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Biomass-Based Supercapacitors Electrodes for Electrical Energy Storage Systems Activated Using Chemical Activation Method: A Literature Review and Bibliometric Analysis

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ABSTRACT

Currently, carbon derived from biomass waste or residues is being intensively utilized as electrodes due to its excellent electrical properties, including high conductivity, appropriate porosity, and a specific surface area suitable for supercapacitor applications. Despite its advantages, the performance of supercapacitors made from biomass-derived carbon is insufficient for engineering applications because of the challenges in obtaining the mesoporous structure of activated carbon (AC). Therefore, this study highlights the potential of biomass-based carbon as the electrodes of a highly efficient supercapacitor, which can facilitate highly efficient current transport in energy storage systems. It comprehensively discusses various biomass material sources and activation methods to produce carbon, with a focus on the physical and electrical properties. Initially, the study discusses carbon activation methods and mechanisms to understand why activating agents and electrolyte solutions have a high specific surface area and specific capacitance. It then concentrates on the chemical activation method and its importance in making AC useful as an efficient electrode. Finally, in this study, various biomass sources were discussed to highlight the performance of supercapacitors electrodes originating from agricultural and wood residues relating to the specific capacitance and capacitance retention. Based on the obtained results, it is concluded that biomass-based carbon materials could be the most advantageous platform material for energy conversion and storage.

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1. INTRODUCTION

In the past, there was a growing concern that fossil fuel reserves would eventually run out at some point (Kong *et al.*, 2020; Maheshvari, 2022; Haritha, 2023). This has prompted efforts toward reducing the rate at which these fuels are widely consumed. One approach towards achieving this has been to explore alternative energy sources, such as hydrogen combustion gas in car engines (Hamidah *et al.*, 2018) and electric-powered vehicles (Cano *et al.*, 2018). To facilitate this transition towards renewable energy sources, machines, and other electrical devices have been designed to align with technological advancements and innovative ideas.

Electricity can be generated by converting different types of energy, such as photon energy (Liu *et al.*, 2021), mechanical rotation and vibration energy (Said *et al.*, 2016; Yunas *et al.*, 2020), heat energy transfer from waste (Seralathan *et al.*, 2020; Tian *et al.*, 2021), electrochemical power generator in fuel cells (Zhang *et al.*, 2021; Qiu *et al.*, 2021), and energy capture from environmental electromagnetic pollution (Surducan *et al.*, 2020; Shi *et al.*, 2018).

One significant breakthrough in the shift towards renewable energy sources is the fast development of electric vehicles, and this coincides with the development of various energy storage technologies such as sodium-ion, zinc-air, lithium-ion, and aluminum-air batteries (Chuhadiya *et al.*, 2021; Sellali *et al.*, 2019). Meanwhile, supercapacitors are expected to have a comparative advantage over batteries, making them a promising alternative for energy storage systems that play a significant key in preparing a continuous power supply for portable mobile electronic equipment (Vukajlović *et al.*, 2020).

However, hybrid energy storage batteries/supercapacitors were employed in electric vehicles because of their high energy density (Zhang *et al.*, 2020; Rahman *et al.*, 2020), while a voltage stabilizer is added to the automobile to stabilize power consumption (Hamidah *et al.*, 2020). To meet the requirements of the automobile industry, energy storage applications must be highly efficient, cost-effective, compact, and produce low harmful exhaust gas (Zou *et al.*, 2015). Furthermore, with the increasing need for high-performance energy storage devices in compact and highly mobile applications, such as the use of implanted biomedical devices (Veneri *et al.*, 2018; Seman *et al.*, 2017) and aerospace applications (Pan *et al.*, 2014; Xu *et al.*, 2017), the demand for compact and high-performance energy storage devices grows rapidly.

The energy storage system itself is critical for addressing intermittent power generation problems and improving stability in electrical devices. Electric vehicles require kinetic energy storage when accelerating and recharging using electricity. To meet the supply and demand, electrochemical capacitors and batteries are among the most efficient energy storage systems (Sellai *et al.*, 2019; Veneri *et al.*, 2018). However, both have limitations. Batteries have a higher energy density than supercapacitors, whereas electrochemical capacitors can be charged and discharged in a matter of seconds but have a lower energy density than Lithium-ion batteries (Seman *et al.*, 2017; Pan *et al.*, 2014).

Supercapacitors are emerging as one of the most promising candidates for batteries due to their improved performance and reduced costs. However, significant improvements in energy storage systems are necessary to address the increasing demand in the need for future energy systems, including hybrid electric vehicles, electronic gadgets, and industrial equipment (Xu *et al.*, 2017). Improving the electrode properties of supercapacitors is one of the most critical elements in enhancing its performance.

Figure 1 shows detailed information regarding the charge transport mechanism of common supercapacitors electrodes. By

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employing Equation 1, enlarging the electrode's surface area permitted a significant boosting of the capacity of the capacitor and shortened the distance between electrodes. This can be achieved by using a material with a huge number of free electrons gathered on its surface (Karaphun *et al.*, 2021). As a result, with careful electrode material selection and the use of simple and low-cost synthesis procedures, larger-scale commercial applications for supercapacitors can be developed (Ghosh *et al.*, 2019).

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{1}$$

where ε_r and ε_0 are, respectively, the permittivity of electrolyte and vacuum. d and A are the distance between two electrodes and the specific surface area, respectively.

Many reports have been published concerning the utilization of carbon-based materials (Anshar *et al.*, 2016; N'diaye, 2023; Ragadhita & Nandiyanto, 2023; Nandiyanto *et al.*, 2017; Nandiyanto, 2018; Sukmafitri *et al.*, 2020; Fiandini *et al.*, 2020; Anggraeni *et al.*, 2021; Nandiyanto *et al.*, 2022a; Nandiyanto *et al.*, 2022b). It has been applied as electrodes, especially for improving energy storage systems. These materials were selected because of their distinct properties, which include tunable porosities (Zhao *et al.*, 2016), large surface areas (Duan *et al.*, 2021), varying morphologies (Chuhadiya *et al.*, 2021), layer-by-layer design (Nabais *et al.*, 2011), and the superior quality of their crystalline products (BoopathiRaja & Parthibavarman, 2020). As shown in **Table 1**, carbon-based material can consist of nanoparticles, carbon nanotubes, graphene, graphite, diamonds, and microfibers.

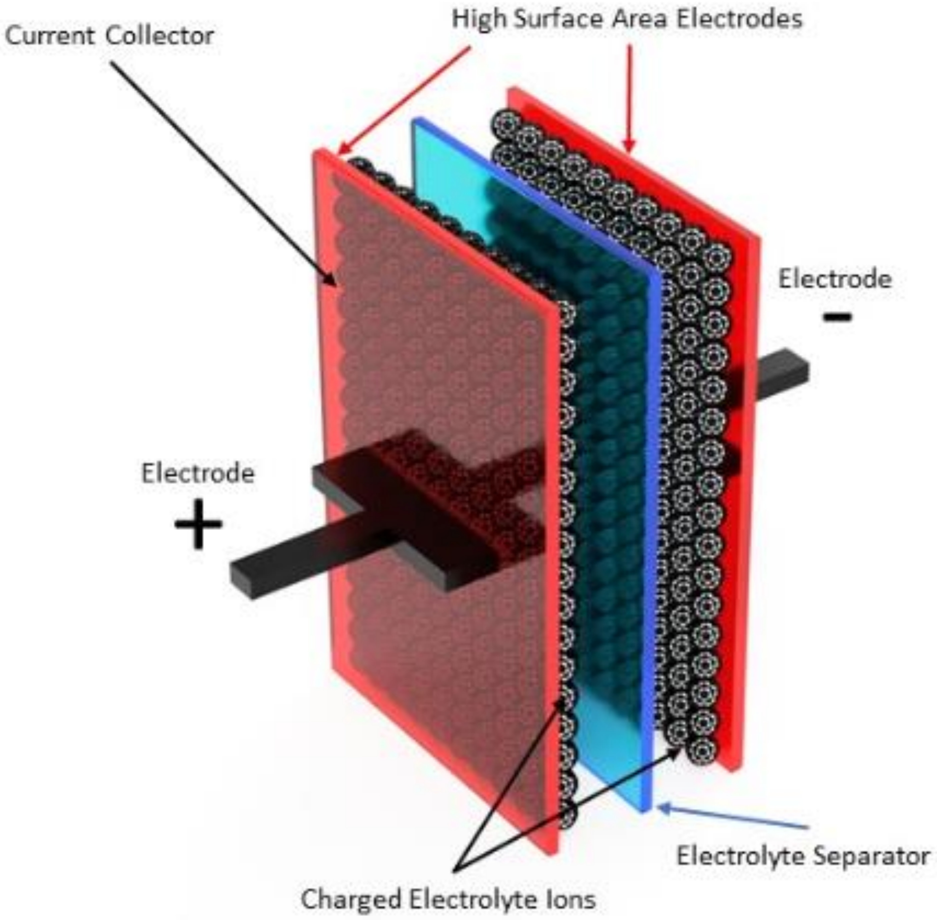

Figure 1. The schematic of the supercapacitors structure highlighting the role of carbon-based electrodes.

Table 1. Carbon-based electrode materials and their potential applications.

Materials	Physical property	Electrical property	Applications	Ref.
Carbon nanotube	1 Dimensional material, porous flexible free-standing films, electrodes coat	Giant thermoelectric power factor, anodes for battery	Sensors, nanomedicine, photocatalyst, thermoelectric, energy storage	Pietrzak and Wardak (2021); Kulakovskaya *et al*. (2021); Zouli (2021); Tefera *et al*. (2021)
Graphene	Two-dimensional material, lightweight, high optical transparency, and excellent mechanical properties	Ion transport requires the opening of 2D channels; For rapid charge storage and low sheet resistance, the entire surface is available.	Sensors, electrochemical nanomedicine, energy storage	Salleh *et al*., (2021); Ke and Wang (2016); Bashir *et al*. (2021); Rahim *et al*. (2021)
Graphite	Three-dimensional materials, Porosity range 22-28%, electrodes coat	Thick electrodes with substantial surface and volume storage capacities, low resistances	Bioelectrochemical systems, sensors	Aval *et al*. (2018); Dai *et al*. (2020); Kim *et al*. (2021)
Boron-doped Diamond	Chemical and mechanical stability	Semiconducting electrodes	Flow injection systems, Retinal electrodes, electrochemical, electrochemical sensors	Liu *et al*. (2011); Dettlaff *et al.* (2021); Bogdanowicz *et al*. (2020); Wood *et al*. (2021)

In addition to the aforementioned carbon-based electrode materials, biocarbon-based electrodes derived from biomass have attracted the most interest because of their potential as a source of green and sustainable energy (Saini *et al*., 2021). Biomass refers to organic compounds derived from plants, algae, and organic waste. Accordingly, this compound has been identified as the electrode of a promising supercapacitor due to its abundance, recyclability, and eco-friendliness. The use of this biomass can also help reduce the volume of organic waste globally (Priya *et al*., 2020).

In this regard, this review is structured to first discuss the carbon activation mechanism using chemical or physical activation methods. The key elements of this topic include characterizing the carbon content of various biomass and their usefulness as electrodes for supercapacitors applications, as well as understanding chemical activation processes used to enhance the attributes of biomass-based electrodes. The second section of this review concentrates on various types of biomass sources that can be converted into value-added carbon products to serve as a critical component of supercapacitors electrodes.

2. METHODS

2.1. Presentation of the Study Area

This paper is a literature survey. Data were obtained from internet sources, specifically, articles published in international journals. Data were collected and compiled to form explanation. Data were also compared to the current situation. To support analysis, we

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also used VOS viewer. Detailed information for the use of VOSviewer is explained in previous studies (Azizah *et al*., 2021; Al Husaeni & Nandiyanto, 2022).

3. RESULTS AND DISCUSSION

3.1. The Structure and Charge Transfer Mechanism of Supercapacitors

The structure of supercapacitors, as shown in **Figure 1**, consists of electrodes, electrolytes, electrolyte separators, and current collectors. The active component of supercapacitors is electrodes, as the charge within them is dependent on the type of electrode-active materials used. Therefore, electrodes should have high electrical conductivity, a large surface area, a mesoporous structure, and a standard electrode potential to perform redox activity.

The power density of carbon is significantly influenced by its electrical conductivity, which is fully reliant on its morphology (Sharma & Kumar, 2019) and because electrodes have a large surface area, electrolyte ions can easily diffuse through their pores, thereby improving their performance (Sun *et al*., 2016). Moreover, materials with a high porosity structure can store a large number of voids on the atomic, nanometer, or molecular scales and have tunable dimensions, enhancing their ability to interact with their environment (Hassan *et al*., 2021). It is also noteworthy that redox activity could be advantageous for supercapacitors with a high specific capacity (Lakraychi *et al*., 2020), hence, selecting electrode-active materials is a prerequisite for optimal performance.

During an electrochemical analysis, two primary forms of electrode characteristics exist, they are the Faradaic and non-Faradaic processes. At electrodes, charge transfer occurs during the redox reaction in the Faradaic process, whereas in the non-Faradaic process, the charge is collected through induction (Fleischmann *et al*., 2022).

The ionic and electronic charges should remain at or in electrodes, similar to the adsorption and desorption processes. Non-Faradaic processes are exhibited by intercalation, Electric Double-Layer Capacitor (EDLC), and electrodes with redox-active surface functionalities (Bartzis & Sarris, 2021). In charge transfer electrodes, both Faradaic and non-Faradaic processes occur concurrently. However, for supercapacitors to overwhelm the bottleneck of low energy density, a faradaic process must be implemented right away (Wei *et al*., 2020). In this regard, synergistic interactions between redox-active electrolytes and binder-free functionalization are being explored to enhance the performance of supercapacitors (Mai *et al*., 2013; Wang *et al*., 2019).

3.2. Carbon Activation Mechanism and Method

To make biomass material usable as electrodes in supercapacitors, carbon activation techniques are required to increase activated carbon (AC) surface area. AC synthesis consists of two fundamental steps, the include activation and carbonization (Ayinla *et al*., 2019; Kleszyk *et al*., 2015). Carbonization is the process of reducing the volatile content of raw materials by pyrolyzing carbon raw materials/precursors, resulting in the production of AC with high fixed carbon content and primary porosity. Activation, on the other hand, is the process of increasing the specific surface area or pore volume of AC through the formation of new pore structures and the expansion of existing ones (Gao *et al*., 2020).

From these two steps, activation is more important than carbonization in terms of AC properties, which is why increased emphasis has been placed on activation. Currently, three primary activation procedures are utilized to create AC (namely physical activation) (Shrestha *et al*., 2021; Ettish *et al*., 2021), chemical activation (Duan *et al*., 2021; Hu *et al*., 2021), and physiochemical activation (Tobi *et al*., 2019; Fan *et al*., 2013).

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Figure 2 illustrates the use of biomass-derived carbon for energy and environmental purposes. Initially, pyrolysis and hydrothermal carbonization were the main biomass carbon extraction technologies. Hydrothermal carbonization is a thermochemical process that converts biomass into carbon, while pyrolysis is carried out in a low-oxygen or inert atmosphere at a set temperature. Chemical and physical processes can then be used to convert biomass into value-added carbon products, with the resulting carbon materials being affected by chemical, surface properties, time, and availability (Thomas *et al.*, 2019; Anggraeni *et al.*, 2022a; Anggraeni *et al.*, 2022b).

3.2.1. Pyrolysis

Pyrolysis is a process that occurs in an oxygen-free, inert environment at a specific temperature, and the biomass of its products is determined by the feedstock, an activation reagent catalyst, a temperature controller, and the AC impregnation ratio (Zhang *et al.*, 2020; Pebrianti & Salamah, 2021). The AC derived through pyrolysis of biomass usually results in more micropore structures, which has large pore volume and a substantial specific surface area (Fu *et al.*, 2020). Carbon nanofibers, for instance, can be produced by solar pyrolysis of pinewood and exhibit a substantial specific surface area and a rich microstructure as binder-free electrodes, which is critical to their electrochemical performance relating to specific capacitance (Wang *et al.*, 2020). Furthermore, a study found that CoMoO4 electrodes for lithium-ion batteries and supercapacitors could be efficiently prepared through a polymer-pyrolysis method. These electrodes have been found to have a high specific capacitance and capacity retention (Wang *et al.*, 2020).

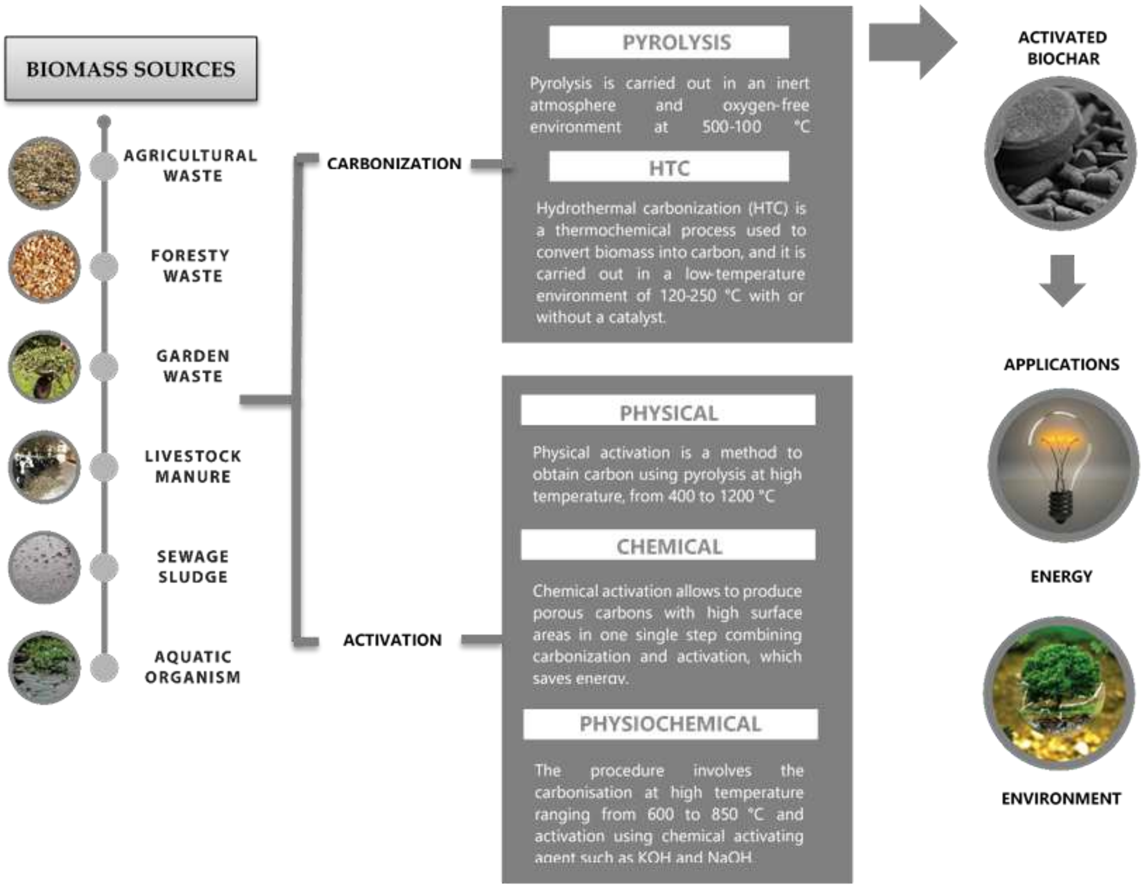

Figure 2. The schematic overview of AC originating from biomass for energy and environment applications.

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3.2.2. Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a thermochemical process (Nandiyanto, 2019). It turns biomass into carbon with or without the presence of a catalyst. This process takes place in environments with temperatures within the range of 120 and 250 °C (Wang *et al.*, 2014). The resulting materials from hydrothermal carbonization typically have a low specific surface area and contain functional groups that are good for adsorption. To preserve some functional groups while increasing the surface area of these materials, higher-temperature steam activation was employed (Beri *et al.*, 2021). Similarly, it was concluded in another study that an increase in temperature and time during the hydrothermal carbonization process potentially permits an increase in the amount of carbon that is contained within the material (Wilk *et al.*, 2021).

3.2.3. Physical activation

The physical activation of carbon involves a high-temperature pyrolysis process, typically between 400 and 1200°C (Wang *et al.*, 2014). This type of activation is less complicated and more environmentally friendly than chemical activation. Also, activating agents commonly used in this activation method include CO_2, steam, and air (Mai *et al.*, 2021). Physical activation can be combined with pyrolysis to create a cost-effective and advantageous activation method for biomass materials. The combination of these two methods causes or contributes to the development of high porosity and larger surface area (Lima *et al.*, 2010). It is also important to note that AC can be increased by raising the temperature of activating agents (Mopoung & Dejang, 2021).

3.2.4. Chemical activation

Chemical activation requires less activation time and temperature than physical activation. In a single phase, which is a combination of carbonization and activation, chemical activation makes it possible to produce porous carbon with large surface areas. This ultimately results in a lower energy requirement for the process (Mayoral *et al.*, 2021). It has also been proven that chemical activation can boost carbon material capacitance (Xiong *et al.*, 2020). Chemical activation has two activation steps, they are one-step and two-step activation, which are for the activation of acid-activating agents and, alkaline and neutral activating agents respectively. The activating agent is chemically impregnated into the precursor, and the mixture is then heated to the desired temperature. Regarding the two-step activation, the first step involves carbonizing the precursor at 300-600°C to produce charcoal, which is then mixed with activating agent and heated to a temperature ranging from 400 to 900°C (Oginni *et al.*, 2019). It is important to note that the long heating time and manufacturing process of the two-step activation necessitates the requirement for a lot of energy. However, the most important benefit of this activation method is that it results in a high specific surface area (Heimböckel *et al.*, 2018).

3.2.5. Physiochemical activation

The activation process is carried out either physically, chemically, or through a combination of the two processes, called the physiochemical method (Ayinla *et al.*, 2019; Tobi *et al.*, 2019). Although it costs more and takes longer to prepare, this method is very popular due to its ability to create high-quality AC with increased surface area (Din, 2009). The process involves carbonization at high temperatures ranging from 600 to 850°C and activation with chemical activating agents (e.g. KOH and NaOH) (Erabee *et al.*, 2017). In addition to producing high-quality AC, physiochemical activation can also be used to remove pollutants such as Zn(II) from the surface area of AC (Latiff *et al*, 2016). This process also increases the volume of the mesopore and the surface area of carbon. **Table 2** outlines the summaries of the carbon

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activation methods regarding their advantages and disadvantages.

From the analysis of the advantages and disadvantages of all methods for carbon activation, the chemical activation method was found to be of particular interest for further study and this is because it offers a simple, cost-efficient, controlled, and stable process. Following this point, Hu et al. reported that this method was successfully utilized to produce AC with a large surface area from biomass-based sources like coconut shells (Hu *et al*., 1999). The correlation between AC from biomass using the chemical activation method for supercapacitors applications has been thoroughly analyzed using Vosviewer. The analysis results from 8,403 articles sourced from the Scopus database (data taken by Apr 12th, 2023) show a strong correlation between biomass, supercapacitors, AC, and chemical activation (**Figure 3**). This bibliometric analysis gives additional information regarding current trend research, as discussed in previous studies (Nandiyanto *et al*., 2020; Hamidah *et al*., 2020; Ramadhan *et al*., 2022; Shidiq, 2023; Nandiyanto *et al*., 2024; Ragadhita & Nandiyanto, 2022; Nugraha & Nandiyanto, 2022; Fauziah & Nandiyanto, 2022; Pramanik & Rahmanita, 2023; Wirzal & Putra, 2022; Al Husaeni *et al*., 2023; Nordin, 2022; Al Husaeni *et al*., 2023; Mulyawati & Ramadhan, 2021; Al Husaeni & Nandiyanto, 2023; Hofifah & Nandiyanto, 2024; Nandiyanto *et al*., 2023; Ruzmetov & Ibragimov, 2023; Nordin, 2022; Bilad, 2022; Sudarjat, 2023; Nursaniah & Nandiyanto, 2023; Al Husaeni, 2023; Firdaus *et al*., 2023; Nandiyanto *et al*., 2021; Wiendartun *et al*., 2022; Solehuddin *et al*., 2023; Sukyadi *et al*., 2023).

The strong correlation between biomass, supercapacitors, AC, and chemical activation strengthens the hypothesis that a more in-depth analysis of the relationship between these four variables is needed.

Table 2. The advantages and disadvantages of the activation method.

Method	Advantages	Disadvantages	Ref
Physical Activation	Clean and green production without any secondary waste disposals;	Low specific surface area, high activation temperature, low carbon yield, and long processing time	Wang *et al*. (2014); Mopoung and Dejang (2021); Ettish *et al*. (2021); Taer *et al*. (2020); Yi *et al*. (2021)
Chemical Activation	An effective way for increasing the capacitance of carbon materials; characterized by a low activation temperature, a short processing time, an increasing carbon yield, a broad surface area that is well dispersed and formed microporous structure, well-controlled porosity, and better control of the textural properties.	The drastic corrosively and inevitable washing process	Gao *et al*. (2020); Xiong *et al*. (2020); Kanjana *et al*. (2021); Bhandari and Gogate (2018); Kanjana *et al*. (2021); Yakaboylu *et al*. (2021); Sundriyal *et al*., (2021)
Physiochemical Activation	Can create AC of superior quality with a greater surface area	Higher cost, longer preparation time, higher temperature, higher emission of heavy metals.	Mai *et al*. (2021); Din *et al*. (2009); Ao *et al*. (2018); Rawat *et al*. (2022)

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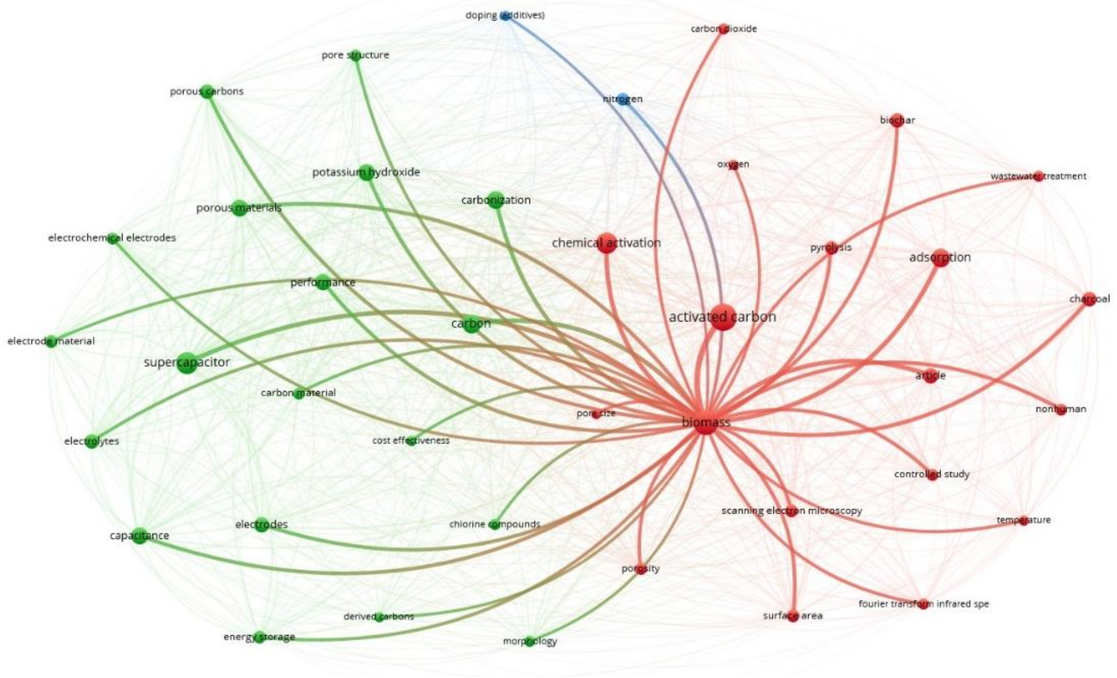

Figure 3. The correlation between biomass, supercapacitors, AC, and chemical activation.

3.3. Evaluation of The Electrochemical Performance of Carbon-Based Supercapacitors Made from Different Sources of Biomass

Carbon materials derived from biomass are the highest-performing electrode materials for a variety of applications. These materials are particularly well-suited for use as effective electrodes in supercapacitors due to their ease of activation with chemical and their ability to be produced in large quantities at low cost. There are five categories of biomass sources, including (1) agricultural biomass, (2) urban and industrial waste, (3) aquatic biomass, (4) livestock waste, and (5) wood and woody biomass. However, the focus of this study is on agricultural biomass as well as wood and woody biomass sources, which can be considered sustainable sources of raw materials for biochar manufacture and their use in supercapacitors.

Agricultural biomass refers to biomass obtained from agricultural products such as fruits, vegetables, and parts of the plant itself such as leaves, flowers, and flower petals. Many research regarding agriculture has been well-documented (Permatasari *et al*., 2016; Ragadhita *et al*., 2023; Bhosale, 2022). It can be further classified into two categories namely agriculture residues/wastes and energy crops (Yadav *et al*., 2017).

Agriculture residues consist of basic by-products such as cornstalk and rice straw, as well as secondary by-products from biomass processing like coffee husk, rice husk, and sugarcane bagasse. Energy crops include poplars, willows, eucalyptus, sugarcane, sorghum, artichokes, rapeseed, and sunflowers, which are produced specifically for biofuel and bioproduct production.

Meanwhile, wood and woody biomass are derived from plant residues such as twigs, powder, and dried leaves. Before plant wastes can be used as electrodes in supercapacitors, they first have to be chemically activated to create pore sizes ranging from micropores to mesopores. Several studies have been conducted on the two types of biomass and their suitability for use in supercapacitors. The properties of these materials are listed in **Table 3**.

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Table 3. The characteristics of supercapacitors derived from biomass sources of agricultural.

Biomass Source	Chemical Solution		Electrical Properties		Physical Properties		Ref.
	Activating Agent	Electrolyte in SC	SpC (F/g)	CR (%)	PD (nm)	SSA (m^2/g)	
Aloe vera*	KOH	Aqueous	410	62	3.8 - 12.5	~1890	Karnan *et al.* (2016)
Arenga Pinnata	KOH	1 M H_2SO_4	202		2-10	1232	Farma *et al.* (2022)
Bamboo Fibers*	KOH	3 M KOH	512	103	1.22	1120	Zequine *et al.* (2016)
Bamboo Shoots*	KOH, NaOH	1 M KOH	412	65.5		972	Chen *et al.* (2017)
Banana Peel	KOH	2 M KOH	227	97	-	-	Tripathy *et al.* (2021)
Banana Stem Fibers	$ZnCl_2$	H_2SO_4	179	-	145.67	788.09	Taer *et al.* (2020)
Beer Leaves	KOH	0.1 M H_2SO_4	188	-	2.2	2584	Lee *et al.* (2011)
Carrot	$ZnCl_2$	6 M KOH	135.5		3.22		Ahmed *et al.* (2018)
Celtuse Leaves*	KOH	6 M KOH	421	92.6	0.5-5	3404	Wang *et al.* (2012)
Cinnamon Sticks	KOH**	$NaClO_4$ in EC/ DMC	225	62	1.91	3405	Thangavel *et al.* (2017)
Cinnamon Sticks	$ZnCl_2$**	$NaClO_4$ in EC/ DMC	212	70	2.24	2440	Thangavel *et al.* (2017)
Cinnamon Sticks	H_3PO_4**	$NaClO_4$ in EC/ DMC	217	80	1.84	1810	Thangavel *et al.* (2017)
Coffee Grounds	KOH	BMIMBF4/AN	121	90.5		1945.7	Yun *et al.* (2015)
Corncob*	KOH	0.5 M H_2SO_4***	401.6	91 after 10000 cycles	-	1899	Wang *et al.* (2015)
Corncob	KOH	6 M KOH***	309.81	93.9	1. 199	215.42	Pramanik *et al.* (2018)
Cornstalk	KCl and NaCl	1 M H_2SO_4***	413	92.6 after 20000 cycles		1588	Wang *et al.* (2018)
Corn Stalk	KOH	6 M KOH***	256-260	97.9	1.97	2495	Cao *et al.* (2016)
Cotton Stalk	KOH	4 M KOH	111.1	79.7		1227.2	Tian *et al.* (2021)
Elm Samara*	KOH	6 M KOH	470	72	2.19	1947	Chen *et al.* (2016)
Ficus Religiosa Leaves	No activation	PVA-H_2PO_4	3.14	88	2	157	Senthilkumar and Selvan (2015)
Garlic Skin*	KOH	6M KOH	461	-	2.36	>2000	Zhang *et al.* (2018)
Garlic Seedling	KOH	6M KOH	320	92 after 5000 cycles	2.22	2370	Li *et al.* (2019)

Table 3 (Continue). The characteristics of supercapacitors derived from biomass sources of agricultural.

Biomass Source	Chemical Solution		Electrical Properties		Physical Properties		Ref.
	Activating Agent	Electrolyte in SC	SpC (F/g)	CR (%)	PD (nm)	SSA (m^2/g)	
Jute Fibers*	KOH	3 M KOH	408	100	2.9	1769	Zequine *et al.* (2017)
Lacquer Wood	H_3PO_4	1 m H_2SO_4	354	95.3 after 1000 cycles	-	1609.09	Hu *et al.* (2021)
Litchi Shell	KOH	6 M KOH	162.7	93.5 after 5000 cycles	-	1486	Zhao *et al.* (2020)
Lotus Leaf	KOH	6 M KOH	379	90	2.45	2450	Qu *et al.* (2018)
Mangosteen	NaOH	6 M KOH	357	80 after 10000 cycles	-	2623	Yang *et al.* (2019)
Miscanthus Grass	KOH	6 M KOH	188	89-91 after 2500 cycles	1.79-1.92	-	Yakaboylu *et al.* (2021)
Onion	KOH	6M KOH	395	92 after 5000 cycles	2.65	2342	Thangavel *et al.* (2017)
Onion Leaves	No activation	3 M KOH	158.6	96	0.6-1.2	551.7	Yu *et al.* (2016)
Orange Peel*	KOH	6 M KOH	407	100	3-4	1391	Ranaweera *et al.* (2017)
Palm Kernel Shell	KOH	1 M KOH	210	95-97	1.4	462.1	Misnon *et al.* (2015)
Pattail	NaCl	1 M	419	86.4	5-10	-	Yu *et al.* (2018)
Peanut Shell	NaOH	6 M KOH	339	80 after 10000 cycles	2.36	2936.76	Zhan *et al.* (2018)
Perilla Frutescenes	No activation	6 M KOH	270	96.1	1.2	655	Liu *et al.* (2017)
Pine Pollen-cone	KOH	1 M Na_2SO_4	117	98-100 after 10000 cycles	2.23	2314	Hor and Hashmi (2020)
Pine Tree Powder	KOH	IL EMIMBF4	224	67	0.32	1018	Wang *et al.* (2017)
Pistachios Nutshell	KOH	6 M KOH	330	-	0.5 – 2.0	1665	Xu *et al.* (2014)
Rice Husk	KOH	6 M KOH	278	76.6	0.5-3	2804	Liu *et al.* (2019)
Rice Straws	KOH	6 M KOH	324	95 after 10000 cycles	-	2651	Divya & Rajalakshmi (2020)

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Table 3 (Continue). The characteristics of supercapacitors derived from biomass sources of agricultural.

Biomass Source	Chemical Solution		Electrical Properties		Physical Properties		Ref.
	Activating Agent	Electrolyte in SC	SpC (F/g)	CR (%)	PD (nm)	SSA (m^2/g)	
Sisal Leaves	KOH, NaOH, Na_2CO_3	1 M LiOH	204	85.5		171	Li *et al*. (2015)
Solanum Lycoperium Leaves	No activation	1 M H_2SO_4	345	87.3	10	325,046	Divya & Rajalakshmi (2020)
Soybean Pods	$ZnCl_2$	6 M KOH	321.1	91.1	3.03 and 1.92	2245	Liu *et al*. (2018)
Syzygium Oleana Leaves	KOH	1 M H_2SO_4	188	-	2.51	1218	Taer *et al*. (2020)
Tamarind Fruit Shell*	KOH	H_2SO_4	412	93	23.5	1040	Senthilkumar *et al*. (2013)
Tea Leaves	KOH	2M KOH	330	92% after 2000 cycles		2841	Peng *et al*. (2013)
Tea-Waste	KOH	6 M KOH	332	97.8 after 100000	-	1610	Khan *et al*. (2020)
Green Tea-Waste	KOH	H_2SO_4	162	121	2.35	1057.8	Sankar *et al*. (2019)
Tobacco Rods	KOH	6 M KOH	286.6	96	~2.6, ~3.7, ~45.8	1761-2115	Zhao *et al*. (2016)
Walnut Shell	K_2CO_3	1 M KOH	255	96	-	62	Xu *et al*. (2017)
Wood Carbon Monolith	No activation	2 M KOH	234	97	3.7	467	Liu *et al*. (2012)

Note: SpC = specific capacitance; CR = capacitance retention; PD = pore diameter; SSA=specific surface area

**Biomass that produces specific capacitance over 400 F/g.*

***Different activating agents applied to the same biomass*

**** Different electrolytes in SC applied to the same biomass*

Table 3 presents the physical and electrical characteristics of each type of biomass with various chemical solutions. Among the different activating agents, KOH is the most commonly used and has been found to produce better specific capacitance compared to other agents. Due to its environmental friendliness, KOH has also garnered a lot of interest as an activator, and the treatment with this substance results in porosity with a narrow pore size distribution (Li *et al.*, 2020). Additionally, this activator has been shown to enhance specific surface area, specific capacitance, and specific energy (Zhan *et al.*, 2021). Thangavel *et al.* (2017) demonstrated the effectiveness of

KOH in producing a high specific surface area when they AC from cinnamon sticks.

The activation process using KOH calls for more intricate procedures, but the resulting structure is extremely porous (Wang & Kaskel, 2012). The following are some suggested equations to describe the concrete process of carbon activation using KOH (Otowa *et al*., 1993):

$2 KOH \rightarrow K_2O + H_2O$ (dehydration) (2)

$C + H_2O \rightarrow H_2 + CO$ (water-gas reaction) (3)

$CO + H_2O \rightarrow H_2 + CO_2$ (water-gas shift reaction) (4)

$K_2O + CO_2 \rightarrow K_2CO_3$ (carbonate formation) (5)

Once the activation temperature was higher than 700°C, a significant amount of metallic potassium was spotted. This element is considered to be formed as a result of the reduction of K_2O by carbon or hydrogen at high temperatures:

$K_2O + H_2 \rightarrow 2K + H_2O$ (reduction by hydrogen) (6)

$K_2O + C \rightarrow 2K + CO$ (reduction by carbon) (7)

Considering the fact that metallic potassium is easily moved and shifted (mobile) at activation temperatures, the element intercalated with the carbon matrix. As a consequence, the atomic layers of carbon were stretched, creating pores that can be used to boost the material's surface area and capacitance.

Figure 4 shows the specific capacitance of all biomass previously listed in **Table 3**, which have a value over 400 Fg^{-1}. In **Figure 4**, it can be seen that bamboo fibers exhibit the highest specific capacitance (reaching 512 F/cm^{-1}) compared to other biomass. The outstanding features of bamboo fibers include a large specific surface area (1120 m^2/g) with an excellent pore diameter (1.22 nm) and capacitance retention (103%). These good characteristics of bamboo fibers have attracted the interest of many, hence, it is crucial to evaluate further the effect of the KOH concentration on its physical properties (see **Figure 5**). **Figure 5** shows that AC from bamboo without KOH activation (**Figure 5a**) possesses numerous pores uniformly distributed across its entire surface. However, when AC from bamboo is activated by 1M KOH, the atomic layer of carbon widens due to the intercalation of potassium (as explained in the process of carbon activation). This intercalation increased with an increase in the concentration of KOH (see Fig. 5b to Fig. 5e), but it starts to decrease when the concentration reached 5M.

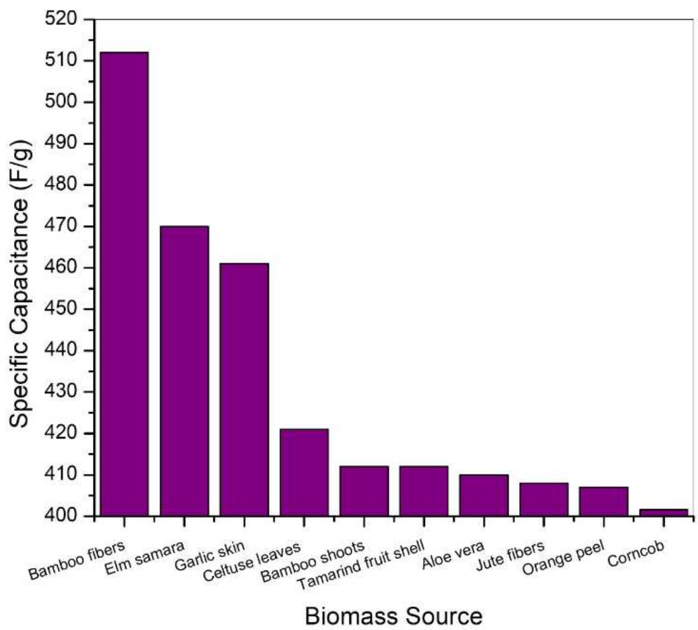

Figure 4. The specific capacitance of biomass activated by KOH.

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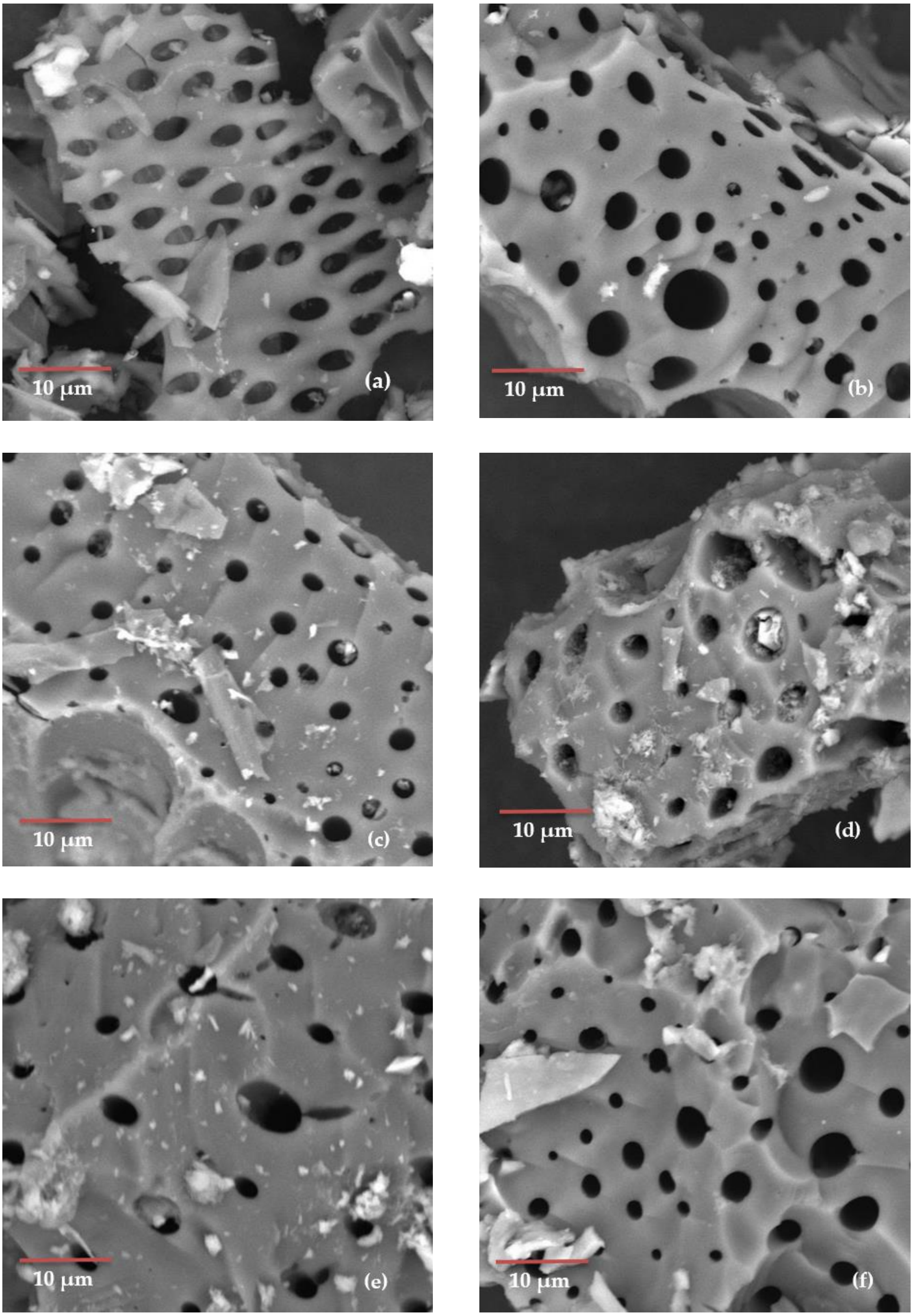

Figure 5. SEM micrograph for bamboo sticks using KOH activating agent: (a) no activation, (b) 1M, (c) 2 M, (d) 3M, (e) 4 M, (f) 5M.

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Upon further analysis of the role of KOH as an electrolyte, the element was found to produce higher capacitance retention compared to that of H_2SO_4 (see the triple asterisk in **Table 3**). On the other hand, H_2SO_4 as an electrolyte produced a capacitance with a higher specific value than KOH.

According to Liu *et al*. (2022), the K^+ ion is smaller in size than SO_4^{2-}, enabling it to enter the microporous AC through its small pores, which SO_4^{2-} cannot penetrate. The penetration of ions into the pore of microporous AC creates an Electric Double Layer (EDL) capacitance. However, when the pore diameter of the microporous AC is larger than 0.6 nm, SO_4^{2-} will be able to penetrate the pore and form EDL capacitance.

In addition, when the pore size is sufficiently large, a redox reaction occurs. The hydration of H^+ in the redox reaction can result in the pseudocapacitance of supercapacitors. By combining EDL with SO_4^{2-} and pseudocapacitance with H^+, micropore carbon attained a higher capacitance in H_2SO_4 than KOH.

Even though biomass has more generated specific capacitance with KOH activation, the percentage of capacity retention needs improvement. Lastly, the carbon activation method used for this biomass source is the chemical activation method carried out using KOH. After undergoing the characterization process, these agricultural biomass sources produce an average of microporous to mesoporous size pores.

4. CONCLUSION

Carbon materials derived from biomass have shown great prospects as excellent electrodes for supercapacitors. This is because biomass comprises diverse chemical and structural properties that can be easily tailored as per the requirements. This study focuses on the chemical activation of carbon, which was obtained from biomass. The pore structure and the surface area created through this carbon activation method resulted in an increased current collection at electrode surfaces. Furthermore, specific capacitance is directly proportional to the highest surface area of AC. Among all biomass analyzed in this study, bamboo fibers show the highest specific capacitance with capacitance retention, a pore diameter, and a specific surface area. KOH-activated bamboo-based carbon has a higher specific surface area than unactivated carbon. The KOH activating agents produced a very porous structure due to their more complex activation.

The average pore diameter of carbon, which produced high specific capacitance, was within the range of microporous (<2 nm) and mesoporous (2<d<50 nm). Generally, biomass with mesoporous pores yields a high capacitance value because of the larger pore size, which captures both cations and anions in electrodes. It was also found that the meso and macro-sized pores are not always more effective than the micro-sized pores in the production of high capacitance values. Lastly, this subject matter has excellent potential for further study in scientific fundamentals and applications.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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