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Evaluation of Low Cost Industrial and Agricultural Wastes for Phenol Removal from Water

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Abstract

Phenol pollution in industrial effluent has been a serious environmental issue due to its toxicity and bioaccumulation and an aquatic life hazard and also a health risk to human beings. In an attempt to offer a low-cost and environmentally friendly treatment process, this research investigates the potential for applying low-cost industrial and agricultural solid waste products like waste paper, banana peels, and sawdust as low-cost alternative adsorbents in phenol removal from water. Some experiments were carried out for investigation of the effect of varied conditions of operation like initial concentration of phenol (30–120 mg/L), pH (3–13), adsorbent dose (0.5–2.5 g), contact time (30–150 min), and agitation modes. Amongst experimented materials, waste paper proved to have the highest adsorption of 90% maximum percent removal and 4.11 mg/g adsorption capacity at optimal conditions (pH 9, 30 mg/L, 2 g, 120 min).Banana peels and sawdust showed lower percentage removals of 65% and 61%, respectively, at the same conditions. The equilibrium data were applied to both Langmuir and Freundlich isotherm models to determine the nature of the adsorption behavior. The data were more suitably fitted to the Freundlich model (R^2 = 0.999), indicating a heterogeneous surface and multilayer adsorption. . The research confirms that waste materials, in this instance, paper waste, can serve as effective water treatment adsorbents and that process parameter optimization could enhance the removal efficiency. These investigations justify the use of recovered materials in environmentally friendly processes of water treatment for pollution control and resource conservation.

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Keywords:, waste paper , phenol, isotherm model, adsorption, Low-cost adsorbents, Industrial wastewater treatment.

تقييم النفايات الصناعية والزراعية منخفضة التكلفة لإزالة الفينول من المياه

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الملخص

يُعد تلوث المياه بالفينول في المخلفات الصناعية مشكلة بيئية خطيرة نظرًا لسميته وقدرته على التراكم الحيوي، مما يشكل خطرًا على الحياة المائية وصحة الإنسان. تهدف هذه الدراسة إلى استكشاف إمكانية استخدام النفايات الصناعية والزراعية منخفضة التكلفة، مثل نفايات الورق، وقشور الموز ، ونشارة الخشب، كمواد ممتزة بديلة لإزالة الفينول من المياه بطريقة صديقة للبيئة وفعالة من حيث التكلفة. أُجريت تجارب لدراسة تأثير ظروف التشغيل المختلفة، بما في ذلك التركيز الابتدائي للفينول (30–120 ملغ/ل)، ودرجة الحموضة (3–13)، وكمية المادة الماصة (0.5–2.5 غرام)، ومدة التلامس (30–150 دقيقة)، وأنماط التحريك. أظهرت النتائج أن نفايات الورق تمتاز بأعلى كفاءة إزالة بنسبة 90٪ وسعة امتصاص بلغت 4.11ملغ/غ عند الظروف المثلى (الرقم الهيدروجيني 9، 30ملغ/ل، 2 غ، 120 دقيقة)، في حين سجلت قشور الموز ونشارة الخشب نسب إزالة أقل بلغت65 ٪ و61٪ على التوالي. كما تم تحليل بيانات التوازن باستخدام نماذج لانغموير وفرويدليش، ووجد أن البيانات تتوافق بشكل أفضل مع نموذج فرويدليش (R^2 =0.999)، مما يشير إلى امتزاز متعدد الطبقات وسطح غير متجانس. تؤكد الدراسة أن المواد المعاد تدويرها، وخصوصًا نفايات الورق ، تمثل مواد ممتزة فعالة لمعالجة المياه، وأن تحسين معايير العملية يمكن أن يعزز كفاءة الإزالة. تدعم هذه النتائج استخدام المواد

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المعاد تدويرها في عمليات معالجة المياه الصديقة للبيئة للتحكم في التلوث والحفاظ على الموارد.

الكلمات المفتاحية: نفايات الورق، الفينول، الامتزاز، نموذج الامتزاز، مواد ممتزة منخفضة التكلفة، معالجة مياه الصرف الصناعي.

INTRODUCTION

Phenol is one of the common pollutants that are usually found in industrial wastewater from factories producing rubber, plastic, textiles, pharmacy medicine, paper, coke, and petroleum products[1]. Phenol is a harmful chemical with both environmental and health consequences as it can easily enter the human body through the skin, lungs, or gastrointestinal tract, where it can affect the control of important functions like the regulation of breathing[2] . Due to these threats, conservation organizations like the U.S. USEPA have placed severe limits on the presence of phenol in water surface water, 1.0 mg/L maximum, and only 0.002 mg/L in drinking water[3].

Additionally, when phenol is mixed with chlorine in treated drinking water, the byproducts are toxic chlorophenols, which not only possess a foul taste but are also deadly poisonous. There have been different methods developed for the removal of phenol from water, including chemical treatment, filtration, biological treatment, and electrochemical treatment. Among these, adsorption has gained wide attention for being simple, cost effective, and reliable even when dealing with toxic substances[4] [5].

In recent years, researchers have been focusing on using waste materials from farms and industries like banana peels, sawdust, rice husks, coal, and waste paper as low cost alternatives for removing phenol. These natural materials have shown great potential. For example, activated banana peels have absorbed up to 48 mg of phenol per gram within an hour, and waste paper, which contains a lot of cellulose and has a porous surface, has also proven effective[6][7]. Another method gaining interest is ultrasound-assisted adsorption .Ultrasonic waves employed distribute contaminants and promote their contact with the adsorbing material by small bubbles that bring about increased mixing. However, a great deal of study is still required to establish optimal parameters of this process[8]. In order to find out how these materials adsorb

http://www.doi.org/10.62341/naeg0109

phenol, scientists will typically employ models like the Langmuir and Freundlich isotherms .Phenol would adsorb in one layer upon a smooth surface by using the Langmuir model, while the Freundlich model is used if taking into account more complex, rough surfaces upon which the phenol will adsorb in numerous layers[9]. The study is adopting the philosophy of "treatment of waste using waste" by establishing the efficiency of three usually utilized waste materials waste paper, banana peels, and sawdust to desorb phenol from water. For batch experiments, the study investigates the effects of different parameters like pH, concentration of phenol, dosage, contact time, and stirring in the presence or absence of ultrasonic on performance. By data analysis through isotherm models, the focus is to bring to the limelight a green, sustainable method of purifying polluted water using otherwise discarded material.

2.Materials and Experimental Work

2.1Materials (Adsorbents):

The three adsorbents chosen for this study banana peels , sawdust , and waste paper are easily obtained and made from regular household or commercial waste. Each material was cleaned thoroughly using distilled water to remove any unwanted dirt, dried in an oven at 60 °C for a full day, and then ground into powders with a particle size between 0.5 and 1 mm. The powders produced from this process were preserved in airtight containers until further use.

2.2Phenol Solution Preparation:

A stock solution of phenol 1000mg/l was prepared using analytical grade phenol crystals dissolved in purified water. Working solutions of needed concentrations (10_100mg/l)we reattained by suitable dilution.

2.3Batch Adsorption Experiments:

Batch experiments were conducted in 125 mL Erlenmeyer flasks containing 20 mL of phenol solution and a defined amount 0.5–2.5g of each adsorbent. The solutions were stirred at 250 rpm for contact times ranging from 30 to 150 minutes. The pH of the solutions was adjusted within the range of 3 to 13 using 0.1 M HCl or NaOH. Four mixing methods were applied: laboratory shaker, mechanical agitator, magnetic stirrer, and ultrasonication to explore their effects on adsorption efficiency. All experiments were carried out at ambient temperature 25. After adsorption, samples were filtered through Whatman No. 42 filter paper. The remaining phenol concentration was measured using a UV-Vis spectrophotometer

http://www.doi.org/10.62341/naeg0109

(GBC Cintra 6 series) at a wavelength of 270 nm. After agitation, the samples were filtered through Whatman No. 42 filter paper. A calibration curve was established using standard phenol solutions, and a strong linear correlation was observed, with a slope of 0.0148, as shown in Figure 1. This curve was used to determine phenol concentrations in the filtrate samples.

2.4 Adsorption Capacity and Removal Efficiency:

The amount of phenol adsorbed per unit mass of adsorbent (qe, mg/g) and the removal efficiency (R%) were calculated using the following equations:

$$qe = \frac{(Co - Ce)\,V}{m} \qquad (1)$$

$$R\% = \frac{C_0 - C_e}{C_o} \times 100 \qquad (2)$$

Where:

q_e :The adsorption capacity
C_o: initial concentrations of phenol
C_e: equilibrium concentrations of phenol (mg/L)
V : volume of the phenol solution (L)
m: mass of adsorbent (g)

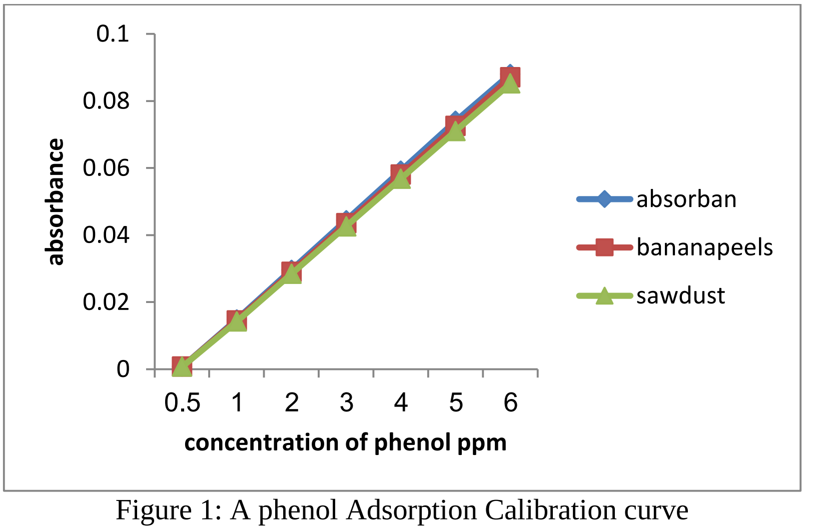

Figure 1: A phenol Adsorption Calibration curve

2.5 Evaluation of Operational Parameters:

2.5.1 Effect of Mixing Techniques

The impact of different mixing techniques on phenol adsorption was investigated by agitating 30 mL of a 30 mg/L phenol solution

http://www.doi.org/10.62341/naeg0109

with 1 g of each adsorbent (waste paper, banana peels, sawdust) at pH 8. The solutions were stirred at 200 rpm for 200 minutes using four agitation methods: laboratory shaker, magnetic stirrer, mechanical agitator, and ultrasonic bath. The experiments were carried out at ambient temperature 25 °C, and the residual phenol concentration was measured using the calibration curve described previously.

2.5.2 Effect of Solution pH

To assess the influence of solution pH on phenol removal, batch adsorption experiments were performed across a pH range of 3 to 11, adjustedemploying0.1 M HCl or NaOH. Each 30 mL phenol solution (30 mg/L) was contacted with 1 g of adsorbent and agitated at 250 rpm for 150 minutes at room temperature. The optimal pH condition was identified based on greatest phenol removal efficiency.

2.5.3 Effect of Initial Phenol Concentration

The effect of initial phenol concentration on adsorption capacity was also studied by varying concentrations from 30 to 120 mg/L. Thirty milliliters of phenol solution was corrected to pH 9 and added to 1 g of the adsorbent in each experiment Mixing was conducted at 250 rpm for 150 minutes, and adsorbed phenol was determined using Equation (1).

2.5.4 Effect of Adsorbent Dose

To determine the effect of adsorbent dosage, various dosages 0.5 to 2.5 g of each adsorbent were added to 30 mL of phenol solution 30 mg/L, pH 9. The solutions were stirred at 250 rpm for 150 minutes at room temperature. Adsorption capacity was calculated for determining the optimum dosage of adsorbent.

2.5.5 Effect of Contact Time

The influence of contact time on phenol adsorption was studied using 30 mL of 30 mg/L phenol solution at optimal pH and adsorbent dosage. The solutions were stirred at 250 rpm, and samples were removed at predetermined time intervals from 30 to 150 minutes to establish the adsorption kinetics.

2.6 Adsorption Isotherm

Adsorption isotherms are required to define the state of equilibrium between adsorbent surface and adsorbate molecules. The models give insight into the distribution behavior of phenol in the solid and liquid phases at equilibrium. The data acquired were discovered to

http://www.doi.org/10.62341/naeg0109

fit perfectly in both the Langmuir and Freundlich isotherm models, which are explained mathematically in Equations (3) and (4), respectively [6].

$$qe = \frac{abC_e}{1+bC_e} \qquad (3)$$

$$qe = K_f \, C_e^{1/n} \qquad (4)$$

Where:
qe : Amount adsorbed at equilibrium in (mg/g)
Ce: Equilibrium concentration (mg/L).
Kf : Freundlich adsorption coefficient (mg/g)(L/mg).
n : Considered to be a number which depicts surface heterogeneity and sorption intensity.
a: The maximum adsorption capacity (mg/g).
b: The Langmuir fitting parameter (L/mg).
The favorability or unfavorability of an adsorption system can be determined by the value of RL, a key characteristic of the Langmuir isotherm. This dimensionless constant, known as the separation factor or equilibrium parameter, is defined by equation (5)

$$R_L = \frac{1}{1+ K_L C_0} \qquad (5)$$

Where:
Co is the highest initial concentration, this parameter suggests the type of isotherm to be irreversible (RL = 0), favorable (0 < RL < 1) or unfavorable (RL > 1)

3. Results and Discussion:

3.1 Influence of Mixing Techniques:

The elimination effectiveness of phenol was assessed with three inexpensive biosorbents waste paper, banana peels , and sawdust under four agitation approaches: laboratory shaker, mechanical stirrer, magnetic stirrer, and ultrasonic bath as shown Figure 2.
Outcomes revealed that mixing technique significantly influences adsorption efficiency. Ultrasonic and mechanical agitation attained superior phenol removal compared to magnetic stirring and shaking. This is due to ultrasonic cavitation and micro-turbulence breaking particle clusters and boosting mass transfer, while mechanical stirring betters fluid contact.

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Among the biosorbents, waste paper presented the best adsorption capacity, probably because of its fibrous structure furnishing more accessible sites, followed by banana peels and sawdust.
These findings stress the importance of selecting effective mixing methods, with ultrasonication combined with waste paper providing a favorable approach for enhanced phenol removal in wastewater treatment.

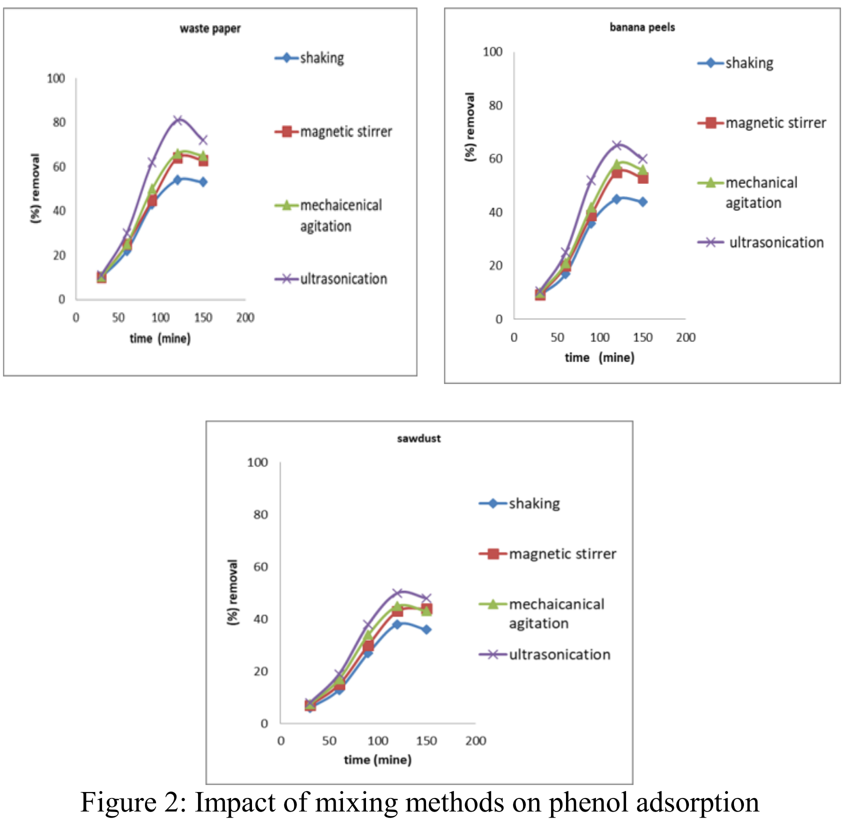

Figure 2: Impact of mixing methods on phenol adsorption

3.2. pH-Dependent Effects:

The effectiveness of phenol removal by three inexpensive biosorbents waste paper, banana peels, and sawdust was found to be significantly influenced by the pH of the solution. As pH increased from acidic (pH 3) to near neutral and slightly alkaline (pH 8–9), removal efficiency was considerably enhanced for all the test materials. Waste paper was the best with approximately 90% removal at pH 9, followed by banana peels with approximately 70%, and sawdust was the worst performer with a maximum of

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approximately 60%. These variations are nicely reflected in Figure 3, showing the profiles of adsorption in the range of pH. Beyond pH 9, all the biosorbents exhibited a reduction in removal efficiency, with reduced adsorption capacity in highly alkaline conditions. This may be due to the higher ionization of phenol at high pH and the alteration in surface charge properties of the biosorbents, which cumulatively influence the adsorption process. Overall, the results demonstrate the improved adsorption capacity of waste paper, suggesting its great potential as a low cost and environmentally friendly biosorbent for phenol elimination in wastewater treatment systems.

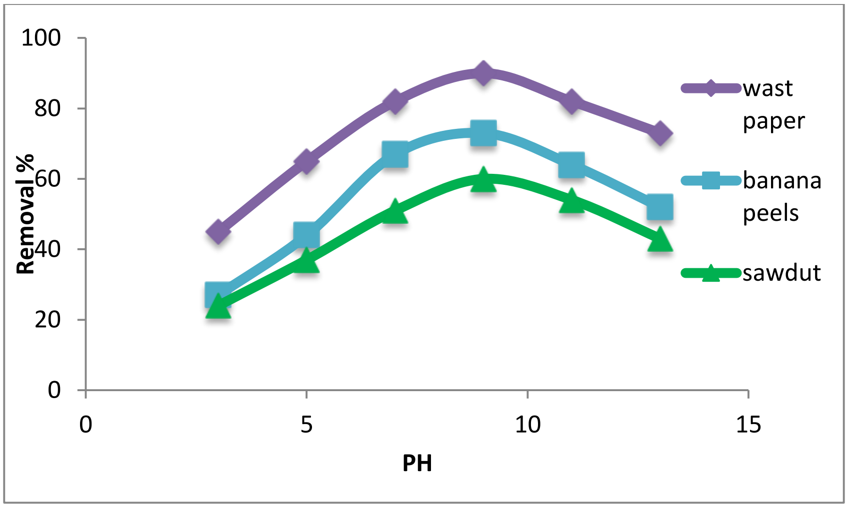

Figure 3: Effect of solution pH on the efficiency of phenol removal

3.3. Initial Phenol Concentration Effects :

For comparison of the influence of the initial concentration of phenol on the adsorption efficiency, three low-cost adsorbents (banana peels, sawdust, and paper waste) were tested under optimized conditions (ultrasonic agitation and pH 9). The concentrations of phenol used in testing were 30, 50, 70, 90, and 120 mg/L. As is evident from Figure 4, waste paper recorded maximum removal efficiency at all concentrations with a maximum of 92% at 30 mg/L which fell gradually to 75–76% at higher concentrations as adsorption sites got saturated. Banana peels registered relatively high efficiency, which was as high as 85% at 30 mg/L and fell to 65–66% at 90–120 mg/L. Sawdust, though still active, showed the worst performance among the three, at removal efficiencies of 78%

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at 30 mg/L falling to 56–57% at the highest level. This trend shows the greater adsorption capacity of paper waste, based on its fibrous structure and large surface area, to be a potential candidate for the removal of phenol from aqueous solution.

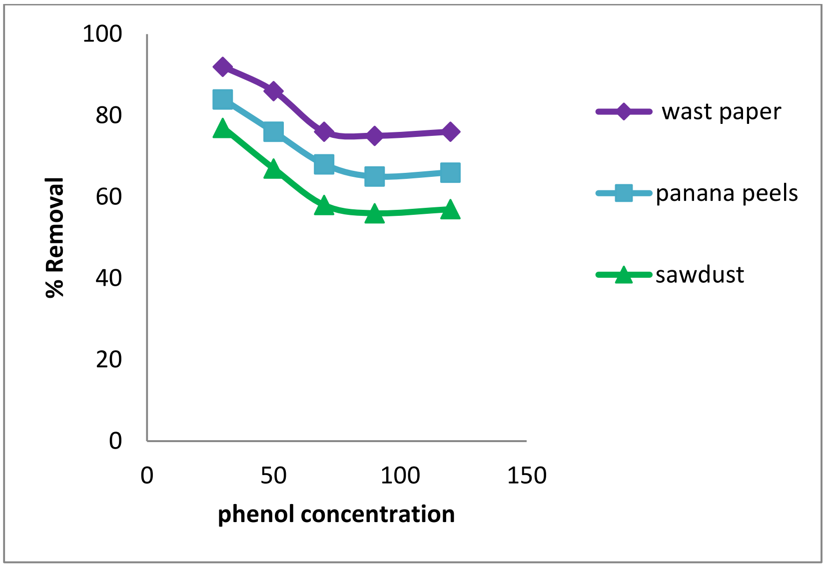

Figure 4: Phenol Concentration Effects on Removal Performance

3.4. Adsorbent Dose Effects:

The effect of adsorbent dose on phenol removal efficiency was investigated using three inexpensive biosorbents: waste paper, banana peels, and sawdust, at pH 9 and an initial phenol concentration of 30 mg/L under ultrasonic agitation. As shown in Figure 5, increasing the adsorbent dose from 0.5 g to 2.0 g significantly improved removal efficiency for all materials. Waste paper achieved the highest efficiency, increasing from 45% to 90%, and plateaued beyond 2.0 g, indicating site saturation. Banana peels showed moderate improvement from 35% to 75%, while sawdust exhibited the lowest performance, rising from 30% to 65%. The plateau in removal efficiency suggests that adsorption sites became fully occupied, limiting further phenol uptake despite additional adsorbent. These results highlight the superior adsorption capacity of waste paper, making it a promising low-cost adsorbent for phenol removal from aqueous solutions.

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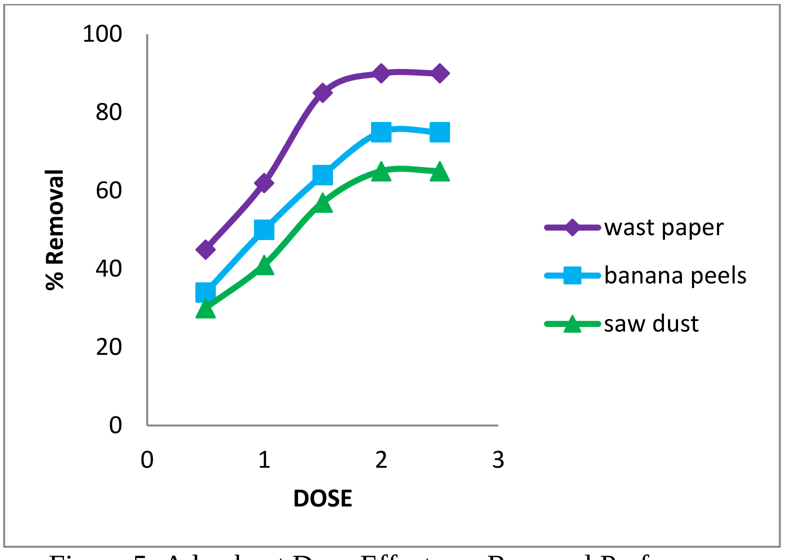

Figure 5: Adsorbent Dose Effects on Removal Performance

3.5. Effect of Contact Time on Phenol Adsorption:

The effect of contact time on phenol removal efficiency was investigated using waste paper, banana peels, and sawdust under identical experimental conditions (initial phenol concentration = 30 mg/L, pH = 9, ultrasonic agitation). As shown in Figure 6, phenol uptake increased progressively with time for all adsorbents.

Waste paper showed the highest removal efficiency, rising from 20% at 30 min to 85% at 120 min. Beyond this point (150 min), no further improvement was observed, indicating that equilibrium had been reached. Similarly, banana peels reached a maximum of 75%, while sawdust leveled off at 65%.

The initial rapid increase in adsorption is attributed to the abundance of available active sites on the adsorbent surface. As these sites became occupied, the rate of adsorption slowed until dynamic equilibrium was established. These findings confirm that 120 min is the optimal contact time under the studied conditions, particularly for waste paper, which exhibited superior adsorption performance.

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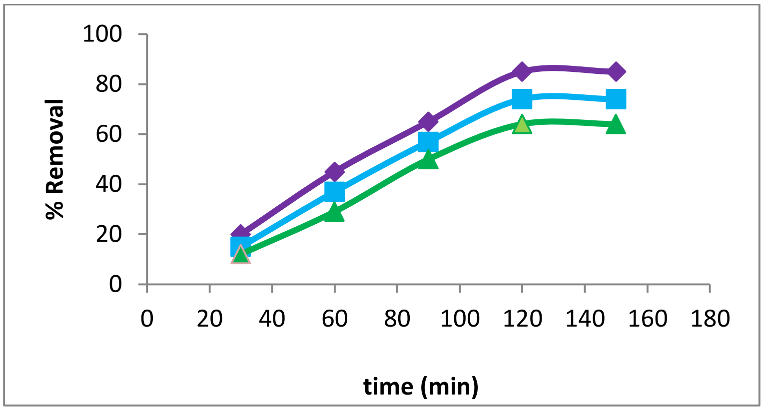

Figure 6: Effect of Time on Removal Efficiency

3.6. Adsorption Isotherm Model:

The understanding obtained from the adsorption isotherm are essential for designing efficient adsorption equipment and also elucidating the complex interaction between the adsorbent and adsorbate molecules once they achieve equilibrium. In our investigation, we explored two notable isotherm models: the Freundlich and Langmuir models, which gracefully describe the balance between the adsorbate clinging to the adsorbent and the remains still present in the solution. Our analysis showed a captivating agreement between our experimental equilibrium data detailed in Table 1 and shown through Figures 7, 8, and 9 and both the Freundlich and Langmuir isotherm equations. Remarkably, it was the Freundlich model that stood out, showing a higher R^2 value compared to its Langmuir counterpart.

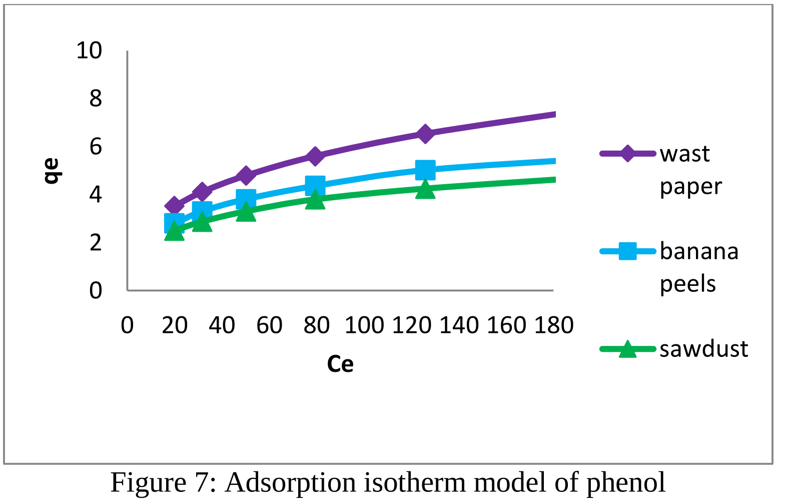

Figure 7: Adsorption isotherm model of phenol

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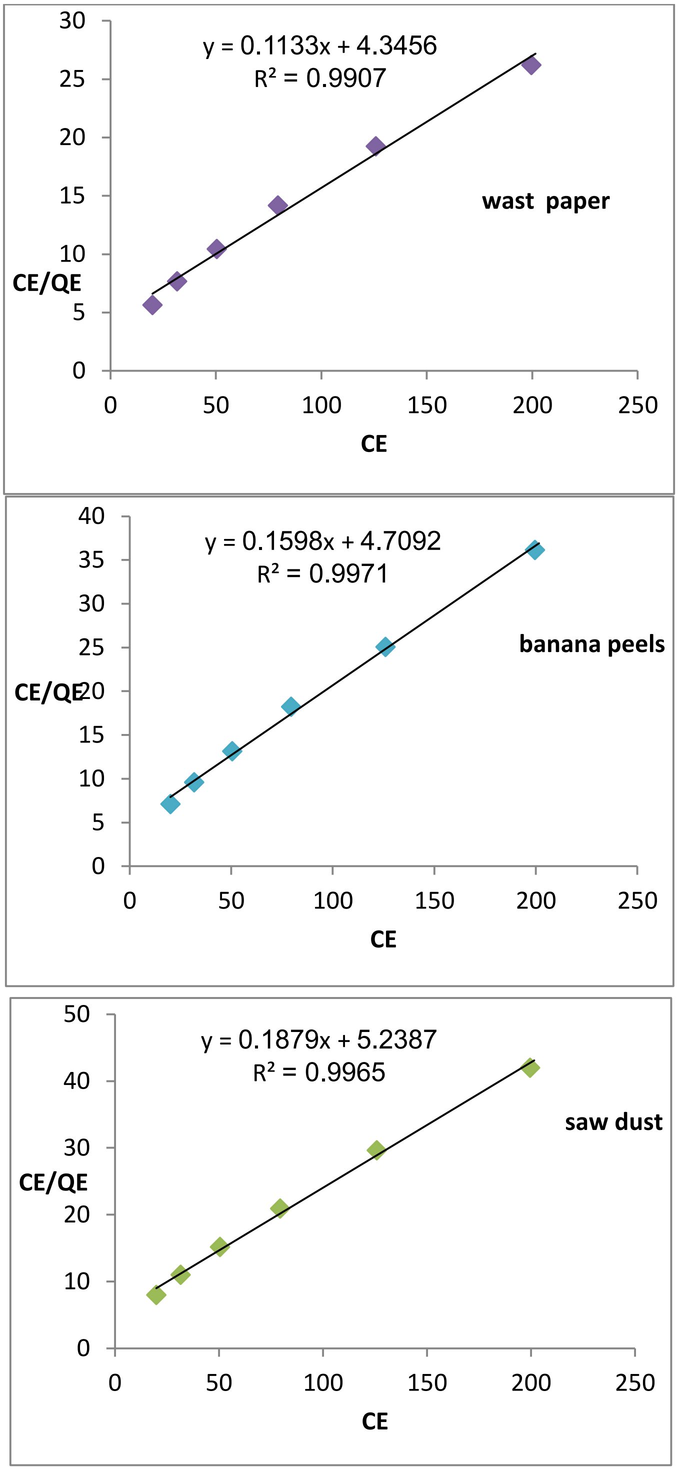

Figure 8: Langmuir Model for Phenol Adsorption Isotherm

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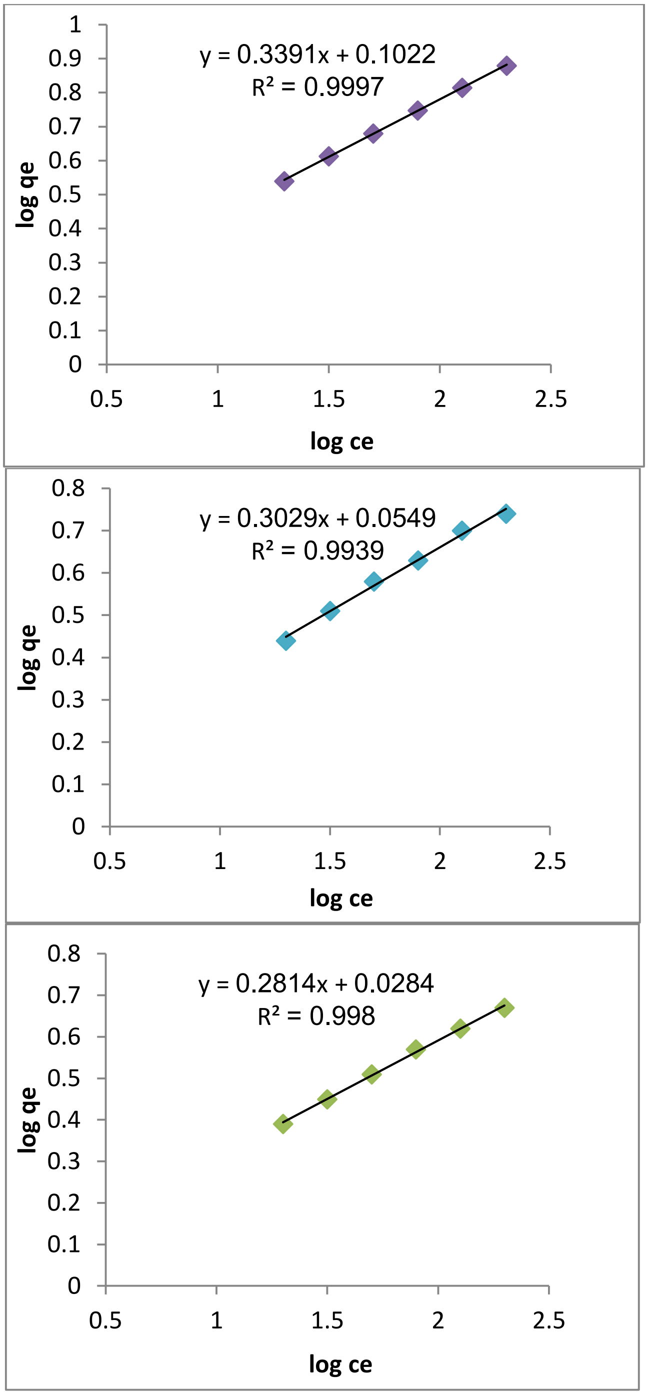

Figure 9: Freundlich Model for phenol Adsorption Isotherm

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Table 1. Phenol Removal Isotherm Constants with Waste Paper as Adsorbent

Langmuir Isotherm Model:

	Maximum adsorption capacity q_m (mg\g)	Energy of adsorption K_l (l/mg)	R^2
Waste paper	8.836	0.025	0.991
Banana Peels	6.259	0.033	0.997
Sawdust	5.324	0.035	0.996

Freundlich Isotherm Model

	Adsorption capacity K_f	1/n	R^2
Waste paper	1.289	0.025	0.999
Banana Peels	1.178	0.033	0.993
Sawdust	1.090	0.035	0.997

Conclusion:

Because of the elevated cost and environmental issues associated with commercial adsorbents, there has been increased interest in the application of low-cost, sustainable materials for wastewater treatment. In this study, the adsorption efficiency of three biosorbents waste paper, banana peels, and sawdust was examined for the removal of phenol from aqueous solutions.

The outcomes indicated that adsorption performance varied depending on the kind of biosorbent, with waste paper showing the highest efficiency, trailed by banana peels and then sawdust. Several operational parameters considerably influenced the removal efficiency, including the type of mixing method, solution pH, adsorbent dosage, initial phenol concentration, and contact time. Among the isotherm models examined, the Freundlich model gave the finest fit to the experimental data, implying multilayer adsorption on heterogeneous surfaces.

Under optimized conditions ultrasonic agitation, pH 9, initial phenol concentration of 30 mg/L, 1 gram of adsorbent, and 120 minutes of contact time waste paper achieved a maximum removal efficiency of around 90%, compared to 75% for banana peels and 65% for sawdust. These findings emphasize the potential of waste paper as a superior, low cost option to conventional adsorbents for effective phenol removal in wastewater treatment applications.

http://www.doi.org/10.62341/naeg0109

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