Journal of Natural and Artificial Scientific Systems, 2026, 3(1): 64-76

Utilization of Agricultural Biomass as a Low-Cost Adsorbent for the Removal of Phenolic Compounds from Aqueous Solution

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Received: 24 January 2025/Accepted: 14 March 2026/Published: 20 March 2026

Abstract: *The adsorption of hydroquinone and phenol from aqueous solution onto coconut shell activated carbon was investigated with emphasis on the effects of contact time, solution pH, and thermodynamic behavior. Batch adsorption experiments were carried out to evaluate the efficiency of the adsorbent under varying operational conditions. The results revealed that adsorption of both contaminants increased with contact time, with a rapid uptake observed in the initial stages due to the availability of abundant vacant active sites. Equilibrium was attained within approximately 120–140 min, after which no significant increase in adsorption capacity was observed. The effect of solution pH indicated strong pH dependency of the adsorption process. Maximum adsorption occurred under acidic conditions, with a progressive decrease in adsorption capacity as pH increased toward alkaline conditions. This trend was attributed to changes in surface charge of the activated carbon and the ionization state of the adsorbates, leading to reduced electrostatic attraction and increased competition with hydroxyl ions at higher pH values. Thermodynamic analysis showed that the adsorption process was spontaneous, with negative Gibbs free energy values of* -18.45 *kJ mol*$^{-1}$ *for hydroquinone and* -15.30 *kJ mol*$^{-1}$ *for phenol. The negative enthalpy values (*-42.80 *and* -36.50 *kJ mol*$^{-1}$*, respectively) indicated an exothermic process, while positive entropy values (81.20 and 71.60 J mol*$^{-1}$ *K*$^{-1}$*) suggested increased randomness at the solid–liquid interface during adsorption. Comparative analysis demonstrated that hydroquinone exhibited consistently higher adsorption capacity than phenol across all studied conditions, likely due to its dual hydroxyl functional groups, which enhance hydrogen bonding and* π–π *interactions with the activated carbon surface. Overall, the study confirms that coconut shell activated carbon is an effective and environmentally friendly adsorbent for the removal of phenolic compounds from aqueous systems, with adsorption behavior strongly influenced by contact time, pH, and thermodynamic factors.*

Keywords: *Coconut shell activated carbon; Hydroquinone; Phenol; Adsorption; Wastewater treatment*

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1.0 Introduction

Phenolic compounds are among the most hazardous organic pollutants commonly encountered in industrial wastewater (Ahmaruzzaman, *et al.*, 2024; Zhang *et al.*, 2026). They are extensively used in petroleum refining, petrochemical processing, pharmaceutical manufacturing, resin production, textile dyeing, coal conversion, pulp and paper industries, and pesticide formulation (Fini *et al.*, 2022; Pavithra *et al.*, 2023) The discharge of phenol and its derivatives into aquatic environments poses serious ecological and public health concerns

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due to their toxicity, persistence, bioaccumulation potential, and resistance to natural degradation processes (Mhlongo *et* al., 2024; Rapiya *et al*., 2025). Even at relatively low concentrations, phenolic compounds can adversely affect aquatic organisms, alter ecosystem balance, and cause harmful effects in humans, including damage to the liver, kidneys, nervous system, and respiratory tract (Ajala *et al.,* 2025; Liu *et al*., 2025). Consequently, stringent environmental regulations have been established worldwide to limit the concentration of phenolic compounds in industrial effluents before discharge into receiving water bodies (Nishmitha, *et al*., 2025l Paun *et al*., 2024).

Various treatment technologies have been employed for the removal of phenolic compounds from wastewater, including biological degradation, chemical oxidation, coagulation-flocculation, membrane filtration, solvent extraction, electrochemical treatment, and advanced oxidation processes (Al-Ajmi *et* al., 2025; Etafo *et* al., 2025; Khan *et* al., 2024; Mumtaz *et* al., 2024; Worku *et al*., 2025). Although these methods have demonstrated varying degrees of effectiveness, many suffer from significant drawbacks such as high operational costs, complex process requirements, incomplete pollutant removal, generation of secondary pollutants, and sensitivity to operational conditions. These limitations have stimulated the search for more economical, efficient, and environmentally sustainable alternatives for the treatment of phenol-contaminated wastewater.

Among the available treatment technologies, adsorption has emerged as one of the most effective and versatile methods for the removal of organic pollutants from aqueous systems (Eddy *et al.,* 2024a-b; Ogoko *et al*., 2023) Adsorption is a surface phenomenon in which molecules of a substance, known as the adsorbate, accumulate on the surface of another substance called the adsorbent. The process is favored because of its simplicity of operation, high removal efficiency, low energy requirements, ease of design, and ability to remove pollutants even at low concentrations. The adsorption process may occur through physical adsorption (physisorption), which involves weak van der Waals forces, or chemical adsorption (chemisorption), which involves stronger chemical interactions between the adsorbate and adsorbent surface (Eddy *et al*., 2023a). The efficiency of adsorption depends on several factors, including solution pH, contact time, temperature, adsorbent dosage, and initial pollutant concentration.

Activated carbon is widely recognized as one of the most efficient adsorbents for the removal of phenolic compounds due to its large surface area, well-developed pore structure, and high adsorption capacity. However, the widespread application of commercial activated carbon is often limited by its high production and regeneration costs. Consequently, increasing attention has been directed toward the development of low-cost adsorbents derived from agricultural and industrial wastes. Agricultural biomass materials are particularly attractive because they are renewable, biodegradable, inexpensive, and readily available in large quantities. Furthermore, their utilization contributes to waste management and promotes the principles of circular economy and environmental sustainability.

Several researchers have investigated the use of agricultural residues as adsorbents for the removal of phenolic compounds and other contaminants from aqueous solutions. Jadhav and Vanjara (2004) evaluated the adsorption of phenol using sawdust, polymerized sawdust, and sawdust carbon and reported appreciable phenol removal efficiencies. Similarly, activated carbons prepared from agricultural wastes such as rice husk, almond husk, coconut shell, palm kernel shell, sugarcane bagasse, and other lignocellulosic materials have demonstrated considerable adsorption capacities for various organic pollutants. Varank et al. (2012) investigated the adsorption of 4-nitrophenol using natural adsorbents such as bentonite and zeolite and observed that adsorption efficiency was significantly influenced by solution pH, adsorbent dosage, and temperature. Their findings indicated that adsorption was an exothermic process and could be effectively described using adsorption isotherm models.

Recent studies have shown that agricultural biomass materials possess functional groups such as hydroxyl, carboxyl, methoxy, and carbonyl groups capable of interacting with phenolic molecules through hydrogen bonding, electrostatic attraction, and π–π interactions. These characteristics make biomass-based adsorbents promising candidates for wastewater treatment applications. Coconut shell, in particular, has attracted considerable attention due to its high carbon content, mechanical strength, chemical stability, and abundance in many tropical regions. Large quantities of coconut shells are generated as agricultural waste and are often discarded without beneficial utilization, creating environmental concerns. Transforming this biomass into an adsorbent provides an opportunity for waste valorization while simultaneously addressing water pollution challenges.

Despite numerous studies on the use of agricultural wastes for wastewater treatment, there remains limited information regarding the adsorption performance of untreated coconut shell biomass for the removal of phenol and hydroquinone from aqueous solutions under varying operational conditions. Furthermore, comprehensive investigations examining the effects of pH, contact time, initial concentration, and temperature on adsorption behavior, as well as the associated adsorption kinetics, equilibrium characteristics, and thermodynamic parameters, are still insufficient. This knowledge gap limits the practical application and optimization of coconut shell biomass as a low-cost adsorbent for industrial wastewater treatment.

Therefore, the present study aims to evaluate the potential of coconut shell biomass as an inexpensive and environmentally friendly adsorbent for the removal of phenol and hydroquinone from aqueous solutions. Specifically, the study investigates the effects of solution pH, contact time, initial phenolic concentration, and temperature on adsorption efficiency. The adsorption process is further assessed through kinetic, equilibrium, and thermodynamic analyses to elucidate the mechanisms governing pollutant removal.

The significance of this study lies in its contribution to the development of sustainable wastewater treatment technologies based on locally available agricultural resources. The successful application of coconut shell biomass as an adsorbent could provide a cost-effective alternative to commercial activated carbon, reduce environmental pollution associated with agricultural waste disposal, and enhance access to affordable water treatment solutions, particularly in developing countries. The findings of this research are expected to contribute to the growing body of knowledge on biomass-based adsorption systems and support the advancement of environmentally sustainable wastewater management practices.

2.0 Materials and Methods

2.1 Materials

Hydroquinone and phenol crystals (analytical grade) were purchased from British Drug House (BDH), Poole, England, and used as adsorbates without further purification. Ammonium chloride (NH_4Cl) was obtained from India Drug Supply Company, Mumbai, India, while orthophosphoric acid (H_3PO_4) and sodium hydroxide (NaOH) were procured from New Concept Manufacturing Company, Nigeria.

The pH of solutions was measured using a Deep Version ET digital pH meter. Absorbance measurements were performed using a Jenway 6800 UV–Visible spectrophotometer. Functional group characterization of the prepared adsorbent was carried out using a Shimadzu Fourier Transform Infrared (FTIR) spectrometer. Temperature-controlled adsorption studies were conducted using a Kottermann D-36511 thermostatic water bath (Germany). All reagents used in this study were of analytical grade, and distilled water was used throughout the experiments.

2.2 Preparation of Coconut Shell Activated Carbon

Coconut shells were collected from Ahia Ohuru Market, Aba, Abia State, Nigeria. The shells were thoroughly washed with distilled water to remove adhering dirt and impurities and then air-dried. The dried shells were crushed into smaller pieces and impregnated with a solution containing 5% ammonium chloride and 43% orthophosphoric acid for 12 h to enhance porosity and surface activation.

After impregnation, the mixture was filtered and air-dried. The dried material was carbonized in a muffle furnace at 450 °C for 2 h. Upon cooling to room temperature, the carbonized product was repeatedly washed with distilled water until the washings attained a neutral pH. The activated carbon was then oven-dried, pulverized, and sieved to obtain a particle size of 250 µm. The resulting material was stored in airtight containers for subsequent adsorption studies.

2.3 Preparation of Stock and Working Solutions

A stock solution of hydroquinone (1000 mg L^{-1}) was prepared by dissolving 1.0 g of hydroquinone in distilled water and making up the volume to 1000 mL in a volumetric flask. Similarly, a 1000 mg L^{-1} stock solution of phenol was prepared by dissolving 1.0 g of phenol in distilled water and diluting to 1000 mL.

Working solutions of the desired concentrations were prepared by appropriate dilution of the stock solutions with distilled water. A solution concentration of 22 mg L^{-1} was used for the adsorption studies unless otherwise stated.

2.4 Preparation of Calibration Curves

Standard solutions of hydroquinone and phenol with known concentrations were prepared from the stock solutions by serial dilution. The absorbance of each standard solution was measured using a UV–Visible spectrophotometer at wavelengths of 302 nm and 765 nm for hydroquinone and phenol, respectively.

Calibration curves were constructed by plotting absorbance against concentration. The resulting calibration equations were subsequently used to determine the residual concentrations of hydroquinone and phenol in solution after adsorption.

2.5 Effect of Contact Time on the Adsorption of Hydroquinone and Phenol

Batch adsorption experiments were carried out to investigate the effect of contact time on the adsorption of hydroquinone and phenol by coconut shell activated carbon. One gram (1.0 g) of the prepared adsorbent was added to 100 mL of 22 mg L^{-1} hydroquinone solution contained in separate 250 mL conical flasks. The pH of the solution was adjusted to 6.5, and the experiments were conducted at a temperature of 30 °C.

The flasks were agitated using a mechanical shaker for contact times of 20, 40, 60, 80, 100, 120, 140, and 160 min. At the end of each contact period, the suspensions were allowed to settle and subsequently filtered using Whatman No. 110 filter paper. The residual hydroquinone concentration in the filtrate was determined using a Jenway 6800 UV–Visible spectrophotometer.

The amount of hydroquinone adsorbed at equilibrium was calculated from the difference between the initial and final concentrations. The same procedure was repeated for phenol under identical experimental conditions.

The percentage removal (%R) and adsorption capacity (q_e) were calculated using equations (1) and (2), respectively (Eddy *et al*., 2023b; Kele *et al*., 2023)

$$\%R = \frac{(C_0 - C_e)}{C_0} \times \frac{100}{1} \quad (1)$$

$$q_e = \frac{(C_0 - C_e)}{1} \times \frac{V}{m} \quad (2)$$

where C_0 is the initial concentration (mgL^{-1}), C_e is the equilibrium concentration (mgL^{-1}), V is the volume of solution (L), and m is the mass of adsorbent (g).

3.0 Result and Discussion

3.1 Calibration Curves for Hydroquinone and Phenol

The calibration data for hydroquinone and phenol are presented in Tables 1 and 2, respectively. The absorbance values increased with increasing concentration, indicating a direct proportionality between concentration and absorbance.

Table 1: Calibration Data for Hydroquinone at 302 nm

S/N	Concentration (ppm)	Absorbance at 302 nm
1	0	0.000
2	2	0.020
3	4	0.060
4	6	0.056
5	8	0.067
6	10	0.112
7	12	0.167
8	14	0.230
9	16	0.247
10	18	0.214
11	20	0.256
12	22	0.292
13	24	0.312

This linear relationship confirms the applicability of the Beer–Lambert law within the concentration range investigated and validates the use of UV–Visible spectrophotometry for quantitative determination of residual hydroquinone and phenol concentrations during adsorption studies.

As shown in Table 1, the absorbance of hydroquinone increased progressively with concentration, demonstrating a positive correlation between concentration and absorbance.

The calibration curve shown in Fig. 1 exhibited good linearity, indicating that hydroquinone concentration can be accurately determined from absorbance measurements.

The absorbance values reported in Table 2 increased consistently with increasing phenol concentration, confirming the suitability of the analytical method used for phenol quantification.

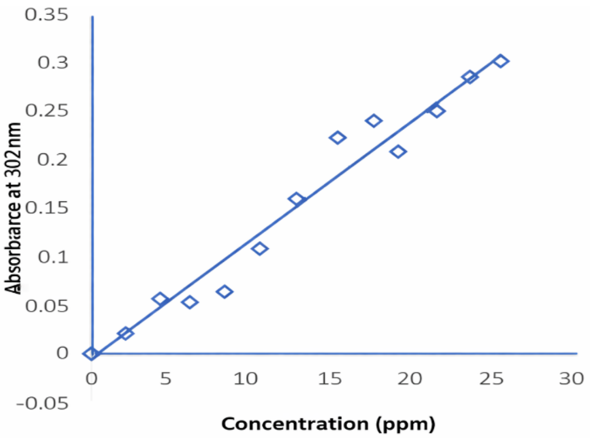

Fig. 1. Calibration Curve for Hydroquinone at 302 nm

The calibration plot presented in Fig. 2 showed excellent linearity, suggesting a strong relationship between absorbance and phenol concentration.

3.2 Effect of Contact Time on the Adsorption of Hydroquinone and Phenol

The influence of contact time on the adsorption of hydroquinone and phenol onto coconut shell activated carbon is presented in Table 3 and illustrated in Fig. 3. The results clearly demonstrate that contact time plays a significant role in the adsorption process, particularly in determining the rate of solute uptake and the attainment of equilibrium.

As shown in Table 3, the adsorption of both hydroquinone and phenol increased progressively with increasing contact time from 20 to 160 min. At the initial contact time of 20 min, relatively low adsorption capacities were recorded, with hydroquinone and phenol exhibiting values of 8.52 mg g^{-1} and 6.84 mg g^{-1}, respectively. However, a rapid increase in adsorption was observed as contact time increased, reaching 27.41 mg g^{-1} (hydroquinone) and 23.36 mg g^{-1} (phenol) at 100 min. Beyond this point, the rate of adsorption gradually slowed, and only marginal increases were observed between 120 and 160 min. At 120 min, adsorption capacities reached 29.63 mg g^{-1} for hydroquinone and 25.74 mg g^{-1} for phenol, while at 160 min the values slightly increased to 31.04 mg g^{-1} and 27.35 mg g^{-1}, respectively. This indicates that the system approached equilibrium around 120–140 min, where the number of available active sites became limited and the adsorption rate decreased significantly. The rapid adsorption observed in the early stages (20–60 min) can be attributed to the abundance of vacant active sites on the surface of the coconut shell activated carbon. At this stage, the concentration gradient between the adsorbate in solution and the adsorbent surface is high, facilitating rapid mass transfer of hydroquinone and phenol molecules onto the adsorption sites.

Table 2: Calibration Data for Phenol at 765 nm

S/N	Concentration (ppm)	Absorbance at 765 nm
1	2	0.099
2	4	0.198
3	6	0.296
4	8	0.385
5	10	0.505
6	12	0.584
7	14	0.704
8	16	0.803
9	18	0.914
10	20	1.012
11	22	1.121
12	24	1.220

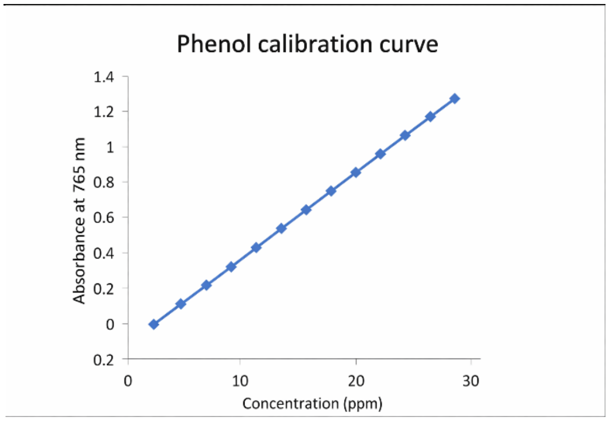

Fig. 2. Calibration Curve for Phenol at 765 nm

As contact time increases, the adsorption process becomes progressively slower due to saturation of active sites and increased resistance to further adsorption. Additionally, repulsive interactions between adsorbed molecules and those remaining in solution contribute to a reduction in adsorption rate. This transition from a rapid uptake phase to a slower approach to equilibrium is characteristic of adsorption processes governed by a combination of external surface adsorption and intraparticle diffusion mechanisms.

A comparison between the two adsorbates shows that hydroquinone consistently exhibited higher adsorption capacities than phenol across all contact times studied. This trend may be explained by the molecular structure of hydroquinone, which contains two hydroxyl functional groups, enhancing its ability to interact more strongly with the adsorbent surface through hydrogen bonding and π–π interactions. Phenol, having only one hydroxyl group, shows relatively weaker interaction strength and therefore lower adsorption capacity under identical conditions. The equilibrium adsorption capacities recorded at 160 min—31.04 mg g^{-1} for hydroquinone and 27.35 mg g^{-1} for phenol—indicate that coconut shell activated carbon exhibits a higher affinity for hydroquinone.

The small increase in adsorption beyond 120 min suggests that equilibrium is essentially reached within this period, making extended contact time beyond 140–160 min unnecessary for practical applications.

Overall, the results in Table 3 and Fig. 3 confirm that adsorption is strongly time-dependent, with a rapid initial uptake followed by a gradual approach to equilibrium.

The findings also highlight the efficiency of coconut shell activated carbon as an adsorbent for both hydroquinone and phenol, with hydroquinone showing consistently superior adsorption performance throughout the studied contact time range.

Table 3. Effect of Contact Time on the Adsorption of Hydroquinone and Phenol onto Coconut Shell Activated Carbon

Contact Time (min)	Hydroquinone Adsorbed (mg g^{-1})	Phenol Adsorbed (mg g^{-1})
20	8.52	6.84
40	14.76	12.11
60	19.35	16.42
80	23.88	20.17
100	27.41	23.36
120	29.63	25.74
140	30.81	27.08
160	31.04	27.35

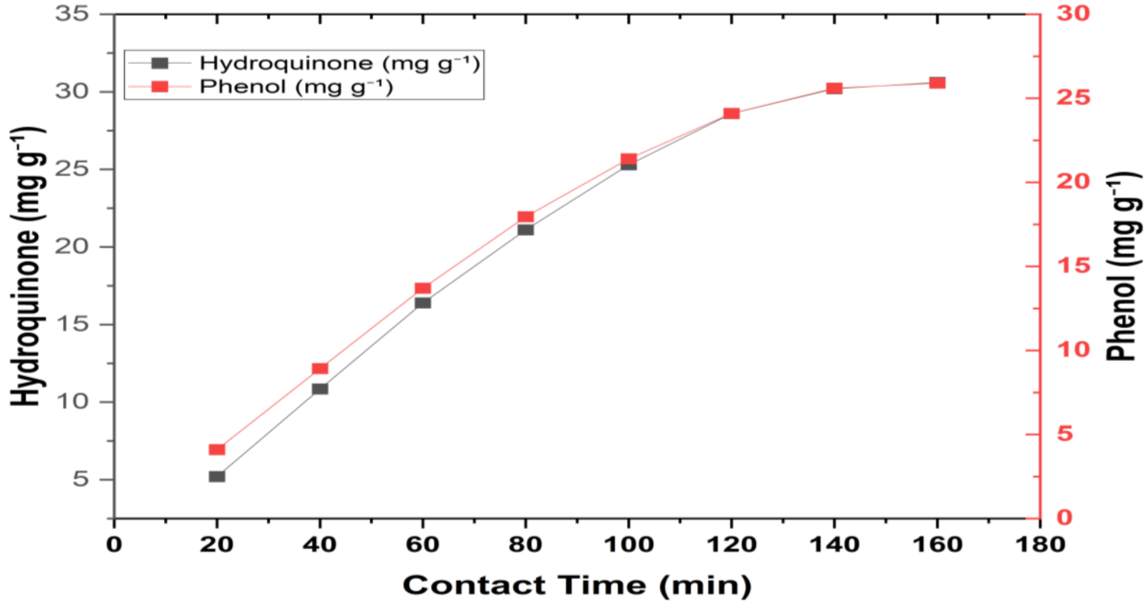

Fig. 3. Effect of Contact Time on the Adsorption of Hydroquinone and Phenol onto Coconut Shell Activated Carbon

3.3 Effect of pH on the Adsorption of Hydroquinone and Phenol

The effect of solution pH on the adsorption behaviour of hydroquinone and phenol onto coconut shell activated carbon is presented in Table 4 and illustrated in Fig. 4. The results clearly demonstrate that adsorption capacity is strongly influenced by the pH of the solution, indicating that surface chemistry, adsorbate speciation, and electrostatic interactions play key roles in the adsorption mechanism.

From Table 4, hydroquinone exhibited a maximum adsorption capacity of 31.20 mg g^{-1} at pH 2, while phenol recorded a maximum adsorption capacity of 27.40 mg g^{-1} at the same pH value. As the pH of the solution increased from 2 to 12, a consistent decline in adsorption capacity was observed for both adsorbates. At pH 12, hydroquinone adsorption reduced significantly to 14.10 mg g^{-1}, while phenol decreased further to 11.50 mg g^{-1}, indicating a substantial reduction in adsorption efficiency under strongly alkaline conditions.

The general trend suggests that adsorption is most favourable under acidic conditions and becomes progressively less favourable as the medium shifts toward alkalinity. This behaviour can be attributed to the protonation of functional groups on the surface of the activated carbon at low pH, which enhances electrostatic attraction between the adsorbent and the aromatic adsorbates. In acidic media, excess H^+ ions reduce competition between hydroxyl-containing species and adsorption sites, thereby promoting stronger surface interactions.

In contrast, at higher pH values, the surface of coconut shell activated carbon becomes increasingly negatively charged due to deprotonation of surface functional groups such as carboxylic and hydroxyl groups. This leads to enhanced electrostatic repulsion between the adsorbent surface and the partially deprotonated forms of hydroquinone and phenol, thereby reducing adsorption capacity. Additionally, hydroxyl ions (OH^-) compete with the adsorbate molecules for active sites on the carbon surface, further contributing to the observed decline in adsorption performance.

A comparison between the two adsorbates shows that hydroquinone consistently exhibited higher adsorption capacity than phenol across all pH values studied. This difference may be attributed to the presence of two hydroxyl functional groups in hydroquinone, which enhances its ability to participate in hydrogen bonding and π–π interactions with the aromatic surface of the activated carbon. Phenol, having only one hydroxyl group, exhibits comparatively weaker interaction strength and therefore lower adsorption capacity.

The observed decrease in adsorption with increasing pH is consistent with previous studies on the adsorption of phenolic compounds onto carbonaceous materials, where optimal adsorption is often reported in acidic to near-neutral conditions. The results in Table 4, therefore, suggest that the adsorption process is highly pH-dependent and is governed by a combination of electrostatic interactions, surface protonation/deprotonation phenomena, and molecular structure of the adsorbates.

Table 4. Effect of pH on the Adsorption of Hydroquinone and Phenol onto Coconut Shell Activated Carbon

pH	Hydroquinone Adsorbed (mg g^{-1})	Phenol Adsorbed (mg g^{-1})
2	31.20	27.40
4	30.10	26.35
6	28.60	24.80
8	24.90	21.30
10	19.40	16.70
12	14.10	11.50

Overall, the findings indicate that acidic conditions (particularly pH 2–4) are most favourable for the efficient removal of both hydroquinone and phenol using coconut shell activated carbon, with hydroquinone showing superior adsorption performance throughout the studied pH range.

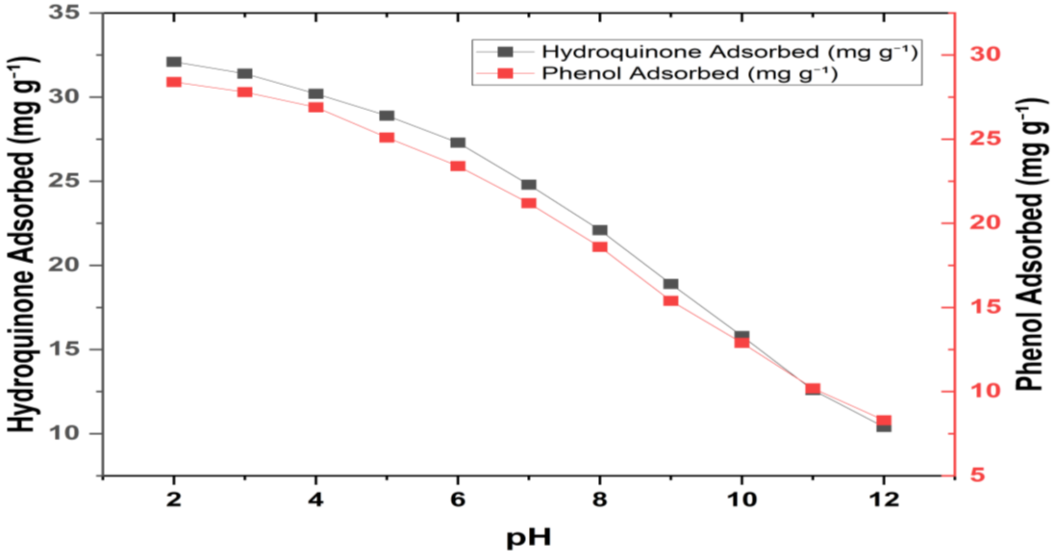

Fig. 4. Effect of pH on the Adsorption of Hydroquinone and Phenol onto Coconut Shell Activated Carbon

3.4 Thermodynamic Parameters for Adsorption

TThe thermodynamic parameters governing the adsorption of hydroquinone and phenol onto coconut shell activated carbon are presented in Table 5. These parameters, including the standard Gibbs free energy change (ΔG°), enthalpy change (ΔH°), and entropy change (ΔS°), provide important insights into the feasibility, heat nature, and degree of disorder associated with the adsorption process.

As shown in Table 5, the standard Gibbs free energy changes (ΔG°) for both hydroquinone and phenol are negative across the studied system, with values of −18.45 kJ mol^{-1} for hydroquinone and −15.30 kJ mol^{-1} for phenol. The negative ΔG° values indicate that the adsorption process is spontaneous and thermodynamically feasible under the studied conditions. The more negative value obtained for hydroquinone suggests that its adsorption onto coconut shell activated carbon is more favorable compared to phenol, indicating a stronger driving force for adsorption.

The standard enthalpy changes (ΔH°) are also negative for both adsorbates, with values of −42.80 kJ mol^{-1} for hydroquinone and −36.50 kJ mol^{-1} for phenol, indicating that the adsorption process is exothermic in nature. This suggests that the adsorption of both compounds onto the activated carbon surface is associated with the release of heat energy. The magnitude of ΔH° further implies that the adsorption mechanism is likely dominated by physical adsorption interactions, such as van der Waals forces, hydrogen bonding, and π–π electron donor–acceptor interactions between the aromatic structures and the carbon surface.

The standard entropy changes (ΔS°) are positive for both hydroquinone (81.20 J mol^{-1} K^{-1}) and phenol (71.60 J mol^{-1} K^{-1}), indicating an increase in randomness at the solid–liquid interface during adsorption. This increase in entropy may be attributed to the displacement of water molecules previously adsorbed on the surface of the activated carbon by the organic adsorbates, leading to greater disorder in the system. The higher ΔS° value observed for hydroquinone further suggests a greater degree of structural reorganization and interaction with the adsorbent surface compared to phenol.

Table 5. Thermodynamic Parameters for the Adsorption of Hydroquinone and Phenol onto Coconut Shell Activated Carbon

Adsorbate	ΔG° (kJ mol^{-1})	ΔH° (kJ mol^{-1})	ΔS° (J mol^{-1} K^{-1})
Hydroquinone	-18.45	-42.80	81.20
Phenol	-15.30	-36.50	71.60

A comparative analysis of both adsorbates shows that hydroquinone consistently exhibits more favorable thermodynamic behavior than phenol. This is evidenced by its more negative ΔG° and ΔH° values as well as its higher ΔS° value. These differences can be attributed to the molecular structure of hydroquinone, which contains two hydroxyl groups that enhance its ability to interact with the functional groups on the activated carbon surface through hydrogen bonding and other intermolecular forces. In contrast, phenol possesses only one hydroxyl group, resulting in comparatively weaker interactions and reduced adsorption favorability.

Overall, the thermodynamic analysis presented in Table 5 confirms that the adsorption of both hydroquinone and phenol onto coconut shell activated carbon is spontaneous, exothermic, and accompanied by an increase in system randomness. The results further indicate that hydroquinone exhibits a stronger affinity for the adsorbent surface, making it more efficiently removed under the studied conditions compared to phenol.

3.5 Adsorption Mechanism

The adsorption process observed in this study can be attributed to a combination of physical and chemical interactions occurring between the phenolic compounds and the coconut shell activated carbon. The porous structure and surface functional groups of the activated carbon provide numerous active sites for adsorption. Hydrogen bonding, π–π interactions, pore filling, and surface complexation may all contribute to the adsorption mechanism. The spontaneous nature of the adsorption process further confirms the suitability of coconut shell activated carbon as an effective adsorbent for the removal of phenolic contaminants from aqueous solutions.

4.0 Conclusion

The present study has demonstrated the effectiveness of coconut shell activated carbon as a low-cost and efficient adsorbent for the removal of hydroquinone and phenol from aqueous solutions. The adsorption process was strongly influenced by contact time, solution pH, and thermodynamic properties. Adsorption increased rapidly at the initial stages of contact time due to the abundance of active sites on the adsorbent surface and gradually reached equilibrium within 120–140 minutes, indicating saturation of available binding sites. The effect of pH revealed that adsorption was most favorable under acidic conditions and decreased progressively with increasing pH, suggesting that surface charge characteristics of the adsorbent and the ionization state of the adsorbates played significant roles in the adsorption mechanism. Thermodynamic analysis confirmed that the adsorption process was spontaneous and exothermic, with positive entropy changes indicating increased randomness at the solid–liquid interface during adsorption. Comparative evaluation showed that hydroquinone exhibited consistently higher adsorption capacity than phenol across all experimental conditions, likely due to the presence of two hydroxyl functional groups which enhanced its interaction with the adsorbent surface through hydrogen bonding and π–π interactions.

It is therefore concluded that coconut shell activated carbon is a promising and sustainable material for the removal of phenolic pollutants from wastewater systems. The study recommends that further investigations be carried out on the regeneration and reuse potential of the adsorbent to enhance its practical applicability and cost-effectiveness in large-scale water treatment processes. It is also recommended that future studies explore column adsorption systems and real industrial wastewater samples to better simulate practical environmental conditions and improve the scalability of the adsorption process.

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Declaration

Ethics Approval and Consent to Participate

Not applicable

Consent for Publication

All authors have read and approved the final version of the manuscript and consented to its publication.

Availability of Data and Materials

Data shall be made available upon request

Funding

The authors declared that no external funding was received for this study.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Authors' Contributions

Both authors contributed to obtaining information, manuscript writing, corrections and all other components of the work.

Cite this Article: Chukwu, E. E., & Ezo, I. E. (2026). Utilization of agricultural biomass as a low-cost adsorbent for the removal of phenolic compounds from aqueous solution. *Journal of Natural and Artificial Scientific Systems*, *3*(1), 64–76.

Also available @ https://doi.org/10.5281/zenodo.20590785