



ARTICLE

Optimization of Pyrolysis Temperature for Activated Carbon Production from Durian Shell and Eggshell for Energy Storage Applications

Fatin Nadhirah¹, Surajudeen Sikiru^{1,2,*} and Mohd Muzamir Mahat^{1,3}

¹School of Physics & Materials Studies, Faculty of Applied Sciences, Universiti Teknologi Mara (UiTM), Shah Alam, Selangor Darul Ehsan, Malaysia

²Sustainable Energy Materials Group, Faculty of Applied Sciences, Universiti Teknologi MARA, Shah Alam, Selangor Darul Ehsan, Malaysia

³School of Chemistry, Chemical Engineering and Biotechnology, Nanyang Technological University, Singapore, Singapore

*Corresponding Author: Surajudeen Sikiru. Email: surajudeen86@gmail.com or surajudeen@uitm.edu.my

Received: 19 March 2026; Accepted: 15 April 2026; Published: 06 August 2026

ABSTRACT: Agricultural waste has received increased attention as a sustainable precursor for activated carbon manufacture because of its availability, inexpensive price, and ecological benefits. However, the search for the right biomass and optimization of the activation process remain one of the major challenges in the production of high-performance composites in energy storage applications. In this study, pyrolysis of durian and eggshells was performed for activated carbon production using sodium sulfite (Na_2SO_3) and orthophosphoric acid (H_3PO_4) as activating agents, then combined both together with a ratio of 1:1 to produce a hybrid activated carbon to increase the performance for energy storage applications. We concentrate on how different activating temperature stages affect their characteristics. Therefore, the optimum conditions for activation were obtained, which was at 700°C for the hybrid activated carbon. The investigation included examining the surface morphological characteristics, functional groups, and composition of the manufacturer's activated carbon. Due to the increased carbon content, the porosity of the durian shell-derived activated carbon was better, as was the surface morphology, but the calcium carbonate present in the eggshell contributed to the structural stability of the surface functioning of the activated carbon. As a result, both materials will be appropriate precursors for activated carbon production in energy storage applications. The electrochemical evaluation demonstrates that biomass-derived activated carbons exhibit promising performance for energy storage applications. Durian shell carbon shows superior conductivity and EDLC behavior, while eggshell carbon contributes pseudo-capacitance despite higher resistance. The hybrid material achieves a balanced performance, combining both mechanisms, making it a sustainable and efficient electrode candidate for supercapacitors.

KEYWORDS: Activated carbon; durian shell; eggshells; energy storage; temperature; electrochemical

1 Introduction

The term used for the materials derived from agricultural waste, including fruits and cattle, is known as “biomaterials from agricultural waste” [1]. These materials can be treated in a manner that results in environmentally acceptable and sustainable substitutes for conventional synthetic materials. Besides the environmentally acceptable attributes of using agricultural waste as a source of biomaterials, there is a chance to utilize resources that would have been wasted in any case, thereby reducing the burden on scarce resources and helping in the mitigation of environmental problems [2]. The most popular fruit in Southeast Asia is durian. Durian was only available during a certain season, but with the advancements in the agricultural

industry, it is now available all the year in a large amount [3]. The flesh, which makes up around one-third of the fruit mass, is the only edible portion. After it was eaten, the shells were thrown away as waste, but some seeds were used for reproduction. Because of its unique flavor, the demand for this spiky fruit has increased in Southeast Asia, especially China. Hence, the durian shell has led to the unavoidably generated waste, which needs to be controlled. It demonstrated that heteroatoms were present in its initial form. For example, nitrogen (N_2), oxygen (O) and sulphur (S) [4]. Thus, from an economic and sustainability perspective, durian shells are very suitable for activated carbon production. Based on a study, a well-porous structure was formed and has the highest BET surface area, which is $1475.48 \text{ m}^2/\text{g}$ with $1475.48 \text{ cm}^3/\text{g}$ total pore volume when they were synthesized by using sodium hydroxide (NaOH) as an activating agent compared to other materials [5]. On the other hand, eggshells, a widely generated food waste, have also been identified as a potential candidate for the production of activated carbon among the various materials under consideration based on their unique composition, high availability and eco-friendliness [6]. In eggshells, 94%–97% of the weight is accounted for by calcium carbonate. Organic compounds, calcium phosphate and magnesium carbonate are the other minor components [7,8]. The porous nature and stability of eggshells provide a sound foundation for the production of activated carbon, although calcium carbonate is not a widely used precursor for activated carbon [9].

Activated carbon (ACs) derived from agricultural waste, such as coconut husk, durian shell and egg shell, has the potential to be a cheap and environmentally friendly alternative compared to the conventionally used activated carbon produced from petroleum-based or hardwood materials [10]. Agricultural wastes are considered promising raw materials for the production of activated carbon due to their abundance and easy availability. Its better adsorption capacity and higher specific area and porosity have attracted considerable interest [11]. Their properties, economic efficiency, and low cost make them one of the most significant materials employed for various purposes. The main steps in the production of activated carbon are the raw materials that are carbonized below 1000°C in an inert gas atmosphere [12]. Then the raw materials are activated by a suitable oxidizing agent. In the carbonization step, the non-carbon materials would be removed from the raw materials. The carbon mass would remain unchanged. Hence, to enhance the adsorption capacity of the activated carbon, the size of the small pores would be increased during the activation step. New pores would be created. Besides, in physical activation, the precursors are carbonized first before being subjected to activation at a high temperature in the presence of an activating agent, which could be carbon dioxide or water vapor [13].

Chemical activation for the durian shell is provided through the use of phosphoric acid. The (H_3PO_4), which leads to dehydration of the lignocellulosic structure and thereby leads to early carbonization and formation of less amounts of tar [14]. Depolymerization of cellulose, hemicelluloses, and lignin will lead to the breakdown of the biomass structure. Moreover, cross-linking reactions induced by phosphoric acid, which preserve the altered carbon structure from collapse when exposed to elevated temperatures [15]. An effective porous framework composed mostly of micropores and mesopores will be achieved as the activation temperature is increased (500°C – 700°C).

In place of conventional chemical activation of eggshells, sodium sulfite creates a technique whereby pore formation is assisted by gas evolution [16]. Upon heating, the eggshell undergoes decomposition into CaO and CO_2 . Sodium sulfite assists in generating other gases such as SO_2 . The simultaneous release of gases results in the exertion of pressure inside the material, thus creating pores and an expanded structure [17]. Unlike phosphoric acid activation, which relies on bond breakage and carbonaceous framework formation, this approach is based on the principle of physical expansion and absence of particle compaction [14]. Due to its main characteristics of mesopore and macropore structures and low specific surface area, this eggshell-based material is appropriate as a structural component of composites.

Due to its large surface area, variable porosity, and surface functional groups, activated carbon derived from durian and eggshells has been extensively examined and utilized for a variety of applications. These adsorbents are utilized in the removal of organic pollutants, dyes, and heavy metals in wastewater treatment, which is one of their most important applications [18]. Moreover, based on their developed microporous texture, adsorbents are utilized in gas adsorption and air purification, especially in the adsorption of carbon dioxide and toxic substances [19]. The porous texture is beneficial in enhancing the activity and stability of catalyst support, which is another important application. Their application in energy storage devices, especially supercapacitors and lithium-ion batteries, has been given more attention in recent times [19]. Activated carbon is an excellent electrode material due to its high surface area, allowing rapid transport of ions, as well as storing them quickly [20]. Moreover, the introduction of pseudo-capacitive effects is possible with the incorporation of heteroatoms, for example, nitrogen and oxygen, thus improving the electrochemical properties of the material [21]. Therefore, the application of durian and eggshell-derived activated carbon has tremendous potential as a green, economic, and innovative material in the field of energy storage devices [9]. Most of the studies related to biomass-based activated carbon have only focused on precursor mixtures that contain a single component. This poses some limitations since it would be hard to improve both pore architecture and functionality simultaneously. Since eggshell, for instance, consists mainly of calcium carbonate (CaCO_3), an inorganic compound, its usage can help in widening pores and strengthening the structure via thermal decomposition reaction. On the other hand, durian shell, as a lignocellulose-type material, can lead to the production of carbonized micropores. However, more studies need to be done on their mixture usage.

This indicates that the synthesized activated carbon has potential for application in energy storage applications, such as a supercapacitor electrode material. It is advocated that future studies be executed on the optimization of the activated carbon, such as the ratio of the agro-waste material and concentration of the activating agent, in order to improve the properties of activated carbon. As well as to determine the electrochemical performance, cyclic voltammetry (CV), galvanostatic charge-discharge (GCD) and electrochemical impedance spectroscopy (EIS). This technique analysis can determine the specific energy capacity and the performance of the activated carbon to make sure that it is compatible in replacing it with the commercialized activated carbon. This research has established that durian shell and eggshell agricultural waste can be used as viable and effective precursors in the formation of activated carbon to be used in energy storage. The discovery of optimization of the activation temperature was crucial, and 600°C was identified as the optimal temperature of durian shell and 700°C for eggshell. The durian shell was converted into activated carbon, which was found to be superior in terms of porosity, carbon content, and surface morphology, which are favorable to the augmented adsorption and electrochemical performance. On the other hand, activated carbon of eggshell, whose composition included a high percentage of calcium carbonate, had better structural stability and surface utility. The activation of sodium sulfite (Na_2SO_3) and orthophosphoric acid (H_3PO_4) also amplified the formation of functional groups and pore structures. The results support the importance of the synergistic approach to various Agricultural wastes since they can acquire complementary properties, making them potential prevention of alternative, low-cost, and green materials toward superior energy storage devices like supercapacitors.

2 Materials and Methods

2.1 Materials and Chemicals

The durian shell and eggshell were collected from a local market (Shah Alam Night Market, Malaysia). It was rinsed and cleaned by using distilled water to remove the dirt and dried in the oven at 105°C for 24 h. Then, the samples were ground into a smooth powder. The chemical used consists of sodium sulfite

(Na_2SO_3), nickel nitrate $\text{Ni}(\text{NO}_3)_2$ and orthophosphoric acid (H_3PO_4). Eggshell and durian shell selection is independent of biological sources and functional materials design strategy. Eggshell, which contains high levels of calcium carbonate, acts as both an activator and templating agent, while the durian shell acts as an effective carbon source [22]. Due to the synergistic effects between the two, their combination enables the hierarchical carbon material to be produced through thermal treatment. Through pore formation, increased surface area, and enhanced ion transport properties, this hybridization method yields a material well-suited for energy storage purposes. The difference in the chemical composition and activation of the two precursors is what causes the differences in the impregnation ratios for durian shells (1:1) and eggshells (1:4). Durian shells have a lot of cellulose, hemicelluloses, and lignins. They undergo dehydration, depolymerization, and cross-linking reactions during their activation, chemically, such as using H_3PO_4 . This leads to the formation of a very developed porous carbon network even at the comparatively lower impregnation ratio. As for eggshell, its composition consists of CaCO_3 , which inherently has no carbon atoms. This means that it acts as an even better catalyst during the process of activation since its purpose is to serve as a better substrate. In addition, it should be noted that using activating agents, such as Na_2SO_3 , to improve porosity is required because the increased impregnation ratio (1:4) is to ensure effective interaction between the substrate and activating agent to create pores. It should be mentioned that CaCO_3 is broken down into CaO and CO_2 upon heating.

2.2 Synthesis of Activated Carbon

2.2.1 Synthesis of Durian Shell Activated Carbon

The durian shell was cleaned and rinsed using distilled water to remove the dirt and dried in the oven for 105°C for 24 h (Fig. 1). Then, it was break into small pieces and ground into a smooth powder form. The activating agent, sodium sulfite (Na_2SO_3) was added with a ratio of 1:1 into the sample [23]. After the impregnation process, the sample was placed in an alumina boat and went into a horizontal tube furnace purged with nitrogen gas (N_2) at 500°C (5°C min^{-1}) for one hour. This step was repeated for 3 different temperatures, which are 500°C , 600°C and 700°C .

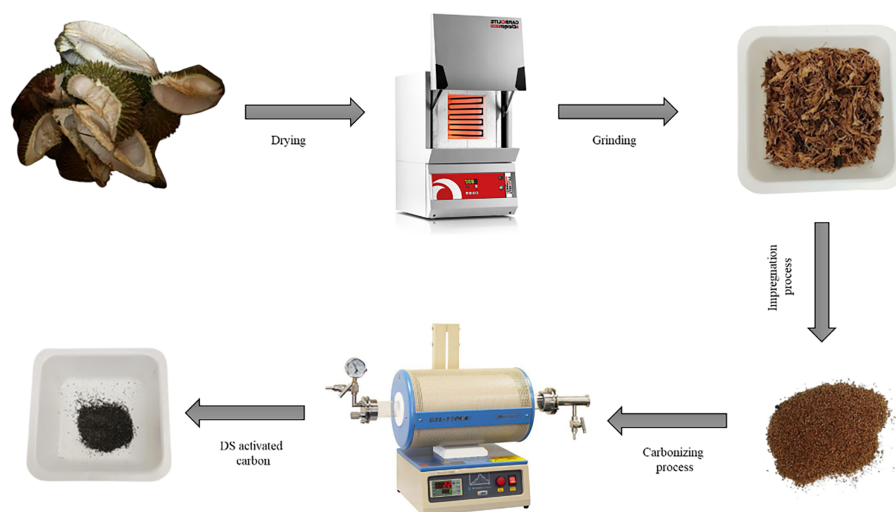


Figure 1: Process of synthesising durian shell activated carbon.

2.2.2 Synthesis of Eggshell Activated Carbon

The eggshell that had been collected was rinsed with distilled water to remove the impurities and dried in the oven for 110°C for 2 h (Fig. 2). Then, it was ground until it turned into a very smooth fine powder. The sample was placed in a crucible and went into the oven for 6 h at 110°C. After that, the powder was thoroughly combined with orthophosphoric acid (H_3PO_4) and let it soak for 24 h with a ratio of 1:4 [24]. The solution was stirred for 2 h and poured through a sheet of filter paper. The filtered solid was collected and put in an oven for another 24 h at 110°C to remove any leftover moisture. After the drying process, the sample obtained was placed in an alumina boat and heated in the furnace for 2 h at 500°C. This step was repeated for 3 different temperatures, 500°C, 600°C and 700°C.

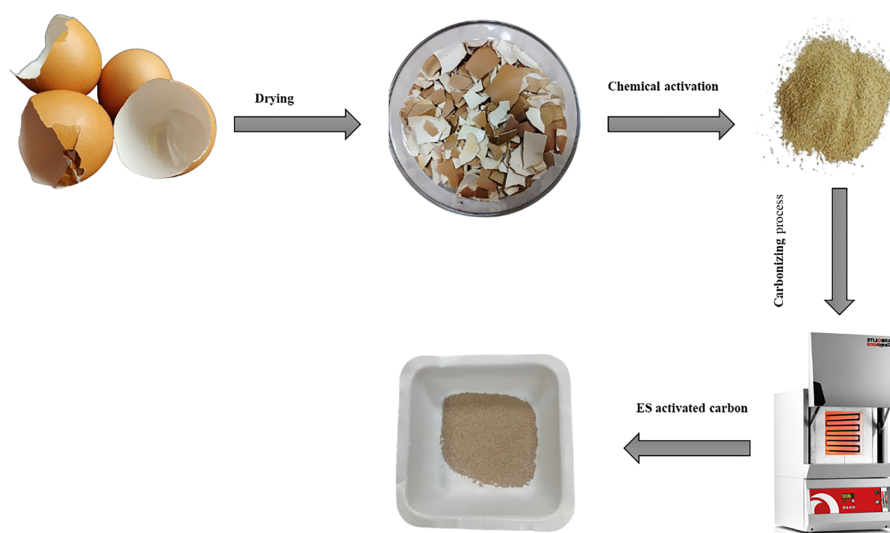


Figure 2: Process of synthesizing eggshell activated carbon.

2.3 Characterization Techniques

The physical properties of the activated carbon were characterized by Fourier Transform Infrared spectroscopy (FTIR), X-Ray Diffraction (XRD), Energy Dispersive X-Ray (EDX) and Scanning Electron Microscopy (SEM) and the electrochemical analysis with cyclic voltammetry, impedance analysis is provided. The FTIR spectra of the synthesized activated carbon was between 500 to 4000 cm^{-1} using AVATAR 360 Spectrophotometer. The chemical bonds in the molecule can be determined by generating an infrared absorption spectrum for functional group classification. The spectrum of absorbance generated by FTIR shows the sample material's molecular structure with a different chemical bond. Other than that, the crystalline structure of the activated carbon was carried out using Malvern Panalytical's X'Pert³ diffractometer. This XRD analysis was used to determine the crystalline or amorphous nature of the synthesized activated carbon formed during the carbonization process. On the other hand, major components like carbon (C), oxygen (O), and calcium (Ca) derived from the samples are confirmed by EDX analysis. The purity of the carbon material and the efficiency of the carbonization process are revealed by the composition.

3 Result and Discussion

3.1 Results

3.1.1 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) analysis was carried out to identify the surface functional groups present on the activated carbon prepared from the waste durian shell, which was activated at three different temperatures, 500°C, 600°C, and 700°C. The FTIR spectra in Fig. 3 exhibited specific bands within the 4000–500 cm^{-1} region, which were due to the presence of aromatic carbon structures and surface functional groups containing oxygen. The asymmetric and symmetric stretching vibrations for the aliphatic C-H bonds, especially those for the CH_2 group, are responsible for the peaks observed at approximately 2920 and 2850 cm^{-1} . The observed peaks imply that the remnant aliphatic hydrocarbon structures from the initial biomass components used in the durian shell may be present [25].

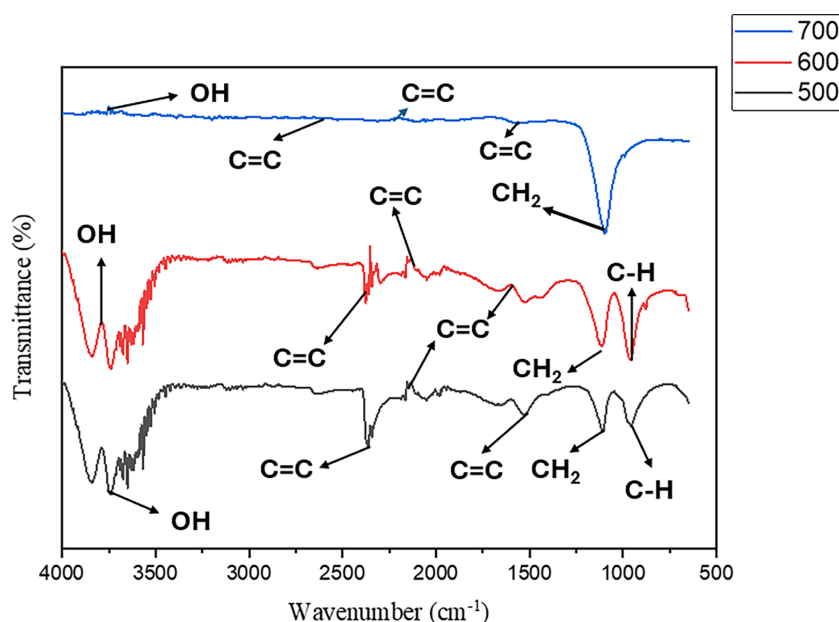


Figure 3: FTIR spectra of durian shell activated carbon.

The C=C stretching vibration for the aromatic rings is depicted by another peak observed approximately at 1650 cm^{-1} . This peak implies that aromatic carbon structures are being formed during the pyrolysis process [26]. This band indicates that as the activation temperature is increased during the thermal treatment, a more compacted carbon structure is formed [27]. On the other hand, from Fig. 4, the stretching vibrations of hydroxyl (-OH) surface functional groups are shown by a broad absorption band, which is typically present in the range of 3450–3440 cm^{-1} . This may be attributed to alcohol functional groups present on the surface of activated carbon, phenolic chemicals, or moisture [28]. The intensity of these peak decreases with an increase in activation temperature, implying that these surface functional groups are removed during the carbonization process [29].

The FTIR results clearly indicate that hydroxyl, carbonate, and carbon-based functional groups are present in the activated carbons derived from both durian and egg shells [30]. Nevertheless, there are clear differences that can be established between the two precursors. The FTIR results indicate that more carbon-based functional groups, especially aromatic C=C and aliphatic C-H, are present in the FTIR spectrum of

the activated carbon derived from durian shells [4]. The FTIR results also indicate that more carbonate-based functional groups are present in the FTIR spectrum of the activated carbon derived from eggshells. This is because the structure of eggshells is composed of calcium carbonate (CaCO_3). In addition, durian shell samples showed a greater reduction in hydroxyl ($-\text{OH}$) peak intensities with increasing temperature, implying the development of porous carbon structures with greater efficiency in the removal of volatile matter [31]. Based on the findings of this study, durian shell may be more suitable for carbon-rich activated material preparation, while eggshell contains inorganic elements that may enhance surface characteristics and structural stability as a composite material.

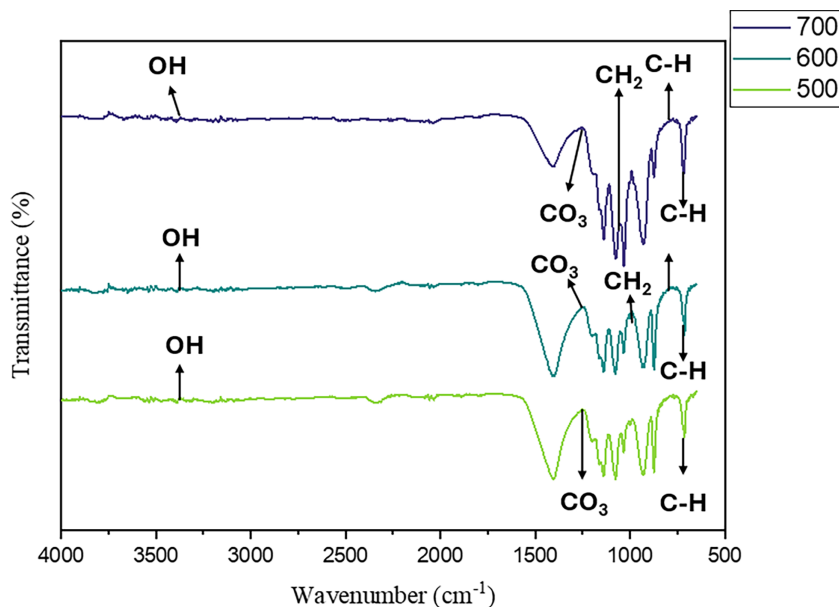


Figure 4: FTIR spectra of eggshell activated carbon.

From Fig. 5, organic and inorganic functional groups appear in the FTIR spectra of hybrid activated carbon. The O-H stretching vibration produces the broad peak between $3200\text{--}3600\text{ cm}^{-1}$, which reduces with increasing temperature due to dehydration and destruction of hydroxyl groups. The formation of graphitic carbon through degradation of lignin is evidenced by the peak of about 1600 cm^{-1} , corresponding to the stretching vibration of aromatic $\text{C}=\text{C}$ bond. Peaks observed in the $1000\text{--}1200\text{ cm}^{-1}$ region arise from the stretching vibration of C-O bonds, which reduce with increasing temperature due to the decomposition of oxygen-containing functional groups. Also, peaks at 1400 , 870 , and 710 cm^{-1} suggest the presence of carbonate ions (CO_3^{2-}) arising from CaCO_3 formed from eggshell.

The FTIR spectra confirms that hydroxyl groups, carbonate groups, and carbon-based groups are present in the activated carbon obtained from eggshells. The presence of carbon-based groups confirms that carbon structures are formed during pyrolysis, whereas the presence of carbonate groups confirms that calcium carbonate is introduced during the eggshell precursor material [32]. The variation of peak intensity during increasing temperature levels indicates that higher temperature helps break down organic components into activated carbon.

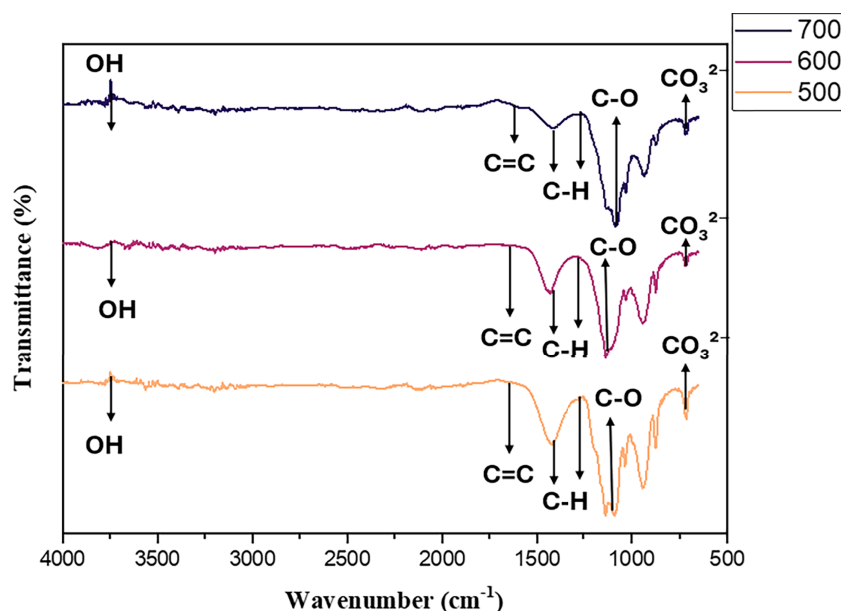


Figure 5: FTIR spectra of hybrid activated carbon.

3.1.2 X-Ray Diffraction (XRD)

XRD of Durian Shell Activated Carbon

The physical analysis was executed by X-Ray diffractometer to characterize the synthesized activated carbon. This study was used to determine the crystalline or amorphous nature of the durian shell and eggshell activated carbon. Figs. 6–8 display the XRD spectra of synthesized waste activated carbon at 500°C, 600°C and 700°C. Fig. 6 shows the XRD patterns of activated carbon samples from durian shell heat-treated at 400°C, 500°C, and 600°C. The diffraction pattern at 500°C is distinguished by a wide and scattered peak around $2\theta = 20^\circ\text{--}30^\circ$, which normally represents the (002) plane in turbostratic and amorphous carbons [33] which is in good agreement with the standard reference pattern (JCPDS Card No. 41-1487) hexagonal graphite (C). This pattern indicates that there is a lack of graphitic layer growth since there are very few organized layers of graphitic carbon. In addition, this means that there is not sufficient heat energy to facilitate any significant structural changes due to the absence of graphitic peaks [34]. Besides the amorphous pattern, there are also some weak, sharp peaks, which may represent inorganic minerals such as silica and other metal oxides found within the durian shells [35]. Even after carbonization, these mineral impurities remain embedded in the carbon matrix.

Even though the sample still retains largely amorphous behaviour, there is a slight increase in clarity of the peak structures upon elevation of the activation temperature to 600°C, as observed from the XRD spectrum in Fig. 6. A gradual build-up of graphite-like order is inferred from the broadening (002) peak becoming more pronounced. This means that in this case, partial reordering of carbon layers is initiated. The removal of organic volatiles might lead to a higher content of the inorganic compounds, thus resulting in an intensified presence of the impurity crystal peaks.

In the case of the diffraction spectrum, the structural transformation occurs at the temperature of 700°C. Although the material appears to have become slightly sharper, thus suggesting an increased amount of structuring and ordering or stacking of aromatic rings, there is still a huge peak for carbon present, thus showing that the sample largely remains amorphous. However, the lack of (100) peak, which is normally observed at about $2\theta = 42^\circ\text{--}44^\circ$ for well-ordered graphite, suggests that there is still turbostratic carbon

present and that graphitization of the material has not occurred [36]. Thermal stabilization or phase transition of the inorganic components of the compound seems to explain the sharpness observed in some crystalline peaks.

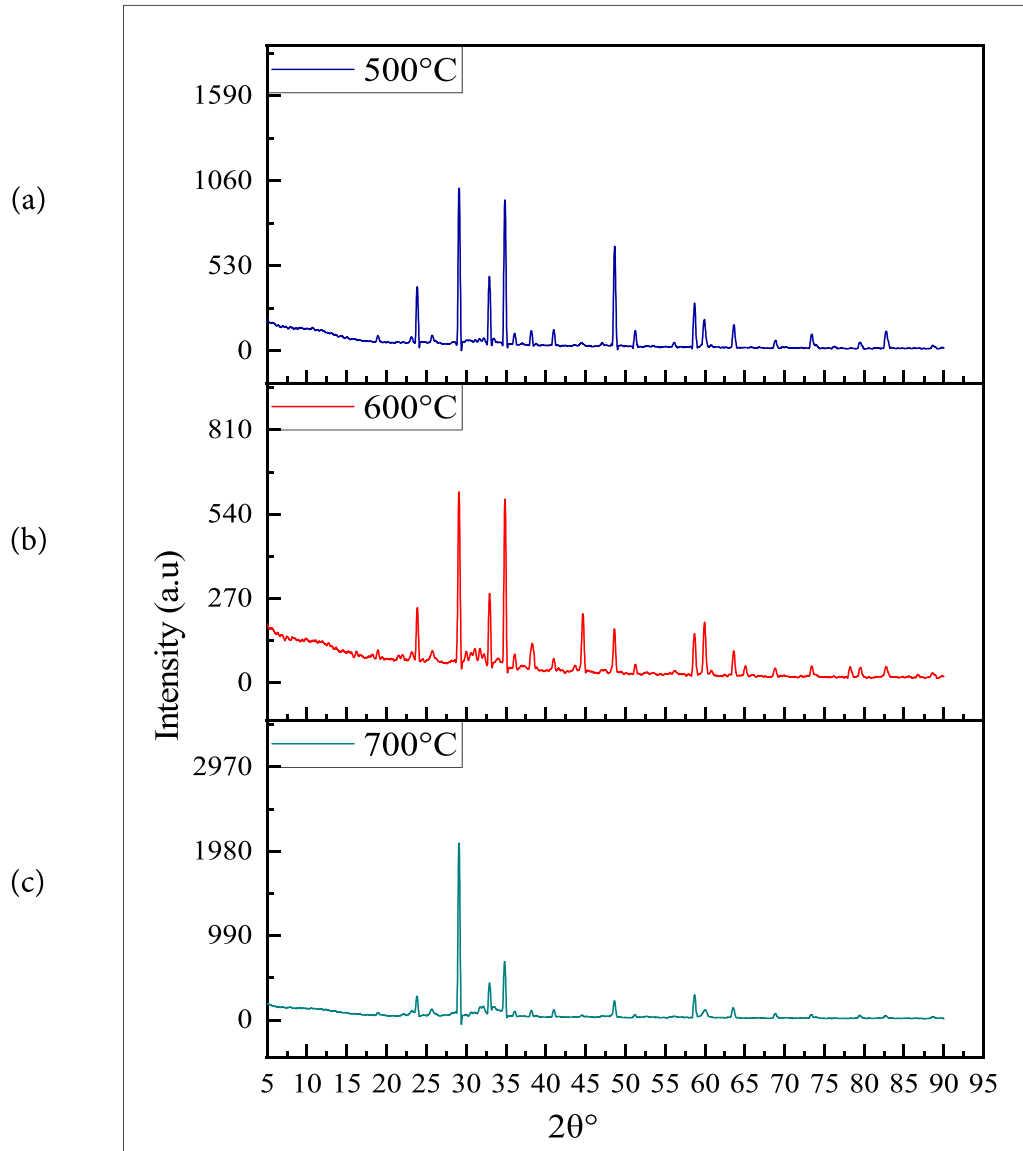


Figure 6: XRD of durian shell activated carbon; (a) the durian shell activated carbon synthesized at 500°C, (b) synthesized at 600°C and (c) carbon synthesized at 700°C.

XRD of Eggshell Activated Carbon

Fig. 7 presents eggshell-derived activated carbon samples heat-treated in the range of 500°C to 700°C X-ray diffraction (XRD) patterns. The diffraction patterns exhibit characteristic peaks at several 2θ positions with a great variation in peak sharpness and intensity while increasing temperature. These are manifestations of the phase transformation and structural rearrangement of the inorganic as well as the carbonaceous components of the eggshell upon carbonization and activation.

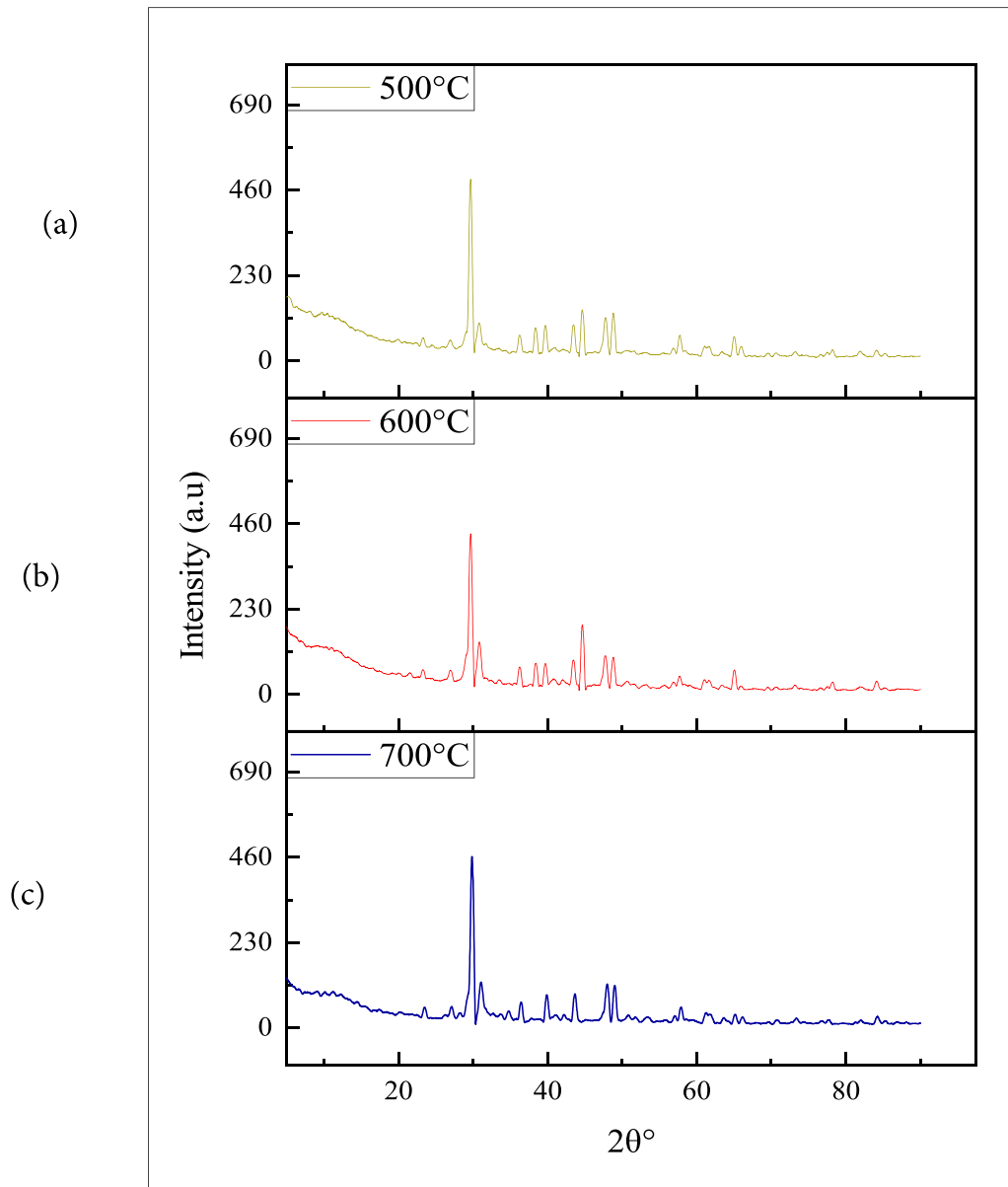


Figure 7: XRD of eggshell activated carbon; (a) the eggshell activated carbon synthesized at 500°C, (b) synthesized at 600°C and (c) carbon synthesized at 700°C.

On the other hand, at 500°C, the principal peaks are at the same values of 2θ ($\approx 29^\circ$, 36° , 39° , 43° , 47° , 48° , 57°), but with slightly lower intensities. This drop indicates the beginning of calcite decomposition, since CaCO_3 decomposes thermally into calcium oxide (CaO) and carbon dioxide [37]. Due to the presence of many sharp peaks and a relatively low amorphous background, the eggshell material obviously remains very crystalline, with its major constituent being calcium carbonate (calcite) from the original composition of the eggshell. At this temperature, carbonization is incomplete and organic matter is partially broken down.

This phase transformation normally starts around 600°C, in much the same way that the initial slight decomposition can occur before heating rate and sample morphology. The stability of these sharp peaks ensures that the inorganic matrix remains primarily crystalline in nature, while organic carbon composition begins to form with a view to amorphous carbon [38]. While some calcite peaks are broadened and weakened,

new diffraction peaks are observed at 600°C. The large-scale decomposition of CaCO_3 and formation of crystalline CaO phases characterize this stage, normally through strong reflections around $2\theta \approx 32^\circ$, 37° , 54° , and 64° representative of CaO characteristic planes. These peaks show that the structure now consists of amorphous carbon and nanocrystalline CaO. This means that a significant breakdown of the eggshell's calcium carbonate has occurred [39].

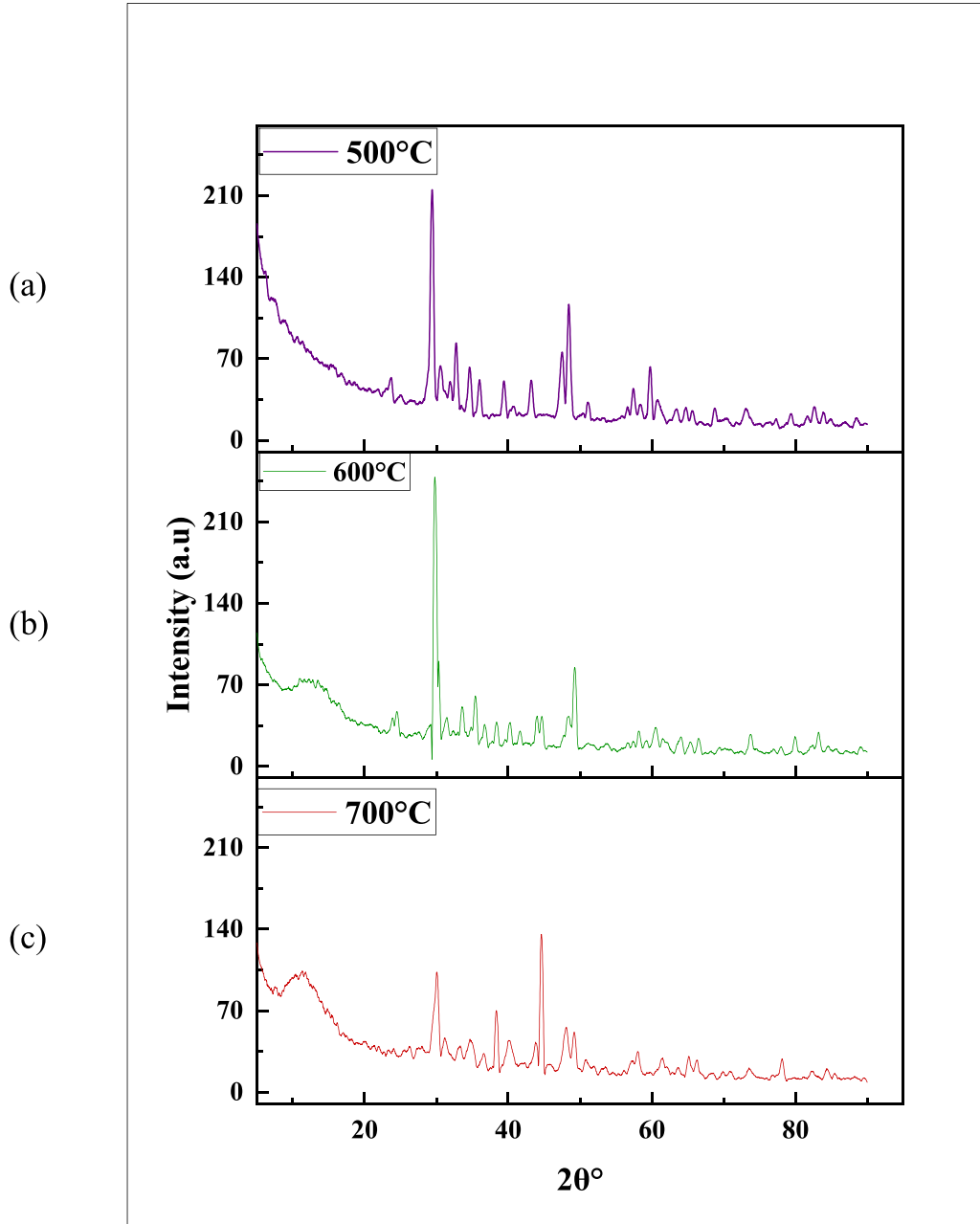


Figure 8: XRD of hybrid activated carbon; (a) the activated carbon synthesized at 500°C, (b) synthesized at 600°C and (c) carbon synthesized at 700°C.

The peaks that refer to CaO are even sharper at 700°C with higher intensity, indicating grain growth and improved crystallinity of the CaO phase. In contrast, the broad peaks observed in the 20° – 25° range become

progressively more defined, which can be attributed to the amorphous carbon matrix from the organic matter of the eggshell. This is a typical association of an amorphous carbon structure with crystalline CaO inclusions in biogenic carbon materials from Ca-rich precursors.

XRD of Hybrid Activated Carbon

The XRD patterns obtained for the durian and eggshell-based hybrid activated carbon in Fig. 8 reveal the presence of both crystalline inorganic materials and amorphous carbon, pointing to the compositeness of the carbon. The samples of hybrid activated carbon have a broad diffraction peak centered at an angle of $2\theta = 20^\circ - 30^\circ$. As the peak is of relatively low intensity and broad, it indicates that the carbon phase in this carbon-based sample is mainly amorphous due to a lack of graphitic long-range ordering [40]. Such structural disorder in the carbon phase of activated carbon produced from biomass is typical and can be favorable for applications like energy storage [41].

The presence of crystal phases within the hybrid material structure is shown by the existence of numerous sharp diffraction peaks, other than the broad diffraction peak for the amorphous carbon. The chemical compounds derived from the eggshell material, whose source is abundant with CaCO_3 , are primarily responsible for the presence of such diffraction peaks. Calcite form of CaCO_3 is responsible for the strong reflections, particularly at approximately $2\theta = 29.4^\circ$, 39.4° , 43.1° , and $47^\circ - 48^\circ$ [42]. Narrowness and intense nature of these peaks suggest that there was much structural integrity maintained in the inorganic part following activation.

In addition to this, based on the specific conditions under which the activation takes place, the occurrence of further smaller peaks can be seen as an indication that the thermal decomposition of CaCO_3 results in the generation of calcium oxide (CaO) and calcium hydroxide ($\text{Ca}(\text{OH})_2$). This is because the thermal decomposition of CaCO_3 , resulting in CaO and CO_2 is a reaction taking place under high temperatures and fits the described case. In this case, the generation of CO_2 helps the carbon matrix develop pores within itself, giving it better texture [43].

Comparison of the diffraction curves shows that there are certain differences between the samples in terms of the amorphous background and the intensity of the crystal peaks. A higher fraction or better retention of the crystal structure of calcium-containing phases is shown by the sharpness and intensity of the peaks in the upper spectrum [44]. In contrast, the lower curve shows an amorphous hump of relatively high intensity and lower peak intensity. This may be due to either increased carbon or effective separation of inorganics from the matrix.

XRD peaks are, in general, weak and broader at 700°C , which may be because of the sintering of CaO particles or interaction of CaO with retained carbon to form calcium carbide (CaC_2) or mixed calcium compounds. The carbon hump at $2\theta \approx 25^\circ$ is more prominent, showing a higher degree of carbonization as well as randomly formed carbon. This amorphous carbon material finds its applications in adsorption and electrochemical energy storage, where there is a need for high surface area and disordered pore networks [45].

3.1.3 Energy Dispersive X-Ray (EDX) and Scanning Electron Microscopy (SEM)

The porosity of an adsorbent can be clearly seen in SEM micrographs of activated carbon, which display disordered surface structures with varying pore sizes and shapes. Some of the macropores were formed on the AC surface, as seen in Fig. 9. It was brought on by the carbon atom reaction and the volatile materials generated from (H_3PO_4). The carbon surface developed new pores, which are represented as holes. The activation process was the cause of it.

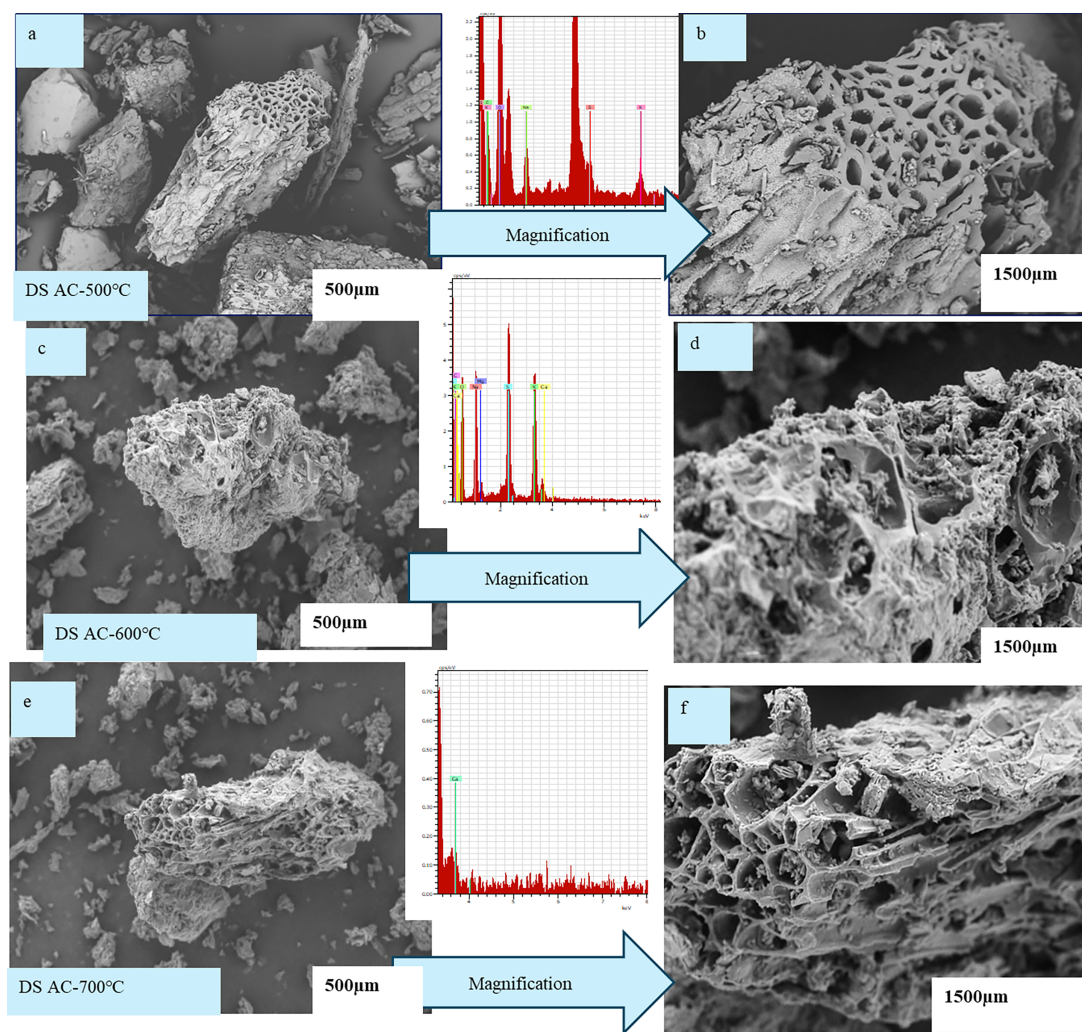


Figure 9: (a) The low Magnification of durian shell activated carbon synthesized at 500°C, (b) The high Magnification of durian shell activated carbon synthesized at 500°C, (c) The low Magnification of durian shell activated carbon synthesized at 600°C, (d) The high Magnification durian shell activated carbon synthesized at 600°C, (e) The low Magnification durian shell activated carbon synthesized at 700°C at different magnification, and (f) The high Magnification of durian shell activated carbon synthesized at 700°C.

The structural morphology of activated carbon was observed through the SEM method. The morphological point of view of activated carbon obtained from eggshell is that its shape is uneven. The SEM images of activated carbon are presented in Fig. 10. The activated carbon under investigation has an uneven structure of carbon, and the surface area is increased through the calcination process. One of the major factors that affect activated carbons is the thermal effect or temperature, where the active sites, which is the material absorption process that leads to micropores are formed through this process on the surface of activated carbon. The activated carbon obtained through the activation agent of NaOH is obtained due to its smooth surface with fewer micropores.

Confirmation of the successful conversion of the biomass precursor into carbonaceous material during the pyrolysis process is demonstrated through the results obtained from the EDX analysis, which indicated that the carbon (C) content is the dominant element within the prepared activated carbon. The presence of oxygen (O) can be related to the presence of functional groups on the surface of the activated carbon,

which contain oxygen, such as hydroxyl, carbonyl, or carboxyl groups, which are often developed during the activation step.

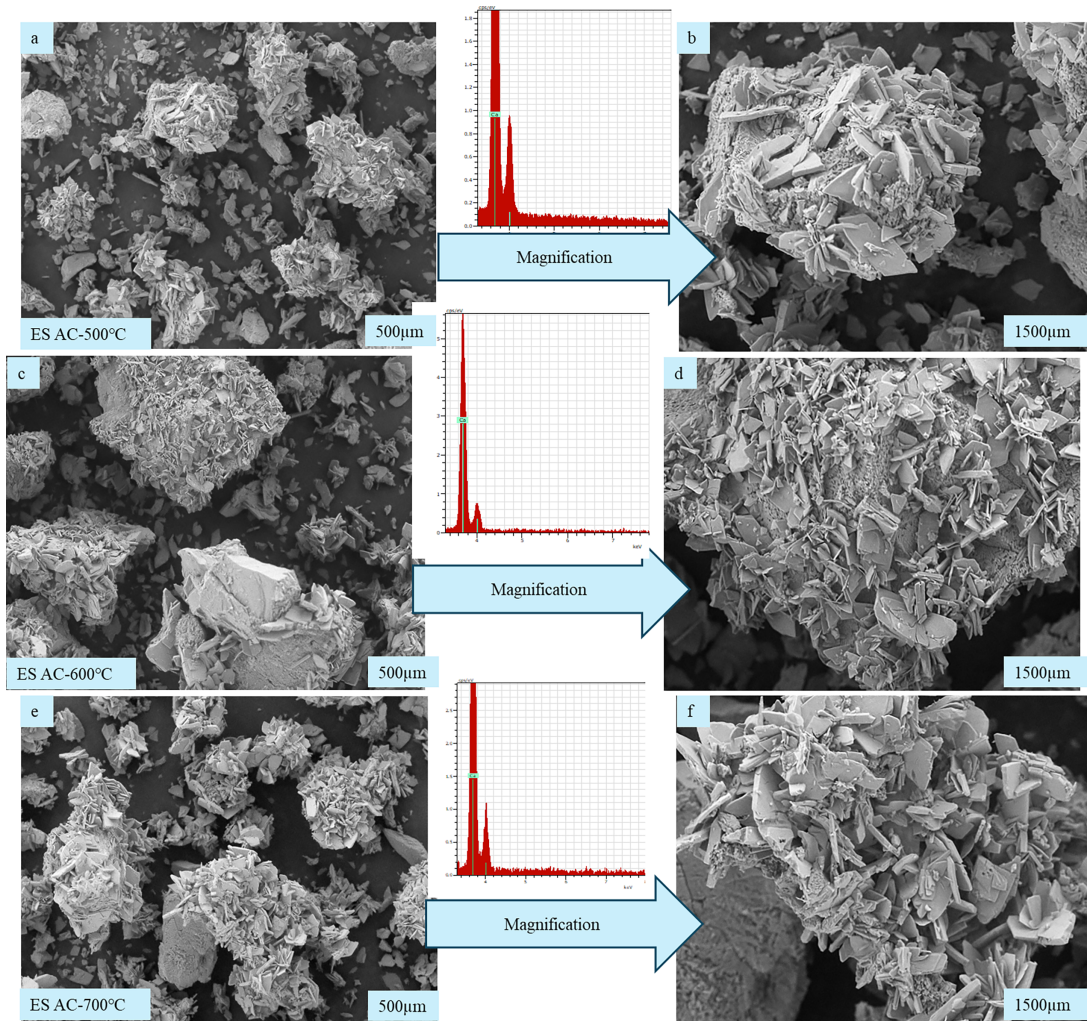


Figure 10: (a) The lower magnification of eggshell activated carbon synthesized at 500°C, (b) The higher magnification of eggshell activated carbon synthesized at 500°C, (c) The lower magnification of eggshell activated carbon synthesized at 600°C, (d) The higher magnification of eggshell activated carbon synthesized at 600°C, (e) The lower magnification of eggshell activated carbon synthesized at 700°C, (f) The higher magnification of eggshell activated carbon synthesized at 700°C.

A remarkable morphological change can be observed in the SEM images of the composite activated carbon prepared from durian shell and eggshell at different temperatures (500°C, 600°C, and 700°C). From Fig. 11, the hybrid activated carbon appears dense and irregular in structure, with larger agglomerated grains and low visibility of porosity, at 500°C. The presence of fragments showing traces of biomass material leads to an uneven and coarse appearance on the surface. The absence of fully formed pores suggests that this activation process is not adequate for improving the formation of pores or fully decomposing the volatile components [46]. However, there are signs of surface etching and small holes, indicating that partial activation and thermal degradation have started to occur. It is proven that the presence of elements such as carbon (C), oxygen (O), and calcium (Ca) through EDS spectra confirms the successful addition of inorganic additives extracted from eggshells. There is a clear difference in the morphology that occurs at an activation

temperature of 600°C. The formation of a highly porous and interconnected network that is characterized by visible pores and channels is illustrated by the SEM images. It is important to note that there emerges an architecture similar to a honeycomb, an indication of successful activation and the release of volatile compounds. This is caused by the decomposition of CaCO_3 to form CaO and CO_2 gas, where CO_2 functions as a pore former within the carbon network [47]. There is a perfect ratio of pore formation and structural maintenance as a result of increased porosity and connectivity at this point. The prominent peaks for carbon and calcium obtained from EDS imply that the inorganic material may still be present within the carbon matrix and help provide structural stability.

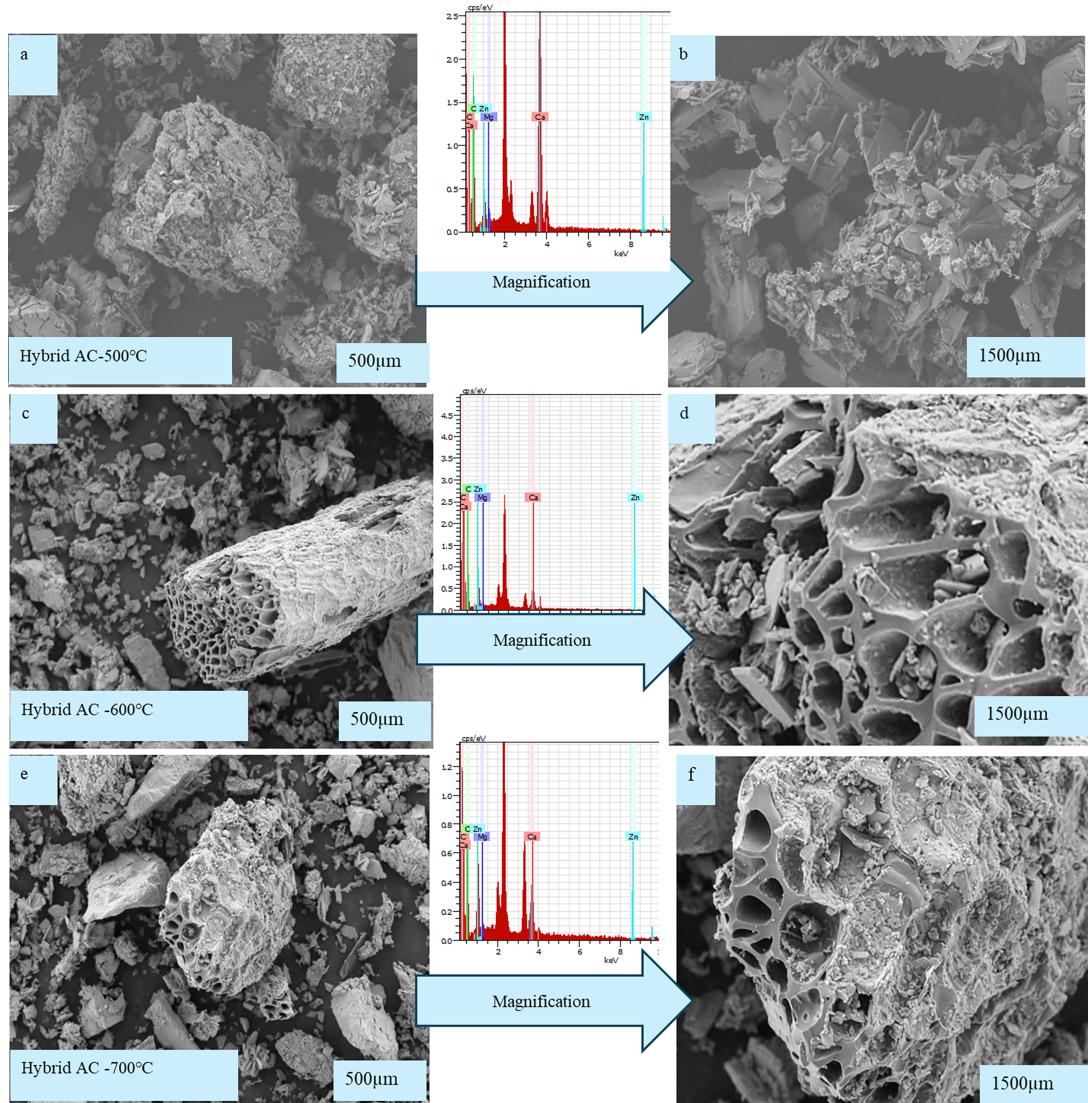


Figure 11: (a) The low magnification of eggshell activated carbon synthesized at 500°C, (b) The high magnification of eggshell activated carbon synthesized at 500°C, (c) The low magnification of eggshell activated carbon synthesized at 600°C, (d) The high magnification of eggshell activated carbon synthesized at 600°C, (e) The low magnification of eggshell activated carbon synthesized at 700°C at different magnification, (f) The high magnification of eggshell activated carbon synthesized at 700°C.

Despite the increased porosity development at 700°C in the activated hybrid material, there is a clear sign of structural degradation and pore expansion. The formation of large macropores, along with partial collapse of the structure, can be observed, implying that the high temperature leads to burn-off and over-activation. There are traces of fracturing in some spots, while the wall thickness is lower than before. However, since the elevated temperature favors the breakdown of CaCO_3 and the release of gases, it could result in the merging of smaller pores and their conversion into larger ones [48]. This will reduce the total amount of micropores and surface area, and yet, there is an extremely porous structure, which could be beneficial for fast diffusion. The formation of calcium compounds, such as CaO at the high temperature might contribute to the rise in the EDS spectrum intensity. The carbon obtained from the shell of the durian fruit possesses an advanced porous system, whereby pores are formed due to the thermal decomposition of the lignocellulosic compounds followed by chemical activation, thus promoting bond breaking and gas liberation to produce a relatively uniform microporous arrangement. In contrast, since CaCO_3 is an inorganic compound, the product obtained from the shell of the eggs exhibits a more diverse surface morphology. Rather than forming a consistent pore system, CaCO_3 decomposes to form CaO and CO_2 upon calcination, hence disrupting the structure and forming irregularly shaped pores and fissures.

The morphological evolution can be seen in the SEM images of the hybrid activated carbon formed from durian shell, eggshell and hybrid at different temperatures (500°C, 600°C, and 700°C). The results provide insights into the roles of temperature and synergistic effects between the precursors and the biomass during activation.

3.2 Electrochemical Analysis

The synthesized activated carbon of durian and eggshell above was tested for electrochemical analysis performance to understand its behavior on energy storage devices. The optimum temperature of 700°C was chosen for both activated carbon and the hybrid parameters. The Fig. 12 illustrates a comparison of cyclic voltammetry (CV) curves of durian shell-activated carbon in 1 M KOH electrolyte under 0.20–0.55 V potential range at varying scan rates (20–100 mV/s). The use of CV to determine the capacitors' performance and electrochemical properties of electrode materials is a common practice. These curves have a quasi-rectangular shape with minor deviation, which is a typical behavior of the capacitance of electric double-layers. This implies that the redox reaction at the electrode-electrolyte interface is mainly electrostatically adsorption of electrostatically charged ions than by a faradaic redox process. The fact that redox peaks are not very strong also proves that the material acts predominantly as a non-faradaic capacitor. The increase of the scan rate (20–100 mV/s) graduates to an equal increase of the current response. This is not surprising since increased scan rates will result in increased ion motions and current flows. The shape of the CV curves was relatively retained at higher scan rates, which is indicative of the good rate capability and efficient movement of the ion in the porous structure of the activated carbon.

Nonetheless, there are minor distortions and deviation of the ideal rectangular shape at the greater scan rates, which replicate internal resistance and diffusion limitation. When such higher scan rates are used, the smaller pores may not be completely penetrated by the electrolyte ions, which decreases the effective capacitance. The area in the loop of each CV curve is the amount of charge stored; therefore, bigger areas at higher scan rates indicate higher currents, but do not necessarily mean bigger capacitance. A more precise comparison of capacitance should take into account the shape consistency as opposed to the mere size of current. Cumulatively, the CV outcome indicates that the durian shell-based activated carbon exhibits excellent electrochemical stability, fast charge-discharge kinetic performances, and has considerable capacitive characteristics, which make it an excellent choice in the usage of durian shell-derived activated carbon as a supercapacitor electrode [49].

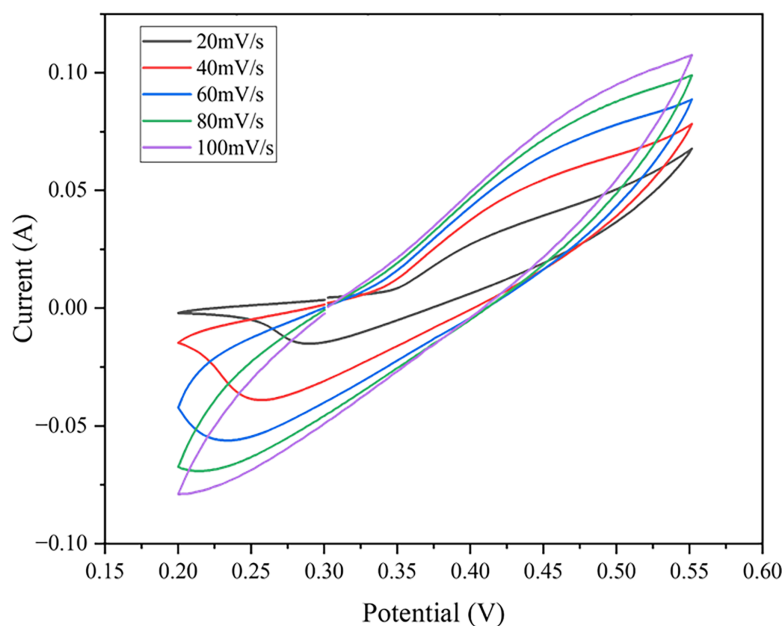


Figure 12: Cyclic voltammetry curves of durian shell activated carbon at optimum temperature of 700°C in 1 M KOH vs. Ag/AgCl, Pt (0.20 to 0.55 V) at different scan rate.

The Fig. 13 shows cyclic voltammetry (CV) curves of eggshell-based activated carbon in 1 M KOH electrolyte with the potential increasing 0.20–0.55 V at various scan rates (20–100 mV/s). CV is a key electrochemical method employed to assess charge storage in behaviour, reversibility and capacitive performance of electrode materials in the applications of supercapacitors. As compared to a perfect rectangular CV profile, which is related to pure electric double-layer capacitance (EDLC), the curves in this case show significant distortion and the existence of large humps, especially at levels to 0.30 to 0.40 V. All these characteristics show that pseudocapacitive behavior can be found on top of EDLC. This is an indication that surface redox reactions aid in charge storage presumably by functional groups or heteroatoms added in the process of activating the eggshell-derived carbon. The result has a good electrochemical response because as the scan rate rises (ranging between 20 and 100 mV/s), the current response rises in lock step with the scan rate. The overall shape of the CV curves is the same in all requested scan rates, indicating a good rate capability and rapid charge propagation through the electrode material.

The growing distortion with a higher scan rate is, however, a sign of kinetic restrictions wherein electrolyte ions are no longer able to reach all the available pores, and particularly the micropores within the limited time permeability. The cathodic and anodic sweeps exhibit asymmetry, and this suggests the irreversibility of the redox processes at the electrode and internal resistance. The effect is usually ascribed to resistance due to ion diffusion and polarization, which increase with scan rates. The area under each CV curve is the sum of the charge stored. Even at higher scan rates, the currents peak, but low scan rates are more useful than high scan rates in measuring effective capacitance, since at higher scan rates the diffusion of ions is not fully accomplished and the curves are less flattened. Eggshell-derived activated carbon analysis shows that the activated carbon has a behavioral mixture of an EDLC and a pseudocapacitive behavior with a fair electrochemical stability and a fair rate performance. These characteristics allow it to be a promising, inexpensive and sustainable low-cost electrode material in energy storage devices like the supercapacitors soon it only needs to be optimized by removing resistances and enhancing ion accessibility.

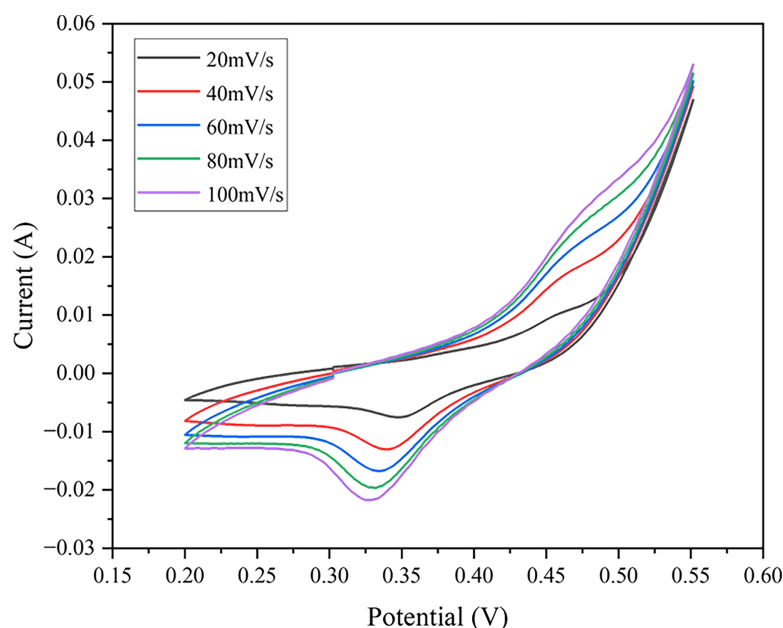


Figure 13: Cyclic voltammetry curves of eggshell activated carbon at 700°C in 1 M KOH vs. Ag/AgCl, Pt (0.20 to 0.55 V) at different scan rate.

Fig. 14 presents cyclic voltammetry (CV) curves of hybrid activated carbon measured in 1 M KOH electrolyte within a potential window of 0.20 to 0.55 V at scan rates ranging from 20 to 100 mV/s. CV analysis is widely used to investigate electrochemical behavior, charge storage mechanism, and the suitability of electrode materials for energy storage devices such as supercapacitors. The CV curves exhibit a semi-rectangular shape with slight distortions and weak humps, indicating a combination of electric double-layer capacitance (EDLC) and pseudocapacitive behavior. The EDLC component arises from the electrostatic adsorption of electrolyte ions on the porous carbon surface, while the small deviations suggest additional faradaic redox reactions, likely due to surface functional groups or heteroatom doping in the hybrid structure. This dual charge storage mechanism is advantageous, as it enhances the overall capacitance compared to pure EDLC materials. As the scan rate increases from 20 to 100 mV/s, the current response increases proportionally, and the CV curves retain a relatively consistent shape [50]. This indicates excellent rate capability and rapid charge–discharge characteristics. The ability of the curves to maintain their profile at higher scan rates suggests efficient ion transport and good electrical conductivity within the hybrid activated carbon. Such behavior is typically associated with a well-developed pore structure that includes both micropores for charge storage and mesopores/macropores for ion diffusion pathways. However, minor distortions and increased polarization at higher scan rates are observed, which can be attributed to internal resistance and limited ion diffusion into smaller pores during fast charging conditions. Despite this, the overall symmetry between the anodic and cathodic sweeps remains relatively good, indicating favorable reversibility and electrochemical stability.

The enclosed area under the CV curves increases with scan rate, reflecting higher current density, though true capacitance is more accurately assessed at lower scan rates where ion diffusion is more complete. Importantly, the absence of sharp redox peaks suggests stable cycling behavior and reduced risk of structural degradation over repeated charge–discharge cycles. The hybrid activated carbon demonstrates several key properties that make it highly suitable for energy storage applications, particularly supercapacitors. These include: (1) high-rate capability, enabling fast energy delivery; (2) combined EDLC and pseudocapacitive

mechanisms, leading to enhanced charge storage capacity; (3) good electrochemical reversibility and stability; and (4) efficient ion transport facilitated by a hierarchical pore structure. Together, these characteristics indicate that the material can deliver both high power density and reasonable energy density, which are critical for advanced energy storage systems.

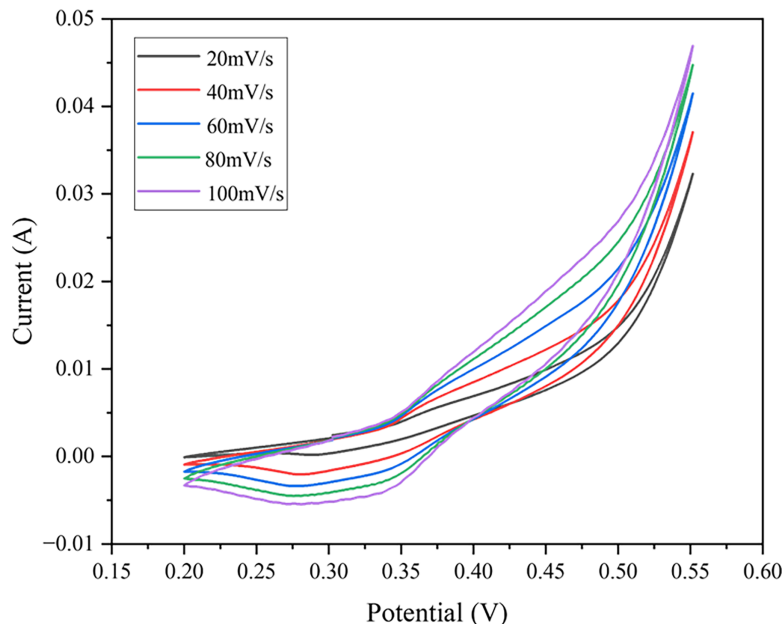


Figure 14: Cyclic voltammetry curves of hybrid activated carbon at 700°C in 1 M KOH vs. Ag/AgCl, Pt (0.20 to 0.55 V) at different scan rate.

3.3 Nyquist Plot of the Electrode Materials

Fig. 15 shows the Nyquist plot of activated carbon obtained by using durian shell (EDSN₂), eggshell (EES) and the hybrid precursor at 700°C wherein the impedance component of the real impedance Z' is drawn against the impedance component of the imaginary impedance $-Z''$. In electrochemical impedance analysis, the low- Z -value intercept of most curves would typically indicate an intrinsic ohmic resistance of the electrode material, whereas the slope and curve shape would indicate charge-transfer resistance and ion diffusion characteristics within the porous carbon structure. Out of the three samples, EDSN₂ (black squares) presents the lower values of both Z' and those of $-Z''$, thus presenting the lowest impedance value of an overall frequency range. This implies that durian-shell-based activated carbon is more electrically conductive and quicker to transport charges, potentially because of a more established conductive carbon framework and a superior connection of the pores. The relatively slightly increase of the EDPN₂ curve also suggests a decreased level of diffusion resistance, i.e., the ions of electrolytes may find their way through its pore system much more conveniently. The carbon (EES, red circles) obtained during the eggshell step shows the highest response in the impedance response, where Z' and $-Z''$ are rapidly rising to very high values. This means the internal resistance is greater and the movement of ions decreases. The sharp linear increase indicates that the material is more resistive, likely due to the high amount of calcium-based inorganic residue in-eggshell that decreases the conductivity of the electrons and precludes the creation of an effective porous carbon network once activated.

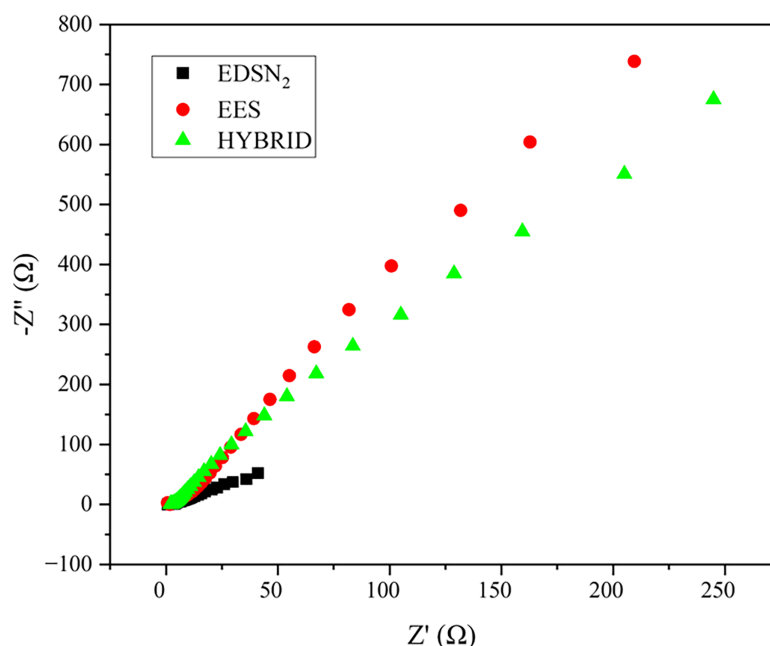


Figure 15: The Nyquist plot of durian shell, eggshell and hybrid activated carbon at 700°C.

The hybrid activated carbon (green triangles) shows medium behavior between EDSN₂ and EES. It has a lower impedance than EES and a higher conductivity than that of EDSN 2 meaning that the partial combination of durian shell and eggshell also boosts conductivity, albeit with some resistive properties aligning with the eggshell constituent. The hybrid structure probably enjoys the advantage of carbon-rich matrix of durian shell and the context of mineral phases of the eggshell that could affect the development of the pores. The fact that all three plots lack a marked semicircle would imply that capacitive behaviour is the dominant one over charge-transfer resistance, whereas the sloping linear tails suggest ion transport is dominated by diffusion. In general, the results of the Nyquist analysis indicate that the activated carbon derived based on durian-shell delivers the best electrochemical performance, the hybrid sample demonstrates a moderate improvement, and the activation of the eggshell-based carbon has the highest resistance at 700°C.

Variations in the performance of the three activated carbons at 700°C were shown by the electrochemical analysis. Durian shell-produced carbon (EDS) has almost perfect rectangular current voltage characteristic, with electric double-layer capacitance (EDLC)-like behavior and good ion transport, excellent conductivity, and low internal resistance. Carbon based on eggshell (M) Eggshell-derived carbon (EES) in turn demonstrates distorted CV curves with observable redox humps, which is evidence of contamination of the pseudocapacitive components, but with an increased resistance and worse ion diffusion potential because of retained inorganic character. The hybrid material has been able to combine both properties, exhibiting combining EDLC and pseudocapacitive properties with better conductivity and moderate impedance. The above results of EIS further validate that EDS has lowest impedance, hybrid intermediate, and EES highest resistance. In general, the hybrid electrode shows balanced charge storage, a good rate capability, and improved electrochemical stability. The results are best applicable in supercapacitor applications, especially when there is a need to trade-off between high power density (EDS) and improved energy density (hybrid).

4 Conclusion

In summary, the activated carbon was successfully synthesized from agricultural waste, which are durian shells and eggshells. Sodium sulfite (Na_2SO_3) and orthophosphoric acid (H_3PO_4) were utilized as activating agents in the pyrolysis method. The use of these agricultural waste materials helps to resolve the disposal of agricultural waste materials while providing a sustainable approach to the synthesis of activated carbon. In conclusion, the results revealed that activated carbon with good prospects for its structure and chemistry can be prepared from agricultural wastes, such as durian shell and eggshells. The optimization temperature for all the waste-based activated carbon was at 700°C . The utilization of these wastes provides a green and environmentally friendly approach for preparing activated carbon, which could be useful for environmental protection and adsorption purposes.

Conclusively, activated carbon produced at 700°C exhibits promising electrochemical behavior in storing energy. Durian shell carbon is the best in conductivity and quick charge-discharge characteristics, whereas eggshell carbon offers pseudocapacitive properties even at high concentrations. The hybrid material is a good mixture of both solutions and has better overall performance because it has good stability and transport. These results are continually confirmed by EIS and CV analysis, through the hybrid being an alternative electrode material with balanced properties. Thus, hybrids made out of biomass are a viable and environmentally friendly future candidate in terms of the manufacturing of supercapacitors, and their further history can be made to increase their conductivity, pore structure, and capacitance levels.

Acknowledgement: The authors wish to extend sincere gratitude to all those who have contributed to making this research study a successful one. In the first place, the authors thank their supervisors for their constant encouragement, invaluable guidance, and constructive criticism during this research study.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: Fatin Nadhirah: Investigations, Write the Original Manuscript, Methodology and Interpretation of Result. Surajudeen Sikiru: Conceptualizations, Supervision, Validation, Methodology, Data Accuracy and Interpretation of Results. Mohd Muzamir Mahat: Supervision, Validation. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Not applicable.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sah MK, Mukherjee S, Flora B, Malek N, Rath SN. Advancement in “Garbage in Biomaterials Out (GIBO)” concept to develop biomaterials from agricultural waste for tissue engineering and biomedical applications. *J Environ Health Sci Eng*. 2022;20(2):1015–33. doi:10.1007/s40201-022-00815-0.
2. Sikiru S, Dele-Afolabi TT, Yeganeh Ghotbi M, Rehman ZU. Recent advancements in technology projection on electric double layer effect in battery recycling for energy storage. *J Power Sources*. 2024;596(1):234056. doi:10.1016/j.jpowsour.2024.234056.
3. Brown MJ. *Durio*, a bibliographic review. Montreal, QC, Canada: McGill University; 1997.
4. Numee P, Sangtawesin T, Yilmaz M, Kanjana K. Activated carbon derived from radiation-processed durian shell for energy storage application. *Carbon Resour Convers*. 2024;7(2):100192. doi:10.1016/j.crcon.2023.07.001.
5. Foo KY, Hameed BH. Textural porosity, surface chemistry and adsorptive properties of durian shell derived activated carbon prepared by microwave assisted NaOH activation. *Chem Eng J*. 2012;187:53–62. doi:10.1016/j.cej.2012.01.079.

6. Yabalak E, Isik Z, Dizge N. Catalytical efficiency, mechanism and characterization of hydrolysed waste eggshell in the subcritical water oxidation of pistachio processing wastewater. *J Environ Manag.* 2022;317:115326. doi:10.1016/j.jenvman.2022.115326.
7. Azarian MH, Sutapun W. Biogenic calcium carbonate derived from waste shells for advanced material applications: a review. *Front Mater.* 2022;9:1024977. doi:10.3389/fmats.2022.1024977.
8. Ahmed TAE, Wu L, Younes M, Hincke M. Biotechnological applications of eggshell: recent advances. *Front Bioeng Biotechnol.* 2021;9:675364. doi:10.3389/fbioe.2021.675364.
9. Tsai C-H, Morgan HM Jr, Tsai W-T. Valorization of eggshell powder as a catalytic activation agent for producing porous carbon materials from lignocellulosic waste. *Catalysts.* 2025;15(8):712. doi:10.3390/catal15080712.
10. Kolawole FO, Kolawole ID, Udebhulu OD, Kolawole SK, Aba MM, Shamaki PB. An overview of the sources, structure, applications, and biodegradability of agricultural wastes. In: *Hybrid polymeric nanocomposites from agricultural waste*. Boca Raton, FL, USA: CRC Press; 2022. p. 21–44. doi:10.1201/9781003170549-3.
11. Saygılı H, Güzel F, Önal Y. Conversion of grape industrial processing waste to activated carbon sorbent and its performance in cationic and anionic dyes adsorption. *J Clean Prod.* 2015;93(10):84–93. doi:10.1016/j.jclepro.2015.01.009.
12. Blachnio M, Derylo-Marczewska A, Charnas B, Zienkiewicz-Strzalka M, Bogatyrov V, Galaburda M. Activated carbon from agricultural wastes for adsorption of organic pollutants. *Molecules.* 2020;25(21):5105. doi:10.3390/molecules25215105.
13. Heidarinejad Z, Dehghani MH, Heidari M, Javedan G, Ali I, Sillanpää M. Methods for preparation and activation of activated carbon: a review. *Environ Chem Lett.* 2020;18(2):393–415. doi:10.1007/s10311-019-00955-0.
14. Neme I, Gonfa G, Masi C. Activated carbon from biomass precursors using phosphoric acid: a review. *Heliyon.* 2022;8(12):e11940. doi:10.1016/j.heliyon.2022.e11940.
15. Wang Z, Zheng H, Chen J, Wang W, Sun F, Cao Y. Effect of crosslinking conditions on the transport of protons and methanol in crosslinked polyvinyl alcohol membranes containing the phosphoric acid group. *Polymers.* 2023;15(21):4198. doi:10.3390/polym15214198.
16. Baláž M, Boldyreva EV, Rybin D, Pavlović S, Rodríguez-Padrón D, Mudrinić T, et al. State-of-the-art of eggshell waste in materials science: recent advances in catalysis, pharmaceutical applications, and mechanochemistry. *Front Bioeng Biotechnol.* 2021;8:612567. doi:10.3389/fbioe.2020.612567.
17. Zhou A, Du CA, Tian J, Xu Z, Wang D, Wang K. Experimental study on coal deformation induced by gas adsorption-instantaneous pressure relief under unconstrained stress state with different pore structures. *Energy.* 2023;276(6):127480. doi:10.1016/j.energy.2023.127480.
18. Rahman MO, Bin Mohd Nor N, Sawaran Singh NS, Sikiru S, Dennis JO, bin Abd Shukur MF, et al. One-step solvothermal synthesis by ethylene glycol to produce N-rGO for supercapacitor applications. *Nanomater.* 2023;13(4):666. doi:10.3390/nano13040666.
19. Yeganeh Ghotbi M, Sikiru SO, Soleimani H, Kou L, Song J. Copper sulfide/N, S-doped carbon nanocomposites as high-performance supercapacitor devices. *ACS Appl Energy Mater.* 2024;7(18):7885–94. doi:10.1021/acsaem.4c01440.
20. Sikiru S, Ghotbi MY, Dele-Afolabi TT. Carbon allotropes in dual uses for supercapacitors and CO₂ Capture doping for a sustainable future. In: *Heteroatom-doped carbon allotropes: progress in synthesis, characterization, and applications*. Washington, DC, USA: American Chemical Society; 2024. p. 55–104. doi:10.1021/bk-2024-1491.ch003.
21. Sikiru S, Olotoki JO, Musa SA, Afolabi LO, Mahat MM. The projection role of surface charge density in electric double-layer capacitance for enhanced energy storage. *J Energy Storage.* 2025;138(12):118728. doi:10.1016/j.est.2025.118728.
22. Roddaeng S, Promvong P, Anuwattana R, Vongpanit P, Suriyachai N, Imman S, et al. Synthesis of durian shell activated carbon by KOH activation using response surface methodology: characterization and optimization of process parameters. *Emergent Mater.* 2024;7(3):1239–51. doi:10.1007/s42247-024-00641-0.
23. Desa SS, Ishii T, Nueangnoraj K. Sulfur-doped carbons from durian peels, their surface characteristics, and electrochemical behaviors. *ACS Omega.* 2021;6(38):24902–9. doi:10.1021/acsomega.1c03760.

24. Balasubramanian V, Daniel T, Henry J, Sivakumar G, Mohanraj K. Electrochemical performances of activated carbon prepared using eggshell waste. *SN Appl Sci.* 2019;2(1):127. doi:10.1007/s42452-019-1921-2.
25. Liu H, Liu J, Huang H, Evrendilek F, Wen S, Li W. Optimizing bioenergy and by-product outputs from durian shell pyrolysis. *Renew Energy.* 2021;164(22):407–18. doi:10.1016/j.renene.2020.09.044.
26. Lu X, Gu X. A review on lignin pyrolysis: pyrolytic behavior, mechanism, and relevant upgrading for improving process efficiency. *Biotechnol Biofuels Bioprod.* 2022;15(1):106. doi:10.1186/s13068-022-02203-0.
27. Kim DG, Kim TH, Ko SO. Enhanced catalytic activity of a coal-based powdered activated carbon by thermal treatment. *Water.* 2022;14(20):3308. doi:10.3390/w14203308.
28. Demiral İ, Samdan C, Demiral H. Enrichment of the surface functional groups of activated carbon by modification method. *Surf Interfaces.* 2021;22:100873. doi:10.1016/j.surfin.2020.100873.
29. Abbas Q, Mirzaeian M, Ogwu AA, Mazur M, Gibson D. Effect of physical activation/surface functional groups on wettability and electrochemical performance of carbon/activated carbon aerogels based electrode materials for electrochemical capacitors. *Int J Hydrog Energy.* 2020;45(25):13586–95. doi:10.1016/j.ijhydene.2018.04.099.
30. Nume P, Sangtawesin T, Ma'Radzi AH, Kanjana K. Green synthesis of durian shell-derived activated carbon with enhanced carboxylic functionalization and graphitization via gamma irradiation in ethanol and ethylene glycol for supercapacitor applications. *Biomass Bioenergy.* 2025;199(10):107945. doi:10.1016/j.biombioe.2025.107945.
31. Tran GT, Van Tran T. Response surface methodology for optimization of alizarin red S dye removal by carbon-based adsorbents derived from durian fruit shells: a waste-to-wealth approach. *Chem Pap.* 2025. doi:10.1007/s11696-025-04521-7.
32. Chulliyil HM, Hamdani IR, Ahmad A, Al Shoaibi A, Chandrasekar S. Enhanced moisture adsorption of activated carbon through surface modification. *Results Surf Interfaces.* 2024;14:100170. doi:10.1016/j.rsufi.2023.100170.
33. Zhang X, Wang S, Chen H, Wang X, Deng J, Li X, et al. Observation of carbon nanostructure and evolution of chemical structure from coal to graphite by high temperature treatment, using componential determination, X-ray diffraction and high-resolution transmission electron microscope. *Fuel.* 2023;332(551):126145. doi:10.1016/j.fuel.2022.126145.
34. Li J, Qin Y, Shen J, Chen Y. Evolution of carbon nanostructures during coal graphitization: insights from X-ray diffraction and high-resolution transmission electron microscopy. *Energy.* 2024;290(3):130316. doi:10.1016/j.energy.2024.130316.
35. Azfaralariff A, Razali N, Abdul Khalil HPS, Ahmad MI, Abdullah CK, Yahya EB, et al. Transforming agricultural waste into sustainable bioadsorbents and advanced bioaerogels from durian (*Durio zibethinus*) peel. *Biofuels Bioprod Bioref.* 2025;19(6):1706–27. doi:10.1002/bbb.2771.
36. Bron M, Melke J, Steimecke M. Characterization of carbon materials. In: *Flow batteries: from fundamentals to applications.* Hoboken, NJ, USA: Wiley; 2023. p. 281–306.
37. Tian XK, Lin SC, Yan J, Zhao CY. Sintering mechanism of calcium oxide/calcium carbonate during thermochemical heat storage process. *Chem Eng J.* 2022;428(1):131229. doi:10.1016/j.cej.2021.131229.
38. Lan H, Wang J, Cheng L, Yu D, Wang H, Guo L. The synthesis and application of crystalline-amorphous hybrid materials. *Chem Soc Rev.* 2024;53(2):684–713. doi:10.1039/d3cs00860f.
39. Ahmed NS, Kamil FH, Ali Hasso A, Abduljawaad AN, Saleh TF, Mahmood SK. Calcium carbonate nanoparticles of quail's egg shells: synthesis and characterizations. *J Mech Behav Mater.* 2022;31(1):1–7. doi:10.1515/jmbm-2022-0001.
40. Zhang S, Li Z, Luo K, He J, Gao Y, Soldatov AV, et al. Discovery of carbon-based strongest and hardest amorphous material. *Natl Sci Rev.* 2022;9(1):nwab140. doi:10.1093/nsr/nwab140.
41. Teimouri Z, Nanda S, Abatzoglou N, Dalai AK. Application of activated carbon in renewable energy conversion and storage systems: a review. *Environ Chem Lett.* 2024;22(3):1073–92. doi:10.1007/s10311-023-01690-3.
42. Diningsih C, Rohmawati L. Synthesis of calcium carbonate (CaCO₃) from eggshell by calcination method. *Indones Phys Rev.* 2022;5(3):208–15. doi:10.29303/ipr.v5i3.174.
43. Serafin J, Dziejarski B. Activated carbons—preparation, characterization and their application in CO₂ capture: a review. *Environ Sci Pollut Res.* 2024;31(28):40008–62. doi:10.1007/s11356-023-28023-9.

44. Rey C, Combes C, Drouet C, Grossin D, Bertrand G, Soulié J. 1.11 bioactive calcium phosphate compounds: physical chemistry. In: Comprehensive biomaterials II. Amsterdam, The Netherland: Elsevier; 2017. p. 244–90. doi:10.1016/b978-0-12-803581-8.10171-7.
45. Putri AMH, Ramadhoni BF, Yuliusman, Ali Muhammad Yuzir M, Muharam Y. Activated carbon from tea twig waste via low-temperature KOH activation for efficient CO₂ capture: development mesoporous structures under mild conditions. Adsorpt Sci Technol. 2025;43(17):02636174251383610. doi:10.1177/02636174251383610.
46. Wu W, Wang Y, Hu X. Mass transfer driven pore engineering of activated carbon from the activation of biomass. Green Chem. 2026;28(8):3486–511. doi:10.1039/d5gc05946a.
47. Zhang X, Zhang Y, Zhang S, Yao L, Hao Y. Lignocellulosic biomass pyrolysis: a review on the pretreatment and catalysts. Fuel Process Technol. 2025;279:108352. doi:10.1016/j.fuproc.2025.108352.
48. Syamsunur D, Wei L, Ahmed Memon Z, Surol S, Md Yusoff NI. Concrete performance attenuation of mix nano-SiO₂ and nano-CaCO₃ under high temperature: a comprehensive review. Materials. 2022;15(20):7073. doi:10.3390/ma15207073.
49. Choudari BN, Hegde SS, Herbert MA, Kumar GN, Bhat BR. Thermochemically activated *Ficus benghalensis* leaf-derived porous activated carbon for sustainable supercapacitor electrodes. RSC Adv. 2026;16(13):11864–73. doi:10.1039/d5ra09628f.
50. Hegde SS, Bhat BR. Sustainable energy storage: *Mangifera indica* leaf waste-derived activated carbon for long-life, high-performance supercapacitors. RSC Adv. 2024;14(12):8028–38. doi:10.1039/d3ra08910j.