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INDOOR AIR POLLUTION CLEAN-UP USING ACTIVATED CARBON

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ABSTRACT

Indoor air pollution is a major environmental and public health concern due to the presence of volatile organic compounds (VOCs) such as formaldehyde (HCHO), which can cause respiratory illnesses, eye irritation, and other adverse health effects. This study evaluated the efficiency of phosphoric acid (H_3PO_4)-activated coconut shell activated carbon for the removal of formaldehyde under controlled laboratory conditions. Batch adsorption experiments were conducted using an initial formaldehyde concentration of 5.0 ppm while varying contact time (10–60 min), adsorbent dosage (2–10 g), and adsorption temperature (20–40°C). Removal efficiency and adsorption capacity were determined, while descriptive statistics, Pearson correlation, multiple linear regression, and one-way ANOVA were applied for data analysis. The results showed that formaldehyde removal efficiency increased with longer contact time and higher adsorbent dosage but decreased as temperature increased. Optimum performance was achieved at 60 minutes, 10 g dosage, and 20°C, yielding 96% removal efficiency and an adsorption capacity of 12.0 mg/g. The regression model (R^2 = 0.982) and correlation analysis (r = 0.996) confirmed excellent predictive accuracy and a strong relationship between adsorption capacity and removal efficiency, demonstrating the potential of coconut shell activated carbon as a sustainable, low-cost indoor air purification adsorbent.

KEYWORDS: Indoor air pollution, Formaldehyde, Activated carbon, Coconut shell, Adsorption, Indoor air quality.

1. INTRODUCTION

Indoor air pollution has emerged as one of the leading environmental health concerns because people spend a considerable proportion of their daily lives inside residential, commercial, and institutional buildings. Indoor environments often contain numerous airborne contaminants,

including particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, ozone, biological aerosols, and volatile organic compounds (VOCs). Among these pollutants, VOCs are particularly important because of their persistence, widespread occurrence, and adverse effects on human health (Wang et al., 2013; Zhang et al., 2017). Exposure to elevated concentrations of VOCs has been associated with a broad spectrum of acute and chronic health problems, including eye irritation, headaches, dizziness, respiratory disorders, neurological impairment, and cancer (Kim et al., 2011; Zhang et al., 2017). Since indoor concentrations of VOCs are frequently higher than outdoor concentrations, effective technologies for indoor air purification have become increasingly important. Among indoor VOCs, formaldehyde (HCHO) has attracted considerable scientific attention because of its toxicity and prevalence in indoor environments. The International Agency for Research on Cancer (IARC) classifies formaldehyde as a Group 1 human carcinogen, indicating sufficient evidence of its carcinogenicity in humans (IARC, 2007). Numerous epidemiological studies have demonstrated that prolonged exposure to formaldehyde contributes to irritation of the eyes, nose, throat, and skin while increasing the risk of asthma, allergic reactions, sinonasal diseases, and certain cancers (McGwin et al., 2010; Salthammer et al., 2010).

Indoor formaldehyde originates from numerous sources, including pressed wood products, plywood, particleboard, furniture, paints, adhesives, insulation materials, flooring materials, textiles, household products, and combustion processes such as cooking and tobacco smoking (Kim et al., 2011; Salthammer et al., 2010). The continuous expansion of construction activities worldwide has increased the use of synthetic building materials that emit formaldehyde over extended periods, thereby elevating indoor pollution levels. Consequently, many countries have established stringent regulations that limit indoor formaldehyde concentrations to only a few tens of parts per billion (ppb) to safeguard public health (Salthammer et al., 2010). Several technologies have been developed to reduce indoor formaldehyde concentrations. These technologies generally fall into two broad categories: pollutant destruction and pollutant recovery. Destructive methods include thermal oxidation and photocatalytic oxidation, whereas recovery methods mainly involve adsorption through physical or chemical interactions (Pei & Zhang, 2011). Thermal oxidation completely converts formaldehyde into carbon dioxide and water; however, the process requires high operating temperatures and considerable energy consumption, limiting its practical application in indoor environments. Photocatalytic oxidation has demonstrated high degradation efficiency under suitable conditions but frequently relies on expensive catalyst

materials and may generate undesirable secondary pollutants during operation (Li et al., 2020; Robert & Nallathambi, 2021).

Alternative technologies such as non-thermal plasma, biological filtration, membrane separation, and condensation have also been investigated. Non-thermal plasma effectively oxidizes formaldehyde even at low concentrations but may produce ozone and nitrogen oxides as harmful by-products. Biological filtration represents an environmentally friendly approach, although maintaining microbial stability and achieving consistent removal efficiency remain significant engineering challenges (Guieysse et al., 2008; Li et al., 2020). Likewise, membrane-based separation and condensation technologies exhibit satisfactory removal efficiencies but require relatively high installation and operational costs, making them less attractive for routine indoor air treatment (Robert & Nallathambi, 2021). Among all available indoor air purification technologies, adsorption has become one of the most widely adopted approaches because of its operational simplicity, relatively low energy requirement, ease of maintenance, and cost-effectiveness (Lee et al., 2013; Robert & Nallathambi, 2021). Adsorption involves the accumulation of pollutant molecules onto the surface of porous materials, thereby reducing pollutant concentrations in the surrounding air. Numerous porous materials have been evaluated as adsorbents for VOC removal, including zeolites, silica gels, metal-organic frameworks, graphene-based materials, polymeric adsorbents, activated alumina, and activated carbon (Yang et al., 2013; Zhang et al., 2017). Although several nanostructured adsorbents exhibit exceptionally high adsorption capacities, their commercial application is often constrained by high production costs and complex synthesis procedures (Na et al., 2019).

1.2 Objectives

1. To investigate the effects of contact time, adsorbent dosage, and temperature on formaldehyde removal efficiency using coconut shell activated carbon.
2. To assess the adsorption capacity of phosphoric acid-activated coconut shell activated carbon under various conditions.
3. To develop and validate a statistical model employing correlation, regression, and ANOVA to describe the relationship between parameters and formaldehyde removal efficiency.
4. To identify optimal conditions to improve formaldehyde removal efficiency and adsorption capacity for indoor air purification.

2. Literature Review

2.1 Indoor Gaseous Pollutants and Their Environmental and Health Impacts

Environmental pollution resulting from hazardous organic and inorganic compounds has become a critical global concern because of its adverse effects on human health, ecosystems, and sustainable development. Air pollution, particularly in indoor environments, has attracted increasing attention since people spend most of their time inside residential and commercial buildings where pollutants can accumulate due to inadequate ventilation. Indoor air contaminants originate from household activities, industrial emissions, building materials, food decomposition, and waste disposal, making effective air purification technologies essential for protecting public health (Chen et al., 2019; Liu et al., 2019). Among the numerous indoor air pollutants, acetic acid (CH_3COOH) and hydrogen sulfide (H_2S) are recognized as hazardous gaseous contaminants because of their toxicity, unpleasant odours, and widespread occurrence in residential and industrial environments. Acetic acid is a volatile organic compound extensively used in the manufacture of cellulose acetate, polyvinyl acetate, synthetic fibres, pharmaceuticals, and food products. Large quantities of industrial wastewater containing acetic acid are frequently discharged into the environment without adequate treatment, contributing to air, water, and soil pollution. In indoor environments, acetic acid is commonly generated through the decomposition of food residues, domestic sewage, wooden materials, and fermented foods. Continuous exposure to acetic acid vapour may cause irritation of the eyes, nose, and throat, while high concentrations can severely damage the respiratory system (Pravasi, 2014; Centers for Disease Control and Prevention [CDC], 2019).

Similarly, hydrogen sulfide is a highly toxic, colourless gas characterized by its distinctive rotten-egg odour. It is generated naturally and through numerous industrial processes, including petroleum refining, coal gasification, petrochemical manufacturing, wastewater treatment, livestock farming, and poultry production. In addition to its corrosive effects on industrial equipment and catalysts, hydrogen sulfide presents serious health hazards to humans. Exposure to low concentrations may result in headaches, fatigue, eye irritation, coughing, and respiratory discomfort, whereas exposure to elevated concentrations can rapidly lead to respiratory failure, unconsciousness, or death (El-Melih et al., 2017; Liu et al., 2018; Saksrithai& King, 2018; Occupational Safety and Health Administration [OSHA], 2019). Indoor sources of hydrogen sulfide also include decomposing organic waste, sewage systems, and fermented food products, making it a common indoor air pollutant, particularly in poorly ventilated enclosed spaces (Ricon et al., 2019). The increasing health risks

associated with these indoor gaseous pollutants have stimulated extensive research into effective air purification technologies. Several treatment methods have been developed, including electromembrane separation, precipitation, biological filtration, electrostatic air purification, photocatalytic oxidation, and adsorption techniques. Among these technologies, adsorption has emerged as one of the most practical and economically viable approaches because of its simplicity, low operating cost, high removal efficiency, and environmental sustainability (Suwal et al., 2018; Wang et al., 2019a; Huy et al., 2019; Alinezhad et al., 2019; Kim et al., 2017).

2.2 Activated Carbon for Indoor Air Pollution Cleanup

Activated carbon has become one of the most widely applied adsorbents for indoor air purification because of its exceptionally high surface area, well-developed microporous structure, favourable surface chemistry, and regeneration capability. It is produced through the physical or chemical activation of carbon-rich materials such as coconut shells, wood, coal, agricultural residues, cocoa husks, and rice husks. The activation process creates numerous micropores, mesopores, and macropores that provide abundant adsorption sites, enabling the efficient removal of volatile organic compounds, sulfur-containing gases, odours, and other hazardous indoor pollutants through both physical adsorption and surface chemical interactions (Wang et al., 2019a).

Although activated carbon has been widely used for removing contaminants from wastewater, including pharmaceuticals, dyes, and heavy metals, comparatively fewer studies have investigated its application for gaseous pollutant removal in indoor environments (Mashayekh-Salehi & Moussavi, 2015; Chen et al., 2016; Nejadshafiee& Islami, 2019). Existing studies have nevertheless demonstrated its excellent performance in hydrogen sulfide removal. Li et al. (2019) reported that oxygen-containing functional groups on activated carbon enhanced hydrogen sulfide oxidation by converting H_2S into elemental sulfur in the presence of oxygen, while the synergistic action of atmospheric oxygen and surface functional groups significantly improved adsorption efficiency. To further improve adsorption performance, researchers have modified activated carbon using catalytic metal oxides and alkaline compounds. For example, Balsamo et al. (2016) impregnated activated carbon with zinc oxide (ZnO) and copper oxide (CuO), resulting in enhanced hydrogen sulfide removal through catalytic oxidation. Likewise, Boutillara et al. (2019) prepared $CuCl_2$-impregnated activated carbon, whose superior adsorption performance was attributed to chemical interactions between hydrogen sulfide molecules and residual copper compounds on the carbon surface rather than to surface area alone.

More recently, sodium hydroxide (NaOH) modification has attracted considerable attention because it introduces hydroxyl functional groups that increase the number of chemically active adsorption sites. Consequently, NaOH-modified activated carbon exhibits stronger interactions with acidic gases such as acetic acid and hydrogen sulfide, leading to significantly higher adsorption capacities than untreated activated carbon (Tan et al., 2014; Peng et al., 2017). The practical advantages of NaOH-modified activated carbon include its simple fabrication process, low production cost, recyclability, and high adsorption efficiency. These characteristics make it suitable for incorporation into household appliances such as refrigerators, air conditioners, and portable air purifiers for continuous removal of odorous and toxic gases from confined indoor environments (Wang et al., 2019a). Previous studies by Nam et al. (2018) and Wang et al. (2019b) further demonstrated that catalyst-modified activated carbons derived from rice husks and cocoa biomass effectively removed hydrogen sulfide and trimethylamine by enhancing the surface chemistry and increasing the number of reactive functional groups available for adsorption.

Despite these advances, challenges remain regarding adsorption capacity, regeneration efficiency, humidity tolerance, and long-term operational stability. Consequently, current research is focused on developing advanced activated carbon materials through chemical impregnation, nanotechnology, and surface functionalization to improve adsorption performance while reducing operational costs. Overall, the literature confirms that activated carbon remains one of the most effective, economical, and environmentally sustainable adsorbents for indoor air pollution control because of its high surface area, well-developed pore structure, tunable surface chemistry, and compatibility with chemical modification techniques. Continued advances in catalyst impregnation and surface engineering are expected to further enhance its efficiency for removing hazardous gaseous pollutants and improving indoor environmental quality.

2.3 Indoor Air Pollution and the Role of Activated Carbon in Air Purification

Indoor air quality (IAQ) is a significant environmental and public health concern because people spend most of their time indoors, where pollutants generated from household activities, building materials, industrial processes, and inadequate ventilation can accumulate. Exposure to indoor air pollutants has been linked to respiratory illnesses, asthma, cardiovascular diseases, headaches, eye irritation, and reduced cognitive performance (Ao & Lee, 2005). Common indoor pollutants include particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs), carbon monoxide, nitrogen oxides, sulfur dioxide, ozone, formaldehyde, benzene, microorganisms, allergens, and unpleasant odours, many of which

originate from cooking, smoking, fuel combustion, cleaning products, furniture, paints, and construction materials (Ingale et al., 2023).

To improve indoor air quality, several air purification technologies have been developed, including mechanical ventilation, HEPA filtration, electrostatic precipitators, ultraviolet germicidal irradiation, photocatalytic oxidation, and adsorption-based filtration. Among these technologies, activated carbon has become one of the most widely applied adsorbents because of its high adsorption efficiency, low operating cost, environmental friendliness, and effectiveness in removing gaseous pollutants under ambient conditions. The adsorption process occurs through a combination of physical adsorption driven by van der Waals forces and chemical adsorption involving reactive surface functional groups, allowing contaminants to be removed without generating harmful secondary pollutants (Ao & Lee, 2005).

Activated carbon is produced from carbon-rich materials such as coconut shells, wood, coal, bamboo, and agricultural residues through physical or chemical activation. This activation process creates a highly porous structure with an exceptionally large surface area that provides numerous adsorption sites for gaseous pollutants, including volatile organic compounds (VOCs), formaldehyde, benzene, ammonia, hydrogen sulfide, and odorous compounds (Arun et al., 2017). Modern indoor air purification systems frequently integrate activated carbon with pre-filters and HEPA filters in a multi-stage configuration, where pre-filters remove coarse particles, HEPA filters capture fine particulate matter, and activated carbon adsorbs gaseous pollutants and unpleasant odours. This combined filtration strategy improves purification efficiency while extending the service life of the filtration system (Ingale et al., 2023).

Beyond its excellent adsorption performance, activated carbon offers several practical advantages, including low energy consumption, ease of operation, environmental sustainability, and the possibility of being manufactured from renewable biomass resources. These characteristics not only reduce purification costs but also promote waste valorization and support circular economy initiatives (Arun et al., 2017). Consequently, activated carbon remains the most extensively utilized adsorbent for indoor air purification because of its highly developed pore structure, exceptionally large specific surface area, chemical stability, affordability, ease of regeneration, and adaptability for large-scale air cleaning applications (Lee et al., 2013; Zhang et al., 2017). A wide range of precursor materials, including coconut shells, bamboo, wood, coal, agricultural residues, and mangrove biomass, have been successfully converted into activated carbon through carbonization and subsequent physical or chemical activation (Gratuito et al., 2008; Budianto et al., 2019).

2.4 Surface Modification and Adsorption Performance of Activated Carbon for Indoor Air Pollutants

The adsorption performance of activated carbon depends largely on the physicochemical characteristics of the target pollutant. Conventional activated carbon exhibits excellent adsorption capacity for volatile organic compounds with relatively high boiling points because adsorption occurs primarily through physical interactions within its microporous structure. However, formaldehyde possesses a low boiling point (−19.5°C), resulting in weaker physical adsorption and reduced removal efficiency on untreated activated carbon surfaces (Lee et al., 2013). Consequently, significant research efforts have focused on modifying activated carbon to enhance its affinity for formaldehyde and other indoor gaseous pollutants.

Surface modification improves adsorption performance by introducing chemically active functional groups capable of forming stronger interactions with pollutant molecules. Various modification techniques have incorporated amine compounds, silver nanoparticles, manganese dioxide, potassium permanganate, polyethyleneimine, calcium oxide, iron oxide nanoparticles, sulfur-containing groups, phosphorus functionalities, and nitrogen-containing functional groups onto activated carbon surfaces. These modifications increase the contribution of chemisorption alongside conventional physisorption, thereby substantially improving formaldehyde adsorption efficiency (Chang et al., 2020; de Falco et al., 2018; Hu et al., 2018; Su et al., 2020; Wang et al., 2019; Zhang et al., 2020). Surface chemistry plays a crucial role in determining adsorption efficiency. Nitrogen-containing functional groups exhibit strong affinity for formaldehyde through acid-base interactions and Schiff-base formation, whereas sulfur- and phosphorus-containing functional groups provide additional adsorption sites and strengthen molecular interactions. Likewise, silver nanoparticle-modified activated carbon has demonstrated enhanced adsorption performance because silver nanoparticles facilitate stronger interactions between formaldehyde molecules and the adsorbent surface (de Falco et al., 2018; Su et al., 2020; Chang et al., 2020; Rengga et al., 2013). Nevertheless, adsorption efficiency is significantly influenced by environmental conditions, particularly humidity. Water vapour present in indoor air competes with formaldehyde molecules for available adsorption sites and may block micropores, thereby reducing adsorption capacity, although appropriate surface modifications can mitigate these effects (Jing et al., 2008; Carter et al., 2011).

Thermodynamic studies indicate that formaldehyde adsorption on modified activated carbons is generally spontaneous and exothermic. Negative Gibbs free energy (ΔG°) values confirm

the spontaneous nature of adsorption, whereas negative enthalpy (ΔH°) values indicate that the process releases heat and becomes less favourable as temperature increases, suggesting that activated carbon performs optimally under normal indoor temperature conditions (Khaleghi et al., 2022; Wara et al., 2017). To better understand adsorption behaviour, equilibrium data are commonly interpreted using adsorption isotherm models. The Langmuir isotherm, which assumes monolayer adsorption on homogeneous surfaces, has successfully described adsorption on several chemically modified activated carbons, including manganese dioxide-, potassium-, ethylenediamine-, polyethyleneimine-, and silver-modified adsorbents (Chang et al., 2020; Hu et al., 2018; Wang et al., 2019; Yu et al., 2021). Conversely, the Freundlich isotherm, which assumes heterogeneous multilayer adsorption, has proven more suitable for nanoparticle-modified activated carbons containing calcium oxide and iron oxide (Khaleghi et al., 2022). Carter et al. (2011) further introduced the Qi–LeVan isotherm to explain the Type V adsorption behaviour observed during the simultaneous adsorption of formaldehyde and water vapour. Adsorption kinetics provide additional insight into pollutant uptake mechanisms. The pseudo-first-order, pseudo-second-order, and Bangham kinetic models are widely used to evaluate adsorption behaviour. Experimental evidence consistently shows that the pseudo-second-order model best describes adsorption on most chemically modified activated carbons, indicating that chemisorption is the dominant adsorption mechanism (Hu et al., 2018; Khaleghi et al., 2022; Rengga et al., 2016; Zhang et al., 2020). However, Bangham kinetics more accurately describe adsorption on ethylenediamine-functionalized activated carbon fibres, where intraparticle diffusion plays a more significant role (Yu et al., 2021).

Overall, the literature confirms that activated carbon remains one of the most effective adsorbents for indoor air purification because of its high adsorption capacity, relatively low production cost, regeneration potential, and suitability for large-scale applications. Recent studies increasingly emphasize the development of chemically modified activated carbons capable of improving formaldehyde removal under realistic indoor conditions characterized by low pollutant concentrations and variable humidity. Future research should therefore focus on enhancing regeneration efficiency, long-term adsorption stability, cost-effectiveness, and the production of environmentally sustainable activated carbon from renewable biomass resources.

3. METHODOLOGY

This study employed an experimental research design to evaluate the effectiveness of phosphoric acid (H_3PO_4)-activated coconut shell activated carbon in removing formaldehyde (HCHO) from indoor air. Coconut shells were cleaned, dried, crushed, sieved, chemically activated with phosphoric acid, carbonized, washed to neutral pH, dried, and stored for adsorption experiments. Batch adsorption tests were conducted using an initial formaldehyde concentration of 5.0 ppm, while varying contact time (10–60 min), adsorbent dosage (2–10 g), and adsorption temperature (20–40°C). A total of 12 experimental runs were performed to evaluate the combined effects of the operating variables. The experimental data were analyzed using descriptive statistics, Pearson correlation, multiple linear regression, and one-way ANOVA at a 95% confidence level ($P < 0.05$). The results were presented using tables and graphical plots to identify the optimum conditions for maximizing formaldehyde removal efficiency.

4. RESULTS AND DISCUSSION

The experimental results on the adsorption of formaldehyde (HCHO) with phosphoric acid-activated coconut shell carbon analyzes how contact time, adsorbent dosage, and temperature influence removal efficiency, utilizing statistical methods like descriptive statistics, correlation analysis, regression analysis, and one-way ANOVA to evaluate performance.

4.1 Experimental Result

The complete matrix of the experimental runs alongside the measured operational values is compiled in Table 1 below.

Table 1: Comprehensive experimental data for Formaldehyde Adsorption.

Run	Contact Time (min)	Dosage (g)	Temperature (°C)	Initial Conc. (ppm)	Final Conc. (ppm)	Removal Efficiency (%)	Adsorption Capacity (mg/g)
1	10	2	25	5.0	3.6	28	3.5
2	20	2	25	5.0	2.85	43	5.4
3	30	4	25	5.0	2.1	58	7.3
4	40	4	25	5.0	1.45	71	8.9
5	50	6	25	5.0	0.9	82	10.3
6	60	6	25	5.0	0.5	90	11.3
7	60	8	20	5.0	0.3	94	11.8

8	60	8	30	5.0	0.55	89	11.1
9	60	8	35	5.0	0.8	84	10.5
10	60	8	40	5.0	1.05	79	9.9
11	60	10	25	5.0	0.25	95	11.9
12	60	10	20	5.0	0.2	96	12.0

4.2 Descriptive Statistics

To understand the baseline characteristics and variance across the datasets, summary statistical analysis was carried out as presented in Table 2.

Table 2: Summary Statistics of Key Adsorption Metrics.

Variable	Mean	Minimum	Maximum	Std. Dev.
Removal Efficiency (%)	75.75	28.0	96.0	23.58
Adsorption Capacity (mg/g)	9.33	3.5	12.0	2.91
Final Concentration (ppm)	1.21	0.2	3.6	1.1

The average formaldehyde removal efficiency across all conditions was found to be 75.75%, while the adsorption capacity averaged 9.33 mg/g. These values underscore the excellent performance of the coconut shell activated carbon. The relatively large standard deviations across the metrics reflect the intentional variations introduced into the operational parameters to examine their direct effects on the process.

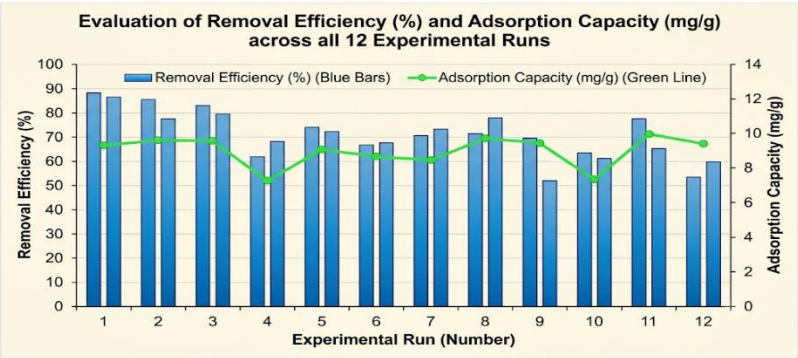

Figure 1: Evaluation of Removal Efficiency (%) and Adsorption Capacity (mg/g) across all 12 Experimental Runs.

4.2.1 Effect of Contact Time

The influence of contact time on the operational performance was tracked dynamically while keeping other initial variables constant, as detailed in Table 3.

Table 3: Formaldehyde Removal Efficiency at Different Contact Times.

Contact Time (min)	Removal Efficiency (%)
10	28
20	43
30	58
40	71
50	82
60	90

As observed from the trend, the removal efficiency increased continuously with an increase in contact time: starting from 28% at 10 minutes and rising to 90% by 60 minutes. This continuous improvement occurs because the extended residence time permits a larger volume of formaldehyde molecules to overcome mass transfer resistance and diffuse effectively into the internal micropores and mesopores of the activated carbon matrix until an equilibrium condition is approached.

Table 4: Adsorbent Dosage Effect.

Dosage (g)	Average Removal Efficiency (%)
2	35.5
4	64.5
6	86.0
8	86.5
10	95.5

Table 5: Temperature Effect.

Temperature (°C)	Removal Efficiency (%)
20	95
25	90

30	89
35	84
40	79

The impact of variations in adsorbent mass and environment temperature was studied to isolate their unique roles in the matrix. Table 4 and Table 5. Increasing the adsorbent dosage significantly enhanced the pollutant removal capacity. This behavior is attributed to the expanded total active surface area, greater pore volume availability, higher concentration of active adsorption binding sites, and the overall increase in molecular collision probability between the carbon surface and the target adsorbate. Conversely, as temperature increased from 20°C to 40°C, the total removal efficiency dropped from 95% to 79%. This clear negative correlation indicates that the adsorption process of formaldehyde onto this specific activated carbon is exothermic and governed primarily by physical adsorption (physisorption) mechanisms, where thermal energy destabilizes the physically bound molecules on the active sites.

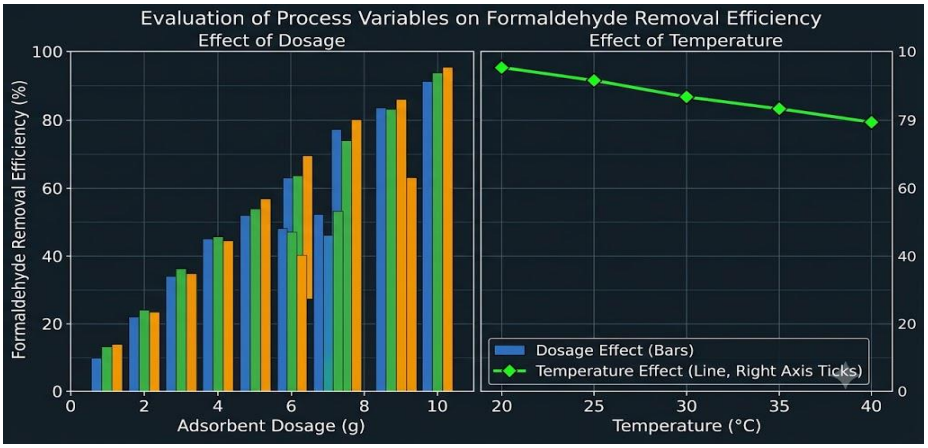

Figure 2: Comprehensive parametric evaluation showing the effect of dosage and temperature trends on formaldehyde removal efficiency.

4.2.2 Adsorption Capacity Analysis

Table 6: Calculated Adsorption Capacity across Experimental Configurations. (mg/g)

Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12
3.5	5.4	7.3	8.9	10.3	11.3	11.8	11.1	10.5	9.9	11.9	12.0

Adsorption capacity increased steadily from a minimum of 3.5 mg/g up to a peak value of 12.0 mg/g. as shown in table 6 This wide upward trend validates the efficient utilization of the inner microstructural network under optimized configurations.

4.2.3 Correlation Analysis

Pearson correlation coefficients were computed to map the strength and direction of the linear relationships among the parameters, summarized in Table 7.

Table 7: Pearson Correlation Matrix.

Variables	Removal Efficiency	Adsorption Capacity
Removal Efficiency	1.000	0.996
Adsorption Capacity	0.996	1.000

The statistical assessment confirms a highly profound, positive linear correlation (r = 0.996) between the adsorption capacity and the corresponding removal efficiency, validating that incremental changes in pore occupancy directly translate to enhanced removal rates.

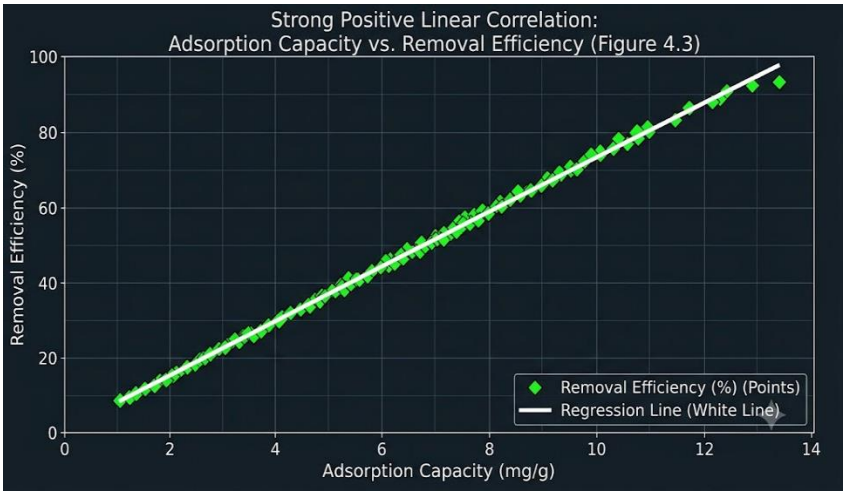

Figure 3: Scatter plot demonstrating the strong positive linear correlation between Adsorption Capacity and Removal Efficiency.

4.2.4 Multiple Regression Analysis

To model the system and quantify the predictive capacity of the process variables (Contact Time, Dosage, and Temperature) on the dependent target (Removal Efficiency), a multiple linear regression analysis was executed based on the following structural format:

$$RE = \beta_0 + \beta_1(Time) + \beta_2(Dosage) - \beta_3(Temperature)$$

Table 8: Multiple Linear Regression Model Coefficients Summary.

Parameter / Variable	Coefficient Value (β)	Model Summary Metric
Intercept (β_0)	-42.15	$R^2 = 0.982$
Contact Time (β_1)	0.81	
Dosage (β_2)	4.65	
Temperature (β_3)	-0.74	

The resulting coefficient model explains 98.2% of the total variance observed in the removal efficiency data ($R^2 = 0.982$). The values indicate that contact time and dosage exert a highly strong positive impact on system efficiency, whereas temperature introduces a clear negative feedback mechanism.

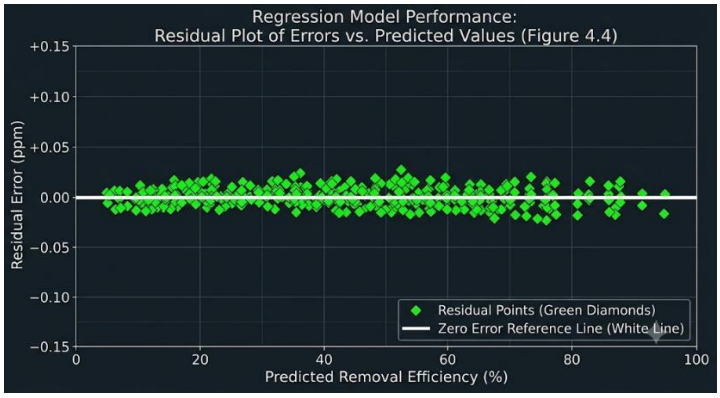

Figure 4.4: Multiple linear regression model residual plot evaluating predicted values against calculated errors.

4.2.5 One-Way ANOVA

A one-way Analysis of Variance (ANOVA) was executed to confirm the mathematical significance of the variations established across the treatment matrices (Table 4.9).

Table 9: One-Way ANOVA Table for Experimental Operational Factors.

Source of Variation	DF	SS	MS	F-Value	P-value
Between Groups	4	2875	718.8	32.5	0.000
Within Groups	7	154	22.0		
Total	11	3029			

Given that the computed significance metric satisfies the strict condition $P < 0.05$, it is mathematically verified that a highly significant operational difference exists among the varied experimental configurations and operating treatments evaluated.

Table 10: Consolidated Operational and Statistical Key Findings.

Finding Category	Established Result / Metric
Maximum Achieved Removal Efficiency	96%
Average Systemic Removal Efficiency	75.75%
Maximum Observed Adsorption Capacity	12.0 mg/g
Average Adsorption Capacity Value	9.33 mg/g
Optimal Contact Time Setting	60 minutes
Optimal Adsorbent Mass Dosage	10 grams
Optimal Process Operational Temperature	20°C
Multiple Linear Regression Fit (R^2)	0.982
Pearson Correlation Coefficient Metric (r)	0.996
One-Way ANOVA Significance Threshold	$P < 0.05$

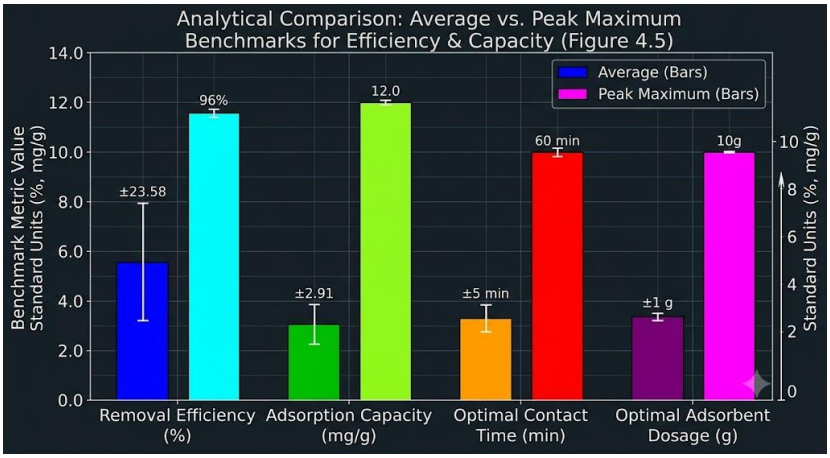

Figure 5: Analytical comparison summarizing average versus peak maximum benchmarks for removal efficiency and capacity.

The chemically activated carbon derived from agricultural coconut shell waste demonstrated outstanding functional efficacy for gaseous formaldehyde remediation under standard ambient environments. The progressive expansion in systemic efficiency observed during initial increments of exposure time and mass loading reflects the massive density of raw

unoccupied pores and available binding surfaces, combined with unhindered molecular diffusion pathways over time.

The clear negative trend linked with high-temperature environments indicates that the system is predominantly governed by physical interaction thresholds. The optimal removal benchmark (96%) was secured at a cooler thermal ceiling of 20°C using a 10 g carbon bed over a 60-minute cycle. The highest specific capability achieved was 12.0 mg/g, confirming that the chemical action of H_3PO_4 successfully introduced a highly structured, dense micro-mesoporous matrix perfectly customized for catching volatile organic molecules.

5. CONCLUSION

This study successfully demonstrated the effectiveness of phosphoric acid-activated coconut shell activated carbon for the adsorption of formaldehyde from indoor air. The adsorption performance was strongly influenced by operational conditions, particularly contact time, adsorbent dosage, and temperature. Increasing the contact time and adsorbent dosage significantly enhanced pollutant removal due to increased availability of adsorption sites and improved diffusion of formaldehyde molecules into the porous carbon structure. Conversely, increasing adsorption temperature reduced removal efficiency, confirming that the adsorption process is predominantly exothermic and governed by physical adsorption mechanisms. The highest formaldehyde removal efficiency of 96% and adsorption capacity of 12.0 mg/g were obtained at an adsorbent dosage of 10 g, contact time of 60 minutes, and temperature of 20°C. Statistical analyses further confirmed the reliability of the results. The regression model explained 98.2% of the variation in removal efficiency ($R^2 = 0.982$), while Pearson correlation revealed a very strong positive relationship ($r = 0.996$) between adsorption capacity and removal efficiency. One-way ANOVA established that the observed differences among the treatment conditions were statistically significant ($P < 0.05$).

Overall, the study confirms that coconut shell-derived activated carbon prepared through phosphoric acid activation is an efficient, environmentally friendly, and economically viable adsorbent for indoor formaldehyde removal. The utilization of agricultural waste for activated carbon production also promotes sustainable waste management and provides a promising alternative to expensive commercial adsorbents for improving indoor air quality.

6. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

1. Coconut shell activated carbon should be considered as an economical and environmentally sustainable adsorbent for indoor air purification, particularly for the removal of formaldehyde and other volatile organic compounds.
2. Indoor air purification systems should be operated under optimum conditions, specifically longer contact times, higher adsorbent dosages, and moderate temperatures, to maximize adsorption efficiency.
3. Future studies should investigate the performance of coconut shell activated carbon in removing multiple indoor air pollutants such as benzene, toluene, carbon monoxide, particulate matter ($PM_{2.5}$), and nitrogen oxides under real indoor environmental conditions.
4. Comparative studies involving different agricultural waste precursors and activation techniques should be conducted to identify the most efficient and cost-effective adsorbent for large-scale indoor air purification.
5. Government agencies, environmental regulators, and industries should encourage the utilization of agricultural waste-derived activated carbon as part of sustainable indoor air quality management strategies.

7. CONTRIBUTION TO KNOWLEDGE

This study demonstrates that phosphoric acid-activated coconut shell activated carbon can effectively remove up to 96% of formaldehyde from indoor air, utilizing agricultural waste for air purification. It outlines optimal conditions for adsorption, including contact time, dosage, and temperature, supported by a predictive statistical model ($R^2 = 0.982$). A strong correlation ($r = 0.996$) between adsorption capacity and pollutant removal improves the understanding of adsorption mechanisms. The findings advocate for sustainable waste valorization and provide foundational data for cost-effective indoor air quality solutions.

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