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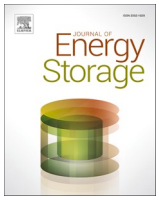

Review article

# Harnessing bamboo waste for high-performance supercapacitors: A comprehensive review of activation methods and applications

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ABSTRACT

Commercial supercapacitors typically have low energy density, making them unsuitable for high energy demand applications. Then, the introduction and application of biomass-derived carbon materials have garnered attention in the industry due to its environmentally friendly nature and reliable performance. These carbon materials are favoured to be used as an electrode material due to their high specific surface area and specific capacitance. Bamboo biowaste, abundantly available in furniture and disposable utensils manufacturing industries, possesses favorable characteristics such as high nitrogen content, low oxygen content and a high graphitization degree. These properties make it a promising candidate for fabricating carbon materials suitable for supercapacitor applications. Recent studies indicated that bamboo-based supercapacitor has higher specific capacitance and higher performance than other carbon materials such as coconut shells. Therefore, numerous studies investigating this novel technology have been reported. Researchers have also made advancements in incorporating bamboo-based carbon materials in energy storage systems. The activation process is the key factor in enhancing the performance of the supercapacitors. However, findings from these studies, which are crucial for further development of this technology, have been scattered without a comprehensive compilation. Therefore, this review paper aims to provide a comprehensive overview of various activation techniques and specific applications of bamboo-derived activated carbon in supercapacitors. Despite recent advancements, challenges such as energy density issues and optimization over operating parameters remain. Addressing these challenges is crucial to fully understanding and realizing the potential of bamboo-derived supercapacitor.

## 1. Introduction

The increase in global population growth, technological advancements, and higher living standards are the primary factors driving the rise in energy demand. According to the Ministry of Economy [1], the energy demand in Malaysia will undergo slight increase of 0.2 % annually, leading to an increase from 97 Mtoe to 102 Mtoe between 2023 and 2050. In the National Energy Policy 2022–2040, Malaysia has

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aimed at transitioning into low carbon nation by 2040 by increasing the total primary energy supply of renewable energy from 7.2 % to 17 % [2]. Despite the success in increasing renewable energy penetration, the reliance on renewable sources poses challenges such as intermittency due to their dependence on natural factors (weather conditions and seasonal changes), resulting in fluctuating and unpredictable energy generation. To ensure a reliable and stable energy supply, energy storage solutions are necessary to store excess energy generated during low demand periods and to be utilized during the peak demand periods.

Energy storage is an essential technique to uphold the equilibrium between energy demand and supply. Energy derived from renewable energy sources are non-dispatchable, which means the energy cannot be derived based on real-time energy demand, and hence the need to be stored and utilized when it is required [3]. At present, various types of energy storage have been developed and adopted, such as electrochemical storage (lead acid and lithium-ion batteries), mechanical storage (pumped-hydro storage and flywheel), thermal storage (molten salt energy storage and adsorption thermal storage system), electrical storage (supercapacitor and superconducting magnet), and chemical storage (hydrogen fuel cell) [4]. Each of these storages have pros and cons due to their power density, energy density, and its life span. Among them, electrochemical storage, especially battery, is the most widely used and commercially available. By referring to the Ragone plot in Fig. 1, batteries and fuel cells demonstrate higher energy density whilst having lower power density. Consequently, this leads to significant energy storage but low energy efficiency due to its slow discharging rates. On the other hand, the capacitor shows higher power density but lower energy density as seen from the Ragone plot. Supercapacitor is observed to be moderate in terms of power density and energy density. As compared to lithium-ion batteries, supercapacitors demonstrate better potential owing to its longer life cycle, rapid charging/discharging rate, and high power density [3]. However, the ultimate goal for researcher is to investigate an energy storage that possess both high power density and energy density.

Supercapacitors, also known as electrochemical capacitors or ultracapacitors, is a capacitor that has higher power and energy density, longer life cycle as well as higher discharge rate as compared to battery. It is widely applied in the power electric vehicles, and electrical energy conversion and storage. Supercapacitors is categorized into three types based on their electrode properties and storage mechanism: electrochemical double-layer capacitors (EDLC), pseudocapacitors, and hybrid capacitors. However, the energy density of the current commercial supercapacitor is not as high as battery [6]. Previous study indicated that commercial supercapacitors possess low energy density (about 5 Wh/kg) [7], which is not sufficient for high energy demand applications (renewable energy integration, electric vehicles and medical equipment). Moreover, it was found that the electrode material is the primary factor dictating the energy density of the supercapacitor [8]. In energy storage applications, carbon-based materials are found to have high specific conductance, large specific surface area, economical, as well as chemical and physical stability, which is a favoured materials to be used as electrode materials [9].

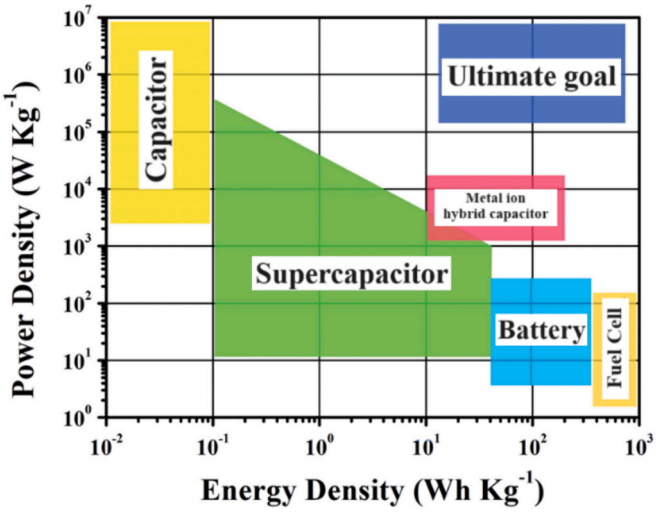


**Fig. 1.** Ragone plot for various energy storage [5].
From "Vanadium nitride for aqueous supercapacitors: a topic review" by Ying Liu, Qianghong Wu, Lingyang Liu, Pantrangi Manasa, Long Kang and Fen Ran, 2020, Journal of Materials Chemistry A, Vol. 8.

Biowaste is derived from biomass, municipal waste and processing by-products. It consists of complex carbohydrates-polymers (cellulose and hemicellulose), lipid, aromatic polymers and protein [10]. To overcome the aforementioned challenges on the low energy density of commercial supercapacitor, biowaste has proven to demonstrate as an emerging feedstock to produce marketable value-added products and bioenergy via thermochemical and biochemical conversion. By utilizing biowaste, it is not only resolving waste management issues but also enhancing circular economy practices. Plant-based biomass, in particular, holds potential as a feedstock due to its high nitrogen content, low oxygen content and high graphitization degree, which enhance the yield, conductivity, charging efficiency and cycling stability [11,12]. Fang et al. [13] highlighted that biochar derived from plants have greater surface area, more stable porous structures, and higher carbon content than the biochar derived from industrial by-products. This suggests that plants-derived biochar possesses superior adsorption capacity. The biochar will then undergo activation process to create porous structures and modified as activated carbon. Through this activation process, the activated carbon will exhibit greater specific surface area and porosity, which are the two vital factors contributing to the high efficiency carbon-based materials. Chu et al. [14] had highlighted that biochar-based electrode is more cost-effective, eco-friendly, and renewable compared to granular activated carbon and graphite electrode. Furthermore, biochar-based electrodes have been found to produce greater power output (457–532 mW/$m^2$) compared to porous carbon and graphite (566–674 mW/$m^2$).

One potential material that is promising to produce biomass-based activated carbon is bamboo. Bamboo, scientifically known as *Bambusa vulgaris*, is abundantly available and widely found in Malaysia. It was reported that the cultivation area of bamboo in Peninsula and Sarawak respectively is 31 % (229,123 ha) and 45 % of the total bamboo crop throughout the country [15]. It is normally used for producing furniture, toothpicks, chopsticks, and other products. From these activities, massive amount of the bamboo biowaste that is discarded during the production process is usually being disposed or burned directly, which aggravates the environmental issues such as increase of landfill usage and greenhouse gases emissions. Bamboo consists of approximately 47.7 % cellulose, 21.9 % hemicellulose, and 24.5 % lignin [16], whilst this might show variation due to the different species and developmental stages [17]. The high lignin lignocellulosic component of bamboo is able to produce carbon materials with high yield, which makes bamboo as a potential biomass feedstock. Its high carbon content coupled with regulated porous structure facilitates effective ion transport with minimal resistance and thus enhance the performance of the supercapacitors [18]. After carbonization, the vascular bundles and parenchyma cells of bamboo will develop into pores [19]. As a result, bamboo charcoal has garnered significant interest due to its superior adsorption properties, large surface area, and high porous structure [20]. For instance, Grima-Olmedo et al. [21] had compared the activated carbon derived from bamboo, orange and paulownia waste. It was found that the activated carbon derived from bamboo had the largest BET surface area and the highest micropore volume (1,182 $m^2$/g and 0.349 $cm^3$/g, respectively) when steam activation was used, compared to that obtained from orange (388 $m^2$/g and 0.163 $cm^3$/g, respectively) and paulownia (1,166 $m^2$/g and 0.318 $cm^3$/g, respectively). It is a potential substrate as an electrode material in the development of high-performance supercapacitor.

Although many studies on biomass-derived supercapacitors exist, and a few recent works on bamboo-based supercapacitors have been reported in the literature, the findings from these studies remain scattered and lack of comprehensive compilation. The novelty of this review lies in focusing on bamboo-derived carbon, which is often overlooked in broader reviews on biomass-based materials. The aim of this review article is to provide a comprehensive overview of the process and methodology for deriving electrode materials from bamboo biowaste, with a particular focus on the innovative activation techniques and specific applications of bamboo-derived activated carbon in supercapacitors. This review consolidates findings, offering a detailed analysis of various activation methods, including physical, chemical, self-activation, and hybrid techniques, and their impact on the performance of supercapacitors. By addressing the challenges and future prospects, this review contributes to a deeper understanding of bamboo-derived activated carbon and its potential in advancing sustainable energy storage solutions, thus highlighting the innovating approach of utilizing bamboo biowaste for high-performance supercapacitor applications. This review addresses a critical knowledge gap by offering valuable insights for researchers on the potential of bamboo biowaste in advancing sustainable supercapacitors.

## 2. Bibliometric analysis

The current research trend of utilizing bamboo biomass as activated carbon in supercapacitor applications is summarized in Fig. 2, which was generated using the VOS viewer program with data collected from Scopus through an initial search employing three keywords (bamboo AND carbon AND supercapacitor). A total of 165 studies published from year 2014 to year 2024 was identified, with a notable surge in interest surrounding the application of bamboo-based activated carbon for supercapacitors observed since year 2019, as depicted in Fig. 3. The network visualization was examined based on the co-occurrence of the keywords at least five times, with 54 keywords meeting the criterion out of 702. Among them, "supercapacitor", "bamboo" and "carbon" emerged as the most frequently used keywords, primarily between year 2020 and year 2021. Between year 2019 and year 2021, research primarily focused on electrochemical electrodes, particularly activated carbon, electrochemical performance, and the characterization of bamboo derived activated carbon. Subsequently, in the following year, attention shifted towards energy storage as well as the production technique of bamboo-based activated carbon, focusing on carbonization and chemical activation processes. Moreover, the latest research has further explored the potential of bamboo-based activated carbon in hybrid materials, along with extensive studies of their performance and electrochemical properties within supercapacitor applications. This analysis revealed that bamboo biomass could be a promising material to produce activated carbon for advancing energy storage technology.

## 3. Bamboo biomass properties

### 3.1. Structural composition

The unique properties of bamboo biomass such as its high lignocellulosic content have captured interest in the chemical industry and the broader domains of energy and environmental sustainability. Biomass is mainly composed of lignocellulosic constituent, which are 35–55 wt% of cellulose, 20–35 wt% hemicellulose and 10–30 wt% lignin [22]. It also contains minor polymers such as proteins, pectin, and minerals. The properties of various bamboo species are depicted in Table 1 and the schematic diagram of bamboo is presented in Fig. 4. It's worth noting that the properties of bamboo vary depending on its age, as reported by Azeez and Orege [23], the cellulose content will reduce as the age of the bamboo increases. Cellulose, the predominant component in biomass, is a linear chain polymer composed of anhydro-D-glucose units $(C_6H_{10}O_5)n$ held by β-1,4-glycosidic bonds. It plays a crucial role in maintaining the stability and mechanical strength of fibers. Hemicellulose, on the other hand, is a branched chain polymer with low polymerization degree

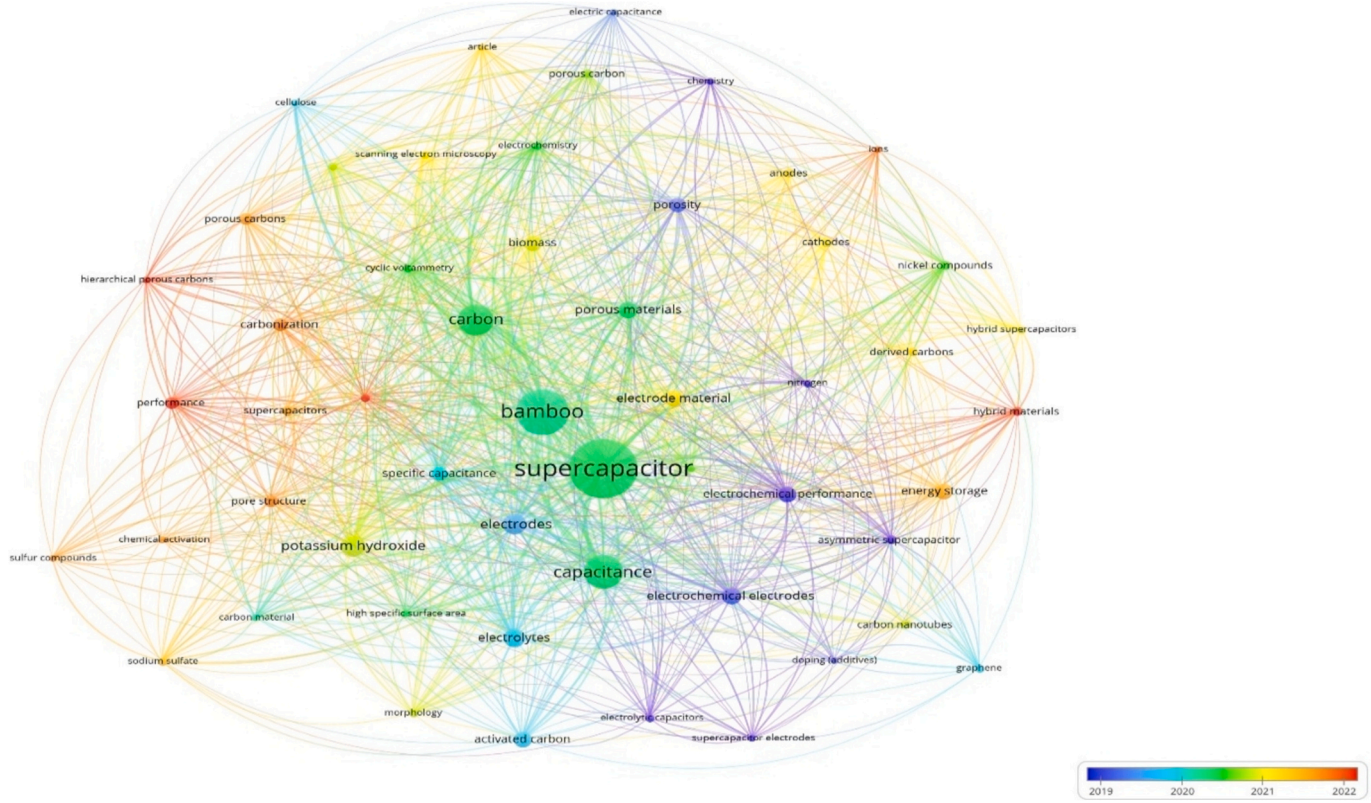


**Fig. 2.** Co-occurrence keywords analysis from year 2019 to 2022. The size of the circle indicates the occurrence frequency of the keywords.

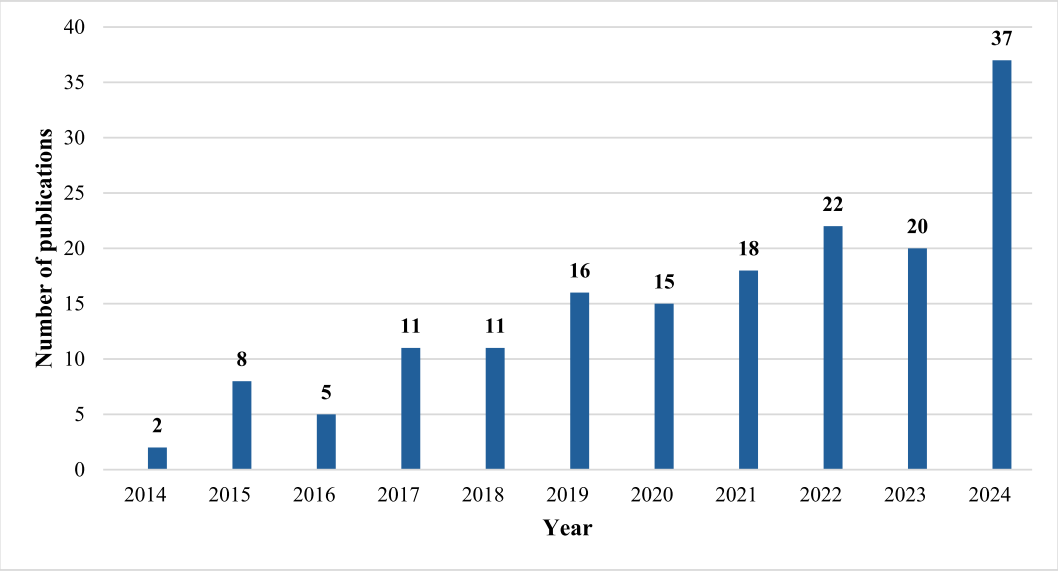


**Fig. 3.** Total publications of utilizing bamboo biomass as activated carbon in supercapacitor application (2014–2024) based on Scopus database.

**Table 1**
Properties of various bamboo species.

| Properties | Percentage (wt%) | | | | | |
|---|---|---|---|---|---|---|
| Bamboo species | *D. giganteus* Munro | N/A | *Gigantochloa scortechinii* | *Yushania alpina* | *B. vulgaris* Scharad | N/A |
| Structural composition (% dry basis) | | | | | | |
| Cellulose | 47.5±0.4 | 41.8 | 51.21±0.14 | 46.76±1.09 | – | 47.29±0.12 |
| Hemicellulose | 15.35±0.42 | – | 16.18±0.18 | 12.18±1.01 | | 21.19±0.10 |
| Lignin | 26.25±0.07 | 29.3 | 28.1±0.11 | 25.27±1.52 | | 24.53±0.15 |
| Extractives | 4.90±0.14 | 3.3 | – | – | | 5.11±0.05 |
| Silica | 0.7±0.0 | – | – | – | | – |
| Holocellulose | – | 59.8 | – | – | | – |
| Proximate analysis (% wet basis) | | | | | | |
| Moisture | 9.37±0.80 | 6.1 | – | 3.92±0.46 | 10.2 | 10.74±0.04 |
| Fixed carbon | 17.75±0.40 | – | | – | 16.7 | 16.03±0.02 |
| Volatile | 70.31±0.44 | – | | – | 72.0 | 71.65±0.08 |
| Ash | 2.57±0.41 | – | | 3.77±0.86 | 1.15 | 1.58±0.04 |
| Elemental analysis (% dry basis) | | | | | | |
| Carbon | 39±3 | – | 47.04±0.11 | – | 49.5 | 46.98±0.05 |
| Hydrogen | 6.1±0.2 | | 6.52±0.02 | | 6.30 | 6.21±0.04 |
| Nitrogen | 0.6±0.3 | | 0.03±0.03 | | 0.43 | 0.16±0.03 |
| Sulfur | 0.018±0.006 | | 0.02±0.00 | | 0.04 | – |
| Oxygen | 54±3 | | 44.83±0.14 | | 43.7 | 46.65±0.02 |
| References | [34] | [35] | [36] | [37] | [38] | [39] |

N/A: no specified.

(typically less than 100–200). It consists of either five-carbon sugars like arabinose and xylose, or six-carbon sugars like glucose, rhamnose, mannose and galactose, that arranged in various configurations to provide structural diversity [24]. The high content of cellulose and hemicellulose in bamboo indicates that bamboo can serve as an excellent feedstock for thermal processing and energy source during burning as both of them have high heating value as compared to lignin [25]. Lignin, another essential component, is a complex branched chain polymer derived from phenylpropane. Essentially, it forms a three-dimensional polymer primarily composed of 4-propenyl phenol, 4-propenyl-2-methoxy phenol, and 4-propenyl-2,5-dimethoxyl phenol [26]. Lignin is recalcitrant that required specific pre-treatment in order for a more complete hydrolysis of cellulose and hemicellulose into their respective sugar. This pre-treatment facilitates the breakdown of biomass components into simpler components, which enable the conversion of biomass into valuable biofuels and bioproducts (bioethanol, biogas and bio-oil) [27]. To analyze the characteristics of bamboo biomass, several measurement techniques are commonly adopted, which are discussed in the following section.

### 3.2. Proximate analysis

Proximate analysis is conducted to understand the characteristics of the biomass feedstock being used and is commonly conducted using thermogravimetric analysis (TGA) method. It provides an insight into the thermal and combustion properties of feedstock. Typically, American Society of Testing Materials (ASTM) standards are used in this measurement such as ASTM E871-80 to determine the moisture content, E1755-II to determine the ash content, and D3174-76 to determine the fixed carbon in the biomass.

Moisture content (MC) is a critical characteristic of biomass, often categorized into two groups: dry feedstock, with a moisture content of

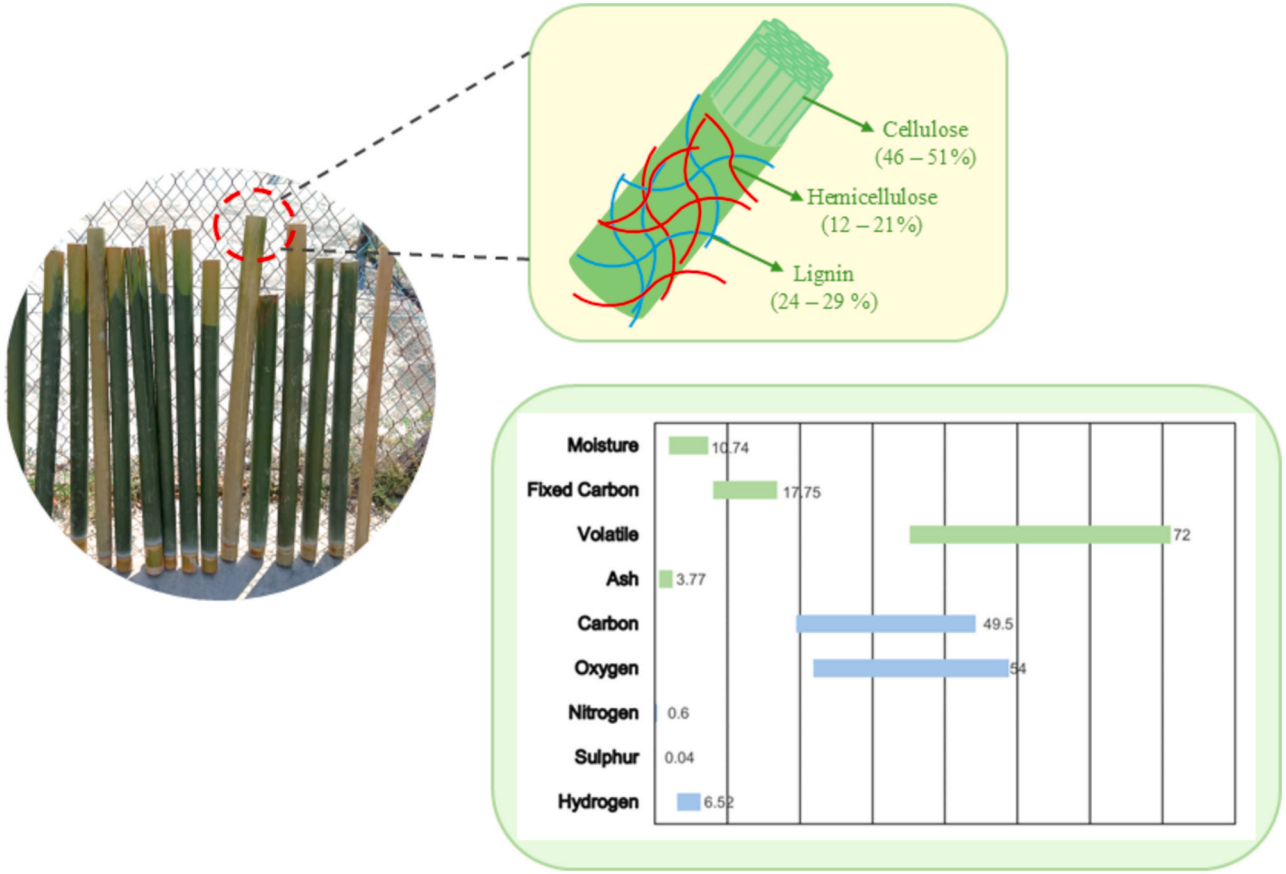


**Fig. 4.** Schematic diagram of bamboo.

less than 30 %, and wet feedstock, with a moisture content exceeding 30 %. Bamboo typically falls into the dry feedstock category, showing a moisture content ranging from 3.9 to 10.2 %, as indicated in Table 1. Huang et al. [28] reported that bamboo tends to have lower moisture content than woody plant when harvested and dried for storage purpose. Meanwhile, Adam and Jusoh [29] suggested that the moisture content is relatively higher at the bottom of the bamboo as compared to the top portion. This variance is attributed to the relatively lower presence of parenchyma tissue at the bottom, which has a stronger water retention capacity compared to the vascular bundle found in the top portion. Consequently, the low moisture content of bamboo biomass presents an energy-efficient pathway for waste-to-energy conversion, requiring minimal energy to evaporate the water content during processing.

Other than MC, volatile matter (VM) is a characteristic that needs to be considered in biomass feedstock analysis. It is defined as the release of condensable and non-condensable vapor during the thermal degradation process. However, it was found that high volatile matter in biomass, such as bamboo, leads to lower biochar yield and higher yield of syngas and bio-oil yield, and vice versa [30].

Another characteristic of biomass feedstock is the ash content (A), namely the solid residue that is left after complete burning. However, ash content is not entirely obtained from biomass. It might be due to the collection process as it subjected to multiple handling, which can result in significant amount of impurities. High amount of ash content in biomass leads to a lower fusion point due to the alkaline nature of ash and arise potential issues such as fouling and slagging [31], which will reduce thermochemical conversion process efficiency [32]. Therefore, the ash content of bamboo typically falls within the range of 1.15 to 3.77 % by weight, is considered low and suitable for thermochemical conversion as it can lower the operational challenges and cost.

Fixed carbon (FC) is the solid carbon that remains in the char after devolatilization process. It is mainly depending on the volatile matter content of the biomass feedstock. Thereby, the key factor that determines the biomass to energy conversion is the ratio of VM to FC (VM/FC). A high VM/FC ratio indicates that the biomass could yield more energy, as a large amount of VM can be combusted, and vice versa [25]. In biochar production, the VM/FC ratio should be high as it will increase the biochar yield and reduce gaseous by-products.

### 3.3. *Ultimate analysis*

In addition to proximate analysis, ultimate analysis has also been adopted in biomass feedstock analysis. Ultimate analysis determines the carbon, hydrogen, nitrogen, sulfur, and oxygen content in the biomass. Bamboo is said to be a favoured carbonaceous material for commercialization due to its high carbon content (39.0–49.5 wt%), which provides a positive aspect in biochar and activated carbon production, as well as enhance the stability and reactivity for more effective removal of impurities and pollutant, and the porosity for increased adsorption surface area [25]. Moreover, the carbon, hydrogen, and oxygen content are the primary contributors of energy content, and hence it is also used to determine the heating value [33]. Thus, high carbon and oxygen content in biomass could enhance the formation of char and product with high calorific value, while also contributes to its economic viability as a fuel source and less air is required during complete burning [25,26]. However, a relatively high amount of oxygen and hydrogen will lead to low heating values [26]. A high nitrogen and sulfur content will lead to environmental pollution, as both are the source of $NO_x$ and $SO_x$ pollutants, respectively. As seen from Table 1, the nitrogen and sulfur content in bamboo are low, indicating that bamboo sources are an environmentally friendly feedstock to be used.

## 4. Preparation of bamboo-derived biochar

To convert bamboo biowaste into biochar, a common technique that is used is thermochemical conversion. It includes pyrolysis, torrefaction, hydrothermal carbonization, and gasification. In order to maximize the biochar yield, it is essential to select an appropriate technique depending on the type of biomass used and process parameters, including temperature, heating rate, and residence time as these factors significantly affect the physical and chemical characteristics of the biochar produced. Among these techniques, slow pyrolysis is commonly being used in biochar production. Initially, dehydration stage occurs around temperature of 100 °C, where only the moisture of the biomass is being removed and the chemical composition remain unchanged. Unstable components such as hemicellulose, will also undergo decomposition during this stage, resulting in release of carbon dioxide, carbon monoxide, and a minor component of acetic acid produced [40]. After that, decomposition, the main process of pyrolysis, takes place under hypoxia condition. During this stage, liquid products such as acetic acid and wood tar are yielded, along with gaseous by-products such as carbon dioxide, carbon monoxide, methane, and hydrogen. A simplified flowchart of the pyrolysis process is presented in Fig. 5. Although pyrolysis process is able to produce a more stable biochar with high carbon content and greater surface area, it requires pre-drying process, high operating temperature and longer residence time which could increase the operating cost and energy required.

Hydrothermal carbonization (HTC) is also another common technique being used in biochar production. However, the product produced is referred as hydrochar to distinguish it from the product produced through pyrolysis and gasification. HTC takes place at a temperature ranging from 180 °C to 250 °C under aqueous environment with oxygen-free atmosphere. Fig. 5 shows the flowchart of the HTC process. The hydrolysed product undergoes reactions such as dehydration, fragmentation, and isomerization to form intermediates product and its derivatives, followed by condensation, polymerization and intramolecular dehydration to produce hydrochar [41]. Moreover, the biochar produced from HTC possesses significant advantages, such as increased calorific value and enhanced hydrophobicity similar to the biochar produced from pyrolysis [42]. Nonetheless, HTC process typically produces biochar with a lower specific surface area and reduced carbon content [43].

The properties of the biochar produced can differ based on the conditions of pyrolysis or HTC process. This is evident in the study by Li et al. [44], where the biochar yield varies depending on the pyrolysis temperature. The Moso bamboo pyrolyzed at 300 °C have a biochar yield of 54.81 %, while the biochar yield decreased to 30.60 % as the pyrolysis temperature increased to temperature 700 °C. In study by Sahoo et al. [39], they compared the biochar properties of bamboo and pigeon pea stalk with 3 different pyrolysis temperatures (400 °C, 500 °C, and 600 °C). It was observed that bamboo exhibited a higher biochar yield as compared to pigeon pea stalk biomass due to higher lignin content and lower VM content in bamboo. This is further elucidated by Gani and Naruse [45] and Tomczyk et al. [46], who mentioned that biomass with higher lignin content will undergo pyrolysis at slower rate, and hence enhance the biochar yield due to longer residence time. Furthermore, when the pyrolysis temperature increases, the BET surface area of the biochar increases. As the temperature increases, the pore-blocking substances are thermally decomposed or expelled, thereby enhancing the externally accessible surface area [46]. Moreover, in HTC process, the hydrochar produced would have higher carbon content as the carbonization temperature increases. An increase in carbonization temperature would also enhance dehydration and decarboxylation reactions, which lower the oxygen content and alter the atomic ratio of O/C and H/C, resulting in improved fuel properties of hydrochar [47]. This is proven by Wu et al. [48], who compared the composition of hydrochar produced from different HTC temperature (300, 350 and 370 °C). The carbon content of the hydrochar increased from 72.80 % to 80.97 %, whereas the oxygen content decreased from 21.40 % to 13.97 % as the HTC temperature increased from 300 to 370 °C.

## 5. Modification/functionalization of bamboo-derived biochar

Modification or functionalization refers to the systematic alteration and enhancement of the chemical and physical properties of biochar, transforming it into activated carbon. Compared to biochar, activated carbon possesses a larger surface area and porosity, which increases the active site and enhances ion accessibility, making it ideal for energy storage applications. There are various modifications, such as physical modification, chemical modification, self-activation and hybrid

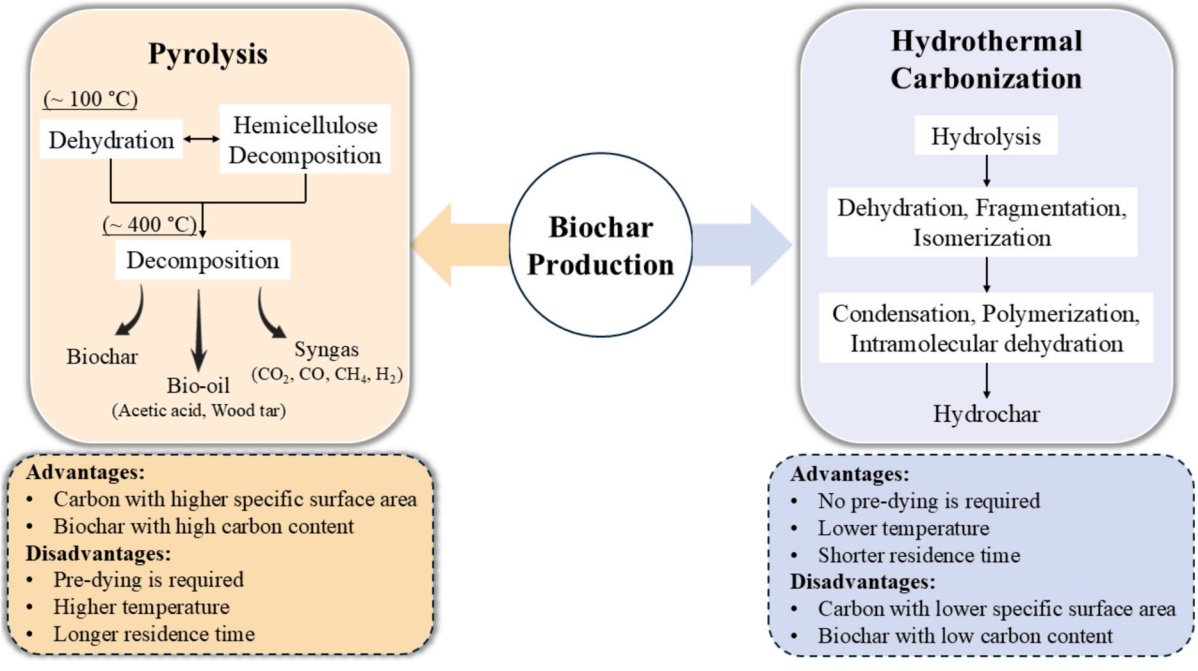


**Fig. 5.** Comparison of pyrolysis and hydrothermal carbonization.

modification (as shown in Fig. 6). This section discusses various modification methods, along with their advantages and disadvantages, which is summarized in Table 2.

### 5.1. Physical modification of bamboo-derived biochar

Physical modification of biochar is a common and direct method by introducing steam ($H_2O$), gas ($CO_2$, $N_2$), heat or plasma at various stages of the biochar manufacturing process. It usually modifies the physical characteristics of biochar such as pore structure and surface area [49]. Two common physical modifications are $CO_2$ and steam activation, which usually involves two steps. The first step involves pyrolysis and carbonization under the temperature of 300–800 °C, followed by the activation process of the biochar at relatively higher temperature conditions (800–1000 °C) [50]. The oxidizing gas will initially penetrate the biochar through the inherent pores for carbon atoms removal and volatile fractions will be released which can impede the pores through condensation and polymerization process. Once it reaches a specific temperature, the oxidizing gases will react with the carbon element of the biochar and generate gaseous products. Moreover, the reaction between oxygen or air and carbon is very rapid, thereby might resulting in uncontrollable combustion to be occur, which will affect the carbon surfaces and generate significant amount of surface oxide [51]. On the other hand, both $CO_2$ and steam are endothermic in nature, meaning it requires heat absorption [52]. Hence, the reaction rate can be controlled, and runaway condition is less prone to occur as compared to oxygen and air. Therefore, steam and $CO_2$ are preferable to be used as an activating agent as compared to oxygen and air. Moreover, the types of activating gases will result in developing various pore structures on the biochar. It was found that $CO_2$ activation could promote the formation of new pores rather than enlargement of existing pores. Conversely, steam activation could promote the formation of meso- and macropores [53]. This can be explained by the fact that $CO_2$ only reacts with specific types of active sites, leading to the selective etching of micropores, and the limitations of diffusional prevent $CO_2$ from significant pore expansion. Additionally, steam can easily diffuse into pores and enlarge them [54].

**Table 2**
Advantages and disadvantages of various modifications.

| Types of modification | Advantages | Disadvantages |
|---|---|---|
| Physical modification | • Steam can easily diffuse into pores<br>• Carbon dioxide ($CO_2$) and steam are endothermic, reaction rate can be controlled | • High activation temperature<br>• Low carbon yield<br>• Low specific surface area of the pore structure |
| Chemical modification | • Higher yield<br>• Greater surface area<br>• Higher porosity | • Costly<br>• Time and energy consuming<br>• Corrode the equipment<br>• Environmental pollution |
| Self-activation | • Higher rate of activation<br>• Environmentally friendly<br>• Reduce production cost | • High activation temperature<br>• Longer residence time |
| Hybrid modification | • Enhance ions adsorption sites<br>• Greater specific surface area<br>• Greater total pore volume<br>• Higher yield | • Complex process<br>• High investment |

Generally, physical activation induces non-uniform gasification from the external surface of carbon particles and their microdomains, consequently resulting in lower degree of pore formation [55]. Moreover, activated carbon derived from physical activation required high activation temperature, and possess the characteristics of low carbon yield and low specific surface area of the pore structure [56].

During $CO_2$ activation, the $CO_2$ will react with carbon to produce carbon monoxide. In this process, oxidation reaction will occur when the activating gas diffuses into the biochar, which aids in generating pores and expanding the existence porous structure. The chemical reaction can be expressed in Eq. (1):

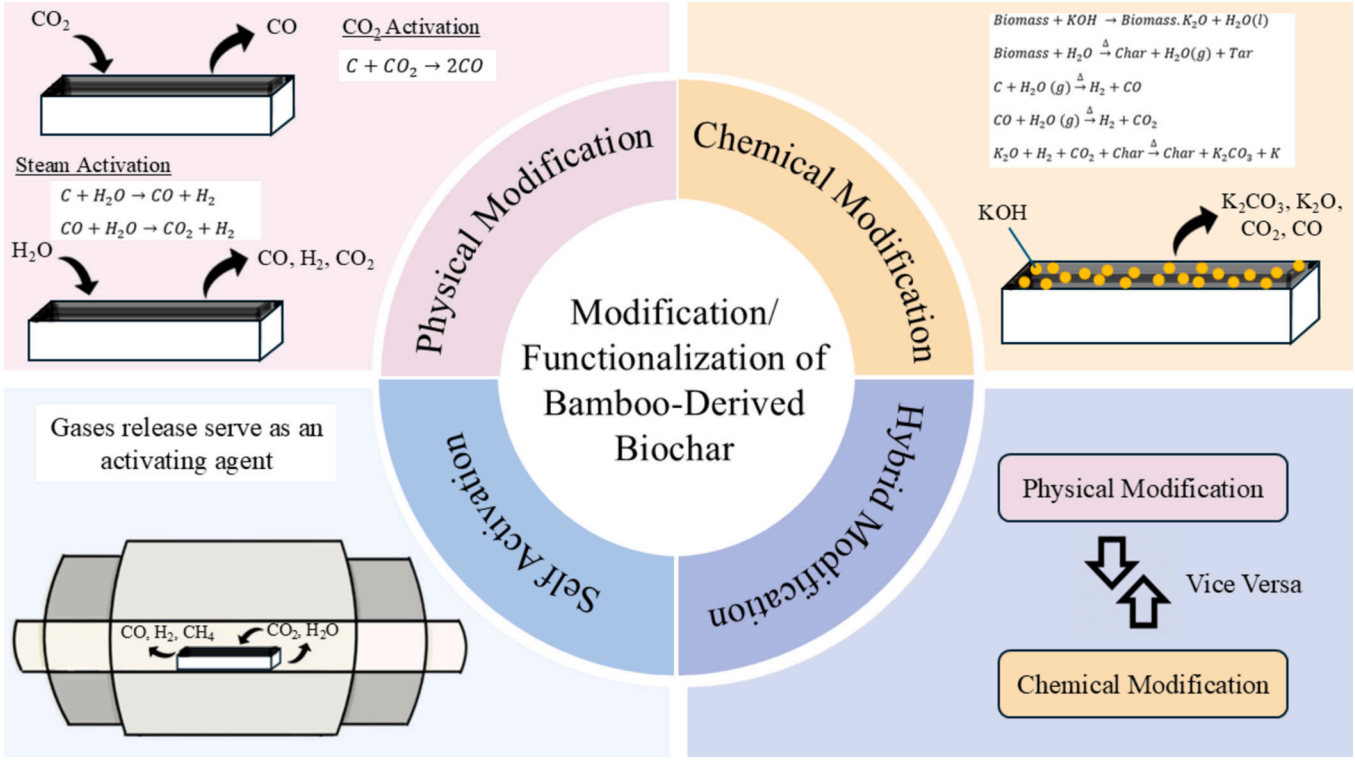


**Fig. 6.** Various modifications of bamboo-derived biochar.

$$C + CO_2 \rightarrow 2CO \quad (1)$$

In steam activation, the steam will react with the carbon to also produce carbon monoxide and hydrogen. The excess steam will then react with carbon monoxide and generate carbon dioxide and hydrogen during the reaction. The chemical reaction in steam activation can be expressed as Eqs. (2) and (3).

$$C + H_2O \rightarrow CO + H_2 \quad (2)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (3)$$

From Table 3, it can be seen that most of the studies are carrying out $CO_2$ and steam activating process. In study by Grima-Olmedo et al. [21], they compared the specific surface area of bamboo by using steam and $CO_2$ activation process. It was revealed that steam activation can generate pores with higher specific surface area as compared to $CO_2$ activation. The authors explained that steam (2.75 Å) has smaller molecular size as compared to $CO_2$ (3.30 Å), hence it can penetrate the porous carbon network faster and increase the porosity more easily.

### 5.2. Chemical modification of bamboo-derived biochar

Chemical activation involves both carbonization and activation by impregnating raw materials with chemical agents during the thermal decomposition process in a single step. The feedstock is first mixed with

**Table 3**
Summary of modification/functionalization of bamboo-derived biochar.

| Biomass source | Activation method | Activation agent | Activation temperature (°C) | Activation time (mins) | Mass ratio (activating reagent: sample) | Surface area ($m^2$/g) | Pore volume ($cm^3$/g) | Micropore volume ($cm^3$/g) | Average pore diameter (nm) | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Bamboo stem | Physical | $CO_2$ | 700 | 120 | – | 911 | 0.477 | 0.407 | 3.22 | [21] |
| | | Steam | | | | 1182 | 0.52 | 0.349 | 4.32 | |
| Bamboo charcoal | Physical | Steam | 550 | 60 | – | 191.22 | 0.29 | 0.05 | 6.05 | [61] |
| | | $CO_2$ | | | | 174.09 | 0.29 | 0.01 | 6.65 | |
| Bamboo (*Bambusa vulgaris*) wastes | Physical | $CO_2$ | 800 | 60 | – | 856.78 | 0.45 | 0.33 | 2.11 | [76] |
| Waste bamboo materials | Physical | Steam | 550 | 60 | – | 459 | 0.192 | 0.171 | 0.77 | [77] |
| | | | 650 | | | 612 | 0.256 | 0.225 | 0.84 | |
| | | | 750 | | | 773 | 0.329 | 0.280 | 0.93 | |
| | | | 850 | 60 | | 870 | 0.375 | 0.317 | 0.93 | |
| | | | | 80 | | 995 | 0.434 | 0.364 | 0.94 | |
| | | | | 100 | | 1022 | 0.448 | 0.373 | 0.94 | |
| | | | | 120 | | 1210 | 0.542 | 0.447 | 0.96 | |
| | | | | 150 | | 1149 | 0.519 | 0.426 | 1.07 | |
| Bamboo charcoal | Chemical | $ZnCl_2$ | 550 | 60 | 1:1 | 96.93 | 0.17 | 0.01 | 7.10 | [61] |
| | | $H_3PO_4$ | | | | 85.52 | 0.16 | 0.01 | 7.64 | |
| | | KOH | | | | 526.36 | 0.46 | 0.16 | 3.47 | |
| Bamboo shavings | Chemical | $K_2CO_3$ | 900 | 120 | 2:1 | 1875 | 0.9 | 0.627 | 2.327 | [66] |
| Bamboo shavings cellulose | | | | | | 1628 | 0.755 | 0.605 | 2.096 | |
| Bamboo shavings lignin | | | | | | 1985 | 1.044 | 0.607 | 2.501 | |
| Hemicellulose-free bamboo shavings | | | | | | 1727 | 0.849 | 0.536 | 2.373 | |
| Bamboo sawdust | Chemical | KOH | 700 | 60 | 1:1 | 728.38 | 0.29 | 0.25 | 2.67 | [78] |
| | | | | | 0.5:1 | 364.07 | 0.15 | 0.12 | 2.72 | |
| | | | | | 0.2:1 | 351.97 | 0.14 | 0.12 | 2.42 | |
| Bamboo carbon | Chemical | KOH | 800 | 120 | 1:1 | 1386 | 0.8 | 0.62 | – | [79] |
| Cross-cutting bamboo carbon | | | | | | 1317 | 0.78 | 0.58 | | |
| Bamboo shoot | Chemical | KOH | 600 | 60 | 2:1 | 1370 | 0.61 | 0.39 | 1.78 | [80] |
| | | | 700 | | | 3133 | 1.64 | 0.46 | 2.09 | |
| | | | 800 | | | 3250 | 1.85 | 0.44 | 2.28 | |
| Bamboo (*G. angustifolia*) | Chemical | NaOH | 300 | 60 | 4:1 | 619±9 | – | – | 7.7±0.4 | [81] |
| | | | 500 | | | 487±7 | | | 4.3±0.3 | |
| | | | 600 | | | 406±6 | | | 4.3±0.3 | |
| | | | 700 | | | 684±5 | | | 3.4±0.3 | |
| Moso bamboo shoot shells (*Phyllostachys edulis*) | Self-activation | – | 800 | 240 | – | 373 | 0.206 | 0.129 | 2.2 | [69] |
| | | | 900 | | | 869 | 0.447 | 0.303 | 2.2 | |
| | | | 1000 | | | 1377 | 0.726 | 0.502 | 2.1 | |
| | | | 1100 | | | 1855 | 1.220 | 0.312 | 2.6 | |
| | | | 1200 | | | 1360 | 1.204 | 0.226 | 3.5 | |
| Bamboo | Self-activation | – | 900 | 360 | – | 1108 | – | 0.407 | – | [82] |
| Moso bamboo | Self-activation | – | 1050 | 150 | – | 1456 | 0.94 | 0.62 | – | [70] |
| | | | | 300 | | 2001 | 1.10 | 0.73 | | |
| | | | | 600 | | 2348 | 2.30 | 0.52 | | |
| Bamboo | Hybrid activation | $H_3PO_4$/$H_2O$ | 900 | 20 | – | 960 | 0.41 | 0.36 | – | [74] |
| | | | | 30 | | 1350 | 0.56 | 0.51 | | |
| | | | | 40 | | 1630 | 0.68 | 0.61 | | |
| | | | | 50 | | 1890 | 0.86 | 0.69 | | |
| | | | | 60 | | 2700 | 1.46 | 0.81 | | |
| Bamboo (*Bambusa vulgaris*) | Hybrid activation | $H_3PO_4$/$H_2O$ | 500 | 60 | 1:2 | 1354.42 | – | – | – | [83] |
| Bamboo | Hybrid activation | $K_2CO_3/CO_2$ | 850 | 120 | 1:1 | 1724 | 1.071 | – | 2.485 | [84] |

the chemical agents and activated under inert atmosphere at the temperature of approximately 500 °C. The cellulose structures will then break down, resulting in charring and aromatization of the carbon skeleton. The end-product, which is the activated carbon will undergo washing process to recover the activating agent. There are two types of activating agents, which are strong activating agent (such as KOH and $ZnCl_2$) and mild activating agent ($K_2CO_3$ and $Na_2CO_3$). It was reported that the chemical activation process is generally more preferrable as compared to physical activation owing to its ability in achieving higher yields, greater surface area at lower operating temperatures and higher porosity [57,58]. It also required shorter activation time as compared to physical activation. Among the chemical activating agents, KOH is the most common activating agent that is being utilized due to its capability in providing superior properties such as high specific surface area and various range of pore size distribution [59], which will result in high specific capacitance [60]. For instance, Zhang et al. [61] investigated the bamboo charcoal derived carbon shavings hierarchical porous carbon via the utilization of various activating agents such as $ZnCl_2$, KOH and $H_3PO_4$. It was discovered that KOH activation has the largest specific surface area and total volume of pores (526.36 $m^2/g$ and 0.46 $cm^3/g$, respectively) followed by $ZnCl_2$ (96.93 $m^2/g$ and 0.17 $cm^3/g$, respectively) and $H_3PO_4$ (85.52 $m^2/g$ and 0.16 $cm^3/g$, respectively).

Nonetheless, chemical activation also possess disadvantages, such as costly, time and energy consuming as the activated carbon produced is necessary to undergo post-activation washing by using acid and deionized water in order to eliminate excess chemical activating agents [62]. The chemical activating agents might also corrode the equipment, as well as causing environmental pollution if it is not handled and disposed of properly due to its corrosiveness.

The chemical reactions for the chemical activation via KOH involve the potassium cycle concept. They are described as below [57,63]:

$$Biomass + KOH \rightarrow Biomass.K_2O + H_2O(l) \quad (4)$$

$$Biomass + H_2O \xrightarrow{\Delta} Char + H_2O(g) + Tar \quad (5)$$

$$C + H_2O\,(g) \xrightarrow{\Delta} H_2 + CO \quad (6)$$

$$CO + H_2O\,(g) \xrightarrow{\Delta} H_2 + CO_2 \quad (7)$$

$$K_2O + H_2 + CO_2 + Char \xrightarrow{\Delta} Char + K_2CO_3 + K \quad (8)$$

Initially, the primary transformation is where dehydration, cracking, partial polymerization occurs during the reaction (4). During this phase, the biomass components (cellulose, hemicellulose and lignin) are distorted from the lignocellulosic biomass. In the secondary transformation, the lignocellulosic biomass is converted into char through aromatization under pyrolysis condition, as represented by Eq. (5). The $CO_2$ will then react with $K_2O$ to form $K_2CO_3$. The presence of KOH, $K_2O$ and $K_2CO_3$ will react with the carbon, and volatiles such as $H_2O$, CO, $H_2$ and $CO_2$ will be released during the reaction, and this will facilitate in forming porous structures [64]. The accumulation of these volatiles within the carbon matrix generates pressure and causes the trapped volatiles to diffuse out of the carbon matrix, which results in pore formation [65].

Studies on various biomass-derived biochar that have undergone chemical activation have been published in literature and are summarized in Table 3. With many reviews on the utilization of KOH as an activating agent, few studies have been investigated on the use of mild activating agent, which is $K_2CO_3$. For instance, Qiu et al. [66] also conducted a study on bamboo shavings and its components (cellulose, hemicellulose and lignin) by using $K_2CO_3$ to activate the bamboo shavings char into activated carbon. The authors discovered that bamboo shavings lignin carbon had the highest specific surface area, micropore and mesopore volumes compared to bamboo shavings carbon, bamboo shavings cellulose carbon and hemicellulose-free bamboo shavings, as shown in Fig. 7. This indicates that the presence of lignin in biomass is a key factor in developing high specific capacitance and rate performance in supercapacitor, due to its abundant micropores and mesopores that provide a high surface area for electrolyte ions adsorption.

### 5.3. Self-activation of bamboo-derived biochar

Self-activation, also known as one-step pyrolysis process, is a novel technology that produced activated carbon from biomass. It takes advantages from the gases release during pyrolysis process. During the pyrolysis process, gaseous such as $CH_4$, $H_2$, $CO_2$, CO and $H_2O$ will be released. These gaseous can serve as an activating agent in the subsequent activation stage. Self-activation is conducted within an enclosed reactor, vacuum environment [67] and recycled the gases release during the pyrolysis process as activating agent to enhance micropore formation in the biochar under an autogenerated pressure, which increase the rate of activation (see Fig. 8). It is known that self-activation is much more environmentally friendly and can reduce the production cost than physical and chemical modification as it does not require much heat energy and chemical reagent, as well as the release of pollutant [68].

The pore structure of the activated carbon is highly influenced by the pyrolysis temperature and residence time. A study was reported by Gao et al. [69], in which moso bamboo shoot shells (*Phyllostachys edulis*)-derived activated carbon was placed under the activation temperature of 800–1200 °C, with an interval of 100 °C for 240 min. The optimal activation temperature was 1000 °C based on the pore structure. The authors observed that there was a gradual increase in the specific surface area and pore volume of the activated carbon when the activation temperature was below 1000 °C, whereas the micropores was expanding into mesopores or experiencing pore collapse, resulting in the reduction of micropore volume when the activation temperature exceeds 1000 °C. Ma et al. [70] also compared the pore structure of the activated carbon with different residence time of 150 min, 300 min, and 600 min at the pyrolysis temperature of 1050 °C. The specific surface area and total pore volume increased as the residence time increased. However, the micropore volume increase significantly as the pyrolysis time was increased till 300 min and decreased again when the pyrolysis time further increase to 600 min. The reduction in micropore volume after 300 min could be attributed to the blockage of tar or volatile matter on the micropores channel [71]. Although self-activation is more environmentally friendly and save cost, it requires higher activation temperatures and longer residence time as compared to other conventional modifications method. Therefore, in-depth study is still required to optimize the activation temperature and residence time to enhance the efficiency of self-activation.

### 5.4. Hybrid modification of bamboo-derived biochar

Hybrid modification, also known as physico-chemical activation, is a process that involves both physical and chemical activation sequentially to enhance the properties and performance of the bamboo-derived activated carbon. This approach is typically utilized after the carbonization process, where the chemical agents may persist even after washing with distilled water, which could possibly hinder the pores formation [72]. As this modification is still novel, limited studies have been conducted based on bamboo-derived biochar. Saputra et al. [73] utilized physico-chemical activation involving heating followed by $H_3PO_4$ to synthesize bamboo charcoal derived activated carbon. The bamboo charcoal derived activated carbon displayed smoother and more uniform surface compared to bamboo charcoal derived biochar due to the elimination of impurities and organic compound on the bamboo charcoal surface and pores during the activation process. The authors also investigated that the physico-chemical activation can increase the interaction sites availability on the activated carbon surface.

Additionally, Kim et al. [74] produced activated carbon derived from

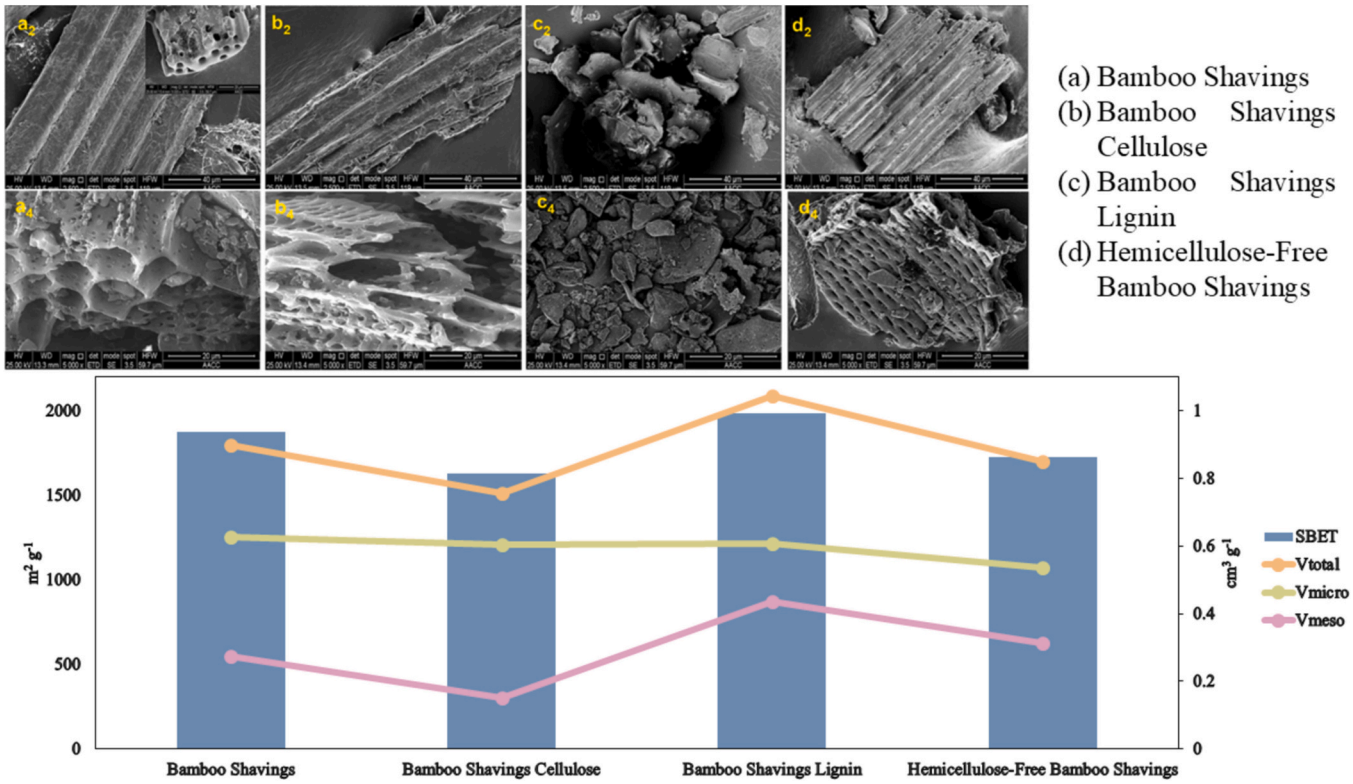


**Fig. 7.** Field emission scanning electron microscope (FESEM) and pore structure parameters of bamboo shavings, bamboo shavings cellulose, bamboo shavings lignin and hemicellulose-free bamboo shavings [66].
From "Bamboo-based hierarchical porous carbon for high-performance supercapacitors: the role of different components" by Guofeng Qiu, Zekai Miao, Yang Guo, Jie Xu, Wenke Jia, Yixin Zhang, Fanhui Guo, Jianjun Wu, 2028, Colloids and Surfaces A: Physicochemical and Engineering Aspects, Vol. 650.

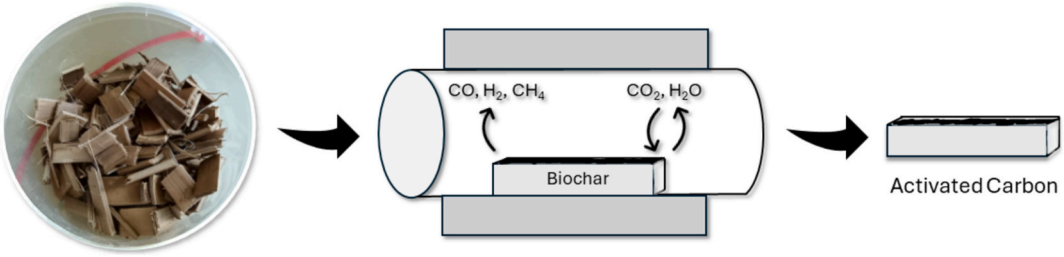


**Fig. 8.** Schematic diagram of self-activation.

bamboo using $H_3PO_4$ and steam. They compared the properties of bamboo-derived activated carbon with solely steam activation and hybrid activation (steam and $H_3PO_4$). The study revealed that the activated carbon that undergoes hybrid modification has a greater specific surface area, greater total pore volume, as well as yield. For instance, at the activation period of 20 min, the activated carbon with hybrid activation has increased 1.2 times of the specific surface area, 1.3 times of the total pore volume and 1.2 times of the yield than solely steam activation activated carbon. This could be due to the mass transfer enhancement within the carbon matrix, resulting in superior adsorption capabilities [75].

Overall, hybrid modification is considered a balance approach as it can balance the limitations of each chemical and physical modification. Also, it produced carbon materials with superior properties such as higher specific surface area and greater pore volume than the individual modifications, owing to enhanced mass transfer within the carbon matrix [75]. This also indicated that it could provide more ions adsorption sites and rapid ion adsorption and desorption, which demonstrate efficient charging cycles and charge storage. However, hybrid modification is considered as a complex process and required high investment [72]. Therefore, in-depth research on hybrid modification is still necessary to fully understand and optimize the complexity of this technique.

## 6. Specific applications of bamboo-derived carbons in supercapacitors

Bamboo-derived carbons are emerging as a potential electrode material in supercapacitors due to their high surface area, porous structure, and renewable nature. The electrolytic ion would be adsorbed to the interface of the bamboo-derived carbon electrode and the charge (energy) would be stored, as shown in Fig. 9. Researchers also develop considerable approaches to enhance the performance of the supercapacitors. In atom-doping process, heteroatoms such as nitrogen, sulfur, or phosphorus is introduced into the carbon structure, increasing defect density and modifies the surface of electron density, thereby accelerating charge transfer within the materials and augmenting ion storage sites. For composites-based bamboo biowaste carbon materials, the composite materials aim to enhance conductivity and mechanical

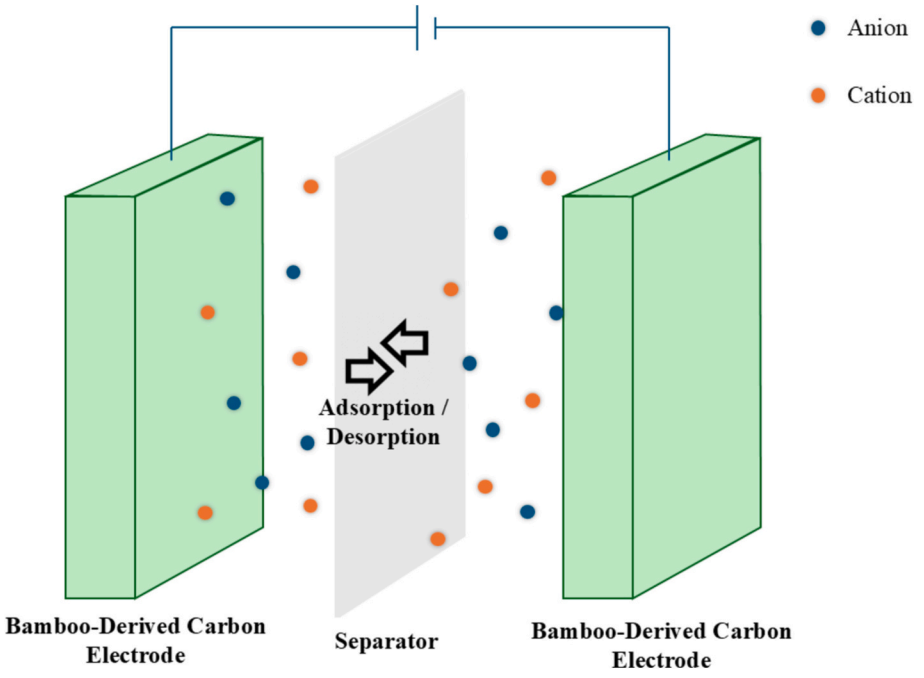


**Fig. 9.** Simple mechanism of bamboo-derived carbon electrode.

stability of the supercapacitors. In addition, introducing heteroatom and composite materials into bamboo-derived carbon will create synergistic effect, resulting in supercapacitors with improved energy density, power density and life cycle. A referenced data Ragone plot based on literature studies is presented in Fig. 10. A summary of bamboo-derived supercapacitor is also tabulated in Table 4, with the comparison of three electrode system and two-electrode system. The three-electrode system is used to evaluate the electrode performance whilst the two-electrode system is used to evaluate the supercapacitor performance.

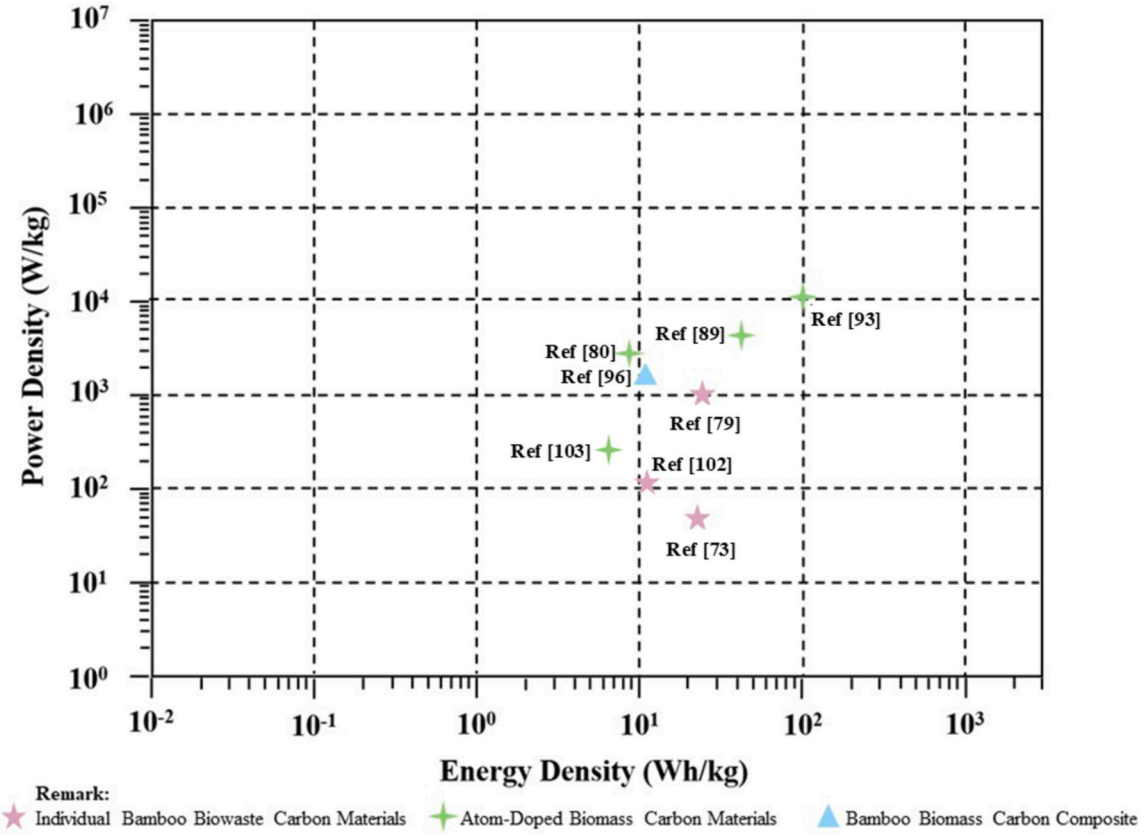


**Fig. 10.** Ragone plot for literature studies.

**Table 4**
Applications of bamboo-derived carbons in supercapacitor.

| Applications | Precursor | Electrolyte | Three-electrode system | | Two-electrode system | | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | | Specific capacitance (F/g) | Cycling stability | Specific capacitance (F/g) | Power density (W/kg) | Energy density (Wh/kg) | Cycling stability | |
| Individual bamboo biowaste carbon materials | Bamboo | 1 M $TEABF_4$/PC | – | – | 86.7 | 14.7 | 22.1 | – | [74] |
| | Natural bamboo powder (with $KMnO_4$ activator) | $H_2SO_4$ | 225 | – | – | – | – | – | [85] |
| | Natural bamboo powder (with KOH activator) | $H_2SO_4$ | 209 | – | – | – | – | – | |
| | Bamboo | $Na_2SO_4$ | 280 | 100–103 %/5000 cycles | 23.3 | 1000 | 24.6 | 100 %/30,000 cycles | [79] |
| | Bamboo shoot shells | 6 M KOH | 172.65 | – | – | 252 | 11.11 | 100 %/7000 cycles | [102] |
| Atom-doped biomass carbon materials | Bamboo woods biomass (N-doping) | 6 M KOH | 475 | – | 295 | 4500 | 42 | 150 %/10,000 cycles | [89] |
| | Bamboo shoot (N-doping) | 6 M KOH | – | – | 209 | 2915 | 8.9 | 95 %/10,000 cycles | [80] |
| | Bamboo leaves (S-doping) | 3 M KOH | 107.9 | 98.1 %/30,000 cycles | – | – | – | – | [90] |
| | Bamboo powder (N,S Co-doping) | 1 M $LiPF_6$ | – | 85.8 %/2000 cycles | – | 10,005 | 158 | 79.19 %/8000 cycles | [93] |
| | Bamboo shoot shells (O-self doping) | 6 M KOH | 308.2 | – | 320.05 | 250 | 7.36 | 100 %/7000 cycles | [103] |
| Bamboo biomass carbon composites | $MnO_2$ nanosheets with bamboo leaf carbon | 1 M $Na_2SO_4$ | 76 | – | 32.25 | 1600 | 11.47 | 85.3 %/5000 cycles | [96] |
| | Bamboo-derived cellulose fibers/RGO carbon aerogel composite | 6 M KOH | 351 | 99 %/5000 cycles | – | – | – | – | [98] |
| | Bamboo shoot synthesis of RGO/$MnO_2$ nanocomposite | 1 M KCl | 827 | – | – | – | – | – | [101] |

### 6.1. *Individual bamboo biowaste carbon materials for supercapacitors*

Bamboo-derived biochar have received considerable interest as a carbon material due to its interconnected, multichannel, and porous structure in facilitating electrolyte penetration and ion movement. Its unique properties not only aid in enhancing efficiency pathway for electron transport but also provide large specific surface area, which are crucial for electrochemical processes. Researchers have been investigated the viability of producing bamboo-derived activated carbon through various activation and innovative techniques to enhance the properties of bamboo-derived carbon.

Typically, commercial activated carbons are produced from coconut shells, as well as other nut shells, petroleum coke, lignite coals, bituminous and various wood by-products such as bark and sawdust. Kim et al. [74] synthesized mesoporous activated carbon using bamboo at different activation time (20–60 min with 10 min interval) and compared the performance of the supercapacitors made from commercial coconut shells-derived activated carbon. The bamboo-derived activated carbon obtained through 60 min activation, displayed remarkable properties, including higher specific surface area (2700 $m^2/g$), micropore volume (0.81 $cm^3/g$) and mesopore volume (0.65 $cm^3/g$) than the coconut shells-derived activated carbon (specific surface area of 1780 $m^2/g$, micropore volume of 0.81 $cm^3/g$ and mesopore volume of 0.13 $cm^3/g$). The specific capacitance of bamboo-derived activated carbon was approximately 6.9 % and 29.1 % higher than coconut shells-derived activated carbon at a current density of 0.1 A/g and 10 A/g, respectively. Hence, Kim and the co-author determined that the maximum energy and power density for the bamboo-derived activated carbon materials were 22.1 Wh/kg and 14.7 W/kg, respectively at a current density of 0.1 A/g. The volume of the micropore and mesopore amplified the ion diffusion resistance, affecting the energy and current density of the supercapacitor.

Zheng et al. [85] employed natural bamboo powder to synthesize activated carbon featuring a unique micro-, meso-, and macro- structures by using $KMnO_4$ and KOH activating agent. The activated carbon derived with $KMnO_4$ activating agent demonstrated exceptional performance as the KOH-derived activated carbon in the three-electrode system, delivering a specific capacitance of 225 F/g and 209 F/g for $KMnO_4$ and KOH based activated carbon, respectively (at the potential scan rates of 2 mV/s). However, the tendency of KOH based activated carbon tend to decrease more significantly as compared to $KMnO_4$ based activated carbon when the potential scan rate increase. The activating agent of $KMnO_4$ aids in enhancing meso- and macro- pore structures, as well as surface functional groups, which develop both storage capacity and transport behaviour that elevated the electrical conductivity and wettability of the activated carbon, ensuring superior electrode performance. The pore structure and surface functional groups of the carbon materials emerged as a crucial factor in determining the performance of the supercapacitor.

In another study, Han et al. [79] utilized cross-cutting bamboo and bamboo carbon in synthesized the carbon materials through carbonization and KOH activation. In the three-electrode system, the cross-cutting bamboo displayed remarkable properties, with a specific capacitance of 280F/g at 0.5 A/g and cycle performance of 100–103 %

after 5000 cycles. In the two-electrode system, the symmetric supercapacitor of cross-cutting bamboo exhibits high specific energy of 24.6 Wh/kg at a specific power of 1000 W/kg and no capacitance loss after 30,000 cycles at 50 A/g as compared to bamboo carbon. Moreover, the electrochemical impedance spectroscopy (EIS) test shows that the total resistance of cross-cutting bamboo carbon is much lower than bamboo carbon. Moreover, cross-cutting bamboo carbon has faster ion diffusion and enhanced rate performance, as the operating frequency is higher, and the relaxation time constant is shorter in cross-cutting bamboo carbon (0.855 Hz and 1.17 s, respectively) as compared to bamboo carbon (0.264 Hz and 3.79 s, respectively). The outstanding electrochemical properties of the carbon materials stemmed from the reduction in the length of the natural pole tunnels due to cross cutting, and hence shortens the ion diffusion distance, leading to enhancing the specific surface area.

These literature highlight that bamboo biowaste carbon materials have the potential in synthesizing high performance supercapacitor. Through processing techniques such as activation and cross-cutting process, the pore structure and surface chemistry of carbon materials can be modified and optimized their performance for the application of supercapacitors. This not only provides sustainable solution to carbon materials but also determines the potential of bamboo biowaste in green energy storage.

### 6.2. Atom-doped biomass carbon materials for supercapacitors

Atom-doping has emerged as a method to enhance the performance of biomass carbon materials. By introducing heteroatoms into the carbon structure, the specific capacitance is enhanced through Faraday reaction, while conductivity and wettability are also improved, thereby significantly enhancing the supercapacitor performance. Incorporating heteroatoms such as boron (B), fluorine (F), nitrogen (N), phosphorus (P), and sulfur (S) into the backbone of the carbon matrix by involving chemical attachment could generate different extrinsic defects that modify the carbon structure, ultimately enhance the kinetic reactions and electrochemical performance by adjusting the electronic and chemical properties [86]. The carbon structure and performance of the electrode materials depend on various factors, including the dopant type, concentration of dopant and specific doping arrangements [87].

Nitrogen (N) doping has garnered significant attention for its ability to enhance the performance of the charge-storage. Due to its abundant sources and proximity to carbon in the periodic table, nitrogen is easier to incorporated into the carbon matrix as compared to other heteroatom [88]. It was found that nitrogen doped materials serve as electron donors, and the electronegativity of nitrogen (3.04) is higher than carbon (2.55), which facilitated the electrolyte ions adsorption [87]. Gunasekaran et al. [89] fabricated an asymmetric supercapacitor device using bamboo biomass derived nitrogen-doped carbon as anode, and carbonized char as cathode. Due to the synergistic effect between KOH activation and nitrogen doping, the bamboo biomass derived nitrogen-doped carbon is able to exhibit excellent electrochemical performance, which demonstrated the half-cell specific capacitance of 475 F/g at a current density of 1 A/g with high potential window up to −1.2 V. When applied as an anode in the asymmetric supercapacitor, ca. 295 F/g of specific capacitance was accomplished at the current density of 1 A/g and the solution resistance was 5.3 Ω, indicating excellent contact between the interface of electrolyte and electrode. Remarkable capacity retention of 150 % over 10,000 cycles was also achieved for the asymmetric supercapacitor devices. In another study, Huang et al. [80] also achieved remarkable capacity retention of 95 % at 10 A/g over 10,000 cycles by fabricating nitrogen doped hierarchical carbons derived from bamboo shoots. This was attained by the hierarchical micro-mesopore, exceptional specific surface area (3250 $m^2$/g), and moderate nitrogen species present in the framework. Moreover, the nitrogen doped bamboo shoots derived hierarchical carbon also shows relatively low resistance in the EIS test, as it demonstrates smallest vertical line amplitude at low frequency, which is attributed to its high conductivity and mesoporous structure that enhance both electron transfer and accessibility.

Sulfur (S) considered as a viable dopant in carbon matrix for improving physicochemical properties such as specific capacitance and electrical conductivity by modifying the charge distribution [90]. This is owing to the overlapping of the p-orbital between sulfur atom and carbon atom with $sp^2$-hybridized, leading to an extended p-system with fully occupied valence bond [87]. The bandgap of the carbonaceous materials will increase with sulfur doping, thereby enhance the properties of the electron donor and alter the electronic density states [91]. Wang et al. [90] employed S doping on natural bamboo leaves derived carbon-based hybrid by using $CSiO_2$ via in-situ solvothermal treatment. The carbon material exhibited superior areal capacitance of 643.2 mF/$cm^2$ and specific capacitance of 107.9 F/g at 0.5 A/g in 3 M KOH solution. It also demonstrated exceptional capacity retention of 100 % after 20,000 cycles and retaining 98.1 % after 30,000 cycles.

Although single-doped carbon materials can enhance electrochemical properties to certain extent, the addition of multiple dopants can further enhance the electron transfer owing to their distinct structures and bonding when compared to single-doped carbon materials [92]. Hence, co-doping has been widely introduced by researchers to investigate electrochemical properties recently. Wang et al. [93] employed template method to transform bamboo into carbon materials imbued with sulfur- and nitrogen-doped configuration. It also demonstrated a high-specific surface area of 2288.03 $m^2$/g. When applied as a cathode in the lithium-ion capacitor, the carbon materials exhibited superior coulombic efficiency of 99.7 with a capacity retention of 85.8 % at 5 A/g after 2000 cycles. Furthermore, the sulfur and nitrogen co-doped incorporated with zinc bamboo derived carbon material has shown the lowest charge transfer resistance (63.74 Ω) as compared to bamboo derived carbon and bamboo-derived zinc carbon due to more active site created by nitrogen and sulfur doping.

In summary, atom doping of bamboo carbon materials is a promising factor in tailoring the properties of supercapacitor. Through atom doping by using heteroatom, carbon materials can be engineered with superior electrochemical properties as compared to individual bamboo biomass carbon materials. Although single-doped carbon materials demonstrate notable advancements, co-doping provides better potential in enhancing the electron transfer and overall performance of the supercapacitor. As nowadays researchers are studying deeply into the atom doping technique, further insight into the relationship between the type and concentration of dopant should be investigated to generate better carbon-based materials for energy storage.

### 6.3. Bamboo biomass carbon composites for supercapacitors

Composites materials can also be incorporated into the carbon matrix to enhance the supercapacitor performance. Common pseudocapacitive materials such as metal oxides or hydroxides are being used to provide high capacitance and energy density. This is attributed to reversible Faradaic reactions and ion adsorption between the interface of electrode and electrolyte [94]. However, manganese is widely used in the electrodes for supercapacitors due to its stability and established redox properties [95]. Typically, manganese oxides are deposited onto biomass carbons through hydrothermal process. Yu et al. [96] utilized hydrothermal method to attach $KMnO_4$ onto the bamboo leaf carbon, developing into a carbon-based composite. In the three-electrode system, the carbon-based composite exhibiting a specific capacitance of 76 F/g. Moreover, when this composite was employed in an asymmetric supercapacitor, it exhibits a capacity retention of 85.3 % after 5,000 cycles at 0.5 A/g. It also demonstrated a wide potential range of 0 to 1.6 V and high energy density of 11.47 Wh/kg at 0.5 A/g with a power density of 1600 W/kg, demonstrating the composite material show great potential in the use of supercapacitor.

Graphene, derived by exfoliating graphite into a single carbon layer, possesses two-dimensional planar structure. Due to its remarkable

conductivity (106 S/m) and specific surface area (2,630 $m^2$), it has high theoretical capacitance (550 F/g), robust mechanical strength and high mobility (200,000 $cm^2\ V^{-1}\ s^{-1}$) [97]. Bamboo-derived cellulose fibers/reduced graphene oxide (RGO)-based composite was fabricated using aerogel-based approach with different graphene oxide proportions (1.5 wt%, 2.5 wt% and 3.5 wt%) [98]. With 2.5 wt% of graphene oxide, they exhibit high specific capacitance of 351 F/g and delivered notable cyclic stability, retaining a specific capacity retention of 99 % above after 5,000 cycles at 5 A/g. It also demonstrated small charge transfer resistance of 0.30 Ω, showcasing that the composite carbon materials have small energy consumption and good electrical conductivity, which has the potential to be use as a material of electrode.

Although $MnO_2$ and graphene possess properties that can enhance the electrochemical properties of supercapacitor, the use of $MnO_2$ still brings drawback to the properties of supercapacitor. It is found that the use of $MnO_2$ will inherent low conductivity of electrical and the surface layer thickness [99]. In order to improve the aforementioned drawbacks, it is possible to incorporate high electrically conductive substrates, such as conducting polymers and graphene with transition metal oxide [100]. Ruti and Kumar [101] synthesized a novel nanocomposite of RGO and $MnO_2$ that involving bamboo shoot. The nanocomposite of RGO and $MnO_2$ has larger specific area (260.5 $m^2/g$) as compared to RGO (112.2 $m^2/g$) and $MnO_2$ (197.45 $m^2/g$). RGO and $MnO_2$ has shown a specific capacitance of 58.4 F/g and 69.5 F/g, respectively. As for the nanocomposite of RGO and $MnO_2$, the material has also showed higher specific capacitance of 872 F/g at a scan rate of 10 mV/s, with a charge transfer resistance of 1.02 Ω. The authors explained that the enhancement of the specific capacitance can be attributed to uniform distribution of $MnO_2$ nanoparticles on the RGO surface, aiding the interaction with charges or ions at the surface.

In summary, composite carbon materials show great potential in advancing energy storage applications. By adding transition metal oxide or conducting polymers into carbon matrices, the electrochemical properties can be enhanced to improve the performance of the supercapacitors. However, further research in this field is still required to identify other synthesis methods and optimize material configurations for broader applications beyond supercapacitors.

## 7. Challenges and outlook

The utilization of bamboo as a sustainable alternative for producing activated carbon has gained significant attention in recent years, offering promising prospects for various applications including supercapacitors. However, numerous challenges persist throughout the entire process, from sourcing raw materials to the manufacturing stages, which profoundly impact the yield and quality of the resulting activated carbon. A pivotal aspect of ensuring overall efficiency on a larger scale of production lies in identifying and evaluating the carbon content and composition across various bamboo sources. In a comprehensive study by Chaturvedi et al. [20], the properties of charcoals derived from various bamboo species and sources were evaluated, with bamboo chopstick waste emerging as a highly effective source due to its substantial lignin content, leading to a remarkable charcoal yield of 74.20 %. While bamboo-based activated carbon exhibits remarkable performance as supercapacitor electrode, challenges exist in increasing the energy density of carbon-based supercapacitor, limiting their application. Therefore, further research should concentrate on enhancing the energy density, such as through pore structure modification of bamboo derived carbon by cross-cutting which can increase the hydrophilicity of the carbon surface, and doping with heteroatoms [104].

Moreover, the inherent composition of bamboo characterized by high lignin, cellulose, and hemicellulose content as highlighted by Maniscalco et al. [105] presents challenges during the activation and carbonization process (pyrolysis). Although the activation method utilizing potassium hydroxide is commonly employed for the production of high specific surface area hierarchical porous biomass derived carbons, it has limited control over the pore structure, which can be overcome by combining the potassium hydroxide activation with thermal treatment [106]. Besides that, the robust structural integrity of bamboo often results in minimal alteration to its pore structure after pyrolysis, leading to inefficient utilization of internal space and the formation of numerous and larger macropores, thereby compromising the quality of the synthesized bamboo based activated carbon [64]. To address this issue, alternative approaches such as hydrothermal and microwave carbonization technology or employing a greater variety of activators as well as fully crushing biomass materials are recommended [64]. Hydrothermal carbonization, in particular, has emerged as a promising technology for producing bamboo-based biochar, offering advantages such as being more economically viable, requiring lower energy input, and yielding carbonaceous structures of higher quality than those produced by pyrolysis [104,107]. Also, optimization of hydrothermal carbonization through further research into its mechanisms and control over operating parameters, including temperature, residence time, and ratio of biomass to water is crucial for achieving continuous and cost-effective production [105].

Despite advancements in pyrolysis and hydrothermal carbonization technologies for biomass carbonization, additional research and development are necessary due to the complex formation process, which may lead to inconsistent properties of solid char products, thus compromising overall product performance and energy storage applications. To address these challenges, Yang et al. [111] proposed several outlooks: (a) conducting in-situ tracking and gaining a thorough understanding of the biochar formation process to facilitate precise production and regulation of carbon-based materials and (b) employing machine learning techniques such as regression analysis, artificial neural networks, and decision trees in modelling the processes of pyrolysis and hydrothermal carbonization to improve the accuracy of product prediction.

Bamboo-based carbon electrodes hold considerable potential for advancing supercapacitors and various energy storage technologies, highlighting the need for research in several important areas. Improving carbonization techniques is vital for increasing both conductivity and surface area, which are essential for boosting electrochemical performance and competing with well-established materials like activated carbon and graphene [108]. Additionally, exploring hybrid designs that blend bamboo-derived carbon with materials such as metal oxides or conducting polymers may result in supercapacitors with superior energy and power density, maximizing the advantages of each component [109]. It is also important to evaluate the environmental sustainability of bamboo-derived electrodes in comparison to conventional materials, focusing on their renewable characteristics and lower ecological impact. Investigating the scalability and economic feasibility of production processes will be crucial for enabling widespread industrial use, ensuring these high-quality materials can be produced efficiently and affordably [110]. Lastly, examining the applicability of bamboo-derived carbon across various energy storage platforms, including lithium-ion batteries and fuel cells, will further establish their significance and effectiveness in the changing energy landscape, marking them as a vital contributor to sustainable energy solutions.

## 8. Conclusions

This review highlights the significant advancements in the development and application of bamboo-derived activated carbon for supercapacitors. Key findings from the literature indicate that bamboo biowaste, due to its high specific surface area, abundant micropores and mesopores, and renewable nature, is a highly promising material for high-performance supercapacitors. Various activation techniques, including physical, chemical, self-activation, and hybrid methods, have been shown to enhance the electrochemical properties of bamboo-derived carbon, making it a viable alternative to traditional carbon materials. Furthermore, the incorporation of atom doping, and

composite materials has been demonstrated to further improve the specific capacitance, conductivity, and overall performance of bamboo-based supercapacitors. The review also underscores the importance of optimizing activation processes and exploring novel modification techniques to fully harness the potential of bamboo-derived carbon. Future studies should focus on addressing the challenges related to increasing the energy density of bamboo-based supercapacitors. This includes further exploration of pore structure modifications, advanced doping techniques, and the development of more efficient and scalable activation processes. Additionally, the long-term stability and performance of bamboo-derived carbon materials in supercapacitor applications should be thoroughly investigated to validate their practical viability. Further development of machine learning dedicated to modelling the pyrolysis process and product prediction is necessary to facilitate the performance of supercapacitors applications. Through continuous research and development, bamboo-derived carbon materials hold great promise in contributing to sustainable and efficient energy storage solutions, paving the way for more sustainable technologies.

## CRediT authorship contribution statement

**Sharon Meng Xuang Goh:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Bridgid Lai Fui Chin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization. **Mee Mee Huang:** Writing – original draft, Formal analysis. **Chung Loong Yiin:** Writing – original draft, Formal analysis. **Jundika Candra Kurnia:** Writing – review & editing, Supervision, Formal analysis. **Su Shiung Lam:** Writing – review & editing, Supervision. **Yie Hua Tan:** Writing – review & editing, Supervision, Formal analysis. **Yee Ho Chai:** Writing – review & editing, Formal analysis. **Nor Adilla Rashidi:** Writing – review & editing, Formal analysis.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Bridgid Chin Lai Fui reports financial support was provided by Sarawak Research and Development Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

No data was used for the research described in the article.

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