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RESEARCH ARTICLE

CHARACTERIZATION OF MICROPOROUS ACTIVATED CARBON FROM COCONUT SHELLS BIOCHAR USING SODIUM CHLORIDE AS CHEMICAL ACTIVATION AGENT

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Abstract. Activated carbon (AC) derived from coconut shells is extensively used in various industries due to its remarkable properties, such as high surface area and excellent physical and chemical stability. In this study, coconut shell activated carbon (CSAC) was produced using sodium chloride (NaCl) as a chemical activating agent at room temperature. This study examined how different NaCl concentrations (15%, 20%, and 25%) influenced the quality of the activated carbon produced. The raw coconut shells underwent carbonization at 400 °C, followed by chemical activation with NaCl. The characteristics of the activated carbon were evaluated based on parameters such as pore volume, bulk density, iodine number, and microstructure. Results indicated that increasing the NaCl concentration enhanced both pore volume and iodine number, while reducing density. The best performance was achieved with 25% NaCl, yielding an iodine number of 1068 mg/g and a pore volume of 0.19 cm^3/g after 24 hours of treatment at room temperature. SEM analysis confirmed the presence of a highly porous surface morphology. Overall, the findings highlight NaCl as an effective and economical activating agent for producing high-quality activated carbon from coconut shells. The resulting CSAC exhibited properties comparable to commercial activated carbon, demonstrating its potential for industrial applications such as water treatment.

Keywords: Activated carbon (AC), sodium chloride (NaCl), coconut shell, chemical treatment.

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1. INTRODUCTION

Activated carbon (AC) is a material that has been widely used in various industrial applications such as wastewater treatment, potable water purification, gas filtration, supercapacitor electrodes, the hydrometallurgy industry, bioprocessing, catalyst support, and other industrial processes [1,2]. In domestic water filter applications, activated carbon removes natural organic compounds that negatively affect the taste of potable water. Water sources contain two main types of impurities—suspended solids and microbial pathogens—whose presence can contaminate drinking water and pose health risks to humans [3]. Activated carbon functions in the removal of harmful chemicals from water sources. In the hydrometallurgy industry, AC is used to extract metals such as gold and silver from ore-bearing rocks. In the food industry, it is employed to remove color from sugar and various foods, highlighting its versatility across multiple applications [4]. In biomedical applications, AC is commonly used as an antidote and also as a component in hemodialysis and bioprocessing. Additionally, it is widely used for the immobilization of enzymes and microbes [5].

Previous studies have focused on the utilization of agricultural waste in the preparation of activated carbon [2,6]. Among the raw materials used are nutshells, coconut shells, fruit stones, bagasse, oil palm waste, and agricultural residues from sugarcane, peanuts, sawdust, and various other biomass sources. In Malaysia, coconut shell is a commonly used raw material for producing activated carbon. Coconut shell-based activated carbon possesses high hardness and durability, making it suitable for a wide range of industrial applications. Additionally, it has a high adsorption capacity due to its large surface area (up to 1,500 m^2/g), making it effective for adsorbing a variety of contaminants, including volatile organic compounds (VOCs), heavy metals, and microorganisms. Farah et al. [7] reported that activated carbon derived from coconut shells shows strong potential for reducing organic pollutants and heavy metals in wastewater.

The activation process for producing activated carbon (AC) from agricultural waste can be categorized into two main methods: physical and chemical activation [1]. In physical activation, the material is first carbonized in an inert atmosphere and then activated at high temperatures using steam as the activating agent. In contrast, chemical activation involves treating the carbonaceous raw material with alkaline or acidic chemicals. Chemical activation is generally preferred over physical activation in industrial applications because it often results in higher yield, greater surface area of the porous carbon structure, and enhanced adsorption capacity [1]. Additionally, chemical activation requires lower operating temperatures, which reduces energy consumption and overall processing costs [8].

The chemical activation process can be divided into two approaches: (i) impregnation of a chemical agent into the surface of the biomass feedstock prior to carbonization, and (ii) chemical impregnation after the formation of biochar [9]. Commonly used chemical activating agents at the industrial scale include calcium chloride ($CaCl_2$), zinc chloride ($ZnCl_2$), potassium hydroxide (KOH), phosphoric acid (H_3PO_4), sulfuric acid (H_2SO_4), and sodium hydroxide (NaOH) [1,6]. The properties and quality of the activated carbon produced depend on several parameters, such as surface area, pore volume, impregnation time, concentration of the chemical activating agent, activation time, and temperature [10]. For water treatment applications, the optimal properties of activated carbon include a pore volume of 0.2–1.0 cm^3/g, a bulk density of 0.25–0.55 g/cm^3, and an iodine number ranging from 800 to 1100 mg/g.

In the chemical activation process, the typical temperature used for carbonization to produce biochar is below 1000 °C, whereas physical activation generally requires temperatures above 1000 °C. Biochar is a carbon-rich material obtained from biomass through pyrolysis at temperatures typically ranging from 300 °C to 700 °C under low-oxygen conditions, with oil and gas produced as by-products. It is important to note that the properties of biochar differ from those of activated carbon, even though both are carbon-rich materials. Due to the relatively low pyrolysis temperatures, biochar is often not fully carbonized. However, chemical treatment of biochar significantly enhances its internal pore structure and surface area. As a result, biochar can serve as a precursor for producing activated carbon from various types of biomasses. Excessively high concentrations of chemical activating agents or prolonged reaction times can lead to structural collapse of the carbon matrix, thereby increasing pore formation [11]. The typical feedstock-to-agent ratios (also known as the degree or coefficient of impregnation) range from 1:0.5 to 1:3 on a dry matter basis. The production of activated carbon from coconut shell biochar using chemical activation has been widely reported by researchers [2,7].

While agents such as KOH and $ZnCl_2$ are well-established in activated carbon production, the use of sodium chloride (NaCl) is less conventional and less studied, making it a novel and emerging approach. NaCl offers a non-corrosive, non-toxic, and environmentally safe alternative to more hazardous chemicals [12]. This type of activating agent is readily available and more cost-effective compared to others. Its ability to act as a physical template or porogen during carbon activation presents a green and innovative strategy, particularly suited for sustainable and low-tech applications. Therefore, this research investigates and reports the potential of NaCl as a chemical activating agent for the production of activated carbon from coconut shell biochar. The successful utilization of biomass for activated carbon production not only helps mitigate environmental issues caused by coconut shell waste but also reduces the production costs of effective sorbents that can be applied in wastewater reclamation and water treatment processes.

2. MATERIALS AND METHODS

2.1 Preparation of Coconut Shell Biochar

The raw material used in this research was coconut shell. The coconut shells were collected from Serdang Market, Selangor, Malaysia, and thoroughly cleaned to remove dust and other impurities. The cleaned coconut shells underwent a pyrolysis process in a steel chamber at approximately 370 °C for 10 hours in the absence of oxygen. This process produced coconut shell biochar, which was then used for the chemical activation treatment.

2.2 Chemical Activated of Coconut Shell Biochar

The coconut shell biochar was ground into granules with a particle size of approximately 1 mm and impregnated with a chemical activating agent for 24 hours at 100 °C, using a biochar-to-agent ratio of 1:2 based on dry weight. The activating agent used in this study was NaCl, with concentrations ranging from 15 to 25 wt%. The activated biochar was washed three times with distilled water to remove excess salts. The resulting activated carbon samples were labeled as CS, CSAC1, CSAC2, and CSAC3, corresponding to treatments with 0 wt%, 15 wt%, 20 wt%, and 25 wt% NaCl, respectively, as shown in Table 1. The samples were then stored in a desiccator for further analysis. Commercial activated carbon (CAC) was used as a reference to compare with the activated carbon prepared in this study.

Table 1: Formulation of coconut shell activated carbon (CSAC)

No	Label	NaCl (wt%)
1.	Coconut shell (CS)	0
2.	CSAC1	15
3.	CSAC2	20
4.	CSAC3	25
5.	Commercial AC (CAC)	-

2.3 Characterization of Activated Carbon

Several analyses were conducted to characterize the activated carbon produced in this study as follows:

2.3.1 Pore Volume Determination

Approximately 1 gram of each CSAC sample was immersed in water and boiled for 5 minutes to displace air from the pores. The samples were then dried and reweighed. The pore volume of the CSAC was calculated based on the increase in weight (∂w), divided by the density (d) of water at room temperature. The pore volume was determined using Equation (1):

$$\text{Pore volume} = \partial w/d \quad (1)$$

2.3.2 Bulk Density Measurement

Approximately 5 grams of each CSAC sample were weighed and transferred into a measuring cylinder containing 25 ml of distilled water. The volume of water displaced was recorded, and the bulk density was calculated using Equation (2):

$$\text{Bulk density} = (\text{mass of sample}) / (\text{volume of water displaced}) \quad (2)$$

2.3.3 Determination Iodine Number

Approximately 5 grams of each CSAC sample were weighed and transferred into a 250 ml volumetric flask. Then, 10 ml of 5% hydrochloric acid (HCl) was added to the flask. At this stage, all CSAC samples were in a wet condition. The flask was heated for 30 seconds to ensure the contents boiled, and then allowed to cool to room temperature. Next, 100 ml of 0.1 N iodine solution was added and the mixture was shaken vigorously for 30 seconds. The contents were then filtered, and 50 ml of the filtrate was pipetted and titrated with 0.1 N sodium thiosulfate ($Na_2S_2O_3$) solution until the yellow colour nearly disappeared. About 1 ml of starch solution was added, and the titration continued until the blue colour just disappeared. The volume of $Na_2S_2O_3$ solution used was recorded, and the iodine number, In was calculated using Equation (3):

$$\text{In (mg/g)} = X/m \quad (3)$$

where m = weight of activated carbon in gram. X = (N1 × 12693) – (279.246 × N2 × volume of $Na_2S_2O_3$ solution used), N1 = normality of iodine solution, N2 is the normality of the sodium thiosulphate.

2.3.4 SEM Analysis

The surface morphology and porous structure of the activated carbon were characterized using a field emission scanning electron microscope (FESEM) (model: Hitachi SU 8020 UHR), operated at an accelerating voltage of 2 kV. Prior to FESEM analysis, the samples were coated with a thin layer of platinum to enhance conductivity and prevent charging during scanning.

3. RESULTS AND DISCUSSION

3.1 Pore Volume

Figure 1 shows the effects of NaCl concentration on the pore volume of the CSAC samples produced in this study. As the concentration of the activating agent increased, the pore volume also increased. From Figure 1, it can be observed that the untreated coconut shell (CS) exhibited the lowest pore volume, at 0.094 ± 0.011 cm³/g, compared to 0.188 ± 0.014 cm³/g for the sample treated with 25 wt% NaCl (CSAC3). The results also indicate that CSAC3 achieved a higher pore volume than the commercial activated carbon (CAC), which measured 0.181 ± 0.061 cm³/g. These findings confirm that the concentration of the activating agent, NaCl, significantly influences the final properties of activated carbon derived from coconut shell. A similar observation was reported by Ucar et al. [13], who studied the effect of $ZnCl_2$ concentration on activated carbon derived from pomegranate seeds. They found that zinc intercalates with carbon atoms during the activation process, leading to pore widening and the formation of new pores [14]. In the present study, it is suggested that sodium ions (Na^+) intercalate with carbon atoms during activation, resulting in the formation of wider pores. A higher concentration of Na^+ likely promote stronger interactions with the carbon matrix, thereby creating larger pores within the biochar structure.

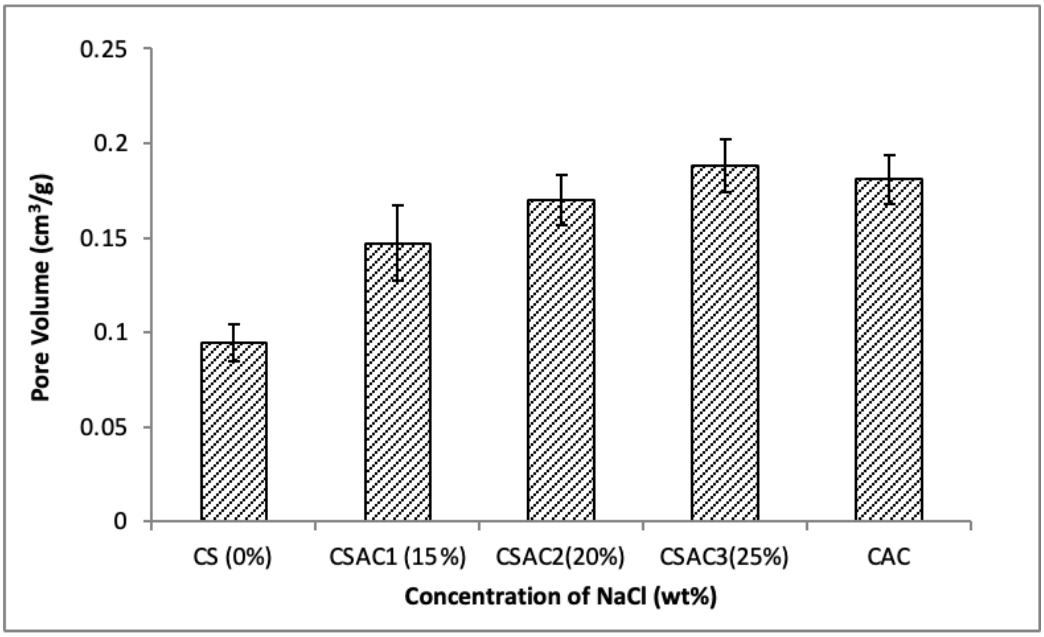

Figure 1: Effect of NaCl concentration on the pore volume of activated carbon produced from coconut shell biochar

3.2 Bulk Density

Figure 2 illustrates the effect of NaCl concentration on the bulk density of CSAC. Bulk density refers to the mass per unit volume of a material, including both the internal pore structure and the voids between particles. It is influenced by the shape, size, and intrinsic density of the activated carbon particles. Bulk density is a key parameter in estimating the packing volume of activated carbon, which directly affects the design and efficiency of filtration systems. The results in Figure 2 show a slight decrease in bulk density for CSAC1 to CSAC3, ranging from 0.16 to 0.14 g/cm³, indicating that variations in NaCl concentration had a limited effect on the density of the activated carbon. This trend is consistent with the pore volume data, as an inverse relationship typically exists between pore volume and bulk density. In this study, the bulk densities of the treated coconut shell activated carbon (CSAC) samples were significantly lower than that of commercial activated carbon (CAC), which recorded a bulk density of 0.26 g/cm³ ± 0.04. Compared to the typical range for activated carbon used in water filtration applications (0.2–0.6 g/cm³), the CSAC samples exhibited relatively low values. Notably, the untreated coconut shell (CS) showed the highest bulk density at 0.27 g/cm³ ± 0.03, likely due to the absence of activation, which introduces porosity and reduces material compactness.

As noted by Gumus et al. [15] and Verla et al. [16], bulk density is critical in determining both the required quantity of activated carbon and the volume of liquid retained within filter media. Higher bulk density is often associated with improved filterability due to greater volume activity and more efficient packing. Although the CSAC samples in this study exhibited lower bulk densities, they remain suitable for batch or non-pressurized applications such as household water filtration. Further processing methods such as granulation or pelletization into granular activated carbon (GAC) or powdered activated carbon (PAC) could enhance bulk density, improving both packing efficiency and flow characteristics [17].

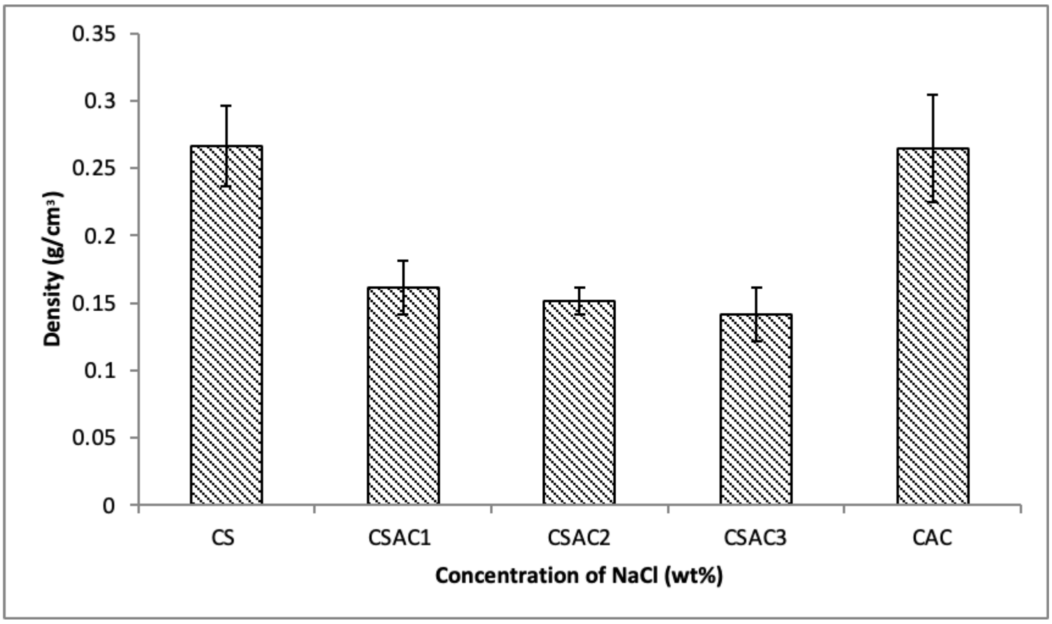

Figure 2: Effects of NaCl concentrations on the bulk density of activated carbon produced from coconut shell biochar

3.3 Iodine Number Analysis

Figure 3 shows the effect of chemical activating agent concentration on the iodine number of activated carbon derived from coconut shell. It was observed that increasing the concentration of NaCl resulted in a corresponding increase in the iodine number of the produced CSAC.

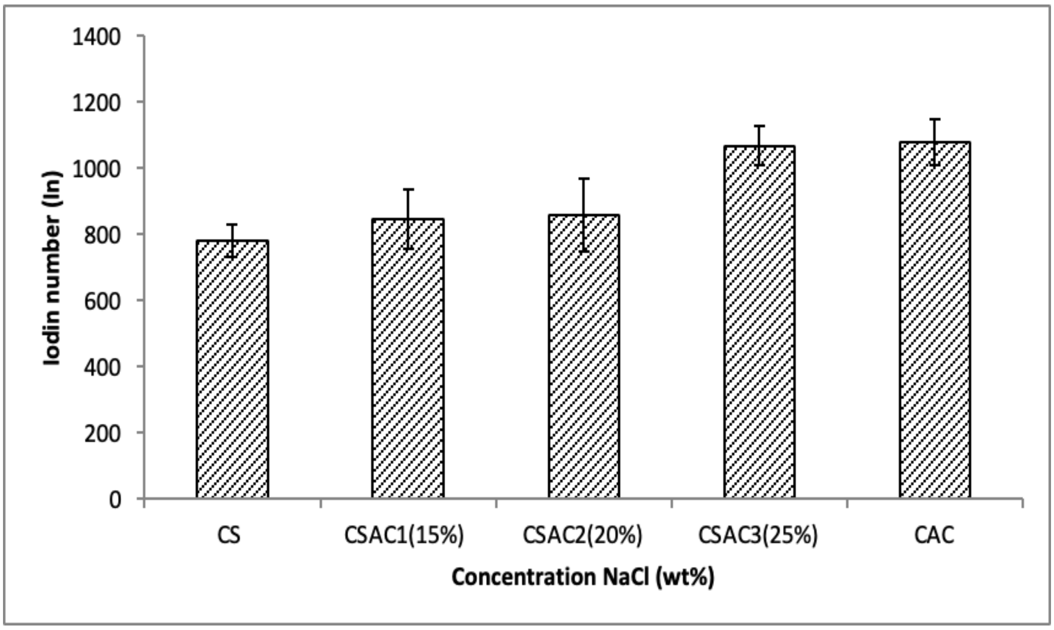

Figure 3: Effects of NaCl concentrations on the Iodine number of activated carbon produced from coconut shell biochar

These results are consistent with the pore volume data shown in Figure 1. The iodine numbers of all samples ranged between 700 and 1150 mg/g, which falls within the typical range for CAC. Additionally, the iodine values of CSAC ranging from 600 to 1100 mg/g are considered suitable for water treatment applications [18].

Nowicki et al. [19] and Qin et al. [20] noted that the iodine number can also be used to estimate the surface area (in m²/g) and the porosity of pores with dimensions between 1.0 and 1.5 nm. The method of activated carbon preparation significantly influences the iodine number. Evbuomwan et al. [21] reported that CSAC prepared using physical activation generally had lower iodine numbers, whereas chemical activation produced higher values, indicating improved porosity. In this study, the highest iodine number 1068 mg/g was achieved for coconut shell biochar treated with 25 wt% NaCl, compared to 1079 mg/g ± 170 for CAC produced via physical activation. Thus, these results suggest that the activated carbon produced in this study is suitable for water filtration applications.

3.4 Morphology Analysis

Figure 4 shows the surface morphology of CSAC samples treated with different concentrations of the activating agent. The FESEM images indicate that the untreated sample exhibits pores with relatively thick walls. Upon treatment with NaCl, macropores (>1 micron) begin to form, and their size increases (>2 microns) with higher NaCl concentrations.

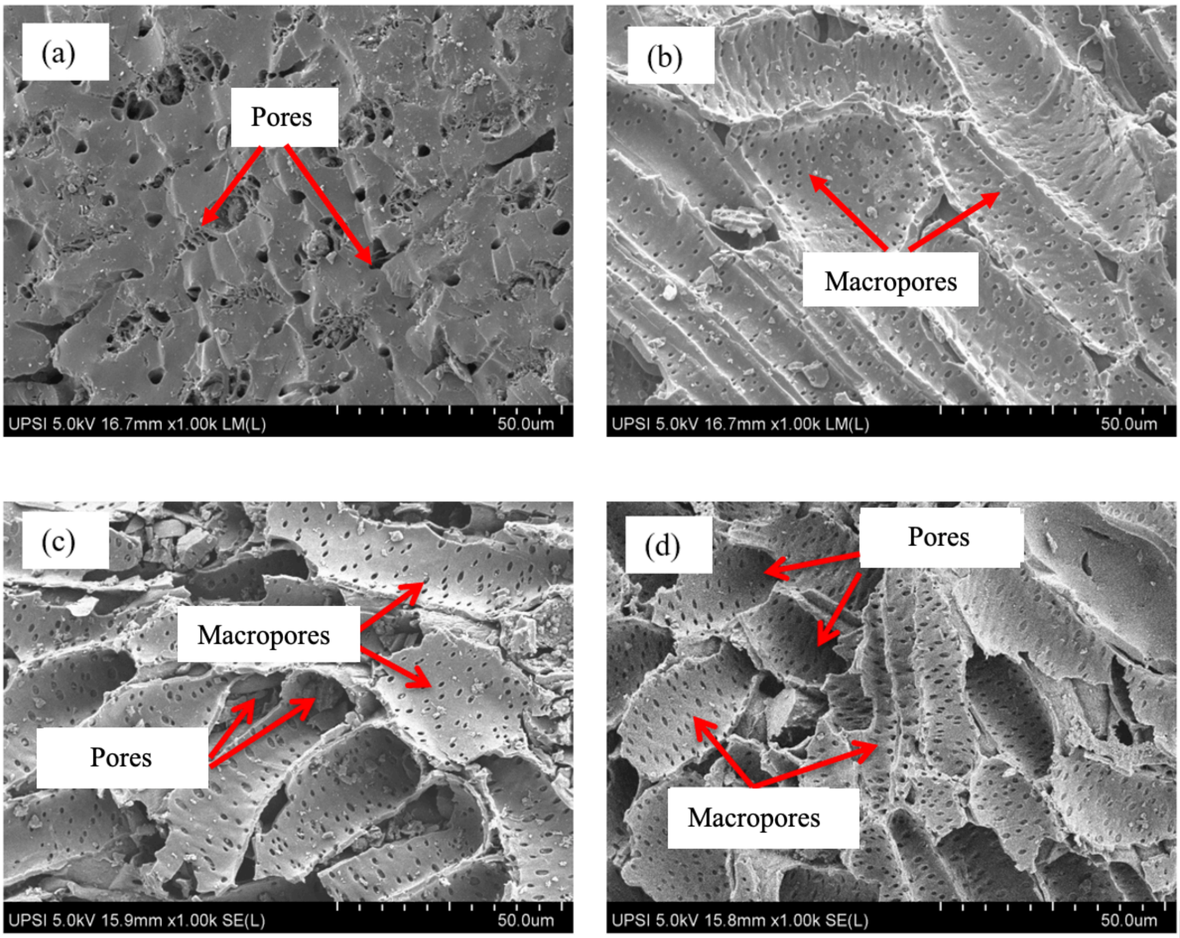

Figure 4: FESEM analysis of coconut shell activated carbon (a) CS (b) CSAC1 (c) CSAC2 and (d) CSAC3

However, the pore size difference between the samples treated with 20 wt% and 25 wt% NaCl is minimal. According to Sugumaran et al. [22], untreated coconut shell biochar displays surface pores with smooth edges, while NaCl-treated activated carbon shows numerous pores with fractured edges. Consistent with this, the FESEM images in this study reveal that the surface pores of CSAC appear rough, with cracked edges likely a result of the interaction between sodium ions and carbon during chemical activation

NaCl primarily functions as a pore-forming agent through physical templating during the activation process. It is safe, cost-effective, and environmentally friendly, making it suitable for producing macroporous activated carbon, particularly for water treatment applications [17]. $CaCl_2$ on the other hand, acts as a mild chemical activator. It promotes micropore formation through dehydration and slight catalytic effects. While also eco-friendly, it is generally less effective than KOH or $ZnCl_2$ in generating extremely high surface areas. However, it is well-suited for gas adsorption applications due to its ability to enhance microporosity. KOH (potassium hydroxide) is a strong alkaline activating agent that chemically reacts with the carbon matrix, producing ultra-high surface area activated carbon, predominantly microporous. This makes it ideal for gas adsorption and energy storage applications, though it requires careful handling and extensive washing to remove residual potassium compounds. $ZnCl_2$ (zinc chloride) is a strong acidic activator that facilitates pore widening and structural swelling, yielding high surface areas with a mix of micro- and mesopores. Despite its effectiveness, $ZnCl_2$ is toxic and requires acid washing to eliminate residual zinc, complicating disposal. Based on the results of this study, a general comparison highlighting the advantages of NaCl over other chemical activation agents is summarized in Table 2.

Table 2: The advantages of NaCl over other chemical agents [23]

Feature	NaCl	KOH	$ZnCl_2$	$CaCl_2$
Safety	Non-toxic, non-corrosive	Strongly corrosive, hazardous	Toxic, environmentally hazardous	Relatively safe
Environmental Impact	Eco-friendly, easy to dispose	Requires special disposal	Can contaminate water systems	Low impact
Cost	Very low	Moderate to high	Moderate	Low
Post-treatment	Easy removal (water soluble)	Requires extensive washing	Needs acid washing	Simple washing
Porosity Control	Good macropores formation	Excellent microporosity	Micro- and mesopores	Micropores
Activation Simplicity	Works at room temperature possible	Requires controlled conditions	Needs careful temp and acid wash	Simple, mild activation
Novelty in Research	Emerging field	Widely studied, conventional	Well-known and documented	Relatively known

Scaling up the production method for industrial applications presents several challenges, along with practical suggestions for overcoming them. First, the variability in coconut shell feedstock—due to differences in size, moisture content, and density based on source and season—can significantly affect carbonization efficiency and the resulting pore structure of the activated carbon. To address this, it is recommended to implement standardized pre-treatment protocols, including thorough drying and size reduction, and to source raw materials from consistent, reliable suppliers. Second, effectively removing residual NaCl from the carbon without excessive water or energy usage is critical, as incomplete washing can leave salt crystals within the pores and compromise performance. A potential solution is to adopt multi-stage countercurrent washing systems and to optimize drying temperatures to ensure thorough purification while minimizing energy consumption. Finally, NaCl can be corrosive to certain metals, particularly under humid or high-temperature conditions, which may lead to accelerated wear and tear of processing equipment. This can be mitigated by using corrosion-resistant materials such as stainless steel or protective coatings on reactors and components that come into contact with salt.

4. CONCLUSIONS

Activated carbon was successfully prepared from coconut shell biochar using NaCl as the activating agent. The optimum NaCl concentration was found to be 25 wt%, producing CSAC3 with an iodine number of 1068 mg/g. This iodine number is very close to that of commercial activated carbon (CAC) and falls within the acceptable range for water filtration applications. The CSAC3 sample treated with 25 wt% NaCl exhibited a pore volume of approximately 0.188 cm^3/g and a bulk density of 0.16 g/cm^3, indicating that the activated carbon derived from coconut shell in this study is suitable for use in domestic water treatment.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards

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