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# Preparation of Electrode Materials from Iron Cobalt Oxide on Carbon Fiber Cloth Used for Asymmetric Supercapacitors

**Abeer A. Radhi** *[a], **Sami I. Jafar Al-Rubaiey** [a], **Shaymaa Al-Rubaye** [b]

*a* Department of Production Engineering and Metallurgy, University of Technology, Baghdad, Iraq.
*b* Department of Physiology, Hammurabi College of Medicine, University of Babylon, Iraq.

***Keywords:***
Carbon fiber cloth; FeCo2O4; Asymmetric supercapacitor; Nanocomposite; Energy storage.

***Highlights:***

- FCO-CFC nanocomposite is effective, cheap, abundant, environmentally friendly, and nontoxic.
- FCO-CFC electrodes provide good conductivity and efficiency in asymmetric supercapacitors.
- FCO-CFC provides 66% capacitance retention at a current density of 10 mA g-1 after 1000 cycles.

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*Corresponding author:

**Abeer A. Radhi**
Department of Production Engineering and Metallurgy, University of Technology, Baghdad, Iraq.

**Abstract**: The primary purpose of this research is to discover new supercapacitor electrode materials to anticipate future requirements for achieving higher-performing materials for energy storage applications. Therefore, iron cobalt oxide was investigated as a more practical and affordable technique to generate multicationic oxide materials for use as supercapacitor electrodes. In this context, one-dimensional nanostructured binary metal oxides have garnered significant attention in the field of supercapacitor (SC) applications due to their exceptional capability for fast-charge transportation. In particular, high-performance pseudocapacitor electrodes could now be made using highly aligned nanospherical arrays directly grown on conducting substrates. The iron cobalt oxide ($FeCo_2O_4$ (FCO)) electrodes on carbon fiber cloth (CFC) have porous structures constructed from several small building blocks of primary nanospherical, contributing to the nanospherical-like morphology. With a surface area of 130.04 $m^2$ $g^{-1}$, the FCO-CFC nanocomposite electrode considerably increased the pseudocapacitors' electrochemical activity. Moreover, the FCO-CFC nanocomposite electrode demonstrated exceptional cyclic stability, i.e., 66% retention of capacitance at a current density of 10 mA $g^{-1}$ after a process of 1000 cycles and a current density of 10 mA $g^{-1}$ at a surprisingly high specific capacitance of 225 F $g^{-1}$ for a nanocomposite electrode. In addition, the unique porous nanospherical texture, the good conductivity, and the high effectiveness can be credited to the asymmetric supercapacitor employing FCO-CFC electrodes that achieved acceptable electrochemical efficiency due to the synergistic interaction between the FCO and the CFC.

# تحضير مواد القطب الكهربائي من أكسيد الكوبالت الحديد على قماش من ألياف الكربون المستخدم في المكثفات الفائقة غير المتماثلة

**عبير عبد الحسين راضي[1]، سامي ابراهيم جعفر[1]، شيماء هادي خضير[2]**

[1] قسم هندسة الانتاج والمعادن/ الجامعة التكنولوجية/ بغداد- العراق.

[2] قسم الفسلجة/ كلية طب حمورابي/ جامعة بابل/ بابل - العراق.

**الخلاصة**

ان الغرض الأساسي من هذا البحث هو اكتشاف مواد جديدة للقطب الكهربي الفائق لتوقع المتطلبات المستقبلية لتحقيق مواد عالية الأداء لتطبيقات تخزين الطاقة المختلفة. لذلك تم دراسة أكسيد الكوبالت الحديدي باعتباره تقنية أكثر عملية وغير مكلفة لتوليد مواد أكسيد متعددة الكاتيونات لاستخدامها كقطب كهربائي في المكثفات الفائقة. حظيت أكاسيد المعادن الثنائية ذات البنية النانوية بالبعد الواحد باهتمام كبير في مجال تطبيقات المكثفات الفائقة (SC) نظرًا لقدرتها الاستثنائية على نقل الشحنات بسرعة. يمكن الآن تصنيع أقطاب المكثفات عالية الأداء باستخدام مصفوفات الجسيمات النانوية والتي تنمو مباشرة على ركائز موصلة. تحتوي أقطاب أكسيد الكوبالت الحديدي ($FeCo_2O_4$ (FCO على قماش ألياف الكربون (CFC) على هياكل مسامية تم إنشاؤها من عدة كتل بناء صغيرة من الحبيبات الكروية النانوية الأولية التي ساهمت في التشكل الشبيه بالكروية. مع مساحة سطحية تبلغ ١٣٠,٠٤ م ٢ /جرام، زاد قطب المركب النانوي FCO-CFC بشكل كبير من النشاط الكهروكيميائي للمكثفات المستعارة. أظهر القطب المركب النانوي FCO-CFC ثباتًا دوريًا استثنائيًا (احتفاظ ٦٦٪ بالسعة بكثافة تيار تبلغ ١٠ ملي أمبير/جرام بعد عملية من ١٠٠٠ دورة) وعند كثافة تيار تبلغ ١٠ ملي أمبير/جرام زادت السعة النوعية بشكل كبير حيث تبلغ ٢٢٥ فهرنهايت/جرام للقطب الكهربائي النانوي. بالإضافة إلى ذلك، يمكن أن يؤدي نسيج الجسيمات النانوية الى المسامية الخاصة والموصلية الجيدة والفعالية العالية في مكثف فائق غير متماثل باستخدام أقطاب FCO-CFC التي حققت كفاءة كهروكيميائية مقبولة بسبب التفاعل التآزري بين FCO وCFC.

**الكلمات الدالة:** قماش ألياف الكربون، أكسيد الكوبالت الحديد، مكثف عالي غير متماثل، مادة مركبة نانوية، خزن الطاقة.

## 1.INTRODUCTION

Supercapacitors (SCs) are devices for storing energy utilizing reversible reduction and oxidation (redox) reactions at the interface of the electrode/electrolyte, electrostatically storing charges in the electrode layers electrochemically active [1, 2]. In this regard, the growing need for electricity in the 21st century has prompted comprehensive studies of energy storage to propose new approaches for converting to clean and green energy sources [3]. As a result, there is considerable attention on electrochemical capacitors (ECs) in energy storage because these ECs provide more power and higher power density than conventional batteries [4, 5]. Additionally, the interest in supercapacitors extends to their use in electric cars and industrial power management [3]. In this regard, nanomaterials with unique and large surface areas are used to boost the aggregation of charges and the movement of ions in electrochemical capacitors [6]. In particular, reduced graphene oxide, a new ultra-thin-2-D carbon material, can enable the efficient and rapid charging and discharging of electric double-layer capacitors (EDLC) and ternary transition metal oxide nanostructures in supercapacitors and can deliver more redox reactions. Moreover, a nanostructure for optimized electrochemical capacitor (EC) electrodes improves the electrochemical performance [7, 8]. Several researchers have focused on using complex oxides, such as $ZnCo_2O_4$, $NiCo_2O_4$, $FeCo_2O_4$, $NiFe_2O_4$, and $ZnMnO_2$, in pseudocapacitors [9-11]. Specifically, $FeCo_2O_4$ (FCO) spinel has received a lot of interest among these complicated oxides due to its abundance, low price, nontoxicity, enhanced theoretical capacitance, and beneficial electrochemical characteristics, e.g., cyclic stability [12]. However, the extensive practical application of FCO as an energy storage system is still constrained by its electronic conductivity, which is similar to that of the major component of spinel systems [13]. Many methods for solving this problem have been investigated, including utilizing nanoparticles, using a composite strategy, adding cations, and various forms of carbon coating, to name a few [14]. The layer's protective properties, which appear when a specific type of oxidation occurs on the metal's surface, should be physically connected to the crystal structure of the passive film [9]. Particularly, spinel iron cobaltite nanoparticles show good electrochemical properties and versatile behavior due to their narrow band gap, low cost, magnetism, and adequate potential for oxidation or reduction; also because they generate minimal recombination of electron holes and nontoxicity [4, 9, 11]. The diffusion length has been improved through the nano-structuring of materials. An approach that shows great promise for enhancing the system's performance would be combining the effects of nanoparticles with coatings made of other conductive carbon materials, including graphene, carbon nanotubes (CNTs), and carbon fiber cloth (CFC). Compared to other carbon phases, CFCs are considered a more practical and economical method of enhancing metal oxide conductivity and energy [15, 16]. One of the chemical synthesis techniques with a high potential for producing nanostructured materials with regulated characteristics is the hydrothermal synthesis of $FeCo_2O_4$ [16]. Recently, the spinel structure of metal oxides and carbon materials has been combined to maximize the potential of each material [17]. To this end, improved electrode materials are widely desired for synergistic effects. Composite materials of multiple carbon materials and transition-metal compounds

perform better than pure carbon materials [18]. In particular, building porous nanostructures with highly specific surface areas simplifies the creation of more electroactive sites, allows quick electron transmission, and improves structural stability [19, 20]. However, the capacitance of commercial CFC in SCs is inadequate because there are not enough active sites and a limited specific surface area of less than 5 F $g^{-1}$. In this regard, various effective and insightful solutions have been suggested to solve these problems, including thermal activation, plasma modification, wet chemical and electrochemical oxidation, active material loading, and others to support the capacitive performance of CFC and its applications in SCs. Although the in-situ application of active substances, such as metal oxides, to CFC, is effective, another option is to examine the utilization efficiency of the material. Currently, the carbon fiber's diameter is between 5 and 10 µm. However, the CFC's stated active layer is frequently less than 150 nm. Plenty of room exists to add new active sites for charge carrier adsorption and desorption. Nevertheless, the activated layer on the surface's block effect has demonstrated that further oxidation of the carbon substrate is invalid. Prior to activation, building linked, hierarchical, and permeable frameworks inside CFC is thus a promising method to fully utilize CFC, which is a novel SC construction. Introducing new device types promises favorable capacitance as well as a high energy density of SCs. In this regard, a compelling strategy is to create flexible asymmetric SCs (FASCs) that increase the device's working voltage using various potential windows electrodes, including positive and negative [21]. Li et al. [22] used the hydrothermal approach to create $FeCo_2O_4$ microspheres with pores producing ($FeCo_2O_4$ MSs) in addition to the $FeCo_2O_4$ nanosheets ($FeCo_2O_4$ NSs) in various solvent systems that resulted in the BET surface areas of 38.5 and 40.9 $m^2$ $g^{-1}$, respectively, for the $FeCo_2O_4$ NSs and MSs. He et al. [23] used active carbon (AC) and $FeCo_2O_4$@polypyrrole (PPy)-6h, where a flexible ASC device was created. At 1 A $g^{-1}$ and 20 A $g^{-1}$, a specific capacitance of 194 F $g^{-1}$ and 146 F $g^{-1}$ for 75% of the capacitance can be maintained to the $FeCo_2O_4$-PPy //AC (ASC) device. The cyclic stability of the ASC device was good after 5000 cycles, showing 91% retention. Chodankar et al. [24] created thin films with nanowired $FeCo_2O_4$ and nanoparticulated $MnO_2$ using a neutral $Na_2SO_4$ electrolyte as negative and positive electrodes to create asymmetric SC. The $MnO_2$//$FeCo_2O_4$ cell impressively managed to cycle successfully across a wide 2.0 V voltage window, resulting in an energy density of 43 Wh $kg^{-1}$ and a specific capacitance of 218 F $g^{-1}$. This paper investigates the electrochemical characteristics of $FeCo_2O_4$ nanospherical manufactured using a fast and easy hydrothermal process and annealing with good electrochemical properties compared to previous studies. This morphology can significantly shorten the diffusion length when combined with a carbon fiber cloth coating. Furthermore, the coatings on the carbon fiber cloth could increase the electrons' conductivity, enhancing the effectiveness of the electrochemical reaction performance. Compared to a pure $FeCo_2O_4$, the $FeCo_2O_4$-carbon fiber cloth exhibited an improved electrochemical reaction performance in the cycling stability and the shape of the specific capacitance. Symmetric supercapacitors are not widely used because it is preferable to have one type of material with positive and negative charges for the electrodes, which is the case with asymmetric supercapacitors. Therefore, in contrast to using symmetric electrodes, this work employs novel, asymmetric $FeCo_2O_4$ and CFC nanospherical arrays with a surface area of 130.04 $m^2$ $g^{-1}$ demonstrating exceptional cyclic stability, i.e., 66% retention of capacitance at a current density of 10 mA $g^{-1}$ after a process of 1000 cycles, and a current density of 10 mA $g^{-1}$ at a surprisingly high specific capacitance of 225 F $g^{-1}$ for a nanocomposite electrode, which are inexpensive, accessible, eco-friendly, and nontoxic for a range of uses in energy storage, such as manufacturing the batteries used in computers and other devices.

## 2.EXPERIMENTAL WORK

### *2.1.Chemicals*

Sigma Aldrich supplied the following analytical-grade compounds: $Co(NO_3)_2.6H_2O$, urea, ferrous chloride tetrahydrate ($FeCl_2.4H_2O$), and ethanol.

### *2.2.Preparation of the FCO-CFC Nanocomposite*

The FCO-CFC was synthesized using a hydrothermal technique. More specifically, the synthesis process was divided into many steps. In a typical experiment, acetone was used to degrease the CFC substrate (2 × 0.1 cm in size), which was later washed with deionized water (DI) and 100% ethanol for 30 minutes each. $FeCl_2.4H_2O$ (1.164g) and $CO(NO_3)_2.6H_2O$ (0.595g) were each melted individually using a hydrothermal method in 30 mL of deionized water while being stirred magnetically. In particular, it took 30 minutes to stir fully, after which a combination of urea was added to the iron and the cobalt mixture. Then, magnetic stirring was performed at room temperature for over 30 minutes. The prepared mixture was then placed into an autoclave made of stainless steel with Teflon TM-lining with 100 mL capacity. The process was conducted for 8 hours at 130 °C. Finally, the autoclave was cooled to ambient temperature. The resultant product was washed with DI water several times before being washed with ethanol. The

material was then dried for an additional 8 hours at 80 °C in a vacuum. Using a programmed and controlled furnace, the final product of the composite FCO-CFC was heated to 450 °C for 2 hours and atmospheric conditions with a rate of 2°C/min. Moreover, the hydrothermal treatment proceeded by annealing resulted in FCO-CFC nanospherical arrays with crystallite development and carbon fiber cloth. Figure 1 shows the electrode material preparation of the pure FCO and the FCO-CFC nanocomposite.

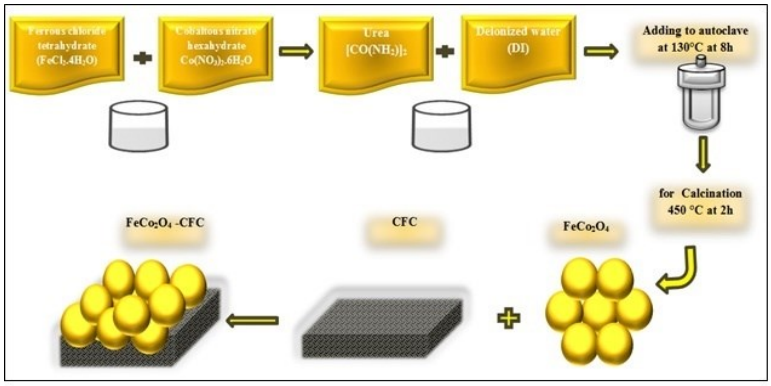


**Fig. 1** Schematic Illustration of the FCO-CFC Composites.

### *2.3.Phase, Morphology, and Electrochemical Characterizations*

Scanning electron microscopy with field emission (FE-SEM, JEOL JSM-7500FA), Shimadzu with Cu K radiation = 1.54, X-ray diffraction (XRD), mini-materials analyzer (MMA) XRD (GBC® Scientific Equipment), and energy dispersive spectroscopy (EDS) were used to examine the morphologies of the $FeCo_2O_4$-CFC. In particular, these techniques were employed to examine the crystalline properties of the produced samples and their morphology at the phase development and formation. CV (cyclic voltammetry) measurements were performed at various scanning rates in a CHI660B (Chenhua, Shanghai, China) electrochemical workstation within the potential range of 0-0.4 V (Hg/HgO). The galvanostatic charging-discharging experiments were conducted using a controlled program and Landt battery testing equipment. A 10 mV AC voltage amplitude measurement of the electromechanical impedance spectroscopy (EIS) (CHI660B) was performed at an open circuit potential with a bandwidth frequency ranging between (0.01 and 100) kHz.

### *2.4.Measurements Setup of the Electrochemical Process*

The electrochemical tests of the FCO and FCO-CFC were achieved using two electrode systems. The active components (70% FCO-CFC or FCO) and 15% polytetrafluoroethylene (PTFE) binder with 15% carbon black were mixed in a solvent of ethylene glycol (EG) to create the electrodes. The resulting mixture was stirred for 6 hours, placed onto a carbon fiber cloth with a surface area of 1.0-2.0 cm, and then squeezed at a pressure of 5 MPa. After that, it was dried for 2 hours at 90 °C after being stirred overnight. The active material of the mass loading was measured by determining the amount of the CFC with coating added to the materials, with a precision of 0.01 mg, using a microbalance. The electroactive material was the working electrode, supported by a carbon fiber cloth measuring 12 cm in area. The mass loading of the FCO-CFC on the carbon fiber cloth was calculated to be 0.82 mg/cm². Figure 2 shows images of the two electrode setups.

### *2.5.Electrochemical Techniques*

The study of electrochemistry examines how an electrode reacts chemically to an electrical stimulus. Electrochemical analysis, which can offer information about the material, including kinetics, concentration, reaction mechanism, and other characteristics at the electrode surface, can determine the material's redox reaction. To evaluate electrochemical capacitors, various parameters are considered, and several tests are performed, including Galvanostatic charge-discharge (GCD), cyclic voltammetry (CV), and electrochemical impedance spectroscopy (EIS). These tests were conducted using an electrochemical workstation (CHI660B). The areal specific capacitance (Ca) of the single electrode (Cs) and the entire supercapacitor (SCs) can be determined from the CV curves using Eq. (1) [25]:

$$\mathbf{Ca} = \frac{\oint \boldsymbol{I}\, \boldsymbol{d}\, \Delta \boldsymbol{V}}{(\boldsymbol{s}.\boldsymbol{v}\, \Delta \boldsymbol{V})} \qquad \textbf{(1)}$$

The mass ratio of the anode to the cathode in all-solid-state asymmetric devices is determined using Eq. (2) to achieve a balanced charge distribution between the two electrodes [12].

$$\boldsymbol{m}^{+}/\boldsymbol{m}^{-} = \frac{\boldsymbol{Cs}^{-}\Delta \boldsymbol{V}^{-}}{\boldsymbol{Cs}^{+}\, \Delta \boldsymbol{V}^{+}\, \mathbf{154}} \qquad \textbf{(2)}$$

The volumetric energy density (E, Wh cm$^{-3}$) and the power density (P, W cm$^{-3}$) of the assembled supercapacitor devices were calculated using Eqs. (3) and (4) [12]:

$$\boldsymbol{E} = \frac{\boldsymbol{C}_{\mathbf{cell}}}{\mathbf{2d}\Delta \boldsymbol{V}^{2}} \qquad \textbf{(3)}$$

$$P = \frac{E}{\Delta t\ 160} \quad (4)$$

where $\oint I\Delta V$ (A•V) is the voltammetric charge, representing the area under the curve of the cyclic voltammetry, v (V $s^{-1}$) is the scan rate, s is the area ($cm^2$) of the electrode, d (cm) is the thickness of the all-solid-state ASCs, ΔV (V) is the potential window, Δt (s) is the discharge time, and m (g) is the mass of the active material in the anode or the cathode.

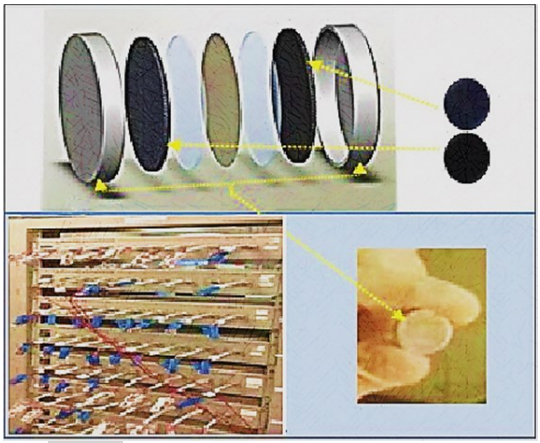

**Fig. 2** Schematic of the Asymmetrical Supercapacitor Structure and the Image of the Assembled Device.

## 3.RESULTS AND DISCUSSION

### *3.1.Mechanism Illustration of $FeCo_2O_4$ Morphologies*

Creating the FCO nanospherical arrays of thin film on the CFC substrate is caused by the chemical reactions. The first stage, involving the reaction of $CO(NH_2)_2$ with water to produce ammonia and metal cations in the mixture, react with $OH^-$ ions to form Co and Fe hydroxide on the CFC substrate. The prepared thin sheet was annealed under atmospheric conditions for 2 hours at 450°C to transform the Fe and Co hydroxide into $FeCo_2O_4$.

### *3.2.Surface Morphology*

Figure 3 shows the patterns diffraction of the X-rays $FeCo_2O_4$ nanospherical arrays after 2 hours of annealing at 450 °C. The sharp, extremely strong peaks confirmed the sample's good crystallinity. All of the peaks were consistent with the data from earlier publications, which could be attributed to the crystal planes of the Fd3m space group spinel structure of $FeCo_2O_4$. The X-ray diffraction patterns were utilized to determine the phase structure of the 2θ range from 20° to 80°. Peak intensities for the diffraction occurred at 2θ values of 31.31°, 36.79°, 38.44°, 44.67°, 55.53°, 59.29°, 65.20°, and 75.89° were respectively consistent with the Miller indices (2 2 0), (3 1 1), (2 2 2), (4 0 0), (4 2 2), (5 1 1), (4 4 0), and (533) planes of the face-centered cubic $FeCo_2O_4$ (JCPDS card no. 98-001-6669) and CFC at 2θ value of 26°, corresponding to the (002). In particular, the XRD results matched well without any other impurity peaks (Fe oxides and Co oxides), suggesting that the current synthetic technique produced an FCO with an extremely pure phase created by employing [25]. The Field Emission Scanning Electron Microscopy (FE-SEM) analysis was conducted during examining the morphological alterations in the $FeCo_2O_4$ on the carbon fiber cloth with various magnifications, as shown in Fig. 4. As one of the most effective techniques for analyzing the surface morphology of the finished product; SEM also provides information on the size, shape, and morphology of the nanospherical texture. As presented in Fig. 4, fiber structures did not appear, and there was a morphological transformation from fiber of CFC to clusters of the nanospherical arrays. The surface morphologies of the $FeCo_2O_4$ nanospherical arrays on the carbon fiber cloth are shown clearly in the SEM, revealing a uniform-sized, spherical texture without agglomeration as a result of the repulsive force provided by the hydrophobic carbon chains that enter the mixed solvents. The increase in the hydrothermal process time may be responsible for the $FeCo_2O_4$ spherical growth because it allows the nucleation site to interact with the high numbers and combine to produce larger nanospherical arrays.

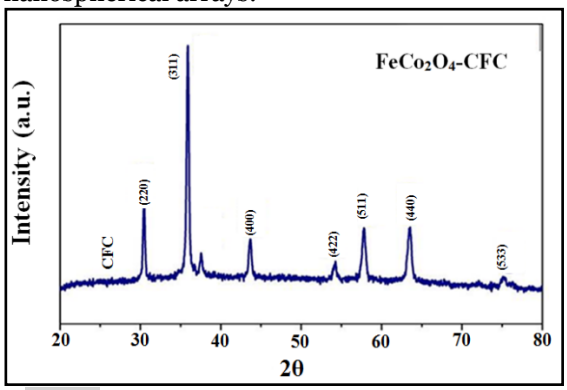


**Fig. 3** XRD Patterns of FCO Nanospherical Arrays.

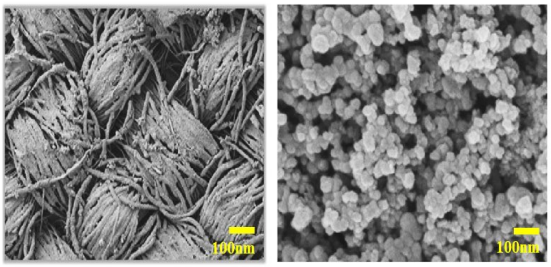


**Fig. 4** FESEM Images of $FeCo_2O_4$ with CFC.

Figure 5 shows the EDS spectrum, demonstrating the presence of Fe, Co, O, C, N, and F. EDS clarifies how the elements are distributed within the nanospherical arrays and further proves that the FCO structure is effectively wrapping the layered CFC.

FCO nanospherical arrays were present in the $FeCo_2O_4$ on the carbon fiber cloth sample, as shown in Fig. 6 images generated by the high-resolution transmission electron microscopy (HR-TEM). Figure 6 (a, c, and d) provides a

significant magnification picture of the FCO-CFC sample. The sample comprises rigidly interconnected nanospherical arrays, creating a very porous structure. The image shows the SAED pattern, Fig. 6 (b), which exhibits spots resulting from bright electron diffraction in the Debye ring compatible with the d-spacing of the lattice planes.

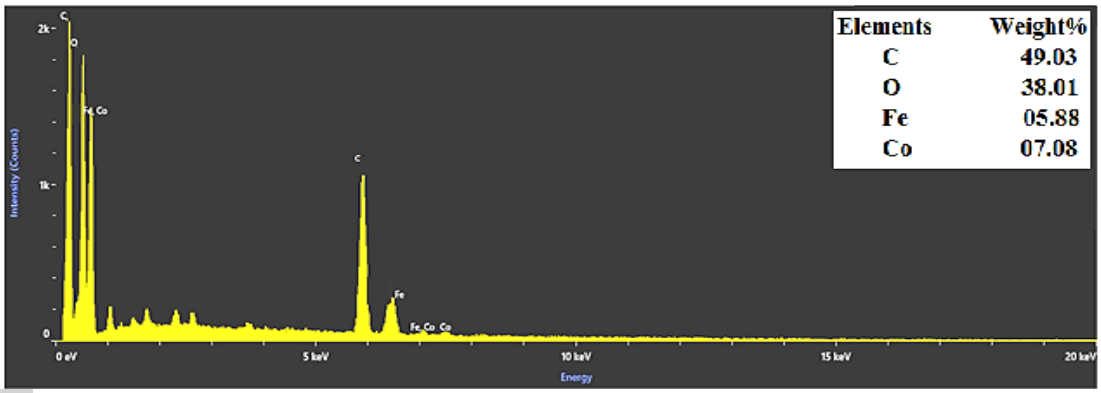


**Fig. 5** Energy Dispersive X-ray Spectroscopy (EDS) Spectrum and the Table for Weight Percentages of Different Elements for $FeCo_2O_4$ with CFC.

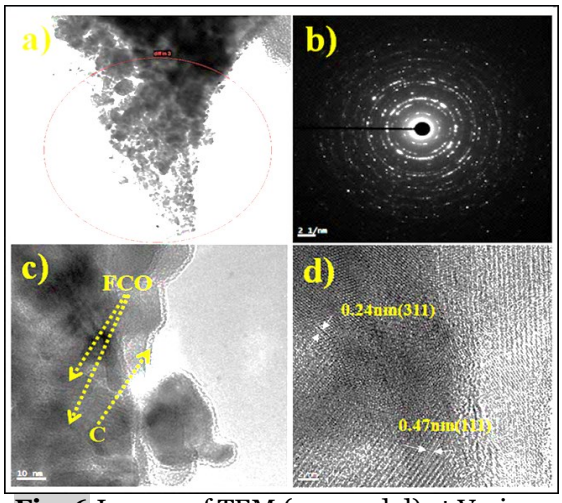


**Fig. 6** Images of TEM (a, c, and d) at Various Magnifications of the $FeCo_2O_4$ on the Carbon Fiber Cloth, and (b) is the Related Pattern for the Selected Area Electron Diffraction (SAED).

Recent studies have shown that forming electrode materials with holes can function as an electrolyte ion reservoir. The electrode material and the electrolyte must remain close to each other to keep the electrolyte's confinement to create a continuous supply of electrolyte ions in space. Therefore, the porous shape may enhance the electrode/electrolyte contact, thereby simplifying the electrochemical processes. A detailed view of the samples is shown in Fig. 6, clearly demonstrating the FCO-CFC presence. The lattice fringe spacing values of the (311) and (111) planes of the FCO were 0.24 and 0.47 nm, respectively. The FT-IR method was used to examine the chemical composition of CFC and FCO-CFC. Figure 7 shows the peak of hydroxyl vibration at 3438 $cm^{-1}$. Two faint peaks at 2854 and 2924 $cm^{-1}$ present for the groupings made are composed of methylene and methyl, respectively [26]. The peaks at roughly 1635 $cm^{-1}$ should match C=C, and 2341-2360$cm^{-1}$ should match C=O. The donor molecule's stretching configuration, corresponding to an extended bond, causes a peak intensity and changes energy, providing the distinctive hydrogen bond's vibrational spectral signature [27].

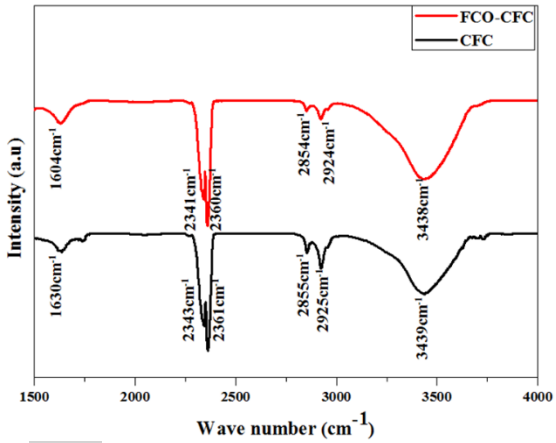


**Fig. 7** The FTIR Spectra of the Electrodes' Materials.

### *3.3.Electrochemical Performance*

Figure 8 (a) displays the standard CV curves of the asymmetric supercapacitor with the $FeCo_2O_4$-CFC over a possible window of 0-0.4 V at different scanning rates, including 5, 10, 20, 30, 40, and 100 mA. All CV curves are rectangular, implying that the asymmetric cell with the $FeCo_2O_4$-CFC nanocomposite electrodes is primarily defined by having an electrical double-layer action. Figure 8 (b) demonstrates how the transfer resistance of the charge at the interface of the electrode is indicated by the semicircle-shaped Nyquist plots for the $FeCo_2O_4$-CFC electrodes. On the other hand, the ion diffusion at the electrode contact was identified as a contributing factor to the inclination line (W: Warburg impedance) in the low-frequency range. Generally, when analyzing the Nyquist plot, the first intercept on the real axis provides the solution resistance (Rs). At the same time, the magnitude of the

semicircle reflects the charge transfer resistance (Rct). In the present study, the FCO-CFC material exhibited very low Rs (3.2 Ω) and Rct (2.1 Ω), indicating a favorable electrochemical response between the electrode material and the electrolyte ions. Figure 8 (c) displays the charge-discharge curves for the asymmetric cell with $FeCo_2O_4$-CFC electrodes at a charge-discharge rate (C-D) of 10 mA $g^{-1}$ throughout a voltage window of 0 to 0.4 V, revealing that the C-D curves were almost symmetrical, showing good reversibility. Figure 8 (d) shows 10 mA $g^{-1}$ current density at a remarkably high specific capacitance for a nanocomposite electrode, i.e., 66% retention of capacitance at 10 mA $g^{-1}$ of the current density after a process of 1000 cycles. The charge curves of the $FeCo_2O_4$-CFC electrodes were almost symmetric to the corresponding discharge equivalent specific capacitance of the $FeCo_2O_4$-CFC with the number of cycles. At a current density of 10 $mAg^{-1}$, the real capacity of the $FeCo_2O_4$-CFC sample was roughly 225°F $g^{-1}$ [28]. In this regard, one of the important factors is the cycle life of the supercapacitor in real-world applications. The role of carbon fiber cloth (CFC) as a current collector is crucial in composite electrode systems. The main electron transport mechanism between spinal $FeCo_2O_4$ and CFC relies on the presence of intact interfacial contacts between them. Including "metallic" CFC in the $FeCo_2O_4$ matrix significantly changes carrier mobility as carrier electrons approach the CFC, attributed to the large relativistic mobility of electrons and holes (Dirac fermions), characterizing CFC. The $FeCo_2O_4$-CFC interface mimics an electronic contact between materials with wider and narrower band gap characteristics. Such interfaces induce carrier depletion accompanied by significant band bending. As a result, a low concentration of interface carriers was effectively produced, preventing the possibility of back injection. This arrangement facilitates unidirectional charge flow hopping through the percolating network, allowing classical carrier transport to occur, which leads to improved current collection properties and reduced net resistance in the composite system [29, 30].

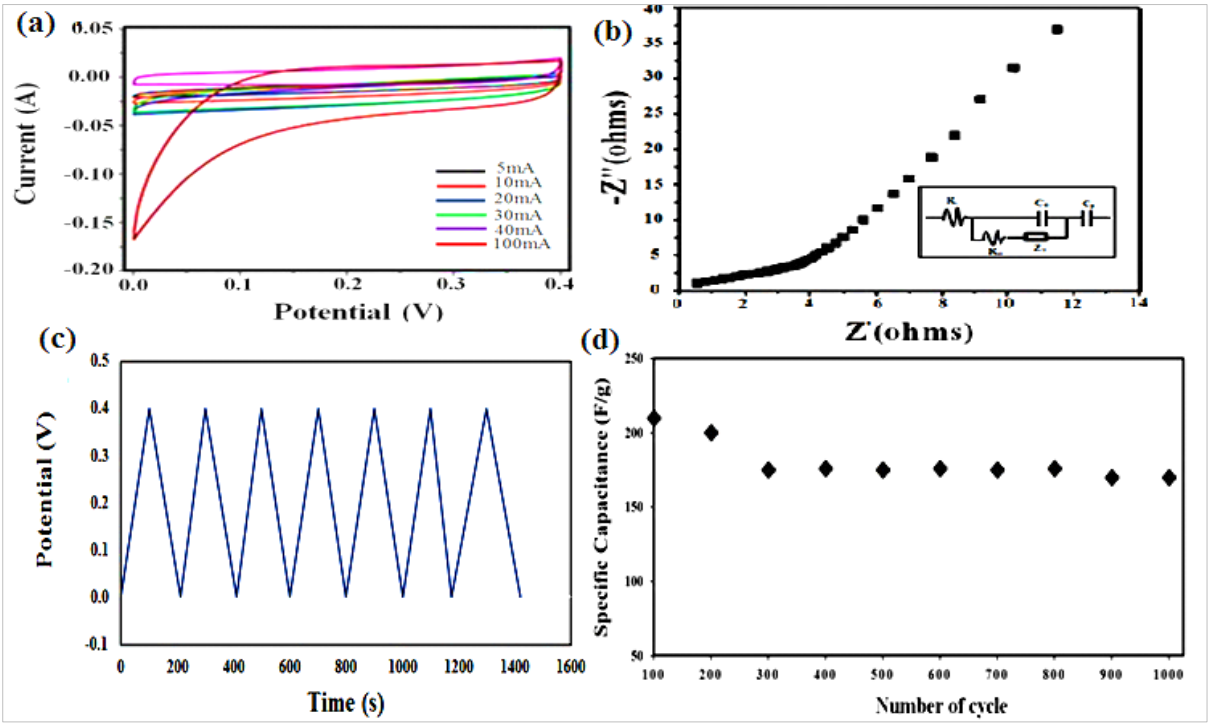


**Fig. 8** (a) Current-Potential (CV) Response at Different Scanning Rates for $FeCo_2O_4$-CFC, (b) Spectra of Electrochemical Impedance, (c) Charging/Discharging Response of $FeCo_2O_4$-CFC, and (d) the $FeCo_2O_4$-CFC Nanocomposite's Cycling Performance.

## 4.CONCLUSIONS

The $FeCo_2O_4$ structure on the carbon fiber cloth revealed a large contact area for the electrochemical reaction between the electrolytes and the electrodes. The $FeCo_2O_4$ samples created had a spinel structure, as indicated by the XRD data. In particular, FE-SEM measurements were used to classify the porous $FeCo_2O_4$ and CFC nanospherical arrays successfully synthesized using a simple hydrothermal process. According to XRD, FE-SEM, and TEM data, the $FeCo_2O_4$-CFC nanocomposite obtained from the hydrothermal reaction had a high crystallinity. As a result, the FCO and CFC nanocomposite showed good electrochemical characteristics when the electrode material was tested for electrochemical supercapacitors. The FCO and CFC nanospherical electrochemical performance demonstrated a high specific

capacitance of 225 F $g^{-1}$ at 10 mA $g^{-1}$ and an exceptional cycling stability of about 66% of the main capacitance after 1000 charging/discharging cycles. This extraordinary performance supports recommending the tested material as a smart selection for energy storage in future applications.

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## NOMENCLATURE

| | |
|---|---|
| *FCO* | Iron cobalt oxide ($FeCo_2O_4$) |
| *CFC* | Carbon fiber cloth |
| *SC* | Supercapacitor |
| *ECs* | Electrochemical capacitors |
| *EDLC* | Electric double-layer capacitors |
| *CNTs* | Carbon nanotubes |
| *FASCs* | Flexible asymmetric supercapacitors |
| MSs | Microspheres |
| NSs | Nanosheets |
| *AC* | Active carbon |
| PPy | Polypyyrole |
| *FCO-CFC* | $FeCo_2O_4$-Carbon fiber cloth |
| *DI* | Deionized water |
| *GCD* | Galvanostatic charge-discharge |
| *CV* | Cyclic voltammetry |
| *SAED* | Selected area electron diffraction |
| $R_S$ | Solution resistance |
| *Rct* | Charge transfer resistance |
| *Ca* | Areal specific capacitance, F/g |
| *IΔV* | Voltammetric charge, A.V |
| *υ* | Scan rate, V $s^{-1}$ |
| *s* | Area of the electrode, $cm^2$ |
| *d* | Thickness of the all-solid-state ASCs, cm |
| *ΔV* | The potential window, V |
| *Δt* | Discharge time, sec |
| *m* | Mass of the active material in the anode or cathode, g |
| *E* | Energy density, Wh $cm^{-3}$ |
| *P* | Power density, W $cm^{-3}$ |
| *Rs* | Solution resistance, Ω $cm^2$ |
| *Rct* | Charge transfer resistance, Ω $cm^2$ |

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