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# Effect of polyaniline on the electrical conductivity and activation energy of electrospun nylon films

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## ABSTRACT

Nano films of nylon 6 and polyaniline (0, 1, 2, 3, 4, 5, and 6 wt. %) were prepared by the electrospinning technique. The addition of polyaniline increased the electrical conductivity of nylon 6. Pure nylon had an electrical conductivity of  $3.8 \times 10^{-3}$  S/cm, while the conductivity of nylon 6 with 1% polyaniline was  $10.2 \times 10^{-3}$  S/cm. In addition, the electrospinning process increased the electrical conductivity of bulk nylon 6 from  $10^{-14}$  S/cm to  $10.2 \times 10^{-3}$  S/cm. The viscosity and surface tension of nylon 6 decreased with increasing polyaniline content. The morphology of the prepared films was observed with SEM, and the average diameter of the fibre diameters, which was measured statically from the SEM images, was found to be 74 nm for a nylon film with 4 wt.% polyaniline, and 180 nm for pure nylon. The nanofibre films showed an enhanced electrical conductivity with increasing polyaniline concentration, from  $2.627 \times 10^{-10}$  S/cm for a pure nylon film to  $3.44 \times 10^{-7}$  S/cm for a nylon film with 6 wt.% polyaniline. The activation energy decreased with increasing polyaniline concentration. The activation energy was 0.135, 0.0899, 0.0864, 0.0811, 0.078, 0.075 and 0.07299 eV for pure nylon, and nylon with 1, 2, 3, 4, 5, and 6 wt.% polyaniline, respectively. The activation energy of the prepared nylon films decreased in comparison with the activation energy of a pure nylon 6 film, while the electrical conductivity increased as the amount of polyaniline was increased.

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## Introduction

During the past few decades, conductive polymers have received a great deal of attention due to their importance in many important and versatile applications [1]. Conductive polymers not only have the electrical properties of metals, but also the properties of organic polymers, including a light weight, flexibility, resistance to corrosion, and low cost. In addition, the properties of conductive polymers can be tailored to specific applications, which should be considered as an important criteria [2]. Some of the important applications of conductive polymers are light weight rechargeable batteries, chemical and thermal sensors, super capacitors,

light emitting diodes, organic solar cells [3], dental resin composite reinforcements [4], etc. There are many methods used to produce conductive polymers, such as chemical and electrochemical methods, in addition to hydrogels, composites, and electrospinning processes [5].

Conductive polymers synthesized with polyaniline have attracted considerable attention due to their structural characteristics such as high aspect ratio; surface area; and electrical, thermal, and mechanical properties [6]. Polyaniline has a large surface area and possess large Van der Waals forces, therefore it has been a challenge to effectively fabricate homogenous polyaniline polymer composites with a strong interfacial adhesion between the polyaniline and polymer matrix [7,8]. Conductive polyaniline has been used as a

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conductive filler to enhance the conductivity of polymeric matrices. For this purpose, a uniform dispersion is essential for the formation of an interconnecting filler polyaniline network. It is important to note that only a small concentration of polyaniline is needed to endow materials with a relatively high electrical conductivity, which is useful in many industrial applications [9,10].

Electrospinning is a versatile process used to produce a wide range of polymers fibres in the nano and micrometre scale. It is one of the simplest techniques used for obtaining polymer nano-fibres, which are characterized by their large surface area to volume ratio [11]. The principle of electrospinning involves the use of a high voltage electrostatic field to draw a jet from a polymer solution. When this jet travels toward the collector electrode, the solvent evaporates, and a polymer fibre is formed. Electrospinning is used to produce conductive polymers by combining the spinnable polymer with conductive additives [12]. A nanofibre is an ultra fine solid fibre notable for its very small diameter, which is lower than 100 nm. Nanofibre has a large surface area per unit mass, as well as a small pore size.

There are many solution parameters that can affect the electrospinning process, such as the molecular weight, viscosity, conductivity, and surface tension of the polymeric solution [13]. The effects of the solution parameters may be difficult to isolate because the variation of one parameter will generally affect the other solution parameters. For example, the conductivity of the solution can be changed by increasing the amount of polyaniline in the polymeric solution. However, this also results in a reduction of the viscosity, and a decrease of the surface tension [14]. The solution parameters of molecular weight, viscosity, electrical conductivity, and surface tension directly affect the dimensions and morphology of the fibres. An increase of the polymeric molecular weight causes an increase in the density of chain entanglements (in solution). Consequently, the minimum concentration to produce polymeric nanofibre is lower for the highest molecular weight nylon 6 [15]. Viscosity is one of the most important solution parameters. Nano-fibres can be obtained without beads when the polymer solution develops a minimum polymeric chain network or, in other words, at the minimum entanglement concentration. In fact, the solution viscosity and concentration are closely related to each other [16]. An increase in the solution conductivity, or charge density, can be used to produce more uniform fibres with fewer beads, and smaller fibre diameters. Increasing the polymeric solution conductivity causes more electric charges to be carried by the electrospinning jet, which will result in higher elongation forces on the jet due to the electrical field. The overall tension depends on the self-repulsion of the excess charges on the jet [17,18]. The surface tension is a function of the solvent composition in the solution, and it is an effective factor in electrospinning. It was found that different solvents induce different surface tensions. If the concentration of the solution is fixed, a reduction in the surface tension of the solution results in the formation of smooth fibres [9]. It is important to mention that the surface tension controls the formation of beads and beaded fibres. The role of surface tension is to make the surface area per unit mass smaller by changing the spherical shape of the jets [19].

This article focuses on the effect of polyaniline on the electrical properties of nylon 6 nanofilms, produced by the electrospinning technique, by studying the electrical conductivity and activation energy of nylon films with different amounts of polyaniline at temperatures ranging between 20 and 100 °C and to identify the range of application of these prepared films as conductive polymers.

## Materials and methods

### Preparations of the solutions

Nylon 6 was purchased from Sigma–Aldrich (CHEMINE GmbH, USA), with the repeat unit having a molecular weight of 113.16 g/mol. First, nylon 6 was dissolved in 25% formic acid at a temperature  $\approx 30\text{--}40$  °C. This solution was then added to a polyaniline dispersion in formic acid. Nano particles of polyaniline were purchased from Sigma–Aldrich (CHEMINE GmbH, USA). These spherical particles had a diameter of 20 nm, a molecular formula of  $[(C_6H_4NH)_2(C_6H_4N)]_n$ , and their colour ranged from green to black. The mixed solution was stirred for 120 min to form a solution with complete homogeneity. Thereafter, different solution compositions were prepared using different concentrations of polyaniline to obtain nylon 6 with 0, 1, 2, 3, 4, 5, and 6 wt.% polyaniline.

The electrical conductivity of the prepared solutions was measured with an electrical conductivity device (C and 7110 inolab) by dipping the probe of the device in the polymeric solution, and the conductivity values were easily read. The conductivity of the solutions was measured as S/cm.

The surface tension of the solutions was measured using a Surface Tensiometer (Model JYW-200A – LARYEE TECHNOLOGY CO). First, the polymeric solution was poured in a standard Petri dish, which was then placed on a device stage, where a lever with a platinum ring hung freely. The device ring was then lowered until it was submerged inside the solution, and the lever was raised gradually until it separated from the solution's surface due to surface tension that was then measured in mN/cmt.

The viscosity of the solutions was measured (in cP) with a viscometer (DV-II – Pro, Brookfield). The top plate was rotated at a controlled rotation rate to apply a shear force on the solution.

### Electrospinning process

After cooling the solution to room temperature, it was electrospun using an electrospinning device (NaBond Technologies Co.). The solution was applied through a 10 ml syringe needle, with an internal diameter of 0.6 mm, using a syringe pump (NaBond Technologies Co) at a flow rate of 3 ml/h. The electric field was generated using a high voltage supply of about 25 kV. The positive end was connected to the syringe needle, and the collector plate was grounded. The needle-collector distance was 15 cm, and the process was performed at room temperature. Films were obtained from the pure nylon 6 solution, as well as nylon 6 solutions containing 1, 2, 3, 4, 5, and 6 wt.% polyaniline.

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