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Preliminary study on the utilization of cabbage waste as a raw material for activated carbon in supercapacitor applications

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ABSTRACT

This study aims to utilize cabbage waste as an active carbon material for supercapacitor electrodes through an environmentally friendly approach without chemical activation. The fabrication process includes pre-carbonization at 200°C for 1 hour, carbonization at 600°C, and physical activation at 850°C. The resulting carbon material exhibits a porous structure essential for ion storage, despite the absence of chemical activation. Electrochemical testing using the galvanostatic charge-discharge method with Na_2SO_4 electrolyte concentrations of 0.5 M, 1 M, and 1.5 M demonstrated a highest specific capacitance of 155.87 F/g at 1.5 M concentration. The increase in electrolyte concentration enhances ion mobility and charge storage capacity. This research indicates that cabbage waste can serve as an effective active carbon source for supercapacitors, with further performance improvements expected through chemical activation in future studies.

Keywords: Cabbage waste; carbon electrode; Na_2SO_4; specific capacitance; supercapacitor

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INTRODUCTION

Electrical energy is a primary necessity used in various aspects of life. Electronic devices such as mobile phones and computers require a supply of electrical energy to function. The high mobility of users drives the need for portable devices that can be used in various locations. The use of these devices demands energy storage media that are efficient and affordable. An ideal energy storage device is one that can balance energy density and power density, as found in supercapacitors. Supercapacitors have several advantages, including fast recharge capability, high power density, large charge storage capacity, short charge and discharge times, and longer lifespan [1].

The electrode and electrolyte are two of the most important components in a supercapacitor system. Various materials can be used as the base for electrodes, including activated carbon, metal oxides, and conductive polymers. Among these, activated carbon stands out due to its abundant availability, low production cost, high electrical conductivity, large surface area, good chemical stability, and relatively simple synthesis process [2]. On the other hand, electrolytes serve as ion-conducting media between the positive and negative electrodes. During the charging and discharging processes, ions in the electrolyte migrate toward the electrodes, forming an electrical double layer or participating in redox reactions on the electrode surface, depending on the type of capacitance involved [3].

One of the commonly used aqueous electrolytes in supercapacitor research is sodium sulfate (Na_2SO_4). This electrolyte is non-corrosive, non-toxic, environmentally friendly, and safe for large-scale energy applications. These advantages make it an ideal choice for energy storage systems that require high stability and operational safety. Several studies have also shown that Na_2SO_4 provides good cycling stability with high capacitance retention after thousands of charge–discharge cycles [4].

The synthesis of activated carbon from sugar palm frond electrodes using 0.5 M KOH as an activator with Na_2SO_4 electrolyte produced a capacitance value of 79 F/g at 0.5 M

concentration, measured by the cyclic voltammetry (CV) method [5]. The synthesis of sodiated manganese oxide P2-$Na_{2/3}MnO_2$ using a hydrothermal method followed by annealing at 900 °C for 12 hours produced a high specific capacitance of 234 F/g, while the non-sodiated Mn_2O_3 annealed at 400 °C delivered only 115 F/g. Both materials were tested in a 1.0 M Na_2SO_4 aqueous electrolyte using a three-electrode system at a current density of 0.4 A/g [4]. This study reports the effect of electrolyte concentration on the electrochemical performance of a supercapacitor based on Reduced Graphite Oxide (RGO) using sodium sulfate (Na_2SO_4) electrolyte at various concentrations of 0.5 M, 1 M, 1.5 M, and 2 M. The supercapacitor achieved a maximum specific capacitance of 176 F/g in 1 M Na_2SO_4 solution, with an energy density of 47 Wh/kg and a power density of 700 W/kg [6].

Agricultural and vegetable waste are abundant sources of biomass that have not yet been optimally utilized. One commonly produced type of vegetable waste is cabbage waste (*Brassica oleracea*), particularly the outer leaves that are not used for consumption or market distribution. This waste is generally discarded or used as animal feed, despite its chemical composition being highly promising for development as a carbon precursor, especially for energy applications such as supercapacitor electrodes [7].

The outer cabbage leaves are known to contain lignocellulosic components consisting of cellulose, hemicellulose, and lignin. The cellulose content in dried cabbage leaves reaches approximately 63%, with hemicellulose and lignin at 15% and 14%, respectively. This composition indicates that cabbage waste has a stable carbon structure and is rich in functional groups that can be carbonized to produce activated carbon materials. Moreover, its abundant availability and low processing cost make cabbage waste an ideal candidate for environmentally friendly electrode materials [8]. The use of cabbage as a vegetable often generates waste that goes unutilized. This cabbage waste is commonly found in markets, where producers frequently discard the outer layers of the cabbage as they are considered unsuitable for consumption due to dirt and potential impact on the selling price [9].

In this study, cabbage waste was carbonized at 600 °C in a CO_2 atmosphere and physically activated at 850 °C using N_2 gas without chemical activation. Na_2SO_4 electrolyte concentrations of 0,5 M, 1 M, and 1,5 M were varied to evaluate electrode performance using CV and galvanostatic charge-discharge methods.

RESEARCH METHODOLOGY

Material Source

The raw material for carbon electrode fabrication, cabbage waste, was sourced from Pasar Selasa, Tampan District, Riau Province.

Activated Carbon Preparation

The preparation of activated carbon from cabbage waste involves three main steps: pre-carbonization, carbonization, and physical activation. In the pre-carbonization stage, 30 grams of cabbage waste are weighed and placed into a stainless steel tube, which is then heated in an oven at 200°C for 1 hour to make the sample brittle and easier to grind. Carbonization were begins at room temperature (30°C) until reaching 302°C, which is maintained for 1 hour. Subsequently, the sample is further heated inside a furnace up to 600°C in a nitrogen (N_2) atmosphere. Finally, in the physical activation stage, nitrogen gas is replaced with carbon dioxide (CO_2) at 600°C, and the temperature is increased to 850°C. This temperature is held for 2 hours and 30 minutes before being allowed to cool gradually to room temperature. The physical activation using CO_2 gas aims to enhance the surface area and remove tar deposits within the pores by creating new pores through reactions with activated carbon [10].

Supercapacitor Cell Fabrication

Several components are required to fabricate a supercapacitor cell, including current collectors, two carbon electrodes, electrolyte, and separator. Chicken egg membrane is used as the separator. To prevent cell leakage through holes, Teflon supports are made with diameters matching the electrodes. The Teflon ring is placed in the center of the support hole, and glue is applied on the back of the support body. Then, stainless steel shaped according to the electrode diameter is placed on top of the Teflon ring. After soaking the carbon electrodes in Na_2SO_4 solution for 48 hours, they are removed and placed on the stainless steel using a spatula or tweezers. The two support bodies are reinforced and clamped to ensure the electrodes and ions fully contact the surface of the stainless steel.

Characterization

Mass loss measurement is conducted to determine how much the material's mass decreases after thermal treatment. The dried cabbage waste is first weighed to obtain the initial mass (m_0), then heated through the pre-carbonization process at a specific temperature and duration. After the process is complete, the sample is cooled and weighed again to obtain the final mass (m_1). The percentage of mass loss is calculated by comparing the difference between the initial and final mass relative to the initial mass. The measurement is repeated three times to ensure data accuracy.

Density is a parameter that reflects the mass compactness of electrode material per unit volume (g/cm³). Too low a density can reduce volumetric capacity, while too high a density can hinder electrolyte ion diffusion into the material's pores. Therefore, an optimal density is crucial to balance specific capacitance and ion transfer efficiency [11]. Density (ρ) can be calculated using the formula [12]:

$$\rho = \frac{m}{v} \quad (1)$$

where, ρ represents density (g/cm³), m is the dry mass of the sample (g), and v is the volume of the material (cm³). Density is the mass per unit volume. To determine the density of the pressed pellets, the diameter and thickness are measured using a caliper, while the pellet mass is weighed using a digital scale. Density measurements are performed before and after pyrolysis. Densities before and after pyrolysis were compared to assess the effects of carbonization and activation on the carbon material's physical properties.

Electrachemical Measurement

Electrochemical characterization using the CV method is conducted with a Physics CV UR RadAs 2508 v.1.0 instrument. The CV method produces voltammogram curves and determines the specific capacitance of the supercapacitor made from active carbon electrodes derived from cabbage waste, using a chicken eggshell membrane as the separator. Specific capacitance is measured at potentials ranging from 0 to 1 V with scan rates of 1 mV/s, 2 mV/s, 5 mV/s, and 10 mV/s. The graphs and data are saved on a computer in JPG and Microsoft Excel formats. The CV test yields data on discharge and charge currents, which are processed using SigmaPlot software.

Galvanostatic Charge-Discharge (GCD) is a method used to determine the specific capacitance of the supercapacitor cell by measuring charge and discharge times [13]. GCD is performed by applying a constant positive and negative current to charge and discharge the material within a predetermined potential range. Specific capacitance is measured at potentials from 0 to 1 V with current densities of 1, 2, 5, and 10 A/g. The measurement results are processed using SigmaPlot to obtain data and curves showing the relationship between current and voltage. The specific capacitance can be calculated from the discharge time using the formula:

$$C_{sp} = \frac{2.I.\Delta t}{m.\Delta v} \quad (2)$$

RESULTS AND DISCUSSION

Physical Property Characterization

Pre-carbonization is the initial stage to transform organic material into carbon, causing the sample to change color to brown and become more brittle, thus facilitating the crushing process. This stage was carried out at a temperature of 200°C for 1 hour. The sample was weighed with an initial weight of 30 grams before the pre-carbonization process, then weighed again after the process was completed.

Table 1. Mass loss data.

M_1 (gr)	M_2 (gr)	Mass loss (gr)	Mass loss (%)
30	22.45	7.55	34
30	22.9	7.1	31
30	23.15	6.85	30
30	23.21	6.79	29
30	22.1	7.9	36
Average shrinkage			32

Table 1 shows the percentage of mass loss before and after the pre-carbonization process. After pre-carbonization, the remaining mass of cabbage waste was 113.81 grams from an initial mass of 150 grams, resulting in a mass loss percentage of 32%. This process caused the evaporation of water from the sample's compounds but did not affect lignin, cellulose, and hemicellulose at temperatures below 300°C. Under these conditions, the sample could be pressed into carbon pellets without the addition of a binder due to its self-binding properties. This characteristic is marked by the change in the sample's texture, becoming more brittle and easier to grind [14].

Density measurement was conducted to determine the change in material compactness before and after the pyrolysis process. Density was calculated based on the mass and volume of the material (g/cm³), and shrinkage was calculated to understand the extent of change caused by pyrolysis. For the KU sample (cabbage waste without activation), the density before pyrolysis was 1.010 g/cm³, and it decreased to 0.734 g/cm³ after pyrolysis.

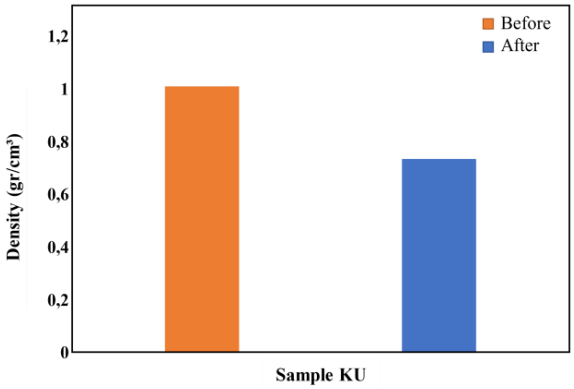

Figure 1. Density measurement results.

Based on Equation (1) and (2), a density reduction of 37.602% occurred, indicating thermal degradation of organic components such as hemicellulose, cellulose, and lignin present in the cabbage waste. During pyrolysis, volatile compounds evaporate, resulting in a porous carbon structure with lower density. This porous structure is advantageous for supercapacitor applications as it allows an increase in specific surface area and charge storage capacity. However, without an activation process (e.g., using KOH), pore development may remain limited, which could affect the overall electrochemical performance.

Electrochemical Characterization

The CV measurement results produced a slightly distorted rectangular-shaped curve, indicating that the supercapacitor exhibits typical Electric Double Layer Capacitance (EDLC) characteristics. A scan rate of 1 mV/s means the voltage is increased gradually by 1 mV every second until reaching the maximum voltage of 1000 mV. At this scan rate, there is a longer time available, allowing ions from the electrolyte solution to diffuse evenly and optimally fill the pores of the carbon electrode. Therefore, the 1 mV/s scan rate is often used to obtain more accurate specific capacitance measurements [15].

Figure 2 (a) shows the electrochemical characterization of cabbage-waste-based carbon electrodes using the cyclic voltammetry (CV) method over a voltage range of 0 – 1 V. The graph displays three curves with an elliptical

shape characteristic of Electric Double Layer Capacitor (EDLC) charge storage mechanisms, indicating that energy storage occurs capacitively without significant faradaic reaction contributions [16].

Figure 2 (b), (c), and (d) present the cyclic voltammetry (CV) curves of cabbage-waste-derived carbon electrodes recorded at scan rates of 1 mV/s, 2 mV/s, and 5 mV/s, respectively. KU-1.5 sample exhibits the largest CV curve area, which corresponds to the highest specific capacitance. This is attributed to the increased concentration of Na^+ and SO_4^{2-} ions in the 1.5 M electrolyte solution, which enhances the formation of the electrical double layer on the electrode surface. In other words, the higher the electrolyte concentration, the greater the charge density that can accumulate [17].

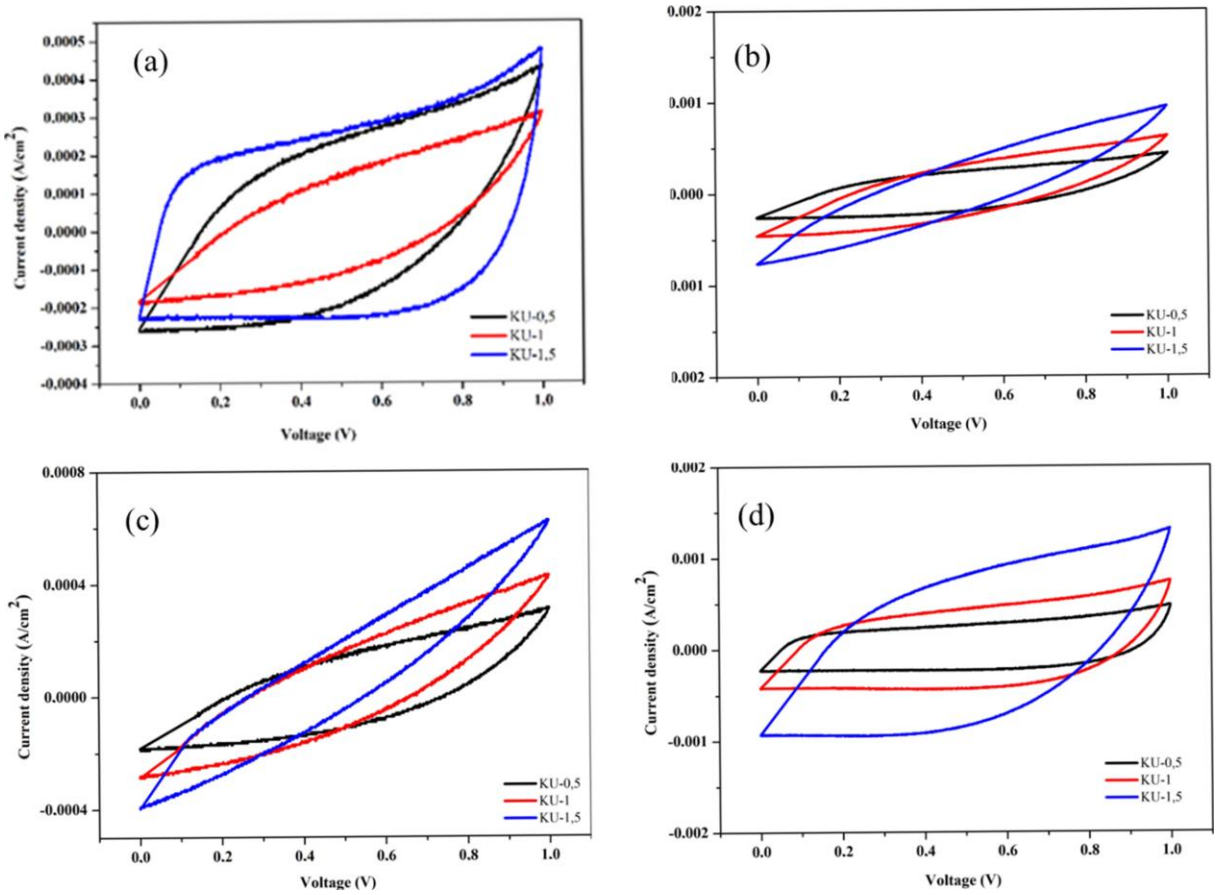

Figure 2. CV curves at different scan rates: (a) scan rate of 1 mV/s comparison and (b) KU-0.5, (c) KU-1, and (d) KU-1.5.

Nevertheless, at excessively high concentrations, diffusion resistance may occur due to increased electrolyte viscosity. However, in this graph, KU-1.5 still demonstrates the best performance, indicating that at this level, the viscosity has not significantly hindered ion diffusion.

Galvanostatic Charge-Discharge (GCD) is a technique used to evaluate the electrochemical kinetics and stability of materials during charge-discharge cycles. In this study, activated carbon electrodes derived from cabbage waste were tested using a constant current of 1 A, as shown in Figure 3. The results are presented in the form of triangular curves, which reflect the ion charging and discharging behavior on the electrode surface.

Figure 3 shows that all three electrode samples KU-0.5, KU-1, and KU-1.5 exhibit curves that are generally symmetrical between the charge and discharge processes. This indicates that the dominant energy storage mechanism is based on the Electric Double Layer Capacitor (EDLC), which stores charge

electrostatically without involving redox reactions [18].

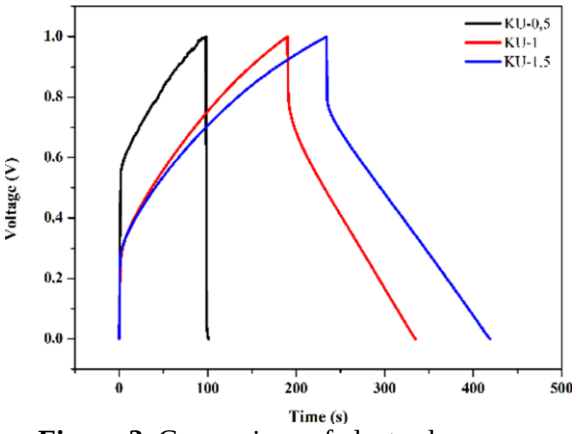

Figure 3. Comparison of electrode curves.

According to the graph, increasing the concentration of Na_2SO_4 electrolyte leads to a longer discharge time in the samples. This suggests that a higher ion concentration in the solution enhances the efficiency of ion transport toward the electrode surface and into the carbon pores, thereby increasing energy storage capacity. The specific capacitance (Cs) values calculated from the GCD curves show an increasing trend with higher electrolyte concentrations. For the KU-0.5 sample, the specific capacitance was 32.52 F/g, which is the lowest value obtained. This is attributed to the limited number of ions in the solution, resulting in suboptimal formation of the electrostatic charge layer. For KU-1, the specific capacitance increased significantly to 121.06 F/g, indicating that a 1 M Na_2SO_4 concentration provides a balance between solution viscosity and ion availability for interaction with the electrode surface [19].

Figure 4 shows The KU-1.5 sample demonstrated the best performance, with the highest specific capacitance value of 155.87 F/g. Its longer discharge time and the most symmetrical curve indicate that a 1.5 M concentration offers a sufficient number of ions for rapid diffusion into the electrode pore structure, without compromising system stability [20].

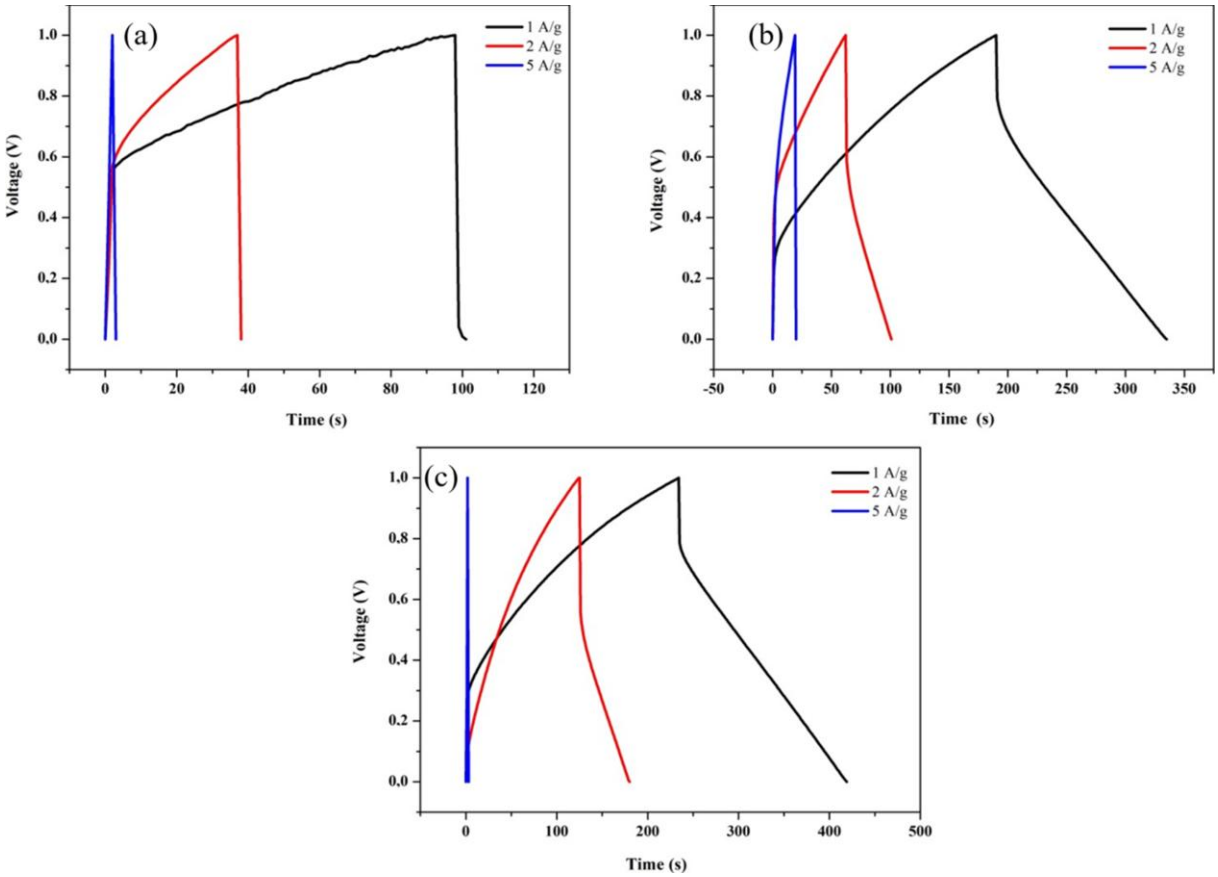

Figure 4. GCD curves at different scan rates (a) KU-0.5, (b) KU-1, and (c) KU-1.5.

Overall, it can be concluded that the electrochemical performance of cabbage-waste-derived carbon electrodes is highly influenced by the electrolyte concentration. Increasing the Na_2SO_4 concentration from 0.5 M to 1.5 M significantly improves the specific capacitance, demonstrating that a simple modification in electrolyte conditions can substantially enhance the energy storage capacity of biomass-based supercapacitors.

CONCLUSION

This study demonstrates that cabbage waste can be utilized as a source of activated carbon for supercapacitor electrodes through an environmentally friendly process without chemical activation. The electrode fabrication involved pre-carbonization at 200°C for 1 hour, main carbonization at 302°C, and physical activation at 850°C using a furnace. These steps successfully produced porous carbon material, as indicated by the reduction in mass and density due to the thermal degradation of organic components.

Electrochemical testing using the Galvanostatic Charge-Discharge (GCD) method with Na_2SO_4 electrolyte at concentrations of 0.5 M, 1 M, and 1.5 M showed an increase in specific capacitance with increasing electrolyte concentration. The highest capacitance value of 155.87 F/g was achieved at 1.5 M, indicating the crucial role of electrolyte concentration in enhancing ion transport and charge storage within the porous carbon structure.

Overall, cabbage waste has significant potential as a carbon precursor for supercapacitor applications, with optimal performance observed at 1.5 M Na_2SO_4 electrolyte concentration. However, to further enhance micropore formation, surface area, and electrode performance, chemical activation (e.g., KOH) is recommended for future studies.

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