Development of Fe$_x$O$_y$ particle onto bacterial cellulose network by forced hydrolysis and its electrical conductivity

Prompong KHAMWONGS$^1$, Poramed WONGJOM$^2$, Andi Magattang Gafur MUCHLIS$^{3,4}$, Chun Che LIN$^{3,4,*}$, Seranee SRISUK$^1$, and Sarute UMMARTYOTIN$^{1,*}$

$^1$ Department of Materials and Textile Technology, Faculty of Science and Technology, Thammasat University, Patumtani, 12120, Thailand
$^2$ Department of Physics, Faculty of Science and Technology, Thammasat University, Patumtani, 12120, Thailand
$^3$ Institute of Organic and Polymeric Materials, National Taipei University of Technology, Taipei, 106344, Taiwan
$^4$ Research and Development Center for Smart Textile Technology, National Taipei University of Technology, Taipei, 106344, Taiwan

*Corresponding author e-mail: sarute@tu.ac.th, cclin0530@mail.ntut.edu.tw

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Abstract

Fe$_x$O$_y$ particle and bacterial cellulose composite sheet was successfully prepared by forced hydrolysis. The presence of Fe$^{3+}$ ions in bacterial cellulose suspension significantly provided the positive charge due to electrostatic force as reported by Zeta potential. With the pH of 12 of bacterial cellulose suspension, particle was nucleated between bacterial cellulose networks. Fourier transform infrared exhibited Fe-O stretching. X-ray diffraction reported that the mixture of Fe$_2$O$_3$ and Fe$_3$O$_4$ was existed onto bacterial cellulose composite. Scanning electron microscope reported that Fe$_x$O$_y$ particle was randomly distributed in bacterial cellulose network. Intensity of Fe was qualitatively observed by energy dispersive analysis. With the existence of Fe$_x$O$_y$ particle, the composite illustrated the inferiority of thermal stability of 150$^\circ$C. Furthermore, it was noted that the resistivity was reduced with respect to increment of Fe$_x$O$_y$ particle, suggesting that electrical conductivity was then enhanced. It was remarkable to note that Fe$_x$O$_y$ particle and bacterial cellulose composite sheet prepared from forced hydrolysis showed the excellent properties as a candidate for flexible electrode.

1. Introduction

Nowadays, the electronics industry was extremely attracted in various sectors of research because of electronic devices were very important to help in facilitating daily use. The role of electronics was well-known in a wide variety of applications such as telecommunication devices, generator and battery. Electronic devices can be designed for use in applications such as mobile phones, televisions and energy materials [1]. Although electronic devices significantly provided numerous benefits in order to facilitate the daily life, they were still limited due to shot lifespan [2]. Novel apparatus will be replaced in order to maintain the performance during usage. As a result, it was consequently created the electronic waste. Electronic waste was typically considered as a hazardous material. The disposal process was still un able to control the efficiency. It was thus harmful to environment. It may cause a trouble to the soil, groundwater and air [2,3]. As a consequence, it was affected to health risk such as skin allergic, respiration failure and immune system disorders.

Up to the present time, one of the most attractive strategies for waste management was to replace with bio-based materials. It was considered as an effective route to environmental remediation such as waste reduction, less consumption of hazardous chemical reagent and ecologically controllable emission. Moreover, the utilization of bio-based materials was typically related to “Green policies” [4].

This policy was extremely encouraged on the use of eco-friendly raw materials and process which minimize the hazardous chemical reagent. In response to “Green policies”, utilization of cellulose as bio-based material was therefore favorable. To the best of authors knowledge, it was remarkable to note that cellulose was considered as one of the most naturally occurring bio-based materials. It can be found in plant and certain bacteria. From the structural point of view, it was presented as a long-chain polysaccharide composed of β(1→4) glycosidic bond of a cellulose unit. It offered chemical resistance as well as high temperature resistance [5]. With outstanding properties of cellulose, it was therefore employed to be a reinforcing for bio-based composite. It enrolled in numerous sectors of application such as medical technology, colorimetric and electrochemical sensor as well as flexible electronic[6].

One of the most important sources is focused on “bacterial cellulose”. It can be prepared by fermentation process of Acetobacter Xylinum Bacteria and reverse engineering process of food waste. It was notable that bacterial cellulose provided the advantage of high purity [7]. It is free from wax, lignin and hemicellulose [8]. Furthermore, bacterial cellulose was structural defined as a nano-fibrous network. It offered the superiority of mechanical properties compared to plant based cellulose materials. Furthermore, in order to develop as a flexible electronic substrate, although bacterial cellulose significantly offered excellent mechanical properties, it was still limited on electrical
conductivity. Therefore, to enhance the electrical conductivity of bacterial cellulose was extremely developed. One way to improve the electrical conductivity was to add metal ions into solution. Ferric chloride (FeCl₃) was considered as one of the most effective chemical reagents. It can be effectively dissociated into Fe³⁺ ion adhered onto hydroxyl group of cellulose network [9]. It can be thus resulted in electrical conductivity enhancement [10].

In 2012, Ummartyotin et al. [11] studied the role of bacterial cellulose sheet composite as a substrate electronic device. It was observed that composite provided the great promise in high transparency, high thermal resistance and excellent flexibility. After that, Ummartyotin et al. [12] also found that modified bacterial cellulose by grafting with strontium ion can be effectively enhanced the electroactive properties. Recently, in 2022, Sun et al. [13] developed polypyrrole and SnCl₂ modified bacterial cellulose as a flexible electrode for supercapacitor. It exhibited a capacitance of 5718 mF/cm² at a current density of 0.5 mA·cm⁻². Bharti et al. [14] investigated the role of bacterial cellulose as an electrode for battery. It illustrated that bacterial cellulose presented uniform interface for efficient redox reaction. It can be used for long term of battery cycle.

From the viewpoint of synthetic strategy, bacterial cellulose can be employed as a nano-particle formation. This concept was conducted based on thermodynamic equilibrium and nucleation growth. In 2019, Phutanon et al. [15] evaluated the task of bacterial cellulose as a template for CuO particle on bacterial cellulose sheet. CuO particle was nucleated by forced hydrolysis within bacterial cellulose network. It can be employed as photocatalyst material and antimicrobial agent. In 2022, Robić et al. [16] investigated the forced hydrolysis of FeCl₃ solution by the existence of guanylurea phosphate. This technique was considered as an effective route in order to prepare giniite (Fe₅(PO₄)₄(OH)₃·2H₂O). It can be designed to be a single-phase with various particle shapes.

To use bacterial cellulose-based composite for electronic device, electrical properties were considered as one of an important way to develop. One way to enhance these properties was to integrate Fe₃O₄ particle onto bacterial cellulose sheet. In 2020, Dacrory et al. [17] developed a flexible film composite from cyanoethyl cellulose (CEC) and magnetite (Fe₃O₄). With the existence of Fe₃O₄, bacterial cellulose composite exhibited the paramagnetic behavior under an external applied magnetic field. Yang et al. [18] developed Fe₃O₄ and cellulose composite for UV sensor. Fe₃O₄ was presented in between cellulose network. It significantly provided the magnetic properties. In order to enhance the electrical conductivity of bacterial cellulose-based composite, bacterial cellulose was employed as a bio-template for Fe₃O₄ formation by forced hydrolysis of FeCl₃. From the fundamental point of view, Fe³⁺ ions accepted the OH ions of water and formed on the bacterial cellulose sheet. It can offer the excellent uniformity and dispersion of Fe₃O₄ particle onto bacterial cellulose network. The range of pH was investigated for Fe₃O₄ particle formation onto bacterial cellulose sheet. Fourier-transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) were employed to evaluate the functional group and crystallinity, respectively. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) were used to study the morphology and distribution of element. Thermal degradation behavior was evaluated by thermogravimetric analysis (TGA). After that electrical conductivity was then reported.
2.3 Characterization

2.3.1 Fourier-transform infrared spectroscopy (FTIR)

The Fourier-transform infrared (FT-IR) spectra were measured using a Thermal Scientific Nicolet iS5 spectrometer with scanning wavenumber from 4000 cm⁻¹ to 500 cm⁻¹. It was operated with a resolution of ±4 cm⁻¹ and a scan frequency of 32 times.

2.3.2 X-ray diffraction

The X-ray diffraction (XRD) patterns were obtained by using a Bruker AXS D8 advanced diffractometer with Cu Kα radiation (λ = 1.54 Å) at 40 kV and 35 mA. The diffraction pattern was recorded over a range of 5° to 60°. The step was set at 2° min⁻¹.

2.3.3 Scanning electron microscopy

The appearance and interface of the obtained samples after air-drying were characterized by Scanning electron microscopy (JEOL, JFC-1200) combined with Energy-dispersive spectroscopy (EDS) mapping. The magnification of 4000X and accelerating voltage of 2 kV were employed.

2.3.4 Thermogravimetric analysis

The TGA characteristics were investigated by TGA. Each sample was heated at a heating rate of 10° min⁻¹ under nitrogen atmosphere from room temperature to 600°C.

2.3.5 Dynamic light scattering

The particle size was investigated by using “particle size analyzer”. The model was ZetaSizer Nano ZS, Malvern Instruments, Ltd., UK). Clear disposable zeta cell was employed. The refractive index was 1.47. Water was employed as a dispersant. The sample was prepared as 10 μL by diluted in 2 mL of DI water.

2.3.6 Four point probe resistivity

A four-point probe is a simple apparatus for measuring the resistivity of semiconductor samples. By passing a current through two outer probes and measuring the voltage through the inner probes allows the measurement of the substrate resistivity. The doping concentration can be calculated from the resistivity using the formulas discussed in the appendices and the PV Lighthouse Resistivity Calculator

Ohm’s law  \( V = IR \)

First law of resistance  \( R = ρL/A \)

3. Results and discussion

3.1 Investigation of FeₓOᵧ in bacterial cellulose suspension sheet by force hydrolysis

FeₓOᵧ was successfully synthesized by using bacterial cellulose sheet as a template. It was homogeneously nucleated at the free space between bacterial cellulose chain. No significant change of properties of bacterial cellulose were observed compared to pristine bacterial cellulose sheet. The color of bacterial cellulose suspension was changed from whitish to orange color. This was probably due to the color of Fe³⁺ ion. This was similar to previous literature of Bai et al. [10]. From the fundamental point of view, FeCl₃ was dissolved into bacterial cellulose suspension. It was dissociated into Fe³⁺ ion and Cl⁻ ion, respectively. The Fe³⁺ ion can be adhered with the hydroxyl group alongside of bacterial cellulose network by electrostatic force. Or, it can be formed to be Fe(OH)₃ by the presence of ammonia. This structure exhibited instability as suggested by Majzlan et al. [20]. It was therefore formed FeₓOᵧ particle within bacterial cellulose network. The formations of FeₓOᵧ particle within bacterial cellulose were presented in equation (1) and (2), respectively.

\[
\begin{align*}
\text{FeCl}_3 + \text{NH}_4\text{OH} & \rightarrow \text{Fe(OH)}_3 + \text{NH}_4\text{Cl} \\
\text{Fe(OH)}_3 & \rightarrow \text{Fe}_{x}\text{O}_y\text{particle}
\end{align*}
\]

In Fe³⁺ and bacterial cellulose suspension, it was presented as a colloidal particle of bacterial cellulose fiber. In order to evaluate the formation of FeₓOᵧ particle within bacterial cellulose network, Zeta potential was considered as an important strategy for colloidal stability determination. Table 1 reports the zeta potential of FeₓOᵧ particle in bacterial cellulose suspension. The range of data was reported to be 30 mV to 60 mV. It can be indicated that FeₓOᵧ particle was uniformly distributed. It exhibited outstanding properties of colloidal stability. The positive data was due to the presence of Fe³⁺ in suspension. Furthermore, the charge was still increased in positive way with respect to the amount of FeₓOᵧ particle [21]. However, in case of pristine bacterial cellulose, the range of zeta potential was reported as negative data. It can be adhered with Fe³⁺ ion onto bacterial cellulose network. It was similar to previous literature of Robic et al. [16].

3.2 Evaluation of FeₓOᵧ and bacterial cellulose composite sheet

FeₓOᵧ and bacterial cellulose composite sheet was successfully prepared from forced hydrolysis technique. All of samples exhibited as a flat sheet. The color of sheet was changed from whitish to orange color, similar to its suspension state. With presence of FeₓOᵧ particle, composite was still in paper sheet form. It was remarkable to note that all samples were easily adsorbed by humidity. It should be stored in desiccator in order to prevent water absorption.

Table 1. Zeta potential analysis of the FeₓOᵧ and bacterial cellulose suspension.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Zeta potential (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacterial cellulose (BC)</td>
<td>-40.6</td>
</tr>
<tr>
<td>10 wt% FeₓOᵧ/BC</td>
<td>38.5</td>
</tr>
<tr>
<td>20 wt% FeₓOᵧ/BC</td>
<td>46.9</td>
</tr>
<tr>
<td>30 wt% FeₓOᵧ/BC</td>
<td>51.4</td>
</tr>
<tr>
<td>40 wt% FeₓOᵧ/BC</td>
<td>55.8</td>
</tr>
<tr>
<td>50 wt% FeₓOᵧ/BC</td>
<td>61.1</td>
</tr>
</tbody>
</table>

In order to determine the functional group of Fe$_x$O$_y$ and bacterial cellulose-based composite, Fourier-transform infrared spectroscopy (FTIR) was employed. Pristine cellulose was provided for comparison. Figure 2 exhibits the FTIR spectra of Fe$_x$O$_y$ and bacterial cellulose-based composites. All of samples showed the similar characteristic feature. It was observed that the wavenumber of 1064 cm$^{-1}$ and 1640 cm$^{-1}$ were presented. They were corresponded to C=O stretching and C=C stretching, respectively. This was in agreement with previous work of Phutanon et al. [15]. These functional group were belonged to $\beta$(1→4) linked D-glucose units of bacterial cellulose. For the Fe$^{3+}$ grafted onto hydroxyl group of bacterial cellulose, no significant change on functional group of bacterial cellulose was observed. Moreover, the characteristic peak at the wavenumber of 3400 cm$^{-1}$ was observed. It was attributed to O-H stretching of bacterial cellulose. This functional group may create the H-bonding formation by adhered with water molecule. Furthermore, it may use to modify by grafting with Fe$^{3+}$. It may create the bonding formation throughout bacterial network, as suggested by Xi et al. [22]. The addition of Fe$^{3+}$ resulted in a decrease in the hydrogen bonds. Only side group was successfully modified. In addition, the characteristic peak at the wavenumber of 584 cm$^{-1}$ was observed. It was corresponded to Fe-O stretching [23]. Significant evidence was observed compared to pristine bacterial cellulose. However, it was controversial that the peak of 1647 cm$^{-1}$ was observed. It regarded as the formation of the C=O bond when FeCl$_3$ was added. It was noted that the double bond was unstable and easily to be oxidized. Fe$^{3+}$ ions exhibited strong oxidizing properties. It was subsequently inferred that the presence of the C=O bond made the electrode reaction faster, resulting in larger reaction rate constant and charge transfer coefficient [24].

In order to determine the crystallinity of Fe$_x$O$_y$ and bacterial cellulose-based composite, X-ray diffraction technique was therefore employed. Figure 3 illustrates the X-ray diffraction patterns of Fe$_x$O$_y$ and bacterial cellulose composite. Investigation of neat bacterial cellulose sheet was provided for comparison. It was observed that the characteristic peaks of 2 theta of 14.5°, 16.5° and 22.5° were presented. They were corresponded to diffraction plane of [101], [010] and [020], respectively. They were indexed to cellulose. These Miller planes were associated with previous literature of Kumar et al. [25]. Furthermore, with the presence of Fe$_x$O$_y$ particle, the peak related to the mixture of Fe$_2$O$_3$ and Fe$_3$O$_4$ was typically observed. It was remarkable to note that the position of Fe$_2$O$_3$ was presented at the diffraction angle of 12° and 27°. Due to small portion of Fe$_2$O$_3$, the intensities were still less compared to pristine bacterial cellulose, as suggested by literature of Kumar et al. [26]. On the other hand, the diffraction peak at 35° was presented, this peak was typically related to the existence of Fe$_2$O$_3$ particle, as suggested by literature of Patwa et al. [27]. With the occurrence of Fe$_2$O$_3$, the crystallinity of bacterial cellulose was still similar [26]. The Fe$_2$O$_3$ particle was located onto the surface of bacterial cellulose and/or it may present throughout bacterial cellulose network. However, the intensities were still less, it resulted in the interference onto the diffraction plane of pristine bacterial cellulose. Although Fe$_2$O$_3$ and bacterial cellulose composite sheet was successfully prepared by forced hydrolysis technique, it provided the difficulty to control the phase and composition of Fe$_x$O$_y$ and Fe$_2$O$_3$ in bacterial cellulose network.

In order to determine the morphological properties of Fe$_x$O$_y$ and bacterial cellulose composite, a scanning electron microscope was employed. This technique allowed us to investigate the microstructure of Fe$_x$O$_y$ and bacterial cellulose composite. Figure 4 exhibits the morphological properties of the Fe$^{3+}$ and bacterial cellulose-based composites. Microstructure of neat bacterial cellulose was provided for comparison. With the presence of Fe$_2$O$_3$ particle, no significant change of morphology was observed. It exhibited as a randomly fiber network of bacterial cellulose. This is identical to previous literature.
Development of Fe\textsubscript{x}O\textsubscript{y} particle onto bacterial cellulose network by forced hydrolysis and its electrical conductivity

![Figure 4. Morphological properties of the Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites (a) bacterial cellulose sheet, (b) 10 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites, (c) 20 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites, (d) 30 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites, (e) 40 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites, and (f) 50 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites.]

of Chanthiwong et al. [28]. The size of bacterial cellulose was estimated to be 10 nm to 100 nm. The size of bacterial cellulose network can be used to predict the size of Fe\textsubscript{x}O\textsubscript{y} with confined geometry. It was expected to form the cluster located throughout bacterial cellulose network. It may form van der Waals interaction between hydroxyl group of bacterial cellulose and Fe\textsuperscript{3+} charge [29]. With the presence of Fe\textsubscript{x}O\textsubscript{y}, the image become clearer. This may imply that Fe\textsuperscript{3+} was sensitive to electron beam during investigation. Furthermore, the porosity was occurred in between bacterial cellulose network. It was created due to the repulsive force of hydroxyl group among bacterial cellulose networks.

In order to ensure the presence of Fe\textsubscript{x}O\textsubscript{y} onto bacterial cellulose sheet, elemental analysis by energy dispersive analysis was employed. This strategy allowed us to determine the presence of Fe atom onto bacterial cellulose sheet. Figure 5 presents the qualitative analysis by EDX technique. The sample was still similar to SEM investigation with different area of observation. It was remarkable to note that two distinct peaks of oxygen and carbon were observed with high intensity. These peaks were corresponded to \beta\textsubscript{-1,4} linked D-glucose unit of cellulose. It can be used to confirm that carbon and oxygen atoms were the main component of composite sheet. Furthermore, with the presence of Fe\textsubscript{x}O\textsubscript{y}, intensity of Fe was observed, as suggested by Zhang et al. [30]. This was very evident compared to pristine bacterial cellulose sheet. The intensity of Fe observed by EDX implied that Fe\textsubscript{x}O\textsubscript{y} was formed by forced hydrolysis technique. This experiment was in agreement with XRD.

![Figure 5. Elemental analysis of the Fe\textsuperscript{3+} and bacterial cellulose-based composites: (a) bacterial cellulose sheet, (b) 10 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites, (c) 20 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites, (d) 30 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites, (e) 40 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites, and (f) 50 wt% Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose-based composites.]

In order to determine the thermal decomposition of Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose composite, thermogravimetric analysis technique was employed. Figure 6 exhibits the thermal decomposition of Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose composite. Neat bacterial cellulose was provided for comparison. It was notable that thermal decomposition characteristic was presented in the similar feature. It can be classified into three different region of weight loss. From ambient temperature to 150℃, only 7% to 13% of weight loss was observed due to water evaporation. It was remarkable to note that to use Fe\textsubscript{x}O\textsubscript{y} and bacterial cellulose composite as an electronic substrate, to avoid the moisture absorption should be considered. It may provide the damage to electric circuit. After that, within the temperature range of 150℃ to 500℃, broad region of weight loss was observed. It was estimated to be 36% to 47% of weight loss. It was typically referred to pyrolysis of bacterial cellulose sheet. It may change from organic structure to volatile gas such as CO\textsubscript{2}. Furthermore, when the temperature was increased up to 600℃, the percent of weight loss was constant [26]. It can be indicated that thermal degradation was completely occurred. No pyrolysis was observed within this temperature region. It was presented as a char and residual. However, comparing to thermal decomposition of neat bacterial cellulose, the feature of curve was different. The presence of Fe\textsubscript{x}O\textsubscript{y} particle may induce on oxidizing ability for bacterial cellulose sheet. The first region of weight loss was observed from room temperature to 200℃. Only 10 wt% of weight loss was observed due to water evaporation. It was notable that although Fe\textsubscript{x}O\textsubscript{y} particle significantly provided the enhancement of electrical properties, it may offer lower thermal stability. The broad region of weight loss was reported to be 74 wt% within the temperature region of 200℃ to 500℃. It involved to pyrolysis of bacterial cellulose. This was in agreement with previous work of Fan et al. [31]. Then, when the
temperature was elevated to 600℃, weight loss was constant. Only 20 wt% of weight loss was observed. It was typically referred to char and residual.

3.3 Preliminary investigation of electrical conductivity

In order to design as flexible bioelectrode, the electrical conductivity was investigated. This property allowed us to determine the feasibility of Fe₃O₄ and bacterial cellulose-based composite for electrode. Four points probe technique was employed to measure the resistivity. The pristine bacterial cellulose sheet was also investigated. It exhibited high resistivity, similar to many previous works [32,33]. It was remarkable to note that bacterial cellulose exhibited low electrical conductivity and high dielectric strength. Furthermore, in case of composite, significant reduction of resistivity was observed with respect to increment of FeCl₃. The range of resistivity was observed between 50 kΩ to 300 kΩ. The variation of resistivity level was occurred due to the position of Fe₃O₄ particle. It can imply that non-uniformity and distribution were presented. Furthermore, to be the flexible electrode, the conductivity level may report. It was notable that with the existence of FeCl₃, it was changed to Fe₃O₄ by forced hydrolysis technique. The electrical conductivity was then enhanced. With the presence of electrical conductivity, it was remarkable to note that Fe₃O₄ and bacterial cellulose-based composite was considered as an excellent candidate for electrode.

Table 2 reports the electrical conductivity and application of cellulose-based composite. The range of electrical conductivity was versatile depending on metal oxide and conductive polymer within cellulose network. It can be used to predict the possibility of application such as sensor and semiconductor. The Fe₃O₄ and bacterial cellulose-based composite illustrated the similar level of electrical conductivity of flexible electrode. It therefore remarkably offered the excellent potential for being as a candidate for the flexible electrode in the near future.

4. Conclusion

Fe₃O₄ and bacterial cellulose composite sheet was successfully prepared by forced hydrolysis. The role of pH of 12 was controllable by aid of ammonia. It can initiate the heterogeneous nucleation of Fe₃O₄ particle throughout bacterial cellulose network. With the increment on Fe³⁺ ions in bacterial cellulose suspension, the positive data of zeta potential was increased with respect to positive charge of Fe³⁺ ions. It referred to excellent colloidal stability. Fe-O stretching was confirmed by FTIR. The mixture of Fe₃O₄ and Fe₃O₄ onto surface of bacterial cellulose was investigated XRD. Bacterial cellulose network was illustrated as random orientation. FeₓOᵧ was inserted between its nano-network. It was qualitatively indicative by EDX that intensity of Fe was occurred. It can be thermally stable within 150℃, as observed by TGA. With the increment of Fe₃O₄ particle, the resistivity was continuously reduced. It can be reported that electrical conductivity was therefore increased. It can be concluded that Fe₃O₄ and bacterial cellulose composite sheet presented attractive properties for being as a candidate of “Green electrode”.

Table 2. Comparison of conductivity levels of conductive cellulose composites.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Conductivity level (S/cm)</th>
<th>Application</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAM/CNC-g-GO/pGO-G-PAA</td>
<td>8.3 × 10⁻⁴</td>
<td>Flexible strain sensors</td>
<td>[34]</td>
</tr>
<tr>
<td>Ionic conductive hydroxypropyl methyl cellulose reinforced hydrogels (PAM/HPMC/LiCl)</td>
<td>9.82</td>
<td>Sensitive skin-like sensors</td>
<td>[35]</td>
</tr>
<tr>
<td>PVA/CNF-AgNWs</td>
<td>3.57 × 10⁻²</td>
<td>Flexible electronics</td>
<td>[36]</td>
</tr>
<tr>
<td>Cellulose nano whiskers, polypyrrole, AgNP assisted with NiO NP</td>
<td>2.5 × 10⁻¹⁵ - 1.1 × 10⁻⁷</td>
<td>Semiconductor</td>
<td>[37]</td>
</tr>
<tr>
<td>Cellulose-based dialdehyde and carboxyl with Fe⁵⁺</td>
<td>N/A</td>
<td>Sensor</td>
<td>[38]</td>
</tr>
<tr>
<td>Fe₃O₄ and bacterial cellulose-based composite</td>
<td>5 × 10⁻⁷ - 3 × 10⁻⁷</td>
<td>Flexible electrode</td>
<td>This work</td>
</tr>
</tbody>
</table>

Figure 6. TGA of the Fe³⁺ and bacterial cellulose-based composites: (a) bacterial cellulose sheet, (b) 10 wt% Fe₃O₄ and bacterial cellulose-based composites, (c) 20 wt% Fe₃O₄ and bacterial cellulose-based composites, (d) 30 wt% Fe₃O₄ and bacterial cellulose-based composites, (e) 40 wt% Fe₃O₄ and bacterial cellulose-based composites, and (f) 50 wt% Fe³⁺ and bacterial cellulose composite.

Figure 7. Resistivity of the Fe₃O₄ and bacterial cellulose-based composites.
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