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# Application of carbon fibers to flexible enzyme electrodes

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ABSTRACT

Flexible carbon fiber electrodes (FCFs) are promising platforms for the fabrication of enzymatic bioelectrodes, mainly because their surfaces improve the direct electron transfer (DET) from redox enzymes. Recently, we introduced new concepts in intravenous implantable bioelectronics based on FCF and special efforts have concentrated on the development of enzyme-based electrodes for biosensors and biofuel cells. In this review, some of our results will be presented as well as the most important properties of FCFs will be discussed with the goal of developing new bioelectrochemical models for understanding the interface between bio-systems (*e.g.*, enzymes and yeasts) and an FCF surface. Moreover, we focus on the strategic use of a modified FCF for the miniaturization of enzymatic biofuel cells to supply power to bionic implants, such as *in vivo* biosensors and biofuel cells.



## 1. Introduction

Flexible electrochemical bioelectronics devices are of great importance, as these devices can deform into complex shapes while maintaining a high level of performance. Moreover, the development of miniaturized flexible electrodes is considered one of the main challenges in implantable bioelectronics and bionics fields such as biopower sources and biosensing systems [1]. For instance, carbon nanomaterials, such as graphene, carbon nanotubes, and highly porous carbon have been attracting considerable attention as a component of biofuel cells (BFC), as they can maximize the interaction between the enzymes and the electrode surface [2].

Over the last few years, our group has been concentrating on the study of flexible carbon fibers (FCFs) as a highly efficient electrode, given the need for a new flexible configuration that would enable the fabrication of a BFC with more feasible applications. In this review, we describe the properties of FCFs, the electrochemistry of the enzymes and their immobilization on the electrode surfaces, and the utilization of FCFs in the development of bioanodes and biocathodes for biofuel cells [3], implantable devices [1,4], and flexible microfluidic devices [5].

## 2. Flexible carbon fiber formed from polyacrylonitrile (PAN)

Carbon materials are widely used in electrochemistry due to their attractive physicochemical and electrochemical properties, which include good electrical and thermal conductivities, adequate corrosion resistance, low density and elasticity, and high purity [6]. Moreover, carbon materials are versatile, thus allowing their application in different forms, such as powder, large blocks, porous sheets, thin solids, and fibers. Notably, FCFs are noteworthy in that they have distinct physical features, such as high flexibility, strength, modulus, stiffness, and electrical/thermal conductivity [7–9]. FCFs can be obtained from a variety of precursors, such as polyacrylonitrile (PAN), mesophase pitch, and rayon [10]. Depending on the precursor, an FCF with distinct mechanical properties can be manufactured. From our point of view, an FCF manufactured from PAN is the most important commercially available variant [11], and an FCF with a diameter of 5 to 30 μm can be easily obtained [9]. Fig. 1a shows the fibers that were extracted from a carbon cloth, while Fig. 1b demonstrates the amount of fibers that are used as a single electrode. Fig. 1c shows a field emission-scanning electron microscope (FEG-SEM) image of fibers that can be used as an electrode, while Fig. 1d compares one fiber and a strand of hair. As can be seen, a single fiber is approximately one-tenth the thickness of a strand of hair.

In general, the process related to the conversion of a PAN precursor in a carbon fiber consists of three steps (Fig. 2). The first step is stabilization by oxidation in air at low temperatures (200–300 °C), the second is high-temperature carbonization (≤1600 °C) to exclude non-carbon atoms, and the last is the graphitization process (>2000 °C) to improve the orientation of the basal planes and the stiffness of the fibers [12].

The graphitic structure formation, aligned in parallel with the fiber axis produces a high tensile modulus and electrical and thermal conductivity parallel to the fiber axis [15].

## 3. Surface treatment of FCF

FCFs are excellent at attaining direct electron transfer (DET) between enzymes and electrode surfaces, such as for glucose oxidase (GOx) [16], and in obtaining catalytic process, such as for glucose dehydrogenase [17] and bilirubin oxidase (BOx) [18]. However, some

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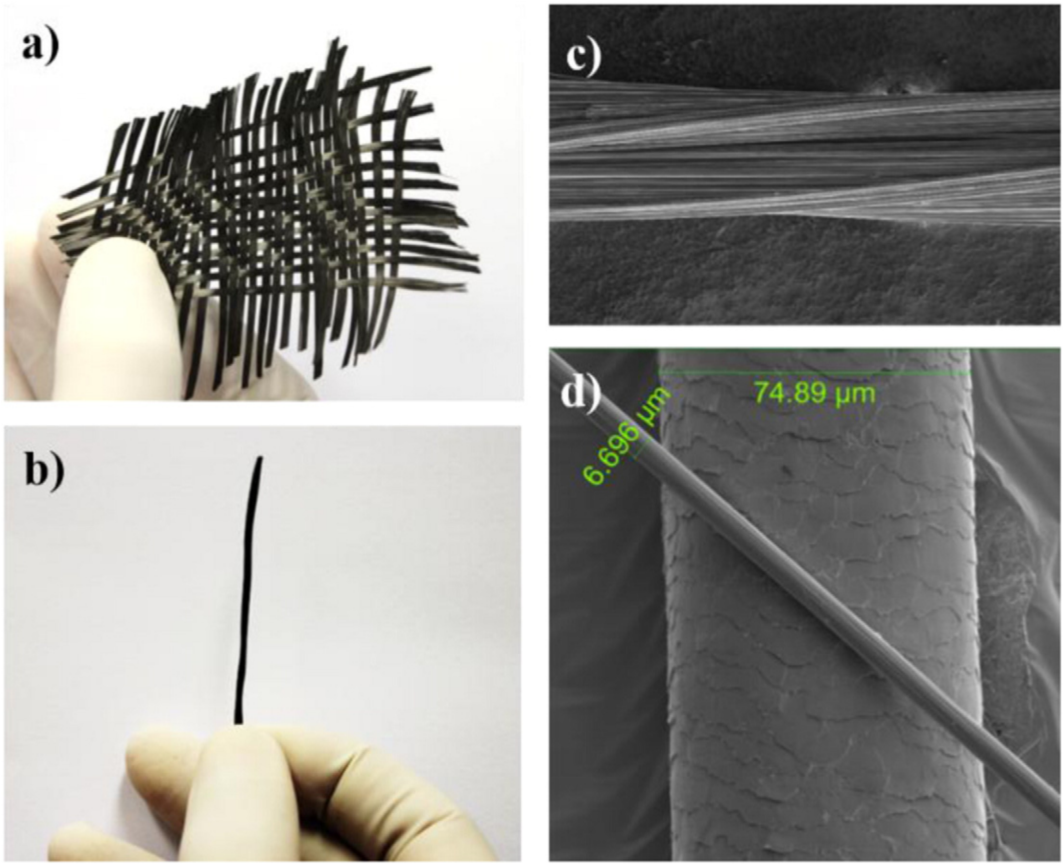


**Fig. 1.** Photographs of (a) carbon cloth (CCS200), and (b) carbon fiber. FEG-SEM of (c) an FCF electrode with fibers that can be used as an electrode, and (d) comparison of the diameter of a strand of hair (74.89 µm) and one fiber (6.696 µm).

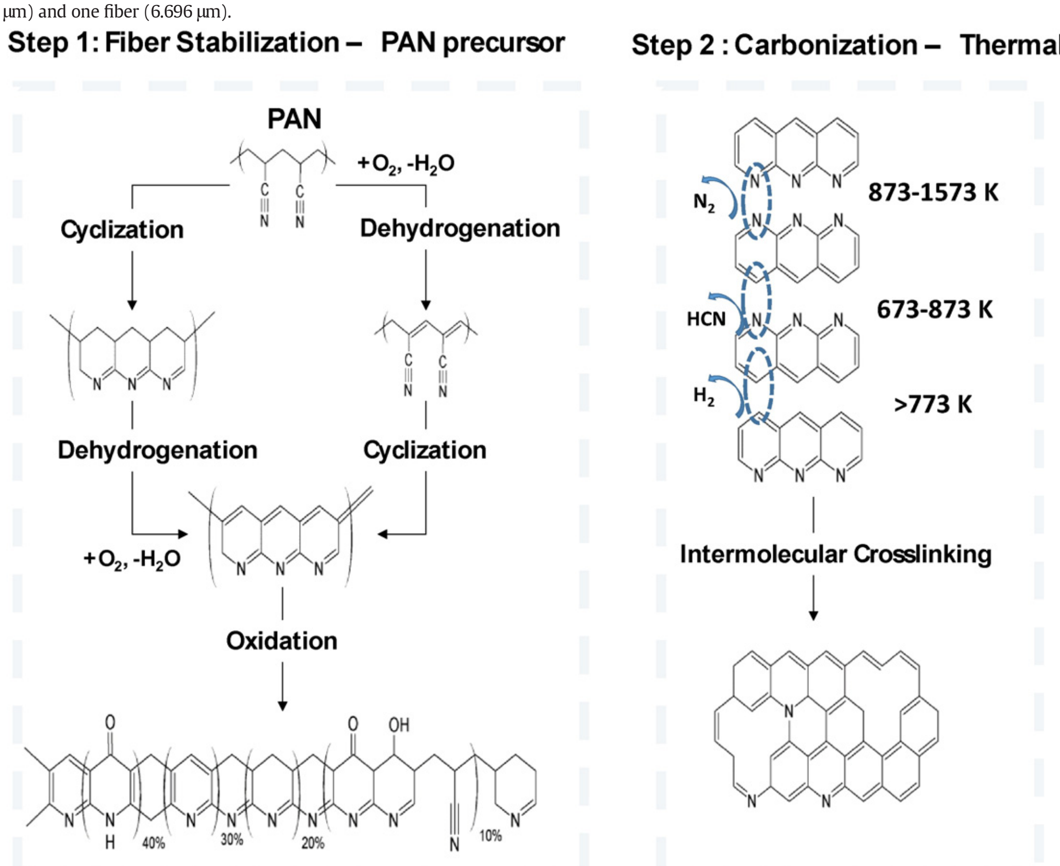


**Fig. 2.** Reaction pathways for producing carbon fiber from PAN. Adapted from [11,13,14].