**Electroconductive hyaluronic acid/gelatin/poly(ethylene oxide) polymeric film reinforced by reduced graphene oxide**

Duygu Kaya,1,2 Neslihan Alemdar1

1Marmara University, Department of Chemical Engineering, 34722, Istanbul, Turkey
2T. C. Atasehir Adiguzel Vocational School, 34779, Istanbul, Turkey

Correspondence to: N. Alemdar (E-mail: neslihan.alemdar@marmara.edu.tr)

**ABSTRACT:** Novel electroconductive polymeric films with enhanced mechanical performance were fabricated by encapsulating reduced graphene oxide (RGO) at different concentrations (0–50 vol %) into a hyaluronic acid/gelatin/poly(ethylene oxide) (HyA/Gel/PEO) polymeric structure. The obtained RGO-reinforced polymeric films were characterized by Fourier transform infrared and scanning electron microscopy analyses. Mechanical performances were measured with a universal mechanical testing machine. The results verified that the RGO reinforcement significantly enhanced the mechanical performances of the films. To determine the biocompatibility of the polymeric films, L929 (murine fibroblast) cell lines were used. The water uptake capacities were measured using swelling tests. A four-probe method was used to measure conductivity characteristics. The conductivity results indicated that HyA/Gel/PEO film containing 20 vol % RGO has the highest average electrical conductivity (1.832 × 10⁻⁶ S/cm). All of the results demonstrated that the obtained electroconductive films could be used in biomedical fields in the future, especially in controlled drug release systems and tissue engineering.


**KEYWORDS:** conducting polymers; films; mechanical properties

Received 5 April 2018; accepted 7 June 2018

DOI: 10.1002/app.46905

**INTRODUCTION**

Reduced graphene oxide (RGO) has a two-dimensional planar structure, a large surface area, mechanical flexibility, electrical conductivity, a low preparation cost, and the ability to disperse in many organic solvents and water.1 These features would make RGO a suitable component for biomedical applications,2 were it not for high concentrations of RGO being potentially toxic.3 To overcome this drawback, RGO containing reactive pendant groups (OH− and COOH−) has been encapsulated in polymeric films. Current studies have focused on the development of electroconductive polymeric materials containing RGO.1,4–7

Electroconductive polymeric thin films are multifunctional smart materials that have a three-dimensional polymeric structure with electrical conductivity. They are used in a wide range of applications such as drug delivery systems, tissue engineering, and biomedical implants, since they have electrical, environmental, optical, chemical, and physical features.8–14

One of the most notable biopolymers used to produce polymeric films is hyaluronic acid, since HyA, also called hyaluronan,15 has many features, such as nontoxicity, biocompatibility, hydrophilicity, biodegradability, nonimmunogenicity, good chemical stability, and considerable water-uptake capacity. These excellent properties allow it to be used in many biomedical applications.16–19 The carboxylic acid (COOH) groups in HyA provide one of the best functional moieties for conjugation to an optimum number of drugs or targeting ligands.20 However, HyA demonstrates a poor mechanical performance.21,22 To overcome this, HyA can be modified by crosslinking with other biomaterials such as gelatin.23 Gelatin has a polypeptide structure, produced by hydrolytic cleavage of collagen,24 which is the major component of human skin and bone and also animal extracellular matrix.25 Since gelatin has a high film-forming capacity, it is used to produce polymeric films. Gelatin (Gel) is also biocompatible and soluble at body temperature, which are desirable properties for biomedical fields such as controlled drug release and tissue engineering.26–28 Poly(ethylene oxide) (PEO) is used to fabricate polymeric films, since it consists of flexible polymer chains that produce soft polymeric films with water-uptake capacity by crosslinking.29,30 1-Ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (EDC) is used as a crosslinker and has been widely used in crosslinking of HyA, Gel, and PEO by amide/ester bond formation of their side groups.16,31–34

Based on this information, polymeric thin films with enhanced electrical and mechanical properties were fabricated by encapsulating RGO (0%, 10%, 20%, 30%, and 50% by volume) in the
novel HyA/Gel/PEO polymeric structure. While RGO-reinforced film with a tensile strength of 108.53 MPa was obtained in this study, previous attempts produced RGO-based hydrogels with poorer mechanical strength.5,35,36 Furthermore, we have managed to obtain a higher conductivity (1.832 × 10−6 S/cm) compared to earlier studies.6,37

All of the results show that not only the electrical conductivity but also the mechanical performances of polymeric films composed of HyA/Gel/PEO were improved by employing the advantages of RGO in this study. While a high mechanical performance protects the integrity of the film during its application, its electroconductive properties allow the programmed release of specific molecules in drug delivery systems.15,14,38,39 It is expected that the obtained films exhibiting these two main properties will be suitable for biomedical applications, especially drug release and tissue engineering, in the future.

EXPERIMENTAL

Materials

Hyaluronic acid (food grade, MW = 8 × 10⁵ Da), poly(ethylene oxide), 1-ethyl-(3-3-dimethylaminopropyl) carbodiimide, and gelatin were bought from Heze Better Biochemical Co. (Shandong, China). Ethanol (EtOH), potassium nitrate (KNO₃), potassium permanganate (KMnO₄), hydrochloric acid (HCl), hydrogen peroxide (H₂O₂, 30% by weight), and sulfuric acid (H₂SO₄, 98% by weight) were obtained from Merck (Darmstadt, Germany) and used without purification. Hydrazine solution (NH₂NH₂, 35 wt % in water), graphite (powder <20 μm, synthetic), and phosphate-buffered saline (PBS) were purchased from Sigma-Aldrich (St. Louis, MO). L929 (murine fibroblast) cell lines were gifts from Prof. Julide Akbuga (Marmara University, Istanbul, Turkey).

Fabrication of Hyaluronic Acid Based Polymeric Films

Hyaluronic acid based polymeric films (HyA/Gel/PEO thin films) were synthesized by solvent-casting. First, 1 g of HyA, 0.5 g of PEO, and 1 g of Gel were each dissolved in 100 mL of deionized water (DIW) at 40 °C under continuous magnetic stirring (150–200 rpm) until clear solutions were observed. Second, these solutions were mixed in the ratio 45 vol % HyA, 45 vol % Gel, and 10 vol % PEO to obtain a polymer solution. Third, an EDC solution was prepared in ethanol (EtOH; 0.5 g of EDC in 100 mL of EtOH) and added to the polymer solution as a crosslinker. The final mixture was cast in Petri dishes (50 mL each) and dried at 37 °C for three days to evaporate the water.

Synthesis of RGO

First, graphene oxide (GO) was synthesized by a modified Hummers method from graphite powder.1,40,41 Briefly, 1 g of graphite and 0.5 g of KNO₃ were slowly added to 23.3 mL of H₂SO₄ (98%) in an ice bath. After about 15 min of stirring, 3 g of KMnO₄ was added gradually to the mixture with continuous stirring. The mixture was then placed in a sand bath at 35 °C and magnetically stirred for 30 min. DIW (50 mL) was then poured into the mixture, which was stirred at 90 °C for 15 min before carefully adding 5 mL of 30% H₂O₂. The solution was centrifuged at room temperature at 6500 rpm for 10 min. The product was filtered and washed with HCl (10 vol %). This centrifugation and washing process was repeated three to four times. The solid particles were placed in an oven at 65 °C for 48 h. The obtained GO was then ultrasonically dispersed in 200 mL of DIW. To reduce GO, 2 mL of hydrazine (35 vol %) was slowly added, and the mixture was kept stirring for 24 h at 100 °C in a fume cupboard. The boiled mixture was cooled to room temperature and filtered using a vacuum flask and a Buchner funnel. After washing with methanol and DIW, the filtrate was dried in a vacuum oven at room temperature.

Synthesis of RGO-Reinforced Conductive Polymeric Films

RGO-reinforced polymeric films were fabricated with five different volume ratios of RGO solution (0%, 10%, 20%, 30%, and 50% by volume). To prepare the RGO solution, 0.6 g of RGO and 60 mL of EtOH in an Erlenmeyer flask were placed in an ultrasonic bath for 30 min. The HyA/Gel/PEO polymer solution was prepared using the procedure described in the section on fabrication of hyaluronic acid based polymeric films. The RGO suspension was added to the polymer solution at the determined ratios. These were placed in the ultrasonic bath again for 30 min. Finally, they were cast in Petri dishes and dried in an oven at 37 °C.

Fourier Transform Infrared Spectroscopic Analysis

The molecular structures of the polymeric films were analyzed by Fourier transform infrared (FTIR) spectroscopy. FTIR measurements were carried out with a PerkinElmer Spectrum 100 FTIR spectrophotometer (Waltham, MA) with an attenuated total reflectance (ATR) unit, and the membranes were scanned between 380 and 4000 cm⁻¹.

Scanning Electron Microscopy Analysis

The surface morphologies of the polymeric films, which were sputter coated with Au/Pd, were analyzed by scanning electron microscopy (SEM, JEOL JSM-5910LV, Tokyo, Japan).

Mechanical Testing

To mechanically test the films, a universal testing machine (Zwick Z100 universal tensile tester, Kennesaw, GA) equipped with a 0.01 N load cell was used. A manual compass was used to measure the dimensions of specimens for tensile testing. For all conditions, five film samples were cut with uniform dimensions (10 × 50 mm) and tested at room temperature, using a 10 mm/min load rate and a 2 mm/min test rate. The tensile strength (MPa), elongation at break (%), and Young’s modulus (MPa) were determined. The tensile strength and elongation at break were calculated using eqs. (1) and (2), respectively:

\[
TS = \text{stress/strain} = \frac{F_{\text{max}}}{A} \quad (1)
\]

\[
E(\%) = \frac{L}{L_0} \times 100 \quad (2)
\]

where \(F_{\text{max}}\) is the maximum force (N) at break, \(A\) is the cross-sectional area of the specimen (mm²), \(L\) is the final length of the specimen at rupture, and \(L_0\) (mm) is the original length of the composite film prior to mechanical testing.

Swelling Capacity

The water-uptake capacity of the polymeric films was determined with gravimetric swelling tests. The weighed dry film samples (HyA/Gel/PEO with and without RGO) were placed in sealed
tubes with 10 mL of DIW for 24 h, and then the tubes were placed in an orbital shaker-incubator at 37 °C and 130 rpm. The swollen hydrogels were subsequently weighed. The swelling ratios (SR) were calculated using eq. (3):

$$SR = \frac{W_s}{W_d}$$

where $W_s$ is the swollen mass of hydrogel (mg), and $W_d$ is the dry mass of polymeric film (mg).

**Cytotoxicity Testing**

The cytotoxicity of the conductive films was determined with the murine fibroblast L929 cell line and the WST-1 cell proliferation and viability assay. For this, sterilized hydrogel samples were placed in 24-well cell culture plates. A cell-DMEM solution (1 mL, $5 \times 10^4$ viable cells/mL) was seeded onto the polymeric films and incubated at 37 °C for 24 h under 5% CO2 in a humidified incubator; $5 \times 10^4$ viable cells in 1 mL of cell-Dulbecco’s Modified Eagle Medium (DMEM) complete medium were seeded into free wells as a control sample. After 24 h, 1000 µL of WST-1 solution was added to each well and incubated for 2 h. The absorbance of WST-1 for each sample was then determined using a Promega GloMax-Multi+ detection system (Madison, WI, USA) at 450 nm.

**Electrical Conductivity**

The electrical conductivity of the polymeric films was derived from the sheet resistivity determined by a four-probe technique, a characterization tool that is widely used to examine the electrical features of thin films and solids.42 The four-probe system has a probe head consisting of four small, thin metallic probes, which make contact with the sample surface. In this study, Lucas Labs S-302 (Gilroy, CA) four point resistivity probing equipment was connected to a Gamry Instruments (Warminster, PA, USA) power source to supply a constant current and monitor the voltage. The applied current passed across two outer probes, and the voltage was determined with the other inner probes. Thus, the sheet resistivity $\rho$ was calculated using eq. (4):

$$\rho = \frac{(\pi t / \ln 2)}{(V/I)}$$

where $t$ is the film thickness, $V$ is the potential difference between the two inner probes, and $I$ is the current through the outer pair of probes. The conductivity $\sigma$ was then calculated using eq. (5):43

$$\sigma = \frac{1}{\rho}$$

**RESULTS AND DISCUSSION**

**Fabrication of Hyaluronic Acid Based Polymeric Films with and without RGO**

The purpose of this study was to synthesize RGO-reinforced, hyaluronic acid based polymeric films (HyA/Gel/PEO-RGO) with improved conductive and mechanical properties by solvent-casting. In producing the films (HyA/Gel/PEO polymer structure), EDC was used as a crosslinker, since carbodiimides were found to be less cytotoxic than other conventional crosslinking agents such as glutaraldehyde and formaldehyde. EDC is a water-soluble crosslinker that has been widely used in crosslinking of polysaccharide and protein through the amide/ester bond formation of their side groups. EDC can react with rich carboxyl groups in HyA and Gel to form an activated intermediate acid anhydride, which may readily react with the amino groups of gelatin to form an amide linkage, or with the hydroxyl groups of PEO and polysaccharides to yield an ester bond, resulting in HyA-Gel-PEO crosslinking.16,31 A schematic representation of the fabrication of biocompatible RGO-reinforced, hyaluronic acid based polymeric films is shown in Figure 1.

**FTIR Analysis**

The FTIR results for polymeric films containing 0 vol % and 20 vol % RGO are given in Figure 2. In the spectrum of the HyA/Gel/PEO polymeric film, the large peak at 3280 cm$^{-1}$ is attributed to N–H stretching coupled with the hydroxyl groups (O–H) in gelatin.43 In the spectrum of the HyA/Gel/PEO-RGO polymeric film, the decrease in intensity of this peak is due to an increase in the stretching vibration of the bonds between NH groups in the polymer film and OH groups in RGO. In the spectrum of the polymeric film without RGO, a peak at 2936 cm$^{-1}$ is attributed to the C–H stretching vibration of PEO, and this is diminished with the addition of RGO.

In the spectrum of the HyA/Gel/PEO polymeric film in Figure 2, the peak at 1630 cm$^{-1}$ is attributed to the stretching vibration of the carbonyl group (C=O) in the polymer film, and the peak at 1538 cm$^{-1}$ is attributed to the stretching vibration of C–N.44,45 The peak at 1401 cm$^{-1}$ represents the stretching vibration of carboxyl groups (COO$^-$) in the HyA polymeric structure in HyA-Gel/PEO polymeric film.35 After incorporation of RGO, the intensity of the peaks at 1630 and 1538 cm$^{-1}$ decreased. This decrease resulted from breaking of sp$^2$ bonds in carboxyl groups (COO$^-$) in the polymeric structure and bonding of hydroxyl groups (O–H) in the RGO structure to the polymer network. The peak at 1034 cm$^{-1}$ represents the C–O–C stretching vibration of PEO in the polymeric film,46 and this shifted to 1028 cm$^{-1}$ after reinforcement with RGO. The change in intensity of the peaks between 1100 and 1450 cm$^{-1}$ is caused by the addition of RGO to the polymeric film.

**SEM Analysis**

SEM images were obtained to characterize the surface morphologies of HyA/Gel/PEO polymeric films with and without RGO, and these were classified according to the RGO content (0% to 50%) and magnification (2500× and 5000×), as shown in Figure 3.

As seen in the SEM images, the roughness of the film increased with the content of RGO reinforcing the polymer. It was noted that RGO contents below 30% were distributed homogeneously throughout the polymeric film structure. However, aggregation of RGO was observed in the film samples containing 30% and 50% RGO.

**Mechanical Performance**

High mechanical durability is essential for biomedical applications such as tissue engineering and drug delivery systems.47 To
determine the effect of reinforcement with RGO on the mechanical durability of the polymeric films, the mechanical performance of the films with and without RGO was characterized with respect to tensile strength, elongation at break, and Young’s modulus (elasticity modulus). The average results for three samples of each polymeric film containing 0%, 10%, 20%, 30%, and 50% RGO by
Figure 3. SEM images of HyA/Gel/PEO polymeric films with and without RGO.
The results demonstrated that the HyA/Gel/PEO-RGO polymeric films exhibit much better mechanical performances than neat HyA/Gel/PEO polymeric films. This confirms that RGO reinforcement of the films enhances both their tensile strength and elongation at break [Figure 4(a, b)]. Since functional groups such as hydroxyl, carboxyl, ketone, and epoxy in RGO interact with other functional groups in the polymeric film matrix, HyA/Gel/PEO-RGO polymeric films have a stronger network than neat polymeric films.48 Additionally, alignment of RGO layers in the polymeric structure with the film surface improves the durability of the film.49 The Young’s modulus of the polymeric film containing 20% RGO (5176.62 MPa) is about 51% more than that of neat HyA/Gel/PEO polymeric film [2642.42 MPa; see Figure 4(c)]. Hydrogen bonds and Van der Waals interactions between oxygen-bearing functional groups of RGO and the HyA/Gel/PEO polymeric structure enhance the mechanical durability.5,50

However, a decrease was observed in the mechanical durability of HyA/Gel/PEO polymeric film containing 30% and 50% RGO. This can be explained by an increase in the nonhomogenous distribution and aggregation of RGO particles in the film, which was confirmed by SEM.47,51

### Water-Absorbing Capacity

When the films are used in biomedical fields, the swelling capacity of polymeric films is considered significant.5 Therefore, the swelling properties of the HyA/Gel/PEO polymeric films with and without RGO were investigated using a 24-h swelling test at 37 °C in 10 mL of DIW. The swelling ratios of films were

<table>
<thead>
<tr>
<th>Sample</th>
<th>Film thickness (mm)</th>
<th>Elongation at break (%)</th>
<th>( F_{\text{max}} ) (N)</th>
<th>Tensile strength (MPa)</th>
<th>Young’s modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(HyA/Gel/PEO)-0 vol % RGO</td>
<td>0.06</td>
<td>1.11</td>
<td>31.95</td>
<td>53.25</td>
<td>2642.42</td>
</tr>
<tr>
<td>(HyA/Gel/PEO)-10 vol % RGO</td>
<td>0.04</td>
<td>1.65</td>
<td>41.60</td>
<td>103.99</td>
<td>3047.06</td>
</tr>
<tr>
<td>(HyA/Gel/PEO)-20 vol % RGO</td>
<td>0.03</td>
<td>2.13</td>
<td>32.56</td>
<td>108.53</td>
<td>5176.62</td>
</tr>
<tr>
<td>(HyA/Gel/PEO)-30 vol % RGO</td>
<td>0.04</td>
<td>1.53</td>
<td>31.68</td>
<td>79.21</td>
<td>4541.33</td>
</tr>
<tr>
<td>(HyA/Gel/PEO)-50 vol % RGO</td>
<td>0.06</td>
<td>1.12</td>
<td>36.20</td>
<td>60.34</td>
<td>2454.87</td>
</tr>
</tbody>
</table>

Values are averages of three samples for each polymeric film.

Figure 4. (a) Tensile strength, (b) elongation at break, and (c) Young’s modulus of polymeric films as a function of RGO content.

Figure 5. Effect of RGO content on swelling ratio after 24 h.

Figure 6. Proliferation of L929 cells in the polystyrene wells (control), on pure polymeric film, and on RGO-reinforced polymeric film.
calculated using eq. (3) and are shown in Figure 5. The thicknesses of samples are given in Table I.

It was shown that, while the HyA/Gel/PEO polymer film without RGO demonstrated the highest swelling capacity, the film containing 50% RGO demonstrated the lowest swelling capacity. Thus, RGO diminished the water-absorbing capacity of the polymeric films. This decrease can be associated with physical cross-linking of RGO in the polymer.49 This confirms that RGO-reinforced HyA/Gel/PEO polymeric films are more stable in water than those without RGO.48,52 This decrease can also be explained in terms of the filling properties of RGO. Since RGO fills the spaces of the polymeric network of the polymeric films, the porosity and water-uptake capacity of the film decreased.

Cytotoxicity
A WST-1 assay and L929 cells were used to determine the cytotoxicity of the polymeric films. The thicknesses of samples are given in Table I. To compare the proliferation of L929 cells, a polystyrene well was used as a control sample. The results of this test (Figure 6) confirmed that pure and RGO-reinforced polymeric films are biocompatible with L929 fibroblast cells according to one-way ANOVA.

Electrical Conductivity
The RGO-reinforced conductive polymeric films were synthesized with four different RGO contents in triplicate. Their conductivities were calculated using eqs. (4) and (5); the obtained results are given in Table II, and a graphic of the average conductivities is shown in Figure 7.

When the results were analyzed, it was observed that the HyA/Gel/PEO polymeric film without RGO had no electrical conductivity, while films containing RGO (especially 10 vol % and 20 vol % RGO) were conductive. The increase in electrical conductivity with the RGO content can be explained by the increase in the specific surface area associated with the graphene layer component and its homogeneous distribution in the polymer.4 RGO particles create electron pathways in the network. The RGO particles move closer together as the RGO content increases. Thus, the electron energy and electrical conductivity increase until the homogenous dispersion of RGO particles is interrupted. However, the electrical conductivity of HyA/Gel/PEO films containing 30 vol % and 50 vol % RGO is lower than that of the film containing 20 vol % RGO. When the RGO particles become too dense in the polymeric film network, they may aggregate,53 which destroys the homogeneity of the distribution and eliminates the planar network. Hence, the energy decreased as the RGO content increased from 20% to 30% and 50% by volume.

CONCLUSIONS
In this work, novel HyA/Gel/PEO polymeric films with enhanced electrical conductivity and mechanical performances resulting from RGO reinforcement were synthesized by the solvent-casting method and analyzed by FTIR, SEM, mechanical, swelling, cytotoxicity, and electrical conductivity tests. The FTIR analysis demonstrated that a strong interaction occurs between HyA/Gel/PEO and RGO. The SEM analysis indicated the homogenous dispersion of RGO in the HyA/Gel/PEO film. The mechanical performance results demonstrated that HyA/Gel/PEO-RGO polymeric films exhibit much better mechanical performances than neat HyA/Gel/PEO polymeric films owing to RGO reinforcement of

<table>
<thead>
<tr>
<th>Film</th>
<th>Film thickness, t (cm)</th>
<th>Current, i (mA)</th>
<th>Voltage, V (mV)</th>
<th>Sheet resistivity, ρ (Ω cm)</th>
<th>Conductivity, σ (S/cm)</th>
<th>Average conductivity, σ (S/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(HyA/Gel/PEO)-0 vol % RGO</td>
<td>0.006</td>
<td>2.0 × 10⁻⁵</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>(HyA/Gel/PEO)-10 vol % RGO</td>
<td>0.004</td>
<td>2.0 × 10⁻⁵</td>
<td>815.50</td>
<td>739,227.94</td>
<td>1.353 × 10⁻⁶</td>
<td>1.398 × 10⁻⁶</td>
</tr>
<tr>
<td>(HyA/Gel/PEO)-20 vol % RGO</td>
<td>0.003</td>
<td>2.0 × 10⁻⁵</td>
<td>768.40</td>
<td>522,399.83</td>
<td>1.914 × 10⁻⁶</td>
<td>1.832 × 10⁻⁶</td>
</tr>
<tr>
<td>(HyA/Gel/PEO)-30 vol % RGO</td>
<td>0.004</td>
<td>2.0 × 10⁻⁵</td>
<td>924.80</td>
<td>838,305.33</td>
<td>1.193 × 10⁻⁶</td>
<td>1.368 × 10⁻⁶</td>
</tr>
<tr>
<td>(HyA/Gel/PEO)-50 vol % RGO</td>
<td>0.006</td>
<td>2.0 × 10⁻⁵</td>
<td>603.90</td>
<td>821,127.69</td>
<td>1.231 × 10⁻⁶</td>
<td>1.319 × 10⁻⁶</td>
</tr>
</tbody>
</table>

Figure 7. Average conductivities of polymeric films with and without RGO.
the films. There is an interaction between the hydroxyl, carboxyl, ketone, and epoxy groups of RGO and the functional groups in the polymeric film matrix. In swelling tests, HyA/Gel/PEO polymeric film without RGO demonstrated the highest swelling capacity in comparison to the films containing RGO. The cytotoxicity test showed that the obtained films are biocompatible. Electrical conductivity measurements demonstrated that HyA-Gel/PEO film has no electrical conductivity, while HyA/Gel/PEO-RGO films are electroconductive. According to the conductivity results, HyA/Gel/PEO film containing 20 vol % RGO has the highest average electrical conductivity (1.832 × 10⁻⁶ S/cm) owing to RGO particles creating electron pathways in the network. Consequently, since the fabricated polymeric films have good mechanical stability, electrical conductivity, and biocompatibility, they can be used in various biomedical fields such as drug release systems and tissue engineering.

ACKNOWLEDGMENTS

We would like to express our deep gratitude to the Research Fund of the Marmara University, Turkey (BAPKO project no. FEN-C-DRP-111017-0584) for financial support.

REFERENCES