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Optimizing the electrospun parameters which affect the preparation of nanofibers

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ABSTRACT

By electrospinning technique, nanofiber can be produced due to applied high potential voltage on polymer solution, leading to the formation of a jet from polymer solution that is collected on a collector in a nanofiber shape. In the last decade of the twentieth century with appearance of nanotechnology, work and publications on optimization of electrospinning and its applications increased exponentially. Morphology of produced nanofiber depends on three groups of parameters: 1- process conditions (applied voltage, flow rate and needle-to-collector distance) 2- solution conditions (concentration, molecular weight and degree of hydrolysis) 3- ambient conditions (temperature and humidity). Brief history from observation of change of the spherical shape of liquid droplet by the effect of the electrical force to conical shape, passing by Formhals patents to use portable electrospinning techniques will be mentioned. Because of various advantages of nanofiber such as high pore density and enormous surface area per volume ratio, there are vital applications based on nanofiber, for example water treatment, air filtration, sensors/biosensors, energy storage, tissue engineering, wound dressing and drug delivery system.

Keywords:*Electrospinning; Nanofiber; Nanotechnology; Water treatment; Sensor and Tissue engineering.*

1. INTRODUCTION

Electrospinning is a famous technique used to produce fibers with diameter ranging between micrometer and nanometer. After the innovation of the modern characterization tools such as electron microscope and atomic force microscope researchers became able to see the dimensions in nanoscale. So that they gave more importance to electrospinning in the last decade of the twentieth century [1-3]. Between various methods such as (gel spinning, wet spinning, melt spinning and dry spinning) which used to produce fibers, high ratios of surface area per volume and nanometer pore sizes are features which mark electrospinning method [4-6]. The main idea of electrospinning is to apply high potential voltage between two electrodes. One of them is a metallic needle of syringe which contains polymer solution or melt and another electrode is a metallic collector [1,7]. The voltage that applied on a droplet solution leads to formation of Taylor cone as a result of balance between gravitational force and electrostatic force [8]. When the electrostatic force overcome on the gravitational force and surface tension, elongation of Taylor cone occurred and a jet or multi-jets formed and reached to collector to close the electrical circuit [9-12]. In the distance between needle and collector the jet obeys to several changes in shape of motion which leads to solidification of a produced fiber and make it very thinner [13]. The jet at the start point is straight for small distance after that it moves in unstable shape due to effect of voltage. The jet drawn in wave shape where droplets are connected to each other by a small fiber, after long distance jet motion become whipping so that the produced fiber will be more smooth [14-16]. There are two types of collectors (static and movable), static collectors for example (plate or screen collector, pins collector, two parallel electrodes and side by side approach [1,17-20]. Movable collectors for example (drum collector, drum with wires collector and rotating disk collector) [21,22,15]. Toe and Ramakrishna published a review entitled"A review on electrospinning design and nanofibreassemblies"to summary some types of collectors [23]. He et al reviewed other techniques used to prepare electrospunnanofibers entitled "Apparatus for preparing electrospunnanofibres: a comparative review", this paper is important to match the main ideas about spinning of nanofibers [24].The produced fibers have different morphologies divided into smooth, beaded, porous and core shell fibers [17, 25,26]. The morphology dependence on three groups of parameter 1: process conditions such as applied voltage, flow rate and distance from needle to collector, 2: Solution properties such as concentration, Molecular weight and degree of hydrolysis, 3: Ambient conditions such as relative humidity and temperature [27-35]. Biopolymers are biomolecules formed by living organisms and divide into three families known as polynucleids (deoxyribonucleic acid (DNA)), polypeptides (proteins) and polysaccharides (cellulose, chitosan and alginate) [36-40]. Several numbers of polymers (natural and synthetic) used to produce nanofibers because of their important properties for example biocompatibility, biodegradability and availability. Because of various advantages of nanofiber such as high pore density and enormous surface area per volume ratio, there are vital applications based on nanofiber, for example water treatment [41,42], air filtration [43], sensors/biosensors [44,45], energy storage [46], tissue engineering[47,48], wound dressing and drug delivery system[49].

2. HISTORICAL SUMMARY

In the seventeenth century William Gilbert said that “indeed it plainly does draw the body itself in the case of a spherical drop of water standing on a dry surface; for a piece of amber applied to it at a suitable distance pulls the nearest parts out

of their position and draws it up into a cone; otherwise, if it were drawn by means of the air rushing along, the whole drop would have moved". This was the first observation of the electrostatic attraction of a liquid, which leads to deformation of a drop of liquid into conical shape [50]. After that some scientists (Morton, Zeleny)[50,52] work hardly and published patents as basic steps to optimize a technique used to electrostatic spinning for fluids until 1934 Formhals recorded his first patent entitled Process and Apparatus for Preparing Artificial Threads [53]. Formhals continue for several years working to develop the technique, he ended his work with more than 20 patents [54-58]. A huge step take placed when Taylor published his paper in 1969 in which he studied effect electrical force on a drop of fluid at a metallic needle [8]. Baumgarten published very important paper in 1971 entitled "Electrostatic Spinning of Acrylic Microfibers",he said that fibers with diameter between 500 to 1100 nm produced [3]. After this history and with the beginning of nanotechnology researching groups gave the technique more effort, they work to produce nanofibers and their applications. One of the most famous groups is Renekergroup; they started in 1995 with a paper entitled "Electrospinning process and applications of electrospun fibers", and continue with experimental and theoretical work about electrospinning technique and its applications. Reneker group published lots of papers and reviews, which contributed toincreasing the knowledge and information about the technique [1, 2, 11 and 59]. After beginning of the first twentieth century, there is an enormous number of publications about electrospinning technique and large number from researchers and scientists established useful of nanofibers produced by electrospinning in industry and create a network between bench scale products and commercial products throw mass production with effective methods [60].

3. PARAMETERS WHICH EFFECT ON THE MORPHOLOGY OF NANOFIBERS PRODUCED BY ELECTROSPINNING TECHNIQUE

There are three main groups of parameters which control the morphology of the produced fibers, process conditions, solution properties and ambient conditions.

3.1. Process conditions such as applied voltage, flow rate and distance from needle to collector affect the morphology of fibers.

3.1.1. Applied voltage. Ding *et al*. reported that average diameter of poly(vinyl alcohol) (PVA) fibers are slightly decreased with increasing the voltage, by study average diameter as a function of voltage at conditions (concentration = 11% and needle-collector distance = 8 cm) [61]. Rodoplu and Mutlu reported that when other parameters are kept constant and voltage increased, PVA nanofiber diameter decreases. By increasing the voltage from 12 KV to 15 KV at conditions (flow rate = 1.6 mL/h and needle to collector distance = 10 cm) the average diameter of produced fibers decreasing from 170-220 nm to 80-150 nm. At increase the flow rate to 6 mL/h beads appeared in the structure, at 12 KV average diameter of produced fibers was 50-100 nm and average diameter of beads was 440 nm, but at 15KV average diameter of produced fibers was 40-70 nm and average diameter of beads was 250 nm [62].Zhang et al. done a series of experiments in which applied voltage was varied from 5 to 13kV at conditions (concentration = 7.4% w/w PVA solution, flow rate =0.2 mL/h and needle to collector distance = 15 cm). They found that a slight increase in average fiber diameter with increasing applied voltage [63].Deitzel et al. studied effect of different values of applied voltage on morphology of polyethylene oxide (PEO) solution with concentration 7% w/w, at 5.5 KV found smooth morphology of the produced fibers and bead structure appeared above 7 KV and beads density increase with increasing the voltage. Also they reported that when the jet initiates on the surface of the syringe needle, the produced fibers have high density of beads [64].Matabola and Moutloali studied effect of applied voltage on morphology of poly vinyledene fluoride (PVDF) at conditions (concentration = 22% w/w, flow rate = 0.05 mL/min and needle to collector distance =15 cm). They found that with increasing applied voltage from 12 KV to 16 KV the beads density decreased and the average diameter of produced fibers increased. At increasing applied voltage to 18 KV the average diameter of the produced fibers decreased and fiber has irregular morphology. Also they reported that when the jet initiated directly from inside the needle and the electrospinning process became complex as multiple jets ejected from the needle so that the average diameter of produced fiber decreased [65].Motamedi et al. studied effect of applied voltage on morphology of (PVDF) at conditions (concentration =30 w/v, flow rate 0.7 mL/h and needle to collector distance =14 cm). They found that at values 10, 15 and 20 KV the average diameter of produced fiber increased with increasing the voltage [66].

3.1.2. Flow rate. Rodoplu and Mutlu studied the effect of different values of flow rate on morphology of PVA they found that at 10 mL/h and 6 mL/h with decreasing flow rate the average diameter of produced fibers decreased also average diameter of beads decreased. At 1.6 mL/h and 1.1 mL/h found that average diameter decreased with decreasing flow rate and non-bead structure [62].Motamedi et al. reported that with increasing the flow rate the average diameter of produced fibers increases and under high flow rates, the fibers do not dry completely prior to reaching the collector [66].Tan et al. studied effect of flow rate on morphology of poly(L-lactid-cocaprolactone) (P(LLA-CL)) (70/30% w/w) and they reported that no significant effect of flow rate especially at low concentration [67].Zargham et al. studied effect of flow rate on morphology of Nylon 6 and they reported that with increasing flow rate fiber diameter distribution became wider. Also under the optimum conditions, the jet originated from inside the needle and the Taylor cone disappeared completely [68].Chowdhury and Stylios reported that electrospun of Nylon 6 witch dissolved in Formic acid at conditions (concentration = 20% w/w, voltage = 15KV and needle to collector distance = 8cm), leads to produce fibers with average diameter 1000 nm, 1126 nm, 1388 nm and 1599 nm at 0.2 ml/hr, 0.25 ml/hr, 0.26 ml/hr and 0.3 ml/hr applied flow rate respectively. Also they reported that fibers produced at (0.2 ml/hr and 0.25 ml/hr) have cylindrical shape and uniform morphology but at higher values (0.26 ml/hr and 0.3 ml/hr) fibers morphology became rougher [69]. Zong et al. studied effect of flow rate on morphology of poly(D,L-lactic acid) (PDLA) at conditions (concentration =25 % with 1 % w/w KH2PO4, voltage =20 KV and needle to collector distance = 15 cm) found that at

lower flow rate smaller fibers produced and with increasing flow rate the average diameter of beads increased (70).Bakar et al. studied effect of flow rates on morphology of electrospunpolyacrylonitrile (PAN) 10% solutions dissolved in N-Dimethylformamide (DMF) at conditions (voltage = 20KV, needle to collector distance = 10 cm). They found that at flow rates (10, 15 and 20 µL/min) average diameter of produced fibers was (2.35, 1.50 and 1.40 µm) respectively, and reported with increasing flow rate average diameter decreased [71].

Jia et al., studied effect of flow rate on morphology of (PVA) aqueous solution electrospun at conditions (concentration = 7% w/w, voltage = 22.5KV and needle to collector distance = 30cm). They concluded that average fiber diameter increased with increasing flow rate and dispersion became higher, also electrospinning process became unstable [72]. Dhakate et al., observed that electrospun of 23% w/w polycarbonate (PC) solution dissolved in mixed solvent 65% Chloroform and 35% DMF at flow rate 0.5mL/h produce ribbon fibers with rough morphology. With increasing flow rate to 1mL/h variation in fiber diameter became less [73].

3.1.3. Needle to collector distance. Ding et al. reported that average diameter of (PVA) fibers is slightly increased with increasing the needle to collector distance, by study average diameter as a function of voltage at conditions (concentration =11% w/w, voltage =19 kV) (61). Zhang et al. studied effect of needle to collector distance on morphology of PVA fibers produced at conditions (concentration = 7.4% w/w, flow rate = 0.2 mL/h and voltage = 5 KV). They found no significant effect [63].

Matabola and Moutloali studied effect of needle to collector distance on morphology of poly vinyledene fluoride (PVDF) at conditions (concentration = 28% w/w, voltage = 12 KV and flow rate = 0.05 mL/min). They found that with increasing needle to collector distance from 15 to 16 cm, the average diameter of produced fibers decreased from 397 to 314 nm with improved uniformity [65].Motamedi et al. studied effect of needle to collector distance on morphology of (PVDF) at conditions (concentration =30 w/v, flow rate 0.7 mL/h and voltage = 15 KV). They found that with increasing needle to collector distance the average diameter of produced fibers decreased [66].Chowdhury and Stylios reported that average diameter of Nylon 6 fiber decreased with increasing of needle to collector distance, at distances 5 cm, 8 cm and 11 cm average diameter of electrospun fibers were 1257 nm, 1002 nm and 936 respectively. Also they concluded that higher distance between needle and collector allowed more time for jet to stretch and for the solvent to evaporate [69]. Jia et al. observed that average diameter of (PVA) fibers slightly decreased with increasing needle to collector distance from 26cm to 38cm, which electrospun at conditions (concentration = 8% w/w, and voltage = 22.5 KV) [72].

3.2. Solution properties such as concentration, Molecular weight and degree of hydrolysis.

3.2.1. ***Concentration.*** Ding et al. studied the effect of concentration of PVA solutions electrospun at conditions (voltage: 19 kV, needle to collector distance 8 cm) found that the diameter of PVA fibers increased as concentration increased. Also beads density decreased as concentration increased. Also they reported that high concentration solution showed high viscosity and high surface tension [61].Rodoplu and Mutlu reported that average diameter of produced fibers increased with increasing polymer concentration [62]. In study done by Zhang et al. PVA solutions with different concentrations 6%, 6.5%, 7% and 8% at conditions (DH = 98%, voltage = 8kV, needle –collector distance = 15cm, flow rate = 0.2ml/h), found that at 6%, beads appeared and the average fiber diameter between beads was 87 ± 14nm. With increasing concentration, the morphology changed from beaded fiber to uniform fiber structure and the fiber diameter also increased. Above the concentration of 8.3%, the polymer solution did not form fibers but formed big droplets falling on the collector regardless of the voltage [63].Deitzel et al. studied effect of concentration on morphology of electrospun PEO solutions with concentrations in range of 4-10% w/w. they reported that at concentrations below 4% w/w mixtures of fibers and droplets deposited on the collector. At concentrations higher than 10% w/w spinning of solutions became more difficult. Also with increasing concentration between 4-10% w/w found that morphology of produced fibers improved and average diameter increased. At concentration 4% w/w there are junctions and bundles which disappeared at 10% w/w [64]. Matabola and Moutloali reported that the variation of PVDF concentrations had a significant effect on morphology of the electrospunnanofibers. They studied effect of different PVDF concentrations (22–28% w/w) in N,N-Dimethyl acetamide (DMAc). They reported that at concentrations below 22% w/w mixture of fibers and beads produced and at concentrations higher than 29% w/w spinning of solutions became more difficult. Also with increasing concentration between 22-28% w/w found that morphology of produced fibers improved with disappearing of beads and average diameter increased. Also in this study found that at low PVDF concentrations (below 17%w/w), only beads formed, while above this value, formation of fibers observed [65].Motamedietal.studied effect of concentration on morphology of electrospun PVDF solutions with concentrations in range of 10-30% w/v. They found that at concentration 10% w/v electrospray process happened and microparticles produced. At concentration 20% w/v non-uniform electrospun fibers produced together with some large beads in between. At concentration 25% w/v bead-less electrospun structure produced with non-uniform average diameter of fibers. At concentration 30% w/v produced fibers had more uniform morphology [66].

Tan et al. studied the effect of concentration on morphology of electrospunpoly(L-lactid acid) (PLLA) solutions dissolved in DCM/pyridine with concentrations in range of 1-4% w/w. They reported that with decreasing concentration from 4% to 1% average diameter of produced fiber decreased and at concentrations below 1% beads appeared in the structure [67]. Zong et al. studied effect of concentration on morphology of electrospunpoly(D,L-lactic acid) (PDLA) solutions dissolved in (DMF) with concentrations in range of 20-40% w/w. They found that no fibers produced below concentration 20% w/w and concentration 20% mixture of beads and fibers produced. With increasing concentration beads density decreased and average diameter of produced fibers increased until obtaining uniform structure at concentration 40% w/w [70].Nitanan et al. studied effect of different concentrations on morphology of electrospun polystyrene (PS) (10%, 15% and 20% w/v) solutions which dissolved in (DMF) they found that at minimum concentration

some beads appeared in the produced fibers but at maximum concentration uniform fibers produced without beads [74].

3.2.2. Molecular weight. Tan et al. studied the effect of different molecular weights (100,000 and 300,000 g/mol) on morphology of electrospun PLLA solutions dissolved in the pure (DCM). They found that low molecular weight PLLA solution at concentration 9% w/w produced beads in the fibers and at higher concentrations beads disappeared from the fibers. At high molecular weight and concentration 4.5% w/w uniform fibers produced and at lower concentration 3.5% w/w finer uniform fibers produced [67].Koski et al. studied effect of different molecular weights on morphology of electrospun (PVA) solutions. They found that at molecular weight 9000–13,000 g/mol non-uniform fibers with beads in the structure produced and fibers between beads have circular shape. At increasing molecular weight to 13,000–23,000 g/mol uniform fiber structure without beads produced and shape of fibers still circular. With increasing molecular weight to 31,000–50,000 g/mol flat fibers produced. Also they reported that at low molecular weight circular shape change to flat at higher concentration than high molecular weight [75].Lee et al. studied effect of different molecular weights on morphology of Atactic Poly(vinyl alcohol) (a-PVA). They studied effect of different concentrations at two molecular weights (1700-4000 g/mol) and conditions (voltage = 20 KV and needle to collector distance = 10 cm). At molecular weights 1700-4000 g/mol found that the optimum structure at 10%-7% w/w respectively [76].

Ojha et al. studied effect of different molecular weights (30,000, 50,000, and 63,000 g/mol) on morphology of Nylon-6 at concentrations (10%-15% w/w) and conditions (voltage = 15 KV, flow rate =15 µL/min and needle to collector distance = 15 cm). At concentration 10% w/w with increasing molecular weight morphology of produced structure changed from beaded structure to beads with small fibers to nanofibers with lower beads density. At concentration 15% w/w with increasing molecular weight nanofibers produced at three values, also homogeneity of produced fibers improved with increasing molecular weight and beads density decreased [77].Jacobs et al. studied effect of different molecular weights (3×10^5-9×10^5 g/mol) on morphology of PEO at concentrations (5%-6% w/w) and conditions (voltage = 10 KV and needle to collector distance = 15 cm). They found that at concentration 5% w/w beads with small fibers in between produced at a lower molecular weight and at higher molecular weight beads density decreased. With concentration 6% w/w at lower molecular weight some beads still in structure which disappeared at higher molecular weight. So they reported that beads appeared with lower molecular weight and uniform fibers produced at higher [78].Kim et al. compared effect of molecular weights of two kinds of poly(ethylene terephthalate) (PET) with IV(Intrinsic viscosity) 0.64 and 0.80 dissolved in a mixture of trifluoroacetic acid (TFA) and a methylene chloride (MC) TFA/MC (50/50 v/v),on morphology of produced structure. At concentration 13% w/w with increasing molecular weight the morphology improved and the fibers became uniform [80].

3.2.3. Degree of hydrolysis and degree of polymerization. Park et al. found that the average diameters of the PVA fibers electrospun at conditions (concentration = 8%, voltage =10 KV and needle to collector distance =15 cm) from the solutions with different degree of hydrolysis 88, 92, 96 and 99.9% determined to be 190, 200, 220 and 470 nm, respectively. Also reported that fiber diameter increased exponentially with an increasing degree of hydrolysis of PVA [79].

3.3. Ambient conditions such as relative humidity and temperature.

3.3.1. Relative humidity. Kim et al., reported that the average diameter fibers produced from electrospun PS solution witch dissolved in mixing ratio of THF:DMF = 60:40 increased with increasing relative humidity between(10-70%). Also with various concentrations of PS solutions (7%, 11% and 16% w/w) the results have the same behavior [81].Hardick et al., observed that increasing the relative humidity between (20-70%) at temperature 25^{o}C leads to increase average fiber diameter from 300 to 352 nm, meaning that the average change in fiber diameter equal to 0.30% per 1% RH. The electrospun solution was cellulose acetate (CA) dissolved in in acetone/dimethylformamide/ethanol (2:2:1) [82].Huang et al., reported that with increasing the relative humidity the average diameter fibers of electrospun poly(acrylonitrile) (PAN) solution witch dissolved in DMF increased, at conditions (concentration = 10% w/w, voltage = 28 KV, flow rate = 1mL/h and needle to collector distance =18 cm). Also they electrospunpolysulfone (PSU) with concentration 28% w/w and the same process conditions, found that average diameter of produced fiber increased with increasing relative humidity and fiber size distributions became broader[83].Oğulata and İçoğlu studied effect of relative humidity on morphology of electrospunpolyetherimide (PEI) solutions dissolved in 1-methyl-2 pyrrolidinone at conditions (concentration = 18% w/w, voltage = 20KV and needle to collector distance = 15cm). They observed that the average diameter of produced fiber increased by 103% with increasing relative humidity from 30% to 70%. Also the same behavior observed at concentration (19 and 20%) average diameter increased by 144% and 300% respectively with increasing relative humidity from 30% to 70% [84].Pelipenko et al. studied effect of different values of relative humidity on morphology of PVA electrospun at conditions (voltage = 15KV, flow rate = 0.6mL/h and needle to collector distance =15 cm). With increasing values of relative humidity from (4% to 60%) average of produced diameter decreased from (667 ± 83 nm to 161 ± 42 nm) but increasing relative humidity to 70% beads appeared in the structure and the fibers became non-uniform. They found almost the same results with PEO [85].Nezarati et al. reported that electrospunpoly(carbonate urethane) (PCU) at relative humidity 5% produced beads connected by small fibers. Increasing relative humidity between 20%-70% leads to smooth morphology and uniform fibers, also fiber density decreased at increasing relative humidity between 50%-70% [86]. Vrieze et al. studied effect of different values of relative humidity (20%, 30%, 45% and 60%) on morphology of Poly(vinylpyrrolidone) (PVP) solution 10% w/w dissolved in ethanol at conditions (voltage = 10KV, flow rate = 3mL/h, needle to collector distance = 12cm and temperature = 293 K). They found that with increasing relative humidity produced fibers became thinner to reach 60% the fibers fused and had irregular morphology [87].Cai and Gevelber reported that average fiber diameter produced from electrospun (PEO) aqueous solution at temperature 22^{o}C decreased by 43% at increasing relative humidity by 25%. Also average fiber diameter of

electrospun 12% w/w (PVP/ethanol) solution decrease by 30 % as relative humidity increases from 38 to 57%[88].

3.3.2.Temperature.Rodoplu and Mutlu reported that at solution temperature lower 40 ^{o}C beaded fiber structure produced but with increasing temperature higher 60^{o}C fibers became flat , because of increasing temperature leads to increase viscosity and decrease the mobility of polymer molecules. Also they said that beads disappeared at low temperature by change other electrospinning parameters [62].Hardick et al., reported that average fiber diameter decreased from 360 to 284 nm with increasing temperatures from 17.5^{o}C to 32.5 ^{o}C. Increasing temperature leads to decrease viscosity of solution and increase stretching, which produces finer fiber [82]. Oğulata and İçoğlu reported that average fiber diameter decreased with increasing temperature from 15^{o}C to 35 ^{o}C. At concentration 18% and relative humidity 30% with temperature (15, 25 and 35^{o}C) average fiber diameter was (381 ± 57, 317 ± 55 and 305 ± 57 nm) respectively (84).Wang et al., studied effect of temperature on morphology of electrospun (PAN) solution dissolved in (DMF) at conditions (concentration = 6% w/w, voltage =8.9KV, flow rate = 0.3 mL/h and needle to collector distance = 7cm). They reported that increasing temperature from 32.2^{o}C to 88.7^{o}C increased average fiber diameter from 170 ± 38 nm to 84 ± 41 nmrespectively [89].Pelipenko et al. studied effect of different temperatures (283, 293 and 303 K) on morphology of PVP fibers they reported that At 283 and 303 K, average diameter of the produced fibers is lower than at 293 K, almost the same results obtained from electrospun cellulose acetate (CA) solution. This difference in results due to decrease the evaporation rate of ethanol exponentially with decreasing temperature, and effect of the rigidity of polymer chains [85].Desai and Kit studied effect of temperature on morphology of electrospun chitosan/ poly(acrylamide) blendsdissolved in acetic acid at conditions (voltage = 30 KV, flow rate 0.08 mL/min and needle to collector distance = 15cm). A blend containing 95% chitosan and room temperature produced a few fibers with beads but increasing temperature improving the morphology which became without beads at 70 ^{o}C. Also blend containing 90 and 75 % results have the behavior [90].

4. APPLICATIONS

Because of various advantages of nanofiber such as thickness controllable, good mechanical properties, high pore density and enormous surface area per volume ratio. Also, there are more than one hundred polymers and lots of inorganic materials could be electrospun into nanofibers. There are vital applications based on nanofiber, here some application will be introduced briefly.

4.1. Water treatment.

There are lots of processes which do to wastewater by different methods to have treated water or to do water treatment process. But nanofibers general used in tow famous processes, filtration (removal of heavy metal ions and dye from wastewater) and desalination (removal salts from sea water).

4.1.1. Filtration.

Pereao et al. published a review entitled "Electrospinning: Polymer Nanofibre Adsorbent Applications for Metal Ion Removal", they summarized useful and basic information about removal of metal ions by adsorption process from wastewater [91]. Bjorge et al. assessed the possibility of using nanofiber membranes in water treatment inthree ways (pathogen removal, suspended solids removal and traditional using as flat sheets) [92]. Bahramzadeh et al. treated (PS) nanofibers with acrylamide monomer (AAm) that contains amide group by nitrogen gas plasma method. Also they used this treated electrospunnanofibers to remove cadmium (Cd^{2+}) and nickel (Ni^{2+}) ions from wastewater [93]. Malwal and Gopinath prepared nanofiber from CuO-ZnO composite and used it to uptake Arsenic (As) from drinking water [94]. Hosseini et al. prepared chitosan/baker's yeast nanofiber and used it to remove uranium (VI) and thorium (IV) ions from wastewater. Ma et al. prepared resistant composite nanofiber by electrospun water-soluble polyethylenimine (PEI) with (PVDF) and used this composite to uptake chromate and arsenate from drinking water [95]. Zhang et al. prepared (PAO/PVDF-g-PAAc) nanofiber composite and used it to uptake uranium from seawater. The nanofiber composite has functional groups such as (amidoxime (AO) and carboxyl (AC)), so that it achieved high efficiency to remove uranium [96].Cai et al. prepared composite nanofiber from cellulose with organic material and used it to uptake heavy metal ions (Cr^{6+}) from wastewater [97]. Habiba et al. prepared nanofiber composite from Chitosan/(polyvinyl alcohol)/zeolite and used it to uptake heavy metals (Cr^{6+}, Fe^{3+} and Ni^{2+}) from wastewater [98]. Keskin et al. prepared cyclodextrinnanofiber and used it to uptake textile dye and heavy metals (Nickel (II) and Chromium (VI)) from wastewater [99]. Satilmis et al. published a paper entitled " Amidoxime functionalized Polymers of Intrinsic Microporosity (PIM-1) electrospun ultrafine fibers for rapid removal of uranyl ions from water ", also Wang et al. published another paper entitled " Controlled Synthesis of Sodium Alginate ElectrospunNanofiber Membranes for Multi occasion Adsorption and Separation of Methylene Blue" this two papers are examples to work up to date in this trend [100,101]. In this trend there are some publications to uptake heavy metal ions from aqueous solution by using microspheres made from natural polymer and cellulose like material composites [102,103]. Wu et al., Tian et al., Taha et al., Aliabadi et al., Ertas et al., Feng et al. and Roslan et al. published lots of papers in which electrospunnanofiber from polymer or polymer composites with functional materials used to water treatment and to uptake of heavy metal ions [104-110] .

4.1.2. Desalination.

The world suffers from a crisis of water shortage, so that researchers work with hard efforts to find methods to face water shortage. Our planet covered with water by percentage near to 75% but more than 95% is saline or salty water, which need treatment to be useful for human. Desalination is method to treat the salty water by removinghigh percent of salts from salty water. There isnumber of methods used to desalination, membrane distillation one from it. After production of nanofiber, membrane distillation depends on it[111]. Zhang et al. prepared nanofiber composite from (VDF-HFP/Cellulose) and studied applied the product to desalination and remove oil from saline water [112]. Li

et al prepared nanofiber from (PVDF) with hydrophobic composite and applied this nanofiber to desalination of seawater by membrane distillation [113].

4.2. Sensors.

Nanofibers established as a creative innovation in sensing applications. There are lots of sensor applications that dependence on nanofibers such as (medical diagnosis, pressure measurement, diabetes management, security and defense, environment protection and industrial process adjusting) [114-116]. Sharmaet al. prepared electrospunnanofiber from PVDF-TrFE (polyvinyledenedifluoridetetrafluoroethylene) and used it to pressure measurement as a component in a catheter with remote transducers [117]. Saetia et al. decorated electrospunnanofiber with carbon nanotube also by addition of functional groups ($MWNT\text{-}COO^{-}$/$MWNT\text{-}NH_3^{+}$), and used it to detect chemicals or Chemiresistive Sensor [118]. Liu et al. prepared hybrid nanofiber membrane from Ln3+-doped (Yb3+, Tm3+ or Yb^{3+}, Er^{3+} co-doped) $NaYF_4$ nanoparticle/polystyrene and used it to bioinformation detection result from water droplet or biomolecule [110]. Abolhasani et al. prepared nanofiber composite from (PVDF/graphene) and used it as nanogenerator, because of the good electrical properties of (PVDF) [119]. Sun et al. prepared nanofiber from pure (ZnO, Co_3O_4-ZnO, Pd@ZnO) and nanofiber composite from (Pd@Co_3O_4-ZnO) and used these products to detect volatile organic compounds (VOCs) and other applications in chemical and electronic sensitizations [120].Pang et al. prepared (SiO_2/CeO_2/PANI FCN) nanofiber composites by a complex method which contain electrospinning–electrospraying with calcination and in situ polymerization and used it as ammonia sensor [122]. El Fawal et al. prepared nanofiber from (PVA) with addition of titanium dioxide (TiO_2) nanoparticles by different percentages, and used it in gas sensor applications [123].

4.3. Biomedical application.

Because some components of biological systems have dimensions in nanoscale such as (proteins, cells, organelles, bacteria and viruses), nanofiber became an important material in biomedical devices and applications for examples drug delivery, wound healing, and tissue engineering [124,125].

4.3.1. Drug delivery systems.

With drug delivery systems, drugs are sent to specific locations in the body, or to target tissues with control lots of parameters such as pH values, temperature, light, time of loading, redox potential and magnetic fields [126]. Mei et al. published a review containshuge information about using nanofiber in drug delivery systems entitle "Facile electrospinning of an efficient drug delivery system" [127]. Liu et al. used triaxialelectrospinning system to produce core-shell nanofiber. They used the produced nanofiber in drug delivery application [128]. Eslamian et al. produced Poly (lactide-co-glycolide) (PLGA) nanofiber and used it to release dexamethasone (DEX) [129]. Ball et al. used coaxially electrospinning technique to produce nanofiber. Also they used the product to release maraviroc [130]. There are some useful reviews published in this trend for example "applications of electrospinning technique in drug delivery", "electrospinning: a fascinating method for the preparation of ultrathin fibers" [131,133].

4.3.2. Tissue engineering.

Tissue engineering is a match between life science (physics, chemistry, biology and medicine) with engineering to use biopolymers in production of biocompatible scaffolds. The produced scaffolds must have specific properties (physical, chemical and mechanical) to be fixable and compatible with human body. Different methods of electrospinning such as coaxial, triaxial and emulsion) used to produce nanofiber witch used in tissue engineering applications [134-136]. Pant et al. produced nanofiber composite from (gelatin/nylon-6) and studied effect of gelatin concentration on the efficiency of the produced nanofiber and used the product as scaffold to tissue engineering [137]. Yao et al. prepared nanofiber by electrospun of PCL/PLA blend and studied the product to use it in tissue engineering application [138].

5. CONCLUSION

Electrospinning technique introduced with the main idea of its work theory and scientific background of electrospinning process. Also historical summary from the discovery of change the spherical shape of fluid droplet to canonical shape under the effect of electrical voltage to the innovation of electrospinning technique throw Formhals patents also introduced. The parameter which affect the morphology of the electrospunnanofiber discussed and some changes that occurred as a result ofthese parameters. The optimization of parameters is not simple process because all parameters are matching with each other also a change in one parameter can change the effect of all parameters. Some application of the electrospunnanofiber in our life discussed also. Nanofibers play an important role in water treatment this problem which faces the human. Sensors are very vital devices in industrial cities because it is a main step to protect worker life and there are lots of applications of sensors which depend on nanofiber. Electrospunnanofiber became a main component in some medical devices such as diagnosis tools. Now up to data there are devices used to mass production of nanofiber, also there portable electrospinning devices and new trends will appear in the future.

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