Influence of salt addition on polymer-free electrospinning of cyclodextrin nanofibers

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Abstract
Solution conductivity is one of the critical parameters affecting the electrospinning of polymer solutions as the jet formation is directly related to the movement of an electrically charged polymer solution to a grounded target. Hence, the solution conductivity has been studied for the electrospinning of various polymeric systems, but not yet for the electrospinning of polymer-free systems. In this regard, this study investigates the influence of solution conductivity on the electrospinning of CD molecules (i.e., hydroxypropyl (HP) modified β and γ-CDs) at various concentrations in the presence of quaternary ammonium salt (i.e., tetraethylammonium bromide, TEAB) from aqueous solutions. The addition of TEAB significantly boosted the conductivity of the CD solutions. It could lead to smaller particles at low CD concentrations because of electrohydrodynamic spraying, while the transformation from beaded-fibers to bead-free fibers was observed with an increase in the CD concentration. The salt addition decreased the fiber diameter and resulted in thinner nanofibers. Likewise, the incorporation of NaCl—used as an alternative to TEAB—caused thinning of the fibers due to enhanced solution conductivity. On the other hand, at higher salt contents, the fiber morphology was worsened for both CDs, leadings to beads on the fibers. Overall, this paper, for the first time, investigates the effect of solution conductivity of the electrospinning of a polymer-free system (i.e., CD), and the experimental findings show that increasing the solution conductivity with salt addition causes significant changes on the electrospinnability and fiber properties.

1. Introduction

Electrospinning is a fiber generation process that relies on the transport of a charged jet to a grounded collector in the form of solid fibers having diameters in the range of 0.01–10 micrometers [1]. Under an electrical field, the electrostatic force overcomes the surface tension of the solution, resulting in a charged stream of a solution to be ejected from a droplet of a conical shape (i.e., the Taylor cone). The jet flowed away from the Taylor cone, and then, bent into a complex path depending on the solution properties [2, 3]. The charged jet follows a straight line first as its diameter drops down drastically before subjecting a bending instability during the jet diameter continues to reduce significantly and simultaneously solidifies, resulting in a continuous fiber on a grounded collector plate. As this process is based on the transfer of electrical charges, the jet formation from the Taylor cone is mainly due to solution conductivity [3, 4].

Various studies have been investigated the influence of the solution conductivity on the electrospinning of polymeric fibers. In one example, Uyar et al showed that the electrospinning of polystyrene (PS) fibers was highly dependent on solvent conductivity, and even small changes in the conductivity greatly affected the properties of the resultant fibers and significantly enhanced the spinnability of PS solutions [5]. Increasing the solution conductivity...
conductivity led to the bead-free PS fibers at lower concentrations. A similar study was done on the electrospinning of poly(L-lactic acid) (PLA), where the authors observed a drastic drop in the fiber diameter with increasing conductivity: boosting the solution conductivity from 0 to 13 μS cm\(^{-1}\) decreased the fiber diameter from ~300 to ~100 nm. The phenomenon of the fiber thinning was credited to the higher elongation of the jet with enhanced conductivity [6]. Recently, the influence of salt addition on the electrospinning of Polymer of Intrinsic Microporosity-1 (PIM-1) was also studied, and the salt addition drastically improved the spinnability of PIM fibers and decreased the fiber diameter with a salt content rise [7]. Demir et al. explored the influence of salt addition on the mass flow during the electrospinning of polyurethane fibers and observed a higher mass flow by increasing salt content [8]. Likewise, Heikila et al. studied the effect of salt addition on the electrospinning of polycrylonitrile (PAN) and observed thicker fibers with the incorporation of ZnCl\(_2\) [9]. Such an increase in the fiber diameter was associated with the higher mass flow. However, in general, salt addition leads to the formation of thinner fibers. The jet thinning can be attributed to the action of the tangential electric forces, drawing on the charges accumulated on the jet surface [10–12]. Also, studies showed that fiber thinning happens mostly in the whipping zone [1]. In this regard, molecular simulation studies demonstrated the detachment of the daughter droplets from the mother droplets in the presence of salt, eventually a leading thinner jet [13]. Furthermore, they observed that when the salt ions are accelerated by the electrical field, polymer chain segments follow the motion of the ions, resulting in chain stretching and improving the fiber morphology.

Even though the presence of many studies on the influence of solution conductivity for the electrospinning of polymeric systems, to the best of our knowledge, there is no report that investigates the effects of solution conductivity on the electrospinning of small molecules, such as cyclodextrin (CD). Unlike polymeric systems, the electrospinning of polymer-free CD takes place due to the presence of hydrogen bond interactions among CD aggregates at high concentrations [14, 15]. Such interactions drive the elongation of the electrically charged jet in the form of a continuous nanofiber. However, the presence of hydrogen-bonding additives (e.g., urea) can disturb such interactions and give rise to beaded nanofibers or even splashing of CD solutions [15, 16]. The electrospinning of such small molecules is, therefore, highly sensitive to the presence of additives and solution properties. Likewise, their electrospinning is also sensitive to the electrospinning process parameters, which affect the morphology and diameter of the resultant fibers [17]. Although the availability of various reports on the electrospinning of CD of different types, including modified ones, from various solvents [18–21], the influence of salt addition on the electrospinning of CD molecules has not been reported yet.

In this study, the influence of solution conductivity and electrospinning parameters of the polymer-free electrospinning of CD molecules was studied by incorporating a quaternary ammonium salt (i.e., tetraethylammonium bromide, TEAB) into the solutions of hydroxypropyl substituted \(\beta\) and \(\gamma\) CDs. The conductivity and viscosity of the CD solutions were measured, and thereafter, the solutions were electrospun into fibers at the various formulations of TEAB and CD. As an alternative to the TEAB, NaCl was also exploited as a salt additive to explore its influence on the CD electrospinning. The experiments were carried out in a systematical manner by increasing salt content while keeping the other parameters constant, and scanning electron microscopy was used to explore changes on the nanofiber morphology/diameter while conductivity and viscosity measurements were performed in parallel to elucidate the structural properties of the solutions prior to the electrospinning process.

2. Materials and methods

2.1. Materials

Hydroxypropyl-\(\beta\)-CD (HP-\(\beta\)-CD) with a molar substitution degree of 0.6–0.9 and HP-\(\gamma\)-CD with a molar substitution degree of 0.62 were kindly received as gift samples from Wacker Chemie AG (Germany). Tetraethylammonium bromide (TEAB, 98%) was purchased from Alfa Aesar while NaCl (≥99.0%) was received from Sigma Aldrich. The electrospinning solutions were prepared using high-purity water from a Millipore Milli-Q system.

2.2. Electrospinning cyclodextrin fibers

CDs were dissolved in water at various concentrations. Afterward, salt was added, and the solutions were kept stirring overnight. Then, the solutions were directly transferred into plastic disposable syringes (HSW, Henke Saas Wolf GmbH) connected with metallic blunt-edged needles (18 G \(\times\) 1”). The syringe was horizontally placed on a KDS-101 model syringe pump, and a high voltage power (Matsusada Precision, AU Series) was employed to apply a high voltage to the solution. The nanofibers were collected on a metal collector covered with an aluminum foil. During the electrospinning, the applied voltage was 15 kV, tip-to-collector distance was 15 cm, and the flow rate set to 0.5 ml h\(^{-1}\) while the relative humidity and temperature were 50 ± 2% and 24 ± 1 °C.
respectively. The electrospinning of CDs was performed using two different CD types of various concentrations in the presence of TEAB and NaCl. The respective experimental design of the experiments was shown in Table 1.

### Table 1. Experimental design of the conductivity study.

| CD-type | CD concentration (% w/v) | TEAB concentration (wt%) | NaCl concentration (wt%) |
|---------|--------------------------|--------------------------|--------------------------|
| HP-β   | 120, 140, 160, 180       | 0, 0.25, 0.5, 1, 2.5     | —                        |
| HP-γ   | 120, 140, 160, 180       | 0, 0.25, 0.5, 1, 2.5     | —                        |
| HP-β, HP-γ | 180                      | —                        | 0.25, 0.5, 1, 2.5        |

* With respect to the CD content.

### 2.3. Characterization

The conductivity of CD solutions was measured using a Mettler Toledo conductivity meter (LE705, Five EasyTM FE 30) at 25 °C. The measurements were performed in triplicate. Viscosity measurements were performed using Anton Paar MCR 301 rheometer using cone-plate geometry (diameter: 50 mm, angle: 1° and gap size: 104 μm) at a fixed shear rate of 100 s⁻¹. The morphological analysis of electrospun nanofibers was performed by scanning electron microscopy (SEM) (Quanta 200 FEG, FEI). Prior to SEM analysis, the fiber specimens were coated with 5 nm Au with a PECS-682 sputter. The mean diameter of nanofibers was determined from the SEM images over ~100 nanofibers by ImageJ software (NIH, US National Institutes of Health).

### 3. Results and discussion

Prior to the electrospinning process, the influence of TEAB addition on solution properties was explored over conductivity and viscosity measurements. Figure 1 shows the conductivity of the aqueous solutions of (a) HP-β-CD, and (b) HP-γ-CD at different concentrations with increasing TEAB concentration. For all conditions, increasing TEAB concentration boosted the solution conductivity, demonstrating that the conductivity of CD solutions is directly affected by the TEAB content incorporated: for instance, the conductivity of the aqueous HP-β-CD solution at 180% (w/v) increased from 16.30 ± 0.66 to 91.71 ± 0.21 μS cm⁻¹ with the addition of 1 wt% TEAB. A similar trend was observed for HP-γ-CD solutions where the addition of salt drastically boosted the solution conductivity. The respective solutions containing CD content of 180% (w/v) have conductivity of 6.37 ± 0.92 μS cm⁻¹ and increased to 51.49 ± 4.81 with the addition of 1 wt% TEAB. On the other hand, increasing the CD content decreased the solution conductivity for both CD types, which in line with the previous report [22]. Similar reports on the enhanced conductivity with the salt addition were previously reported. In one example, the addition of benzyl triethylammonium chloride as a salt increased the conductivity of electrospinning solutions of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) [23].

The viscosity of the respective CD solutions was also measured, and the corresponding data were plotted against the TEAB content for each CD-type (figure 2). Regardless of CD-type used, increasing the CD concentration boosted the viscosity of the respective solutions: the viscosity of CD solutions increased from 0.078 and 0.065 to 0.496 and 0.730 Pa·s for the solutions of HP-β-CD and HP-γ-CD with increasing their concentrations from 120 to 180% (w/v), respectively. Likewise, the addition of 0.1 wt% TEAB increased the viscosity of CD solutions, while a further rise in the TEAB content gave rise to an apparent reduction in the viscosity of the CD solutions. The initial rise in the solution viscosity can be attributed to the interactions between CD and TEAB, while with a further rise in salt content, the viscosity of CD solutions of various concentrations showed decreasing trends: for instance, the viscosity of the HP-β-CD solutions at different concentrations (120, 140, 160 and 180% (w/v) decreased from 0.103, 0.145, 0.391 and 0.622 to 0.062, 0.126, 0.264 and 0.596 Pa·s with increasing the TEAB content from 0.1 to 1 wt%, respectively. A similar trend was also observed for the aqueous solutions of HP-γ-CD: the viscosity of the HP-γ-CD solutions at different concentrations (120, 140, 160 and 180% (w/v) decreased from 0.134 ± 0.042, 0.387 ± 0.041, 0.465 ± 0.039 ± 0.063 and 0.730 ± 0.063 to 0.064 ± 0.035, 0.167 ± 0.045, 0.445 ± 0.042 and 0.540 ± 0.098 Pa·s with increasing the TEAB content from 0.1 to 1 wt%, respectively. This decrease might mainly be attributed to the occurrence of intermolecular interactions between salt and CD molecules that weaken the interactions between CD molecules. At higher salt concentration, TEAB may disturb hydrogen bonds between CD molecules, resulting in a drop in the viscosity. Similar findings were previously reported for many electrospinning systems, including the electrospinning of PVA solution in the presence of NaCl or Fe(NO₃)₂ [24] and for the electrospinning of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) in the presence of...
benzyl triethylammonium chloride, as well as the electrospinning of chitosan/PEO in the presence of divalent ions [23, 25]. The CD solutions with different TEAB contents (i.e., 0–1 wt% with respect to the CD content) were electrospun/electrosprayed at the HP-β-CD content of 120%–180% (w/v). Figure 3 shows the scanning electron micrographs of the respective structures. At the HP-β-CD content of 120% (w/v), the formation of beads was observed at all TEAB contents screened. The bead formation can be attributed to the occurrence of electro-hydrodynamic spraying as a result of the capillary breakup of the jet by surface tension [26]. While increasing the HP-β-CD content to 140% (w/v), larger CD beads were formed. Increasing the TEAB content at this CD concentration led to extended beads, demonstrating the occurrence of a transition from electrospraying to electrospinning with a TEAB content rise. While a further rise in CD content led to fibers with bead-on-string structures due to the electrospinning. The formation of beads on the fibers can be associated with the solution viscosity, net charge density and surface tension of the solution [27]. While boosting the TEAB content at this CD content gave rise to the thinner nanofibers. Bead-free uniform nanofibers were produced with increasing the CD content to 180% (w/v). Even though the previous studies on the electrospinning of HP-β-CD reports the critical concentration as 160% (w/v) in water for the bead-free fiber formation, here we observed the formation of beaded-nanofibers at this concentration and bead-free fibers at the concentration of 180% (w/v). This difference can be attributed to the higher relative humidity (i.e., 50%) while the relative humidity was about 30% for the previous studies [14, 22]. It is well-known that the electrospinning process is highly influenced by the relative humidity and higher relative humidity deteriorates spinnability and therefore, the fiber morphology [28–30]. The mean diameter of the respective nanofibers decreased from 630 ± 240 to 270 ± 120 nm with the addition of 1 wt% TEAB. This is in line with the viscosity findings, where boosting the TEAB content reduced the viscosity of the CD solutions: the viscosity of the respective CD solution decreased from 0.596 ± 0.034 to 0.547 ± 0.032 Pa·s. The addition of salt generally produced thinner fibers for various polymers, [7] and this

Figure 1. The conductivity of CD solutions containing various concentrations of TEAB and CD is shown with error bars. (i) HP-β-CD and (ii) HP-γ-CD.
decrease in the fiber diameter was attributed to either the reduced viscosity or higher conductivity of the respective polymer solutions.

The conditions and the resultant fiber morphology details of the respective structures produced from HP-β-CD were shown in table 2, where the mean fiber diameter and morphology of the respective structures were listed along with the compositions used during the electrospinning process. It is clearly seen there is a transition from beads to bead-free fibers with increasing CD concentration. Increasing the TEAB content at the identical concentration of CD directly influenced the fiber diameter and led to thinner fibers.

The electrospinning of HP-γ-CD solutions of various concentrations at increasing TEAB contents was also performed. Figure 4 shows the scanning electron micrographs of the respective structures obtained at the different compositions of CD and TEAB. At the 120% (w/v) HP-γ-CD, electrosprayed CD beads were formed while increasing the TEAB content drastically dropped the bead diameter. Further increasing CD content to 140% (w/v) led to larger particles. Increasing the TEAB content drastically reduced the bead diameter, and at the TEAB content of 1 wt%, the formation of discontinuous fibers was evident, demonstrating the occurrence of partial spinning at this TEAB content. While increasing the CD content to 160% (w/v) led to beaded fibers, and a similar trend in the fiber diameter was observed with increasing the TEAB content. Bead-free fibers could be obtained at the HP-γ-CD concentration of 180% (w/v). The diameter of the fibers drastically reduced with a TEAB content rise: the mean diameter of the fibers reduced from 1240 ± 350 to 370 ± 120 nm with increasing the TEAB content from 0 to 1 wt%, respectively. These results are in line with the findings of the HP-β-CD electrospinning where thinner particles or fibers were formed with increasing TEAB content.

The results related to the electrospinning/electrospraying of HP-γ-CD at various TEAB content are compiled in table 3, where the morphology and size of the resultant structures were given with their compositions. The transformation from beads to bead-free fibers was obvious with increasing the CD content from 120% (w/v) to 180% (w/v). Even though the concentration was very high (i.e., 120%), the formation of sprayed beads at this concentration can be attributed to their polymer-free structure.
In addition to the TEAB addition, the influence of NaCl addition on the electrospinning of HP-β-CD electrospinning at various NaCl concentrations was also studied. Figure 5 shows the electrospun fibers produced at the HP-β-CD concentration of 180% (w/v) and various NaCl content (0.25–1 wt% with respect to the CD content). The addition of higher NaCl content reduced the fiber diameter from 680 ± 310 nm to 240 ± 200 with a 4-fold rise in the NaCl content, respectively. A decrease in the fiber diameter can be attributed to the lower viscosity of the solution with a salt content rise. At the NaCl concentration of 2.5 wt%, the fiber morphology

![Figure 3. Scanning electron micrographs of electrospun fibers and electrospayed beads of HP-β-CD from water at various formulations. Insets show the size-distribution diagrams of the respective fibers or beads.](image)

| HP-β-CD content (w/v %) | TEAB content (wt.% with respect to CD) | Morphology          | Mean fiber diameter (nm) | Mean bead diameter (nm) |
|-------------------------|----------------------------------------|---------------------|--------------------------|-------------------------|
| 120                     | 0                                      | Beads               | n/a                      | 1850 ± 620              |
| 120                     | 0.1                                    | Beads               | n/a                      | 1730 ± 505              |
| 120                     | 0.5                                    | Beads               | n/a                      | 1190 ± 365              |
| 120                     | 1                                      | Beads               | n/a                      | 700 ± 185               |
| 140                     | 0                                      | Extended beads      | n/a                      | n/a                     |
| 140                     | 0.1                                    | Extended beads      | n/a                      | n/a                     |
| 140                     | 0.5                                    | Extended beads      | n/a                      | n/a                     |
| 140                     | 1                                      | Discontinuous beaded fibers | n/a                     | n/a                     |
| 160                     | 0                                      | Beaded fibers       | n/a                      | n/a                     |
| 160                     | 0.1                                    | Beaded fibers       | n/a                      | n/a                     |
| 160                     | 0.5                                    | Beaded fibers       | n/a                      | n/a                     |
| 160                     | 1                                      | Beaded fibers       | n/a                      | n/a                     |
| 180                     | 0                                      | Bead-free fibers    | 630 ± 240                | n/a                     |
| 180                     | 0.1                                    | Bead-free fibers    | 500 ± 235                | n/a                     |
| 180                     | 0.5                                    | Bead-free fibers    | 260 ± 125                | n/a                     |
| 180                     | 1                                      | Bead-free fibers    | 270 ± 120                | n/a                     |

n/a: Not applicable.

In addition to the TEAB addition, the influence of NaCl addition on the electrospinning of HP-β-CD electrospinning at various NaCl concentrations was also studied. Figure 5 shows the electrospun fibers produced at the HP-β-CD concentration of 180% (w/v) and various NaCl content (0.25–1 wt% with respect to the CD content). The addition of higher NaCl content reduced the fiber diameter from 680 ± 310 nm to 240 ± 200 with a 4-fold rise in the NaCl content, respectively. A decrease in the fiber diameter can be attributed to the lower viscosity of the solution with a salt content rise. At the NaCl concentration of 2.5 wt%, the fiber morphology
worsened, and the formation of beaded-fibers was evident (figure 6). Regardless of salt type, the incorporation of higher salt content worsened the fiber morphology for all CD types. Thinner fibers were produced in the presence of TEAB than NaCl. This can be attributed to the higher conductivity and reduced viscosity of the respective solutions. The conductivity of the HP-β-CD solutions containing 0.25, 0.5 and 1 wt% NaCl was measured as 297.75 ± 6.5, 490.50 ± 7.8, and 1066 ± 32.4 μS cm⁻¹, respectively. As reported in many electrospinning papers, higher conductivity led to thinner fibers as a result of smaller Taylor cone.

Table 3. Summary of the characteristics of the electrospun HP-γ-CD nanofibers produced at various compositions of TEAB and HP-γ-CD from aqueous solutions.

| HP-γ-CD content (w/v %) | TEAB content (wt.% with respect to CD) | Morphology       | Mean fiber diameter (nm) | Mean bead diameter (nm) |
|-------------------------|----------------------------------------|------------------|-------------------------|-------------------------|
| 120                     | 0                                      | Beads            | n/a                     | 1810 ± 655              |
| 120                     | 0.1                                    | Beads            | n/a                     | 1510 ± 460              |
| 120                     | 0.5                                    | Beads            | n/a                     | 1170 ± 455              |
| 120                     | 1                                      | Beads            | n/a                     | 670 ± 215               |
| 140                     | 0                                      | Beads            | n/a                     | 4060 ± 1095             |
| 140                     | 0.1                                    | Beads            | n/a                     | 2780 ± 835              |
| 140                     | 0.5                                    | Extended beads   | n/a                     | 1970 ± 625              |
| 140                     | 1                                      | Extended beads   | n/a                     | n/a                     |
| 160                     | 0                                      | Bead-on-string   | n/a                     | n/a                     |
| 160                     | 0.1                                    | Bead-on-string   | n/a                     | n/a                     |
| 160                     | 0.5                                    | Bead-on-string   | n/a                     | n/a                     |
| 160                     | 1                                      | Bead-on-string   | n/a                     | n/a                     |
| 180                     | 0                                      | Bead-free fibers | 1240 ± 350             | n/a                     |
| 180                     | 0.1                                    | Bead-free fibers | 610 ± 285              | n/a                     |
| 180                     | 0.5                                    | Bead-free fibers | 600 ± 295              | n/a                     |
| 180                     | 1                                      | Bead-free fibers | 370 ± 120              | n/a                     |

n/a: Not applicable.
Overall, the experimental findings were illustrated in figure 7, where the changes on the morphology and diameter of the resultant structures were shown. The addition of salt drastically affected the morphology and diameter of the resultant structures. Thinner nanofibers and smaller particles were formed with a salt content rise. At low CD concentrations, the incorporation of salt decreased the bead diameter and led to extended beads with a salt content rise (figures 7(a), (b)(i)). Whereas, the addition of salt at high CD concentration (180% (w/v)) decreased the fiber diameter drastically and led to beaded fibers at high salt content (2.5 wt%) (figures 7(a), (b)(ii)). Overall, the salt addition improved the spinnability at lower salt contents. Similar findings on the improvement of the spinnability with the salt addition were previously reported for PEO/chitosan solutions [25]. They observed the addition of salts reduced the fiber diameter and number of beads on the fibers. A decrease in the fiber diameter with the salt addition can be attributed to the higher conductivity since it directly affects the jet formation [31]. In biomedical applications of such nanofibers, the acute toxicity of TEAB should be taken into account. Even though TEAB has been used as a source of tetraethylammonium ions for its ganglionic blocking properties and to block K⁺ channels, above the suggested limits it induces acute toxicity [32].

4. Conclusion

The influence of salt addition on the electrospinning of CD molecules was systematically studied. The salt addition drastically enhanced the conductivity of aqueous solutions for HP-β-CD and HP-γ-CD. At lower concentrations of CDs, the formation of smaller electrospayed particles was obvious with salt addition, while at
higher concentrations of CDs, thinner fibers were formed due to the lower viscosity of CD solutions. Regardless of CD-type used, the electrospinning of CD solutions at higher salt contents led to the formation of thinner nanofibers. The improved spinnability with the TEAB addition might be attributed to the higher conductivity and lower viscosity of the electrospinning solutions. Like the addition of TEAB, the incorporation of NaCl also reduced the viscosity of the CD solutions and led to the formation of thinner fibers by increasing NaCl concentration. The use of high concentrations of both TEAB and NaCl worsened the fiber morphology and resulted in beaded fibers. Overall, this paper, for the first time, reports the effect of salt addition on the electrospinning of a polymer-free system (i.e., CD), and experimental results revealed significant impacts of the salt addition on CD spinnability and the resultant fiber morphology.

**Conflict of interests**

Authors of this research article declare no conflict of interest.

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**References**

[1] Niu H, Zhou H and Wang H 2019 Electrospinning: an advanced nanofiber production technology Energy Harvesting Properties of Electrospun Nanofibers (Bristol, United Kingdom: IOP Publishing) pp 1–44
[2] Reneker D H, Yarin A, Zussman E, Koombhongse S and Kataphinan W 2006 Nanofiber Manufacturing: Toward Better Process Control Polymeric Nanofibers (ACS Symposium Series 918) (Washington, DC: American Chemical Society) pp 7–20
[3] Reneker D H, Yarin A L, Fong H and Koombhongse S 2000 Bending instability of electrically charged liquid jets of polymer solutions in electrospinning J. Appl. Phys. 87 4531–47
[4] Stepanyan R, Subbotin A V, Cuperus L, Boonen P, Dorschu M, Oosterlinck F and Bulters M J H 2016 Nanofiber diameter in electrospinning of polymer solutions: model and experiment Polymer 97 428–39
[5] Uyar T and Besembacher F 2008 Electrospinning of uniform polystyrene fibers: the effect of solvent conductivity Polymer 49 5336–43
[6] Tan S H, Inai R, Kotaki M and Ramakrishna S 2005 Systematic parameter study for ultra-fine fiber fabrication via electrospinning process Polymer 46 6128–34
[7] Topuz F, Satilmis B and Uyar T 2019 Electrospinning of uniform nanofibers of polymers of intrinsic microporosity (PIM-1): the influence of solution conductivity and relative humidity Polymer 178 121610
[8] Demir M M, Yilgor I, Yilgor E and Erman B 2002 Electrospinning of polyurethane fibers Polymer 43 3303–9
[9] Heikila P and Harlin A 2009 Electrospinning of polyacrylonitrile (PAN) solution: effect of conductive additive and filler on the process Express Polymer Letters 3 437–45
[10] Feng J 2002 The stretching of an electrified non-Newtonian jet: a model for electrospinning Phys. Fluids 14 3912–26
[11] Feng J 2003 Stretching of a straight electrically charged viscoelastic jet J. Non-Newtonian Fluid Mech. 116 55–70
[12] Carroll C P and Joo Y L 2006 Electrospinning of viscoelastic Boger fluids: modeling and experiments Phys. Fluids 18 053102
[13] Wang B-B, Wang X-D and Wang T-H 2014 Microscopic mechanism for the effect of adding salt on electrospinning by molecular dynamics simulations Appl. Phys. Lett. 105 121906
[14] Celebioglu A and Uyar T 2010 Cyclodextrin nanofibers by electrospinning Chem. Commun. 46 6903–5

![Figure 7](https://example.com/image) (a) The influence of TEAB content on the diameter of sprayed beads/spun fibers of (i) HP-γ-CDs and (ii) HP-β-CD. (b) A cartoon scheme showing the impact of salt addition on the morphology of the electrospun/electrosprayed beads of CD molecules at (i) low and (ii) high concentrations.
[15] Manasco J L, Saquing C D, Tang C and Khan S A 2012 Cyclodextrin fibers via polymer-free electrospinning RSC Adv. 2 3778–84
[16] Topuz F and Uyar T 2018 Influence of hydrogen-bonding additives on electrospinning of cyclodextrin nanofibers ACS Omega 3 18311–22
[17] Topuz F and Uyar T 2020 Electrospinning of cyclodextrin nanofibers: the effect of process parameters J. Nanomater. 2020 7529306
[18] Celebioglu A and Uyar T 2020 Electrospinning of cyclodextrins: hydroxypropyl-alpha-cyclodextrin nanofibers J. Mater. Sci. 55 404–20
[19] Topuz F, Shaikh A Y, Guler M O and Uyar T 2020 Water-insoluble polymer-free uniform nanofibers of peracetylated cyclodextrin by electrospinning J. Mater. Sci. 55 11752–62
[20] Celebioglu A, Yildiz Z I and Uyar T 2018 Electrospun nanofibers from cyclodextrin inclusion complexes with cineole and p-cymene: enhanced water solubility and thermal stability International Journal of Food Science & Technology 53 112–20
[21] Ahn Y, Kang Y, Ku M, Yang Y-H, Jung S and Kim H 2013 Preparation of β-cyclodextrin fiber using electrospinning RSC Adv. 3 14983–7
[22] Celebioglu A and Uyar T 2012 Electrospinning of nanofibers from non-polymeric systems: polymer-free nanofibers from cyclodextrin derivatives Nanoscale 4 621–31
[23] Choi J S, Lee S W, Jeong L, Bae S-H, Min B C, Youk J H and Park W H 2004 Effect of organosoluble salts on the nanofibrous structure of electrospun poly(3-hydroxybutyrate-co-3-hydroxyvalerate) Int. J. Biol. Macromol. 34 249–56
[24] Ding W, Wei S, Zhu J, Chen X, Rutman D and Guo Z 2010 Manipulated electrospun PVA nanofibers with inexpensive salts Macromol. Mater. Eng. 295 958–65
[25] Su P, Wang C, Yang X, Chen X, Gao C, Feng X-X, Chen J-Y, Ye J and Gou Z 2011 Electrospinning of chitosan nanofibers: the favorable effect of metal ions Carbohydrate Polym. 84 239–46
[26] Yarin A L 1993 Free Liquid Jets and Films: Hydrodynamics and Rheology. (New York: Wiley)
[27] Fong H, Chun I and Reneker D H 1999 Beaded nanofibers formed during electrospinning Polymer 40 4585–92
[28] De Vrieze S, Van Camp T, Nelvig A, Hagström B, Westbrook P and De Clerck K 2009 The effect of temperature and humidity on electrospinning J. Mater. Sci. 44 1357–62
[29] Nezarati R M, Elfert M B and Cougrrill-Hernandez E 2013 Effects of humidity and solution viscosity on electrospun fiber morphology Tissue Eng. Part C Methods 19 110–9
[30] Pelipenko J, Kristl J, Janovič B, Baumgartner S and Kocbek P 2013 The impact of relative humidity during electrospinning on the morphology and mechanical properties of nanofibers Int. J. Pharm. 456 125–34
[31] Zhang C, Yuan X, Wu L, Han Y and Sheng J 2005 Study on morphology of electrospun poly(vinyl alcohol) mats Eur. Polym. J. 41 423–32
[32] Graham A J P 1950 Toxic effects in animals and man after tetraethylammonium bromide Br. Med. J. 2 321–2