, direction changed
1.11	3x3 frame, 5 layers of magnets, on the front of the metal plate
1.12	3x3 frame, 5 layers magnet, the front side of metal plate, the direction changed

Table A4. The second part trial conditions.

No	*Magnet shape*
2.1	7x7 frame, 3 layers magnet (Verify)
2.2	7x7 frame, 3 layers of magnets, in a cardboard box
2.3	7x7 frame, 3 layers of magnets, inverted inside a cardboard box
2.4	7x7 frame, 3-ply magnet, inverted inside a cardboard box, alligator attached to the magnet
2.5	5x5 frame, 3 layers magnet, in a cardboard box, alligator attached to the magnet
2.6	5x5 frame, 3 layers magnet, in a cardboard box, alligator attached to a magnet, magnets placed at the right end of the collector
2.7	40 mm diameter, 5 mm thick round magnet, single ply, S pole towards the collector
2.8	40 mm diameter, 5 mm thick round magnet, single ply, N pole towards the collector
2.9	Without magnet
2.10	40 mm diameter, 5 mm thick round magnet, single ply, S pole towards the collector
2.11	40 mm diameter, 5 mm thick round magnet, single ply, S pole towards the collector
2.12	40 mm diameter, 5 mm thick round magnet, 2 layers, S pole towards the collector
2.13	Frame with 40mm x 15mm x 5mm magnets, 2 layers
2.14	Rectangular, 2 layers with 40mm x 15mm x 5mm magnets
2.15	Round magnet, 5 layers
2.16	Round magnet, 5 layers
2.17	Round magnet, 5 layers
2.18	Rectangular, 2 layers with 40mm x 15mm x 5mm magnets
2.19	Rectangular, 2 layers with 40mm x 15mm x 5mm magnets

Table A5. Trial conditions of Table 3.

No	*Magnet shape*
3.1	Without magnet
3.2	40 mm diameter, 5 mm thickness round magnet, single layer
3.3	Rectangular, 2 layers with 40mm x 15mm x 5mm magnets
3.4	Round magnets, 5 layers

Table A6. Trial conditions of Table 4.

No	*Magnet shape*
4.1	5x5 square, single-layer magnet
4.2	3x3 frame, 5 layers magnet
4.3	7x7 frame, 3 layers magnet
4.4	40 mm diameter, 5 mm thick round magnet, single layer

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