Rice Husk-Derived Mesoporous Silica Nanostructure for Supercapacitors Application: A Possible Approach for Recycling Bio-Waste into a Value-Added Product

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Short Report

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Abstract

We synthesized mesoporous SiO_2 nanomatrix using rice husks as a precursor through a facile thermal combustion process. XRD, FTIR, EDX, and TEM analyses were used to validate the produced mesoporous SiO_2 nanomatrix. Electrochemical measurements were used to determine the specific capacitance of mesoporous SiO_2 nanomatrix, and the results showed that the specific capacitances are 216, 204, 182, 163, 152, 142, 135, 133, 124.4, 124 F/g at current densities of 0.5, 1, 2, 4, 6, 8, 10, 12, 14, and 16 A/g. The benefit of impurities, as well as the large surface area and mesoporous structure of rice husk derived SiO_2 nanostructures, allow Faradaic redox reactions at the electrode surface and the resulting supercapacitive behavior. This research might lead to a low-cost technique of producing supercapacitor electrodes using rice husk-derived SiO_2 as a precursor.

1. Introduction

Environmental concerns and demand for sustainable energy have prompted researchers to develop advanced energy storage systems. Supercapacitors are pioneering energy storage technology in recent decades owing to high power density, fast charge/discharge rates, high storage capacity, reliability, and extended life period[1, 2]. Its unique characteristics find applications in hybrid electric vehicles, regenerative breaking, flashlights, smartphones, electric tools, consumer electronics, memory devices, energy harvesting devices, etc.,[1, 2]. Mesoporous characteristics, specific surface area (SSA), and charge transport available at the electrode have a part in the storage of charges, therefore they are key factors to the performance of the supercapacitors[3, 4]. In the past few decades, nanotechnology has become a driving force in materials research, leading a breakthrough revolution in the discovery of potential materials with improved efficiency for supercapacitor applications[3]. To develop supercapacitors with improved performance, numerous nanostructured materials including metal-organic frameworks, metal oxides, metal nitrides, carbon-based material, conducting polymers, and so on have been investigated[3, 4]. Recently, Silica (SiO_2) nanoparticles have gained a lot of interest as a possible choice for constructing supercapacitor electrodes owed to advantages like non-toxicity, mesoporous structure, exceptional surface chemistry, and large SSA[5, 6]. However, the use of SiO_2 nanoparticles as supercapacitor electrodes has been limited due to poor electron transport processes caused by low conductivity [7]. As a result, few works have already been done towards integrating conductive components into SiO_2 nanostructures to improve their electrochemical characteristics[8–10]. Because of non-toxicity, availability, and cost-effectiveness, SiO_2 nanoparticles can be successfully synthesized utilizing biowaste, which has attracted the huge attention of scientists in recent decades [6]. Rice husk proved to be a suitable alternative to synthetic SiO_2 precursors as a sustainable source of amorphous SiO_2. Rice husk is dumped as biowaste by a lot of rice milling factories, and approximately 100 million tonnes of rice husk are processed each year worldwide and a small proportion being employed for livestock feed [11]. In recent years, there has been a lot of interest in recycling rice husk waste into useful materials from the perspective of both environmental and economic concerns [6, 8]. Thanks to rice husk-derived SiO_2, which contains CaO, MgO, and K_2O, as well as a few trace elements that may play an important role in electrochemical performance besides with advantage of the mesoporous structure and high SSA [6, 11]. Here, the feasibility of rice husk-derived SiO_2 as an electrode material for supercapacitor application is being investigated which may find a new platform for the development of cost-effective energy storage devices.

2. Experimental Methods

Utilizing rice husk as a starting material, a simple thermal combustion technique was employed to produce mesoporous SiO_2 nanomatrix. In a nutshell, an appropriate quantity of rice husk was purchased from a rice processing industry at Tiruchengode, Tamil Nadu, India, and they were washed thoroughly using water to flush away impurities and then dehydrated for 10h at 110°C. Thereafter, 15g dehydrated rice husk was put into an alumina crucible and placed into a muffle furnace for thermal combustion. The thermal treatment process of rice husk was done for 5h at 600°C. After combustion, the obtained white color ash was cooled down to room temperature and stored in a desiccator at room temperature for further characterization.

X-ray diffraction (XRD) data were collected with 0.05° step size over 2θ range of 20-140 degree using Cr Kα radiation (λ = 2.2909 Å) in a Difray-401 X-ray diffractometer. Using the KBr pellet technique, the absorption of IR by the sample over the wavenumber of 4000–400 cm^{-1} was measured using Nicolet 380 Fourier transform infrared (FTIR) spectrometer to identify the functional groups. Elemental mapping was done using a Tescan Vega 3 scanning electron microscope (SEM) equipped with an energy-dispersive X-ray (EDX) microanalyzer. A JSM JEOL-2100 transmission electron microscope (TEM) was used to investigate the selected area electron diffraction (SAED) and morphological features. A Quantachrome Nova 1200e analyzer was used to collect a N_2 adsorption-desorption behavior. Based on N_2 adsorption-desorption, the Brunauer-Emmett-Teller (BET) and Barrett–Joyner–Halenda (BJH) approaches were employed to identify the SSA, pore size, and distribution. The electrochemical characteristics of the synthesized sample were investigated at room temperature using a BioLogic SP-150 research-grade electrochemical analyzer controlled by EC-Lab® software-assisted computer. Platinum wire counter electrode, Ag/AgCl reference electrode, and KOH electrolyte were employed to analyze the electrochemical characterization of the sample coated Ni foam electrode. The sample coated Ni foam electrode was employed as a working electrode which was prepared using the mixture of 80 wt.% of the sample, 10 wt.% of polyvinylidene fluoride, 10 wt.% carbon black, and 2 mL of ethanol. The electrochemical characteristics of the synthesized sample were investigated at room temperature using a BioLogic SP-150 research-grade electrochemical analyzer controlled by EC-Lab® software-assisted computer. Platinum wire counter electrode, Ag/AgCl reference electrode, and KOH electrolyte were employed to analyze the electrochemical characterization of the prepared sample coated Ni foam electrode. The sample coated Ni foam electrode was employed as a working electrode which was prepared using the mixture of 80 wt.% of the sample, 10 wt.% of polyvinylidene fluoride, 10 wt.% carbon black, and 2 mL of ethanol. The supercapacitance of the synthesized SiO_2 sample was evaluated using the cyclic voltammetry (CV) curve and galvanostatic charge/discharge (GCD) attributes of the constructed working electrode.

3. Results And Discussion

Figure 1(a) shows the XRD profile of the prepared rice husk ash, which displays a wide diffraction peak around 2θ of 25-40º. It was found that rice husk ash is composed of the SiO_2 in the amorphous state and it is consistent with previous research [8]. The FT-IR spectrum of prepared rice husk ash is shown in Fig. 2(b). Due to symmetric stretching, asymmetric stretching, and bending vibrations of the O−Si−O functional group, the FTIR spectrum of the prepared rice husk ash displays peaks at 786 cm^{-1}, 1160 $cm^{-1,}$ and 447 cm^{-1}, respectively which further reveals synthesized rice husk ash is constituted of SiO_2 [8, 12]. The elemental mapping of the rice husk-derived SiO_2 is shown in Figure 1(c), which depicts the distribution of silicon (37.7%), oxygen (50.5%), and impurities such as Zn (1.2%), Fe (1.6%), Ca (1.1%), K (1.4%), P (1.9%), Mg (0.9%), Cl (1.3%), and C (2.4%). Depending on the production methodologies, rice husk-derived SiO_2 may contain impurities such as sodium, carbon, iron oxide, potassium, calcium oxide, and magnesium oxide [6, 12]. To remove these impurities and produce pure SiO_2, pre-treatment and post-treatment procedures have been applied successfully [6, 12, 13]. In this work, we ignored pre-treatment and post-treatment processes to produce SiO_2 with impurities that may enable charge transport in a suitable electrolyte. The SAED pattern is shown in Figure 1(d) demonstrates the amorphous characteristics of the prepared SiO_2 which was corroborated with the XRD results.

Figure 2(a-c) shows the rice husk and its typical SEM and TEM observation. According to SEM and TEM investigations, thermal combustion of rice husk yields porous SiO_2 nanomatrix. To prepare spherical SiO_2 nanoparticles, rice husk is typically heated to 400-500°C [8]. The porous SiO_2 nanomatrix was formed in this work was owing to the fusing of SiO_2 particles in rice husk at 600°C. The topological properties found in this study potentially fulfill the fundamental needs of material applicable for supercapacitor applications [5–7]. The N_2 adsorption/desorption curve of the prepared SiO_2 nanomatrix is shown in Figure 2(d). The observed hysteresis loop belongs to type IV isotherm indicating that the synthesized sample has mesoporous properties. The prepared SiO_2 nanomatrix has a SSA of 36.954 m^2/g, according to BET analysis. The BJH analysis revealed that the sample exhibit a cumulative pore volume of 0.094 cm^3/g with median pore sizes of 0.094 cm^3/g.

Figure 3(a) shows the CV plot at a different rate of scanning with an applied potential of 0-0.5 V. The prepared SiO_2 exhibits strong symmetrical oxidation-reduction peaks which are owing to the well-defined Faradaic redox process that occurs at the interface of electrolyte-electrode. It indicates the excellent supercapacitive behavior of the prepared SiO_2-coated electrode. With the increase of sweep rate of 5-50 mV/s, the peak intensities owing to oxidation/reduction move in the direction of positive and negative potentials in the CV characteristic curve. These finding indicate that the Faradaic redox reaction is mediated by ion diffusion at the interface of electrolyte-electrode and impurities play an important role in the electron transport.

Figure 3(b) depicts the charge-discharge curve at current densities ranging 0.5-16 A/g. The charge-discharge curves were observed to be symmetric. It further corroborates the supercapacitance activity of rice husk-derived SiO_2 due to Faradaic redox processes. The specific capacitances are found to be 216, 204, 182, 163, 152, 142, 135, 133, 124.4, 124F/g at current densities of 0.5, 1, 2, 4, 6, 8, 10, 12, 14, and 16A/g (Figure 3(c)). The impurities in rice husk-derived SiO_2 nanomatrix, SSA, and mesoporous structure can facilitate the adsorption/desorption charges and make it possible to store the charges.

4. Conclusion

Using biowaste as a precursor, we produced a mesoporous SiO_2 nanomatrix via a simple thermal combustion technique. The resulting mesoporous SiO_2 nanomatrix was confirmed using different analytical studies. The feasibility of rice husk-derived SiO_2 as an electrode material for supercapacitor application was investigated and indicates that the impurities, SSA, and mesoporous structure of rice husk-derived SiO_2 nanomatrix enable Faradaic redox reactions and resulted in supercapacitive activity. This investigation may find a new platform for the development of cost-effective energy storage devices.

Declarations

* **Ethics approval**: Not applicable

*** Consent to participate**

Not applicable

* **Consent for publication**: Not applicable

* **Availability of data and materials**: Data and materials will be made on request.

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* **Research involving human participants and/or animals**: Not applicable

*** Informed consent**

Not applicable

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Figures

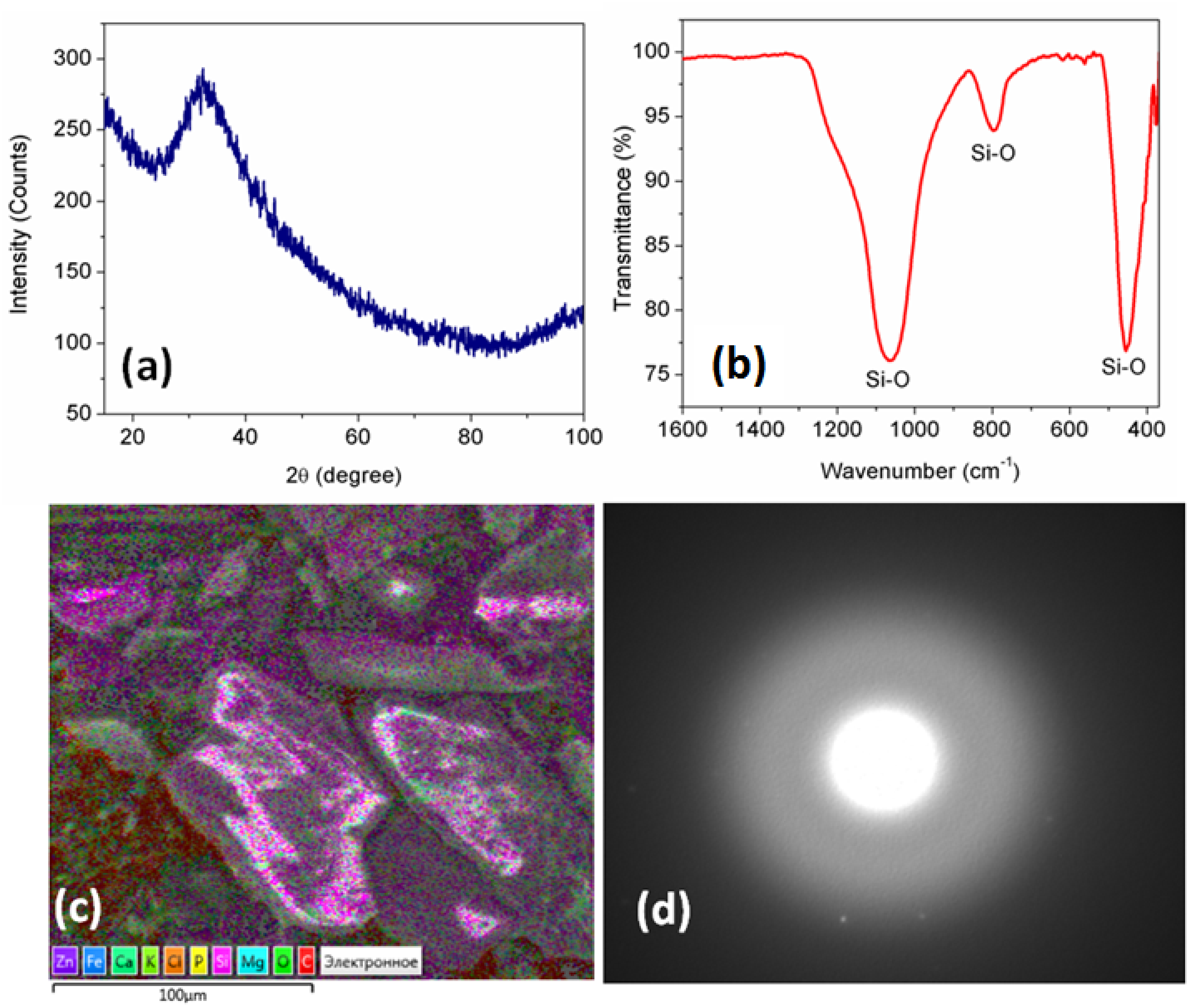

Figure 1

(a) XRD profile, (b) FTIR spectrum, (c) EDX elemental mapping, and (d) SAED pattern of the prepared rice husk ash.

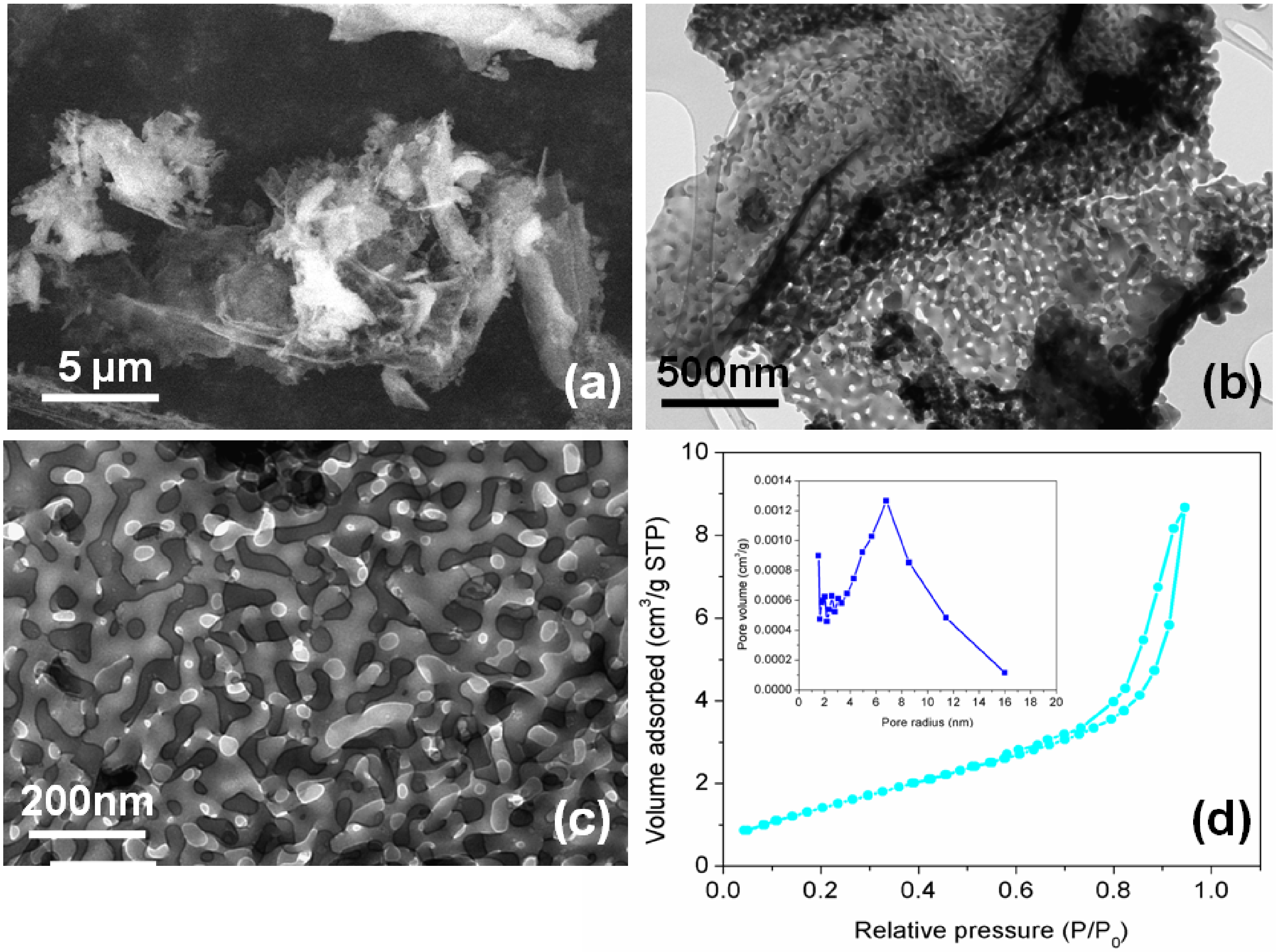

Figure 2

(a) SEM, (b-c) TEM, and (d) N2 adsorption/desorption curve of the prepared SiO2 nanomatrix.

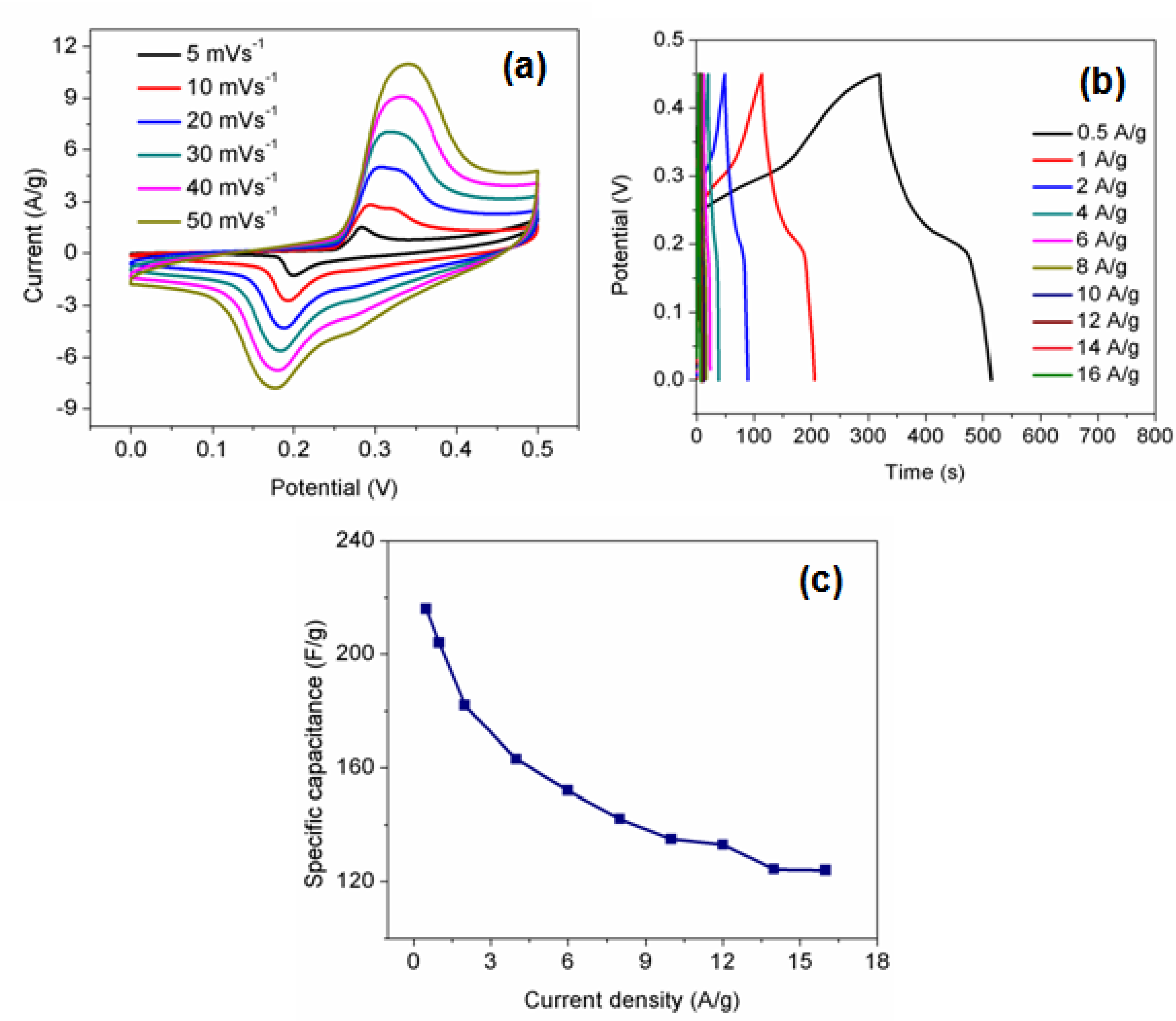

Figure 3

(a) CV plot, (b) charge-discharge curve, and (c) specific capacitance of the prepared rice husk-derived SiO2 as a working electrode.