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# Recent advances in the development of coconut-based activated carbon

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## Abstract

Carbon materials have good characteristics like resistance to corrosion, low and high temperatures, bases and acids, and excellent biocompatibility. Moreover, because of the hybridization of sp electron orbits, it can assume a multitude of forms and characteristics, including those of an insulator, an excellent electrical conductor, and a semiconductor. Activated carbon has a very large surface area—it often exceeds 1,000 square metres per gram. The large surface area provides enough space for the adsorption of contaminants. Activated carbon contains a variety of pores of varying sizes, such as macropores, mesopores, and micropores. These pores enhance the material's capacity to adsorb contaminants by providing a range of surfaces for contaminating molecules to adhere to. Coconut shell has been chosen as a precursor due to its environmentally friendly raw material, high mechanical strength properties, and high pore volume behavior. In this work, the obtained results have proven that coconut-based activated carbon has a large adsorptive capacity for the removal of pesticides, antibiotics, dyes, and heavy metals. Adsorption data have been studied using the Langmuir model and the Freundlich isotherm, while kinetic studies have been investigated using pseudo-second-order kinetic and pseudo-first-order kinetic isotherms. Activated carbon can be reused again to reduce waste output and operational costs because it is available in a range of regenerable forms.

**Keywords:** wastewater treatment, pollution, activated carbon, coconut, surface area, porosity, pollutant removal

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## 1. Introduction

Adsorption is the phenomenon wherein ions, atoms, or molecules will adhere to the surface of a solid material. This process stands in contrast to absorption, where a fluid permeates the complete volume of a material [1]. Adsorption is inherently a physical process, meaning that the substances adhering to the solid substrate do not engage in any chemical reactions with the adsorbent. The entity facilitating the adsorption process is termed the adsorbent, while the substance to be adsorbed from either the liquid or gaseous phase is designated as the solute [2]. The extant waste treatment methodologies are presently deployed in conventional practices. These methods, characterized by substantial capital outlays, render their application economically unviable [3]. Various techniques, including the ion exchange process [4], reverse osmosis technique [5], chemical precipitation method [6], the ultra-filtration process [7], flocculation technique [8], and the nano-filtration method [9], have been employed on an industrial scale to mitigate the presence of toxic metals in wastewater. However, these methodologies exhibit inherent limitations, such as elevated operational and maintenance costs, heightened energy requirements, increased sludge production, nonbiodegradability, and intricate management processes. Consequently, their utility is predominantly confined to developed nations. Developing countries confront fiscal constraints that preclude the adoption of sophisticated treatment technologies for addressing toxic industrial wastewater. As a result, there is a burgeoning interest in exploring inexpensive and cost-effective approaches to wastewater treatment. Therefore, researchers have been initiated to formulate a medium that is both economically viable and practical for widespread use [10]. In this regard, the efficacy of adsorption separation has garnered considerable attention, emphasizing the removal of pollutants from different sources [11]. Adsorption presents several advantages relative to alternative methods [12, 13]. The process operates under mild conditions and over a broad pH

range [14]. Importantly, adsorption avoids the generation of toxic by-products, demands low energy input, and exhibits efficiency and cost-effectiveness [15]. A diverse array of materials, including commercial products, waste materials, and by-products, can serve as adsorbents. Furthermore, adsorption proves versatile for addressing a wide spectrum of target contaminants [16].

Activated carbon, a cost-effective material, is derived from various carbonaceous sources such as pecan shells [17], rice husk [18], mango peel [19, 20], potato peel [21], almond shell [22], jackfruit peel [23], waste wood [24], bagasse [25], coir pith [26], orange peel [27], coffee husk [28], pine cone [29], coconut tree [30] sunflower seed hull [31], pine-fruit shell [32], hazelnut husks, rice hulls, oil palm shell [33] and coconut husk [34], among others. Notably, any organic material boasting a high carbon content could be used for the creation of activated carbons through physical modification and thermal decomposition processes. Prepared activated carbon showed unique properties such as high specific surface area, well-developed porosity structure, and desirable surface functionalization. These attributes render activated carbon versatile for a myriad of applications, spanning adsorption, pollutant removal, water treatment [35], and energy-related processes [36].

For treating wastewater, adsorption is frequently regarded as a reliable and affordable method. This process involves the transfer of mass from a runny phase to a solid phase by removable species or solutes. This process occurs when adsorbed species from liquids (adsorbate) interact physiochemically [37] with a solid surface (adsorbent). Compared to other methods such as membrane filtration, ion exchange, electrochemical precipitation methods, and chemical precipitation methods, adsorption has many advantages [38]. While these techniques offer certain benefits, they also have certain drawbacks, and adsorption is seen as one of the best ways to get around these issues [39]. The details of different techniques and their advantages and disadvantages for contamination removal are displayed in Table 1. In general, the selection of wastewater treatment techniques strongly depends on operation cost [45], environmental impact, economic feasibility [46], power consumption [47], and removal efficiency [48]. In this work, coconut shell has been selected as a precursor due to its environmentally friendly raw materials, high harness, abundant supply, high pore volume, low cost, and high mechanical properties. The activated carbon was produced using the carbonization process, physical activation techniques, and chemical activation. Several activating agents have been used to develop porosity structures and enhance adsorption capacity. Removal of dye compounds, pesticides, antibiotics, and heavy metals has been studied using the Langmuir isotherm, the Freundlich model, pseudo-second-order kinetic and pseudo-first-order kinetic isotherm.

## 2. Removal of various types of pollutants using coconut based activated carbon

Pesticides such as dichlorodiphenyltrichloroethane could be used to kill pests and increase crop production. It is known as DDT and has been observed in fruits, milk, fish, poultry, flour, cereals, and vegetables. The properties of DDT have been highlighted (Table 2), it was banned because of serious health effects (nervous system dysfunction, dysfunction of the immune system, carcinogenic properties, reproductive system, and endocrine disorder). So far, DDT has been removed using different techniques, including mechanochemical ball milling, electrocoagulation, bioremediation, and electrokinetic remediation. However, several disadvantages could be seen, such as the development of secondary pollution, high energy consumption, the fact that large molecular weight pollutants are not readily degraded, sludge generation, and the high cost of chemicals. Raw coconut shell (precursor) was washed with water [49], crushed into smaller sizes (0.5 mm, 1 mm), subjected to carbonization and activation processes (flow rate of carbon dioxide gas was 150 $cm^3$/min) using the microwave irradiation method. Prepared activated carbon (CSAC) showed a higher surface area (625.61 $m^2$/g) and total pore volume (0.42 $cm^3$/g) due to the gasification effect. More pores could be observed when the carbon dioxide gas penetrates deep into the interior of the coconut shell. Also, mesoporous structures (pore diameter=4.55 nm) and pore networks were created after the removal of volatile matter and water via this irradiation technique. Based on the nitrogen adsorption-desorption isotherms (figure 1), isotherms type I (micropores on the precursor) and type IV (adsorption of adsorbate on mesopore structures) could be seen in the obtained samples. In the energy dispersive x-ray analysis (EDAX) analysis, the high composition of carbon (81.75% to 87.15%) and low inorganic elements (13.85% to 18.25%) confirmed that the coconut shell could be utilized as a good precursor. According to the Fourier Transform Infrared Spectroscopy (FTIR) spectral, several functional groups such as OH (3604, 3716), CN (2308), C=C (1625), C=O (2800), C≡C (2012), COOH (2875, 3007, 3525) could be identified on the surface of the activated carbon. Furthermore, a negative surface charge was observed, and the zeta potential reading was -21 mv. The percentages of yield and DDT removal were 37.91% and 84.83%, respectively, in specific conditions (radiation power=502 W, radiation time=6 minutes). In addition, adsorption uptakes (4.32 to 15.32 mg/g) increased with increasing the initial concentration (5 to 30 mg/L) and obeyed the Langmuir model (correlation coefficient, $R^2$=0.9995). Adsorption of carbon dioxide ($CO_2$) is strongly dependent on the surface properties via various types of interactions between the adsorbent and gas [50]. It has been reported that the heat of adsorption ranged from -25 kJ/mol to -40 kJ/mol. Physisorption was a reversible reaction; pressure and temperature affected the gas adsorption onto activated carbon (micropore size=0.33 nm to 1 nm). On the other hand, acidic carbon dioxide gas molecules produced a chemical bond during the chemisorption process (heat of adsorption= -60 to -100 kJ/mol) when the temperature was in the range of 25 °C to 140 °C. Generally, basic groups such as amine were used for the surface modification of porous materials. Researchers have highlighted that the activation process was able to improve the adsorption capacity [51]. Noticeably, bigger pores have been developed, and the number of clogged pores has been significantly reduced via the activation process. Experimental findings revealed that the ash content and charcoal yield are in the range of 2.9%-3.31% and 20.4%-34.6%, respectively. Inorganic substances (Al, S, P, Mg, Si, Na K, Ca, Fe) resulted in the formation of ash. The pH value will increase when the activation time and temperature are increased, because of the formation of lime and the burning of calcite. It was noted that the highest pH

was 9.84 at 1000 °C and 2 hours which showed the highest adsorption capacity of carbon dioxide (14.4 mg/L) if compared to other adsorbents (Table 3). Because of the largest surface area (824 $m^2$/g), microporous structures, and total pore volume (0.502 mL/g). A rich carbon content [61] could be produced through carbonization process (600 °C and 3 hours). Then, activated carbon was treated using different types of activators in specific conditions (85 °C for 120 minutes, and dried at 130 °C for 180 minutes). In the SEM-EDX investigations, activated carbon prepared using phosphoric acid showed a larger grain size, while grayscale color at the grain could be observed using NaOH and $ZnCl_2$. Other textural properties, porosity structures, FTIR analysis, and elemental compositional studies have been reported (Table 4). Total dissolved solid (TDS) investigations in polluted water (well water and household wastewater) were carried out using sodium hydroxide. It was proven that dark brownish well water with a pH value of 7.8, has been changed to a clear solution (with a pH of 7.2) after being filtered. The TDS value has dropped from 250 ppm to 193-248 ppm after the filtration process. On the other hand, cloudy, blackish household wastewater with a pH of 7.9 has been changed to a clear solution, odorless with a pH of 7.1-7.3 after being filtered. Methylene blue is considered a safe drug when the therapeutic dose is less than 2 mg/kg. However, serotonin syndrome happened at a dose of 5 mg/kg and showed adverse effects when the level was greater than 7 mg/kg. The influence of the activating agent on the adsorptive performance was studied. The highest adsorptive performance of methylene blue was 99.9% (phosphoric acid), followed by zinc chloride (94.9%), and KOH (70%). Phosphoric acid can decompose cellulose fibres, create cross-linking structures, and depolymerize hemicellulose and lignin. Zinc chloride showed Bronsted-acidity properties; it donates protons and breaks down the lignin and cellulose structures. Production of activated carbon using tall trees (90 feet) and dwarf varieties has been proposed [62]. The best temperature and pH were 450°C-575 °C & pH 2.07, and 575 °C & 1.98 for the tall tree and dwarf variety, respectively. In the adsorptive performance studies, the highest adsorption capacity (methylene blue dye) could be observed when the concentration of phosphoric acid was 0.3M -0.67M and 0.3M-1M in tall tree and dwarf variety, respectively. Pore structures were destroyed, and adsorptive capacities were reduced when using a higher concentration of phosphoric acid. Based on the pore size distribution analysis, smaller particle sizes could be seen when excessive carbonization occurred. SEM images (figure 2) show finer pores (0.62 μm to 1.76 μm) in the adsorbent prepared at 575 °C due to the higher internal surface area. Pore sizes were found to be 0.73-2.57 μm, 0.68-1.5 μm and 0.77-3.77 μm for the samples carbonized at 450 °C, 700 °C and 850 °C, respectively. The impregnation process [63] was conducted using KHO solution at 70 °C in an oil bath. The carbonization process was carried out in a horizontal furnace (500 °C, nitrogen atmosphere for 180 minutes, carbon dioxide gas atmosphere for 60 minutes). Surface area analysis was performed for the obtained activated carbon. Experimental results showed that KOH affected porosity structure and texture properties. The highest BET surface area was 1389 $m^2$/g using 30% KOH. The removal of dye increased when the pH values and adsorbent dosages were increased. The presence of $H^+$ ions compete with positively charged dyes at low pH value. Adsorption data provide a good fit to the Langmuir isotherm ($R^2$=0.98) with maximum adsorption capacity of 45.9 mg/g. Activated carbon prepared through physical activation (700 °C, furnace, 60 minutes) process [64] showed a removal efficiency of 99.42%, optimum contact time of 60 minutes, and a correlation coefficient of 0.95 (pseudo second order model). Chemical activation (10% of phosphoric acid) has been conducted to produce activated carbons. Removal efficiency and the best contact time were 98.64% and 40 minutes, respectively, in this activated carbon. Both samples indicated an optimized pH of 8 for adsorption process, and the adsorption data supported the Freundlich model ($R^2$=0.99).

NaOH was used as an activating agent [65] to produce activated carbon with a high surface area (2551 $m^2$/g) and a large porous texture (1.3 $cm^3$/g) as reported in Table 5. The percentage of yield (85.05% to 34.95%) decreased when the concentration of NaOH was increased. During the activation process, huge amounts of hydrogen, carbon monoxide, and carbon dioxide will be released (equation 1, 2, 3), micropore structures will be developed. However, excess sodium hydroxide resulted in an enhanced gasification reaction (equation 4), the walls between the pores will be destroyed, and the surface area will be reduced. All the obtained activated carbons indicated type I isotherms, representing predominantly micropore structures with some mesopore structures. Also, the pore size distribution was observed to be 0.5 nm to 4 nm (figure 3). In structural studies, there are two peaks that could be seen in the XRD patterns. The (100) and (002) planes are attributed to the graphite structures and non-graphitic carbon, respectively. The (002) plane disappeared when adding NaOH during the activation process. Further confirmation was offered using Raman spectroscopy, a higher $I_D/I_G$ value could be seen (value=1.02) in the presence of the activating agent. According to the breakthrough adsorption curves, the highest adsorption capacity and the longest breakthrough time were 815.5 mg/g and 50.26 minutes when the ratio was 4:1. Higher removal (94%) of siloxanes if compared to wood-based activated carbon (40%-92%- Cabrera-Codony), commercial activated carbon (70%-80%- Gislon) and NORIT RGM1 activated carbon (50%-Finocchio). Experimental findings showed that the recovery efficiency was 94% and regeneration of the adsorbent could be carried out at a low heating temperature under normal pressure. According to fixed-bed dynamic adsorption studies, the removal of hexamethyldisiloxane reached 898.6 mg/g at 0 °C. It was noted that adsorption capacity increases when the temperature is reduced and the inlet concentration of hexamethyldisiloxane is increased.

$$6NaOH + 2C \rightarrow 2Na + 3H_2 + 2Na_2CO_3 \text{ (equation 1)}$$
$$Na_2CO_3 \rightarrow CO_2 + Na_2O \ (equation\ 2)$$
$$2Na + CO_2 \rightarrow CO + Na_2O \ (equation\ 3)$$
$$4NaOH + C \rightarrow 4Na + CO_2 + 2H_2O \ (equation\ 4)$$

**Table 1:** The advantages and disadvantages for various types of wastewater treatment techniques

| Techniques | Advantages | Disadvantages |
|---|---|---|
| Membrane filtration | Simple processing [40], low energy usage, low investment, high efficiency | Expensive, membrane fouling cause reduction in filtration capacity |
| Ion exchange | Simple equipment, High removal rate, easy operation control and high recovery rate, high concentration of useful substances [41] | Long experimental cycles, high pre-treatment requirements, high salt consumption, poor general applicability, excessive regeneration waste, |
| Electrochemical | Equipment with small volume, selective, versatile, easy automation, and control, reduce precipitates formation [42] | Limited efficiency for pollutant removal, fouling and corrosion, high power consumption, limited stability |
| Chemical precipitation | Low space requirements, easy equipment handling, can also remove suspended solids and other impurities [43] | Energy consumption, required skilled operator and maintenance, slugged generation, requirements of costly reagents |
| Adsorption | High stability, environmentally sustainability [44], low energy consumption, cost effectiveness, broad range of adsorbents, fast process, convenient to process, compatible with other methods, reduction in waste production, adsorbent regeneration, high removal efficiency, highly selective, can remove variety of contaminants. | |

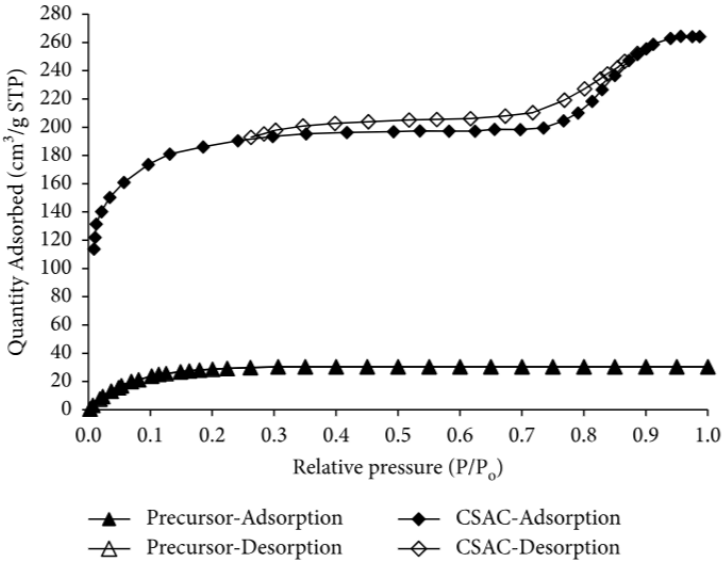



**Figure 1:** Nitrogen adsorption-desorption isotherms for coconut based activated carbon [49].

**Table 2:** Properties of dichlorodiphenyltrichloroethane.

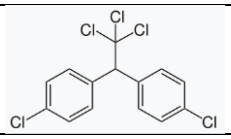
| | |
|---|---|
| Melting point (°C) | 108.5 |
| Molar mass (g/mol) | 354.48 |
| Boiling point (°C) | 260 |
| Density (g/cm$^3$) | 0.99 |
| Chemical formula | $C_{14}H_9Cl_5$ |
| Solubility in water (µg/L) | 25 at 25 °C |
| Structural |  |

**Table 3:** Comparison of the carbon dioxide gas adsorption (1 bar, 25 °C) using different adsorbents

| Adsorbent | Carbon dioxide uptake (mmol/g) | Researchers |
|---|---|---|
| Oliver stone [52] | 2.4 | Xiangzhou and co-workers, 2022 |
| Fungi [53] | 3.5 | Seong-Heon and co-workers, 2023 |
| Almond shells [54] | 2.7 | Dayang and co-workers, 2022 |
| Microalgae [55] | 1.4 | Farihahusnah and co-workers, 2022 |
| Coffee ground [56] | 3 | Chenlei and co-workers, 2022 |
| Palm shell [57] | 3.4 | Wenhe and co-workers, 2022 |
| Corncob [58] | 3.6 | Oneesha and co-workers, 2022 |
| Glucose [59] | 4.1 | Huajing and co-workers, 2022 |
| Oil palm bunch [60] | 3.7 | Xiaoxia and co-workers, 2022 |

**Table 4:** Properties of the activated carbon using different activators [61].

| | ACI (NaOH) | ACII ($ZnCl_2$) | ACIII ($H_3PO_4$) |
|---|---|---|---|
| BET surface area ($m^2/g$) | 516 | 42 | 23 |
| Micropore area ($m^2/g$) | 391.74 | 19.71 | 17.97 |
| Micropore volume ($cm^3/g$) | 71.53 | 0.012 | 0.008 |
| Pore volume ($cm^3/g$) | 0.16 | 0.023 | 0.011 |
| Pore width (nm) | 1.29 | 1.43 | 1.19 |
| Average pore diameter (nm) | 1.79 | 3.46 | 3.48 |
| Elemental composition (%) | C=90.56<br>O=7.66<br>Na=0.93<br>Si=0.3<br>P=0.32<br>Ca=0.24 | C=90.44<br>O=7.45<br>Zn=0.93<br>Cl=1.18 | C=93.32<br>O=7.48<br>P=0.39 |
| Pore size (μm) | 1.33 | 1.36 | 0.14 |
| FTIR peaks ($cm^{-1}$) | 3442.94, 2360.87, 1556.55 | 3415.93, 2357.01, 1543.05, 1122.57 | 3439.08, 2357.01, 1552.7, 1120.64 |

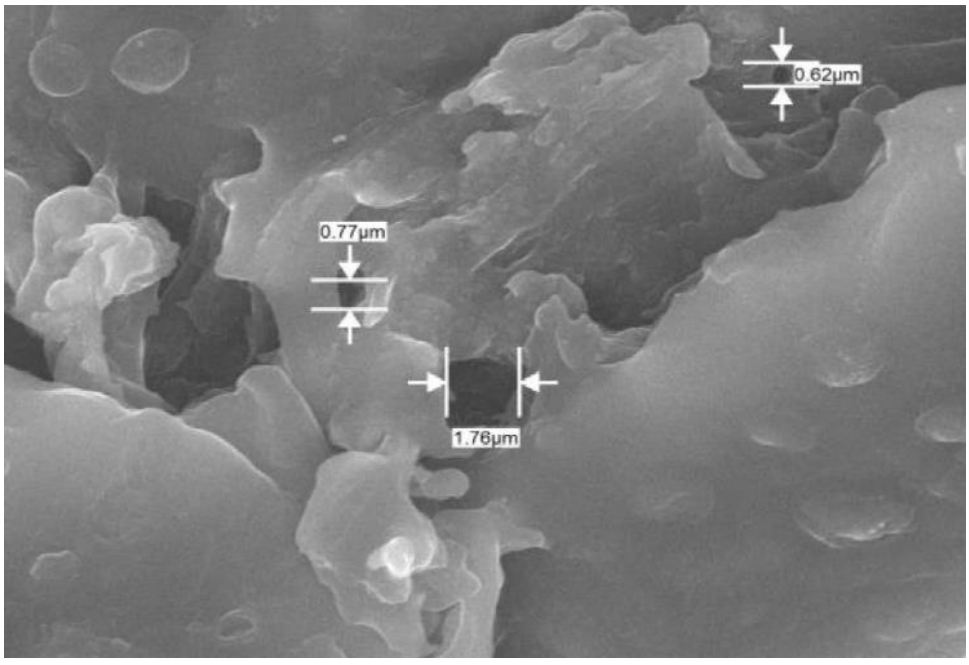



**Figure 2**: SEM image of the prepared activated carbon [62]

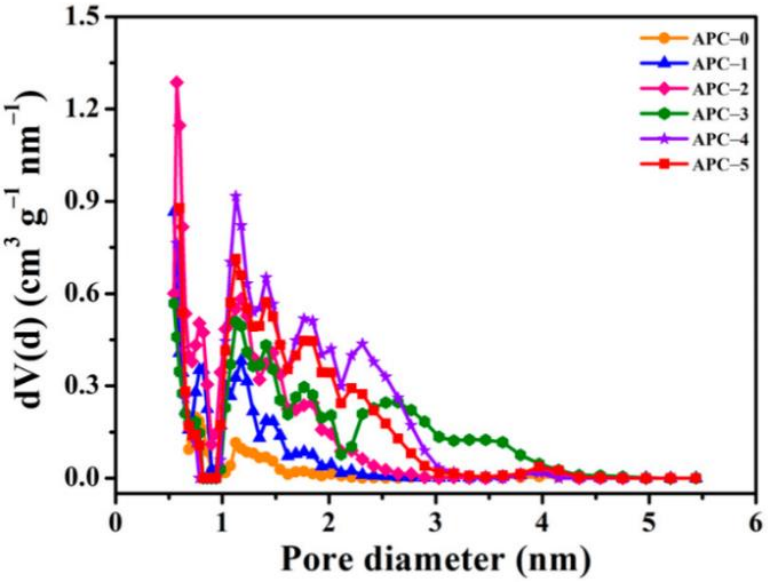
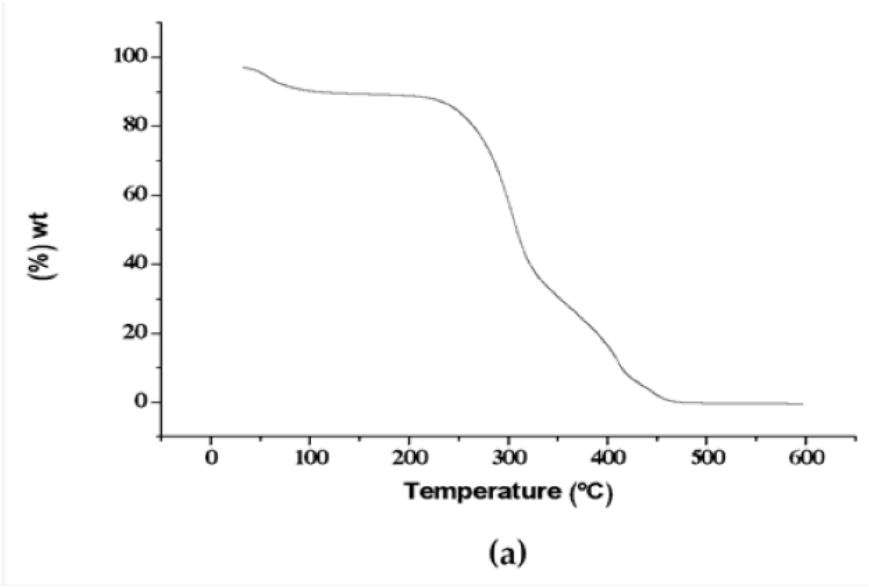



**Figure 3:** Pore size distribution of the prepared activated carbons [65].

**Table 5**: Properties of the obtained activated carbons

| | Ratio of NaOH:charcoal | | | | |
|---|---|---|---|---|---|
| | 1:1 | 2:1 | 3:1 | 4:1 | 5:1 |
| Specific surface area ($m^2/g$) | 988 | 1595 | 1669 | 2551 | 2192 |
| Total pore volume ($cm^3/g$) | 0.56 | 0.87 | 1.02 | 1.3 | 1.18 |
| Micropore volume ($cm^3/g$) | 0.56 | 0.78 | 0.73 | 1.11 | 0.98 |
| Mesopore volume ($cm^3/g$) | 0 | 0.09 | 0.29 | 0.19 | 0.2 |
| Average pore size (nm) | 1.12 | 1.09 | 1.22 | 1.02 | 1.08 |
| Yield (%) | 85.05 | 57.85 | 40.19 | 38.76 | 34.95 |



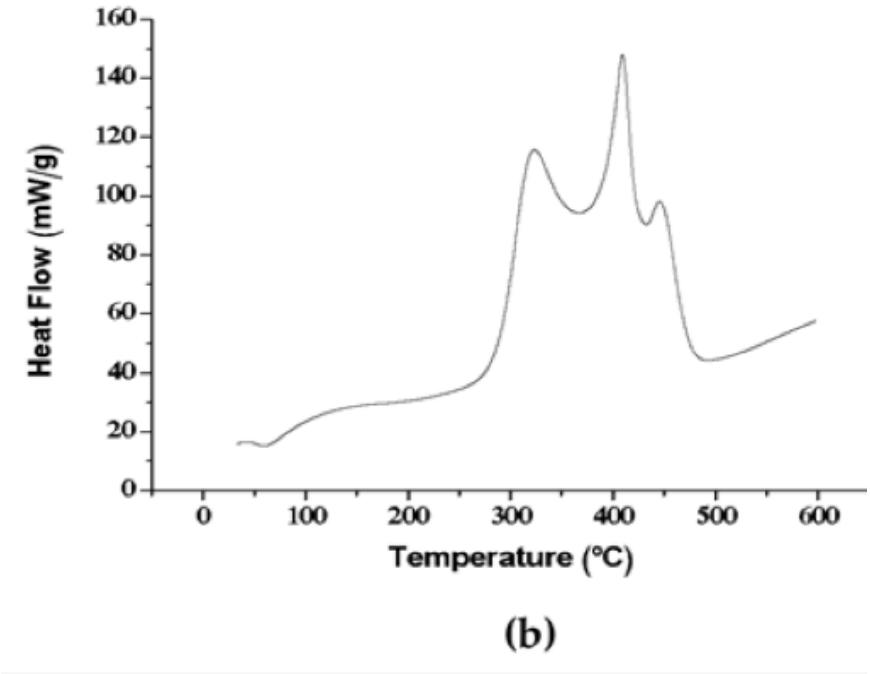
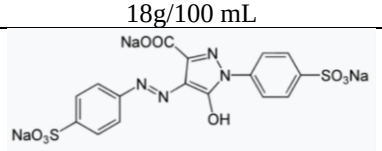




**Figure 4:** Thermogravimetric studies and different scanning calorimetry investigations of cellulose extracted from the precursor (coconut shell) [66]

**Table 6:** Properties of tartrazine

| | |
|---|---|
| Chemical formula | $C_{16}H_9N_4Na_3O_9S_2$ |
| Molar mass | 534.36 g/mol |
| Solubility in water | 20g/100 mL |
| Solubility in glycerol | 18g/100 mL |
| Structure |  |

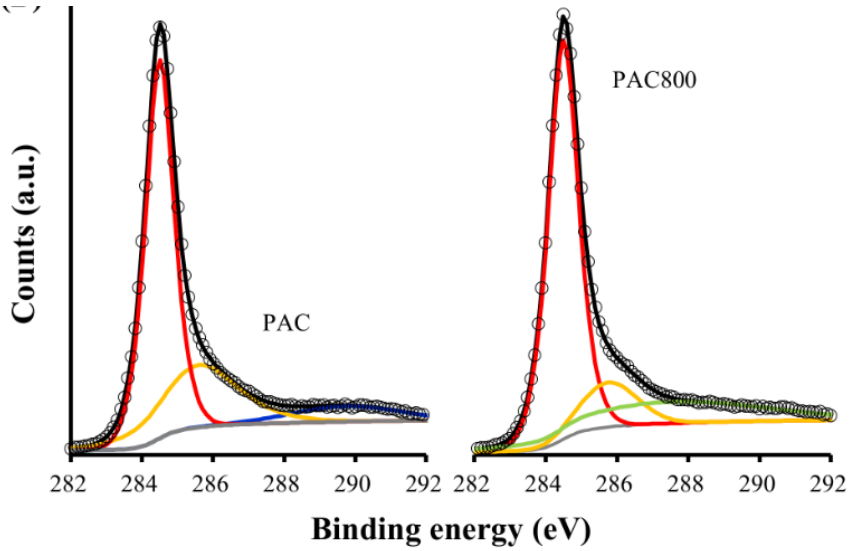



**Figure 5:** XPS studies of PAC and PAC800 [67]

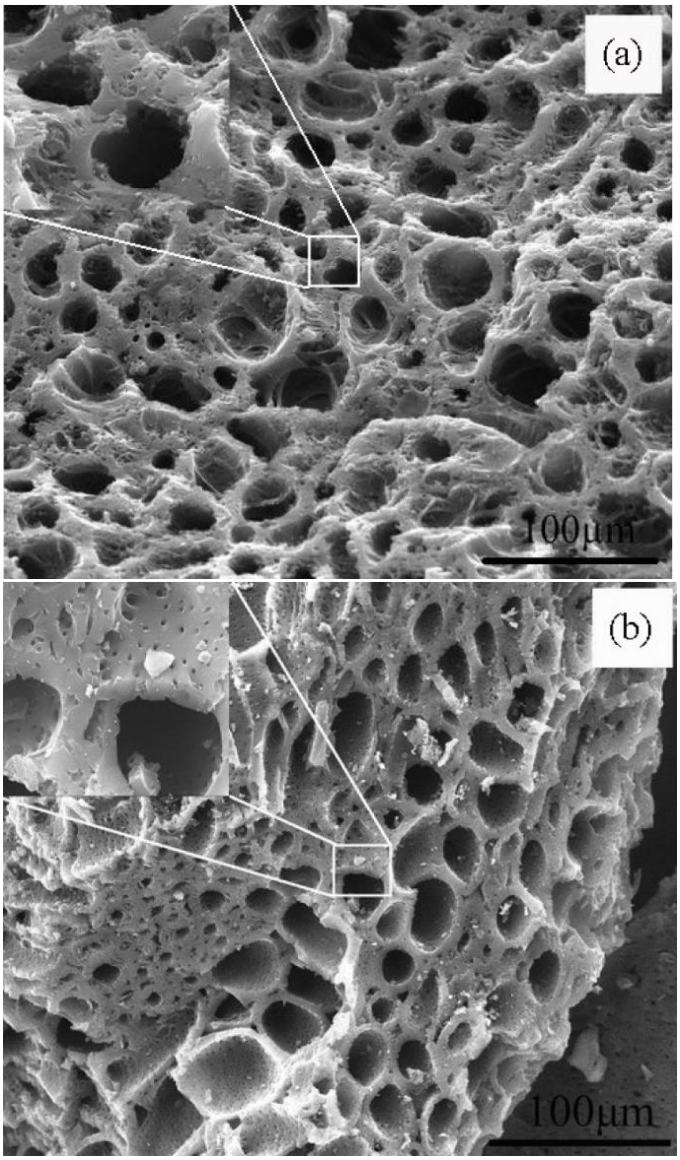



**Figure 6**: SEM images of (a) CSC-A and (b) CSC-B activated carbon [68]

**Table 7:** Properties of PAC and PAC 800 activated carbon

| | PAC | PAC 800 |
|---|---|---|
| Basicity | 2.086 | 2.736 |
| Acidity | 0.89 | 0.174 |
| Phenolic groups | 0.531 | 0.115 |
| Lactonic groups | 0.246 | 0.059 |
| Carboxylic groups | 0.113 | ND |
| Total pore volume ($m^3/g$) | 0.581 | 0.681 |
| Surface area, BET ($m^2/g$) | 1252.9 | 1410.8 |
| Average pore diameter (nm) | 1.855 | 1.93 |

Tartrazine has been used in food, wool, drugs, cosmetics, and silks. It has been noticed that there are side effects of tartrazine, such as allergies, asthma, and food intolerance. It is a synthetic azo dye, used for coloring purposes (lemon yellow). The formula structure and properties of tartrazine are listed in Table 6. In the thermogravimetric studies (figure 4), thermal behavior of the obtained activated carbons [66] could be represented by several stages in specific conditions, such as 75 °C-140 °C (removal of moisture content), 180 °C-340 °C (decomposition of lignin and hemicellulose), above 340 °C (degradation of cellulose), and 400 °C-600 °C (no significant decrease). In the different scanning calorimetry investigations, several observations were highlighted, including an endothermic peak at 80 °C (water evaporation) and an exothermic reaction at 320 °C-350 °C (fusion of cellulose). FTIR studies revealed that some groups such as C=O (2000 $cm^{-1}$), NH (3482 $cm^{-1}$), CH hydrocarbon (2904 $cm^{-1}$), and hydroxyl (3730 $cm^{-1}$, 3563 $cm^{-1}$) could be observed before the adsorption process. The existence of dye in the adsorbent could be supported by many peaks, such as 3400-3800 $cm^{-1}$ and 1600-800 $cm^{-1}$. Removal of tartrazine dye was 97 % within 5 minutes and achieved 99 % after 30 minutes. The adsorption capacity was 11.89 mg/g and 0.85 mg/g in the modified coconut cellulose and coconut cellulose, respectively. Further, researchers have explained that there are two phases (fast stage and the slower step) that could be observed in the adsorption process. It was noticed that both isotherms (Langmuir and Freundlich) were proposed to explain the adsorption process. Tetracycline has been used as an antibiotic to treat a variety of diseases. It is stable in acidic conditions, water-soluble and shows hydrophilic properties. It could be found in wastewater and natural waters, directly harming aquatic organisms (nephrotoxic and hepatotoxic effects). There are numerous techniques, such as ionic exchange, ozonation, chlorination, photocatalysis, and biological treatment, that have been used to remove tetracycline from wastewater. However, limitations of these techniques have been reported, including poor biodegradability, high cost, the formation of toxic by-products, and incomplete oxidation. The powdered activated carbon (PAC) was washed with a hydrochloric acid solution and distilled water [67]. Following that, PAC was heated to different temperatures, such as 500 °C (PAC 500), 600 °C (PAC 600), 700 °C (PAC 700), 800 °C (PAC 800) and 900 °C (PAC 900). It is noticed that thermal treatment can enhance surface area (Table 7), average pore diameter, and total pore volume. In the XPS studies (figure 5), the amounts of carbon and oxygen were found to be 87.36% & 12.64% for PAC, respectively, and 88.52% and 11.48% for PAC 800. Several peaks, such as 284.5 eV (C-C), 285.6 eV (C-O) and 289.7 eV (O-C=O) could be seen in the C1s spectrum. Obviously, the C-C peak (62.9% to 66%) increased, but the CO peak reduced (28% to 13%) and the O-C=O peak disappeared, after the thermal treatment process was conducted. It was noted that tetracycline adsorption improved (124.2 to 178.4 mg/g) when the treatment temperature was increased. Adsorption data fitted well with the Freundlich model; the Freundlich constant increased with increasing temperature from 296.15 K to 318.15 K in powder form (85.8 to 119.5 $(mg/g)(L/mg)^{1/n}$) and treated at 800 °C (132.1 to 178.6 $(mg/g)(L/mg)^{1/n}$). In terms of kinetic studies, the obtained data supported the pseudo-second-order model, rate constant was reported for the powder form (0.8 to 1.59 g/mg.min) and treated at 800 °C (0.72 to 1.29 $x10^{-3}$ g/mg.min). It was suggested that enthalpy and activation energy were 196.7 kJ/mol & 23.7 J/mol and 98.5 kJ/mol & 19.6 J/mol for PAC and PAC800, respectively.

Lead (Pb) is a heavy metal with an atomic number of 82. It is a toxic substance, resulting in water pollution and posing a threat to humans, the environment, and aquatic life. Lead mainly comes from printing, battery manufacturing, metal planting, ceramic, and glass manufacturing. It did not degrade in the environment, causing damage to the brain, neuronal system, liver, kidneys, and reproductive systems. There are several methods that have been used to remove lead ions, such as chemical precipitation, membrane separation, and electrochemical reduction. However, some disadvantages have been pointed out, including that membranes are expensive, have a higher energy cost, solvents can destroy the membrane, form a huge amount of sludge, and are ineffective at removing low concentrations of metal ions. Coconut shells were crushed (1-2 mm), carbonized (nitrogen atmosphere, temperature=500 °C, time=120 minutes, rate=20 °C/min), mixed with water and potassium hydroxide solution (in the activation process). SEM images (figure 6) highlight that a honeycomb shape [68] with big pores could be seen in all samples. A high weight ratio of KOH/sample such as in the CSC-B sample (KOH/sample was 2:1) could form a richer porous structure with a higher surface area (1135 $m^2/g$) and total pore volume (0.442 $cm^3/g$). The influence of agitation time on lead ion removal was studied. It was noted that adsorption capacity increases sharply (a lot

of uncovered surface area), followed by slowly remaining steady with time in both samples. Obviously, CSC-B and CSC-A (KOH/sample was 1:2) reached equilibrium after 2 and 4 hours, respectively. Adsorption data could be described using the Freundlich model ($R^2$=0.99) and the Halsey isotherm ($R^2$=0.99), which represent multilayer adsorption processes. In addition, the higher Freundlich constants ($K_F$) value in CSC-B (value=2.0188) if compared to CSC-A (value=1.3421), confirms higher adsorption ability. The kinetic studies supported the pseudo-second-order model ($R^2$=0.99) and obeyed the intra-particle diffusion process. Coconut-coir-based activated carbon [69] was synthesized through and activation process (KOH, 900 °C, 30 minutes, nitrogen atmosphere). Characteristics of the obtained carbons, such as pH (4.3), bulk density (0.31 g/mL), ash content (14%), average pore diameter (24 angstrom), surface area (826 $m^2$/g), micropore area (551 $m^2$/g) and micropore volume (0.25 mL/g) have been reported. The highest adsorption capacity could be seen at pH 5, contact time of 2.5 hours, and a carbon dose of 8 g/L. Kinetic studies were described using a pseudo-second-order kinetic model ($R^2$=0.997), indicating a chemical adsorption process. It was noted that the adsorption capacities were found to be 7.75 L/mg and 3.63 L/mg as confirmed in the Langmuir model and Freundlich isotherm, respectively. Volatile organic compounds (VOC) are considered carcinogenic, flammable, and toxic substances, causing chronic and acute health effects. These compounds will be discharged into the environment through human activities and industrial processes (smoking tobacco products, pharmaceuticals, paint, auto exhaust, and transportation). Lower pore volume and surface area [70] could be observed in ammonia-treated activated carbon (361.8 $m^2$/g, 0.16 $cm^3$/g) if compared to potassium hydroxide-treated carbon (478 $m^2$/g, 0.61 $cm^3$/g). It was noticed that some of the pores were broken and enlarged by adding the ammonia solution. The Langmuir model and pseudo-second-order kinetic isotherm obeyed the experimental data. The removal percentages of benzene and toluene reached 82.5% and 85.6% using potassium hydroxide carbon, respectively, compared to 91% and 92.3% for ammonia treatment carbon. The results of the regeneration test revealed that 50% of VOC removal was achieved after five cycles. The highest adsorption capacity [71] of phenol was 0.027 mg/g in specific activation conditions (900 °C, 10 minutes, carbon dioxide gas flow rate=96 mL/min, nitrogen flow rate=96 mL/min). It is known that the diameter of phenol is 0.75 nm, adsorption capacity increases when the pore size is smaller than 1.4 nm. It was noticed that the adsorption of phenol onto the adsorbent is very weak, supported by the Freundlich model (Freundlich isotherm constant=0.138). Data obtained from thermodynamic studies revealed that enthalpy, entropy, and free energy were found to be 155.48 kJ/mol, 0.44 kJ/mol.K and 5.89 to 46.3 kJ/mol, respectively. Activated carbon has been synthesized via chemical activation (potassium acetate) to remove aromatic volatile organic compounds [72]. The surface area and yield of the obtained carbon were 622 $m^2$/g and 32%, respectively. Experimental results confirmed a higher removal efficiency for toluene (82%) if compared to benzene (79%). The coconut shells [73] were sieved (20-60 mesh), dried in vacuum (120 °C, 8 hours), heated in tube furnace (1173 K, nitrogen gas), and activation process (steam, 60 minutes). It is found that prepared activated carbon has a lower carbonyl group, a narrower pore size distribution, and a developed micropore structure. It is believed that chlorobenzene is rapidly adsorbed compared to toluene because of the shorter breakthrough time. Powder-activated carbon was observed in powder form, with a particle size of 0.188 mm or less. Powdered activated carbon [74] has been used to remove phenol from an aqueous solution. It is noted that the adsorption rate was rapid; percentage removal reached 80% within 10 minutes. Adsorption data obeyed by the Freundlich model and pseudo-second-order model (rate constant= 0.0305 mg/μg.min). Thermodynamic studies indicated that the adsorption process was exothermic, spontaneous, and entropy-decreasing. The obtained coconut shell [75] was crushed into small pieces (10 mesh), soaked in sodium carbonate solution, heated (240 minutes), dried in an oven (1 day, 105 °C). The granular activated carbon (surface area=494 $m^2$/g) showed the highest adsorption capacity of phenol for sterilized type and unsterilized type at 13.7 mg/g and 17.54 mg/g, respectively, based on the Langmuir model. It was noted that sterilized samples and unsterilized samples will undergo adsorption processes and degradation reactions, respectively.

## 6. Conclusions

In this work, the removal of dyes, phenol compounds, heavy metals, antibiotics, and pesticides was studied using coconut shell-based activated carbon. Coconut shell indicated high mechanical strength properties, high pore volume, and environmentally friendly raw materials. The obtained results have proven that adsorptive data were supported by several isotherms (Langmuir model, Freundlich isotherm, pseudo-second-order kinetic or pseudo-first-order kinetic isotherm). Activated carbon can be reused again to reduce waste output and operational costs because it is available in a range of regenerable forms.

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