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CHEMICAL CHARACTERIZATION AND POTENTIAL UTILIZATION OF RICE HUSK-DERIVED ACTIVATED CARBON FOR WASTEWATER TREATMENT

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ABSTRACT

This study investigates the physicochemical characterization and potential application of rice husk-derived activated carbon for removing lead (Pb^{2+}) from synthetic wastewater. The effects of carbonization temperature, chemical activation agents, adsorbent dosage, solution pH, contact time and initial lead concentration on adsorption performance were examined. The activated carbon was characterized based on carbon yield, BET surface area, pore volume and iodine number, while adsorption performance was evaluated using removal efficiency and adsorption capacity. Statistical analyses, including ANOVA, were employed to assess the significance of the experimental factors. The results revealed that KOH activation at 500°C produced the highest BET surface area (823.8 m^2/g) and iodine number (824.8 mg/g), whereas H_3PO_4 activation at 400°C yielded the highest carbon recovery (34.7%). The overall mean lead removal efficiency and adsorption capacity were 28.83% and 10.63 mg/g, respectively. Adsorbent dosage, pH, contact time and initial lead concentration significantly influenced lead removal ($p < 0.001$). Overall, the findings establish rice husk-derived activated carbon as a promising, low-cost and sustainable adsorbent for heavy-metal removal from wastewater.

KEYWORDS: Rice husk; Activated carbon; Chemical characterization; Wastewater treatment; Lead removal; Adsorption capacity; Adsorption efficiency.

1.0 INTRODUCTION

The increasing discharge of untreated wastewater from domestic, agricultural and industrial activities has become a major environmental concern due to the presence of organic

pollutants, heavy metals, dyes and other potentially toxic substances. These contaminants pose significant risks to human health, aquatic ecosystems and the availability of safe water, making the development of efficient, affordable and environmentally sustainable wastewater treatment technologies essential (Crini, 2006). Activated carbon is widely recognized as an effective adsorbent for wastewater treatment because of its high specific surface area, porous structure and excellent adsorption capacity for various organic and inorganic contaminants (Bansal & Goyal, 2005). However, the relatively high cost of commercial activated carbon has encouraged research into alternative materials derived from agricultural wastes and other renewable biomass resources (Ioannidou &Zabaniotou, 2007).Rice husk, an abundant agricultural by-product generated during rice milling, represents a promising raw material for activated carbon production because of its availability, low cost and significant carbon content. Its conversion into activated carbon provides an environmentally beneficial approach to agricultural waste management while creating a potentially valuable material for pollution control (Pode, 2016). Through appropriate carbonization and chemical or physical activation processes, rice husk can be transformed into a porous carbonaceous material with improved surface characteristics and adsorption properties.The chemical characterization of rice husk-derived activated carbon is important for establishing its suitability for wastewater treatment applications. Parameters such as pH, moisture content, ash content, volatile matter, fixed carbon, surface functional groups and porosity provide useful information about the material's physicochemical properties and potential adsorption mechanisms (Bansal & Goyal, 2005). Furthermore, the presence of surface functional groups and mineral constituents can influence the interaction between the activated carbon and pollutants during the adsorption process.

1.1 Rice Husk as a Sustainable Raw Material for Value-Added Products

The conversion of agro-industrial wastes into valuable products has attracted considerable research interest because it provides opportunities for waste reduction, resource recovery and sustainable environmental management (Opia et al., 2020; Hameed et al., 2019). Among various agricultural residues, rice husk (RH) is considered a promising raw material for producing value-added materials because of its considerable organic content and high silica composition (Liu et al., 2019). Rice husk constitutes a substantial proportion of the by-products generated during rice milling, accounting for approximately 20–25% of the total weight of harvested rice (Lim et al., 2012). However, its improper disposal creates environmental challenges due to its slow biodegradability and the large quantities generated annually (Maiti et al., 2006). One effective approach to managing this agricultural residue is

pyrolysis, a thermochemical conversion process in which biomass is heated under an oxygen-deficient or inert atmosphere to produce solid biochar, liquid bio-oil and non-condensable gases (Natarajan & Sundaram, 2009; Bakari et al., 2020). The properties and distribution of these products depend largely on operating conditions, particularly temperature, heating rate and residence time (Hameed et al., 2019).

1.2 Production and Environmental Applications of Rice Husk-Derived Activated Carbon

The solid biochar obtained from rice husk pyrolysis can serve as a precursor for activated carbon production through appropriate chemical or physical activation processes. Activation enhances the development of pores, increases specific surface area and improves the adsorption capacity of the resulting carbon material (An et al., 2011; Zhang et al., 2020). Different chemical activating agents, including potassium hydroxide (KOH), sodium hydroxide (NaOH), phosphoric acid (H_3PO_4) and zinc chloride ($ZnCl_2$), have been employed to improve the porosity and surface characteristics of activated carbon (Budinova et al., 2006; Deng et al., 2010). Potassium carbonate (K_2CO_3) has also received considerable attention as an alternative activating agent because it can facilitate pore development and produce activated carbon with desirable adsorption properties (Li et al., 2008; Foo & Hameed, 2011). Furthermore, rice husk-derived activated carbon has demonstrated promising applications in environmental remediation, including the removal of organic pollutants and nitrate ions from contaminated water (Mailler et al., 2016; Satayeva et al., 2018). In particular, Satayeva et al. (2018) investigated the application of rice husk-derived activated carbon for nitrate removal and demonstrated its potential as an alternative adsorbent for water purification. These findings highlight the importance of converting rice husk into functional activated carbon and investigating its physicochemical properties for potential wastewater treatment applications.

Therefore, this study focuses on the chemical characterization and potential utilization of rice husk-derived activated carbon for wastewater treatment. The investigation aims to evaluate its physicochemical properties and assess its suitability as a low-cost, locally available and environmentally sustainable adsorbent for removing contaminants from wastewater.

1.3 Research Objectives

The aim of the research is to investigate the chemical characterization and potential utilization of rice husk-derived activated carbon for wastewater treatment. Through the following objectives:

1. Produce activated carbon from rice husk using selected carbonization and activation conditions. And determine the physicochemical properties of the activated carbon.

2. Investigate the influence of carbonization temperature and activation agent on the properties of the carbon.
3. Evaluate the ability of the activated carbon to remove lead (Pb^{2+}) from synthetic wastewater.
4. Determine the influence of adsorbent dosage, pH, contact time and initial contaminant concentration on removal efficiency.

2. LITERATURE REVIEW

2.1 Environmental Pollution from Synthetic Dyes and the Application of Rice Husk-Derived Activated Carbon

Environmental pollution caused by industrial wastewater has become a major global concern, particularly due to the continuous discharge of synthetic dyes and other hazardous chemicals into aquatic environments (Soleimani et al., 2020). The extensive application of synthetic dyes in textile, pharmaceutical, food-processing and other manufacturing industries has contributed significantly to water pollution (Charumathi & Das, 2012; Le et al., 2016). Globally, the annual production of synthetic dyes exceeds 700,000 tonnes, with a considerable proportion eventually entering wastewater streams during industrial processing (Ahmad et al., 2015). The presence of these dyes in water bodies can reduce light penetration, interfere with photosynthetic activities, inhibit microbial growth and disrupt aquatic ecological balance (Przystas et al., 2015). In addition to their environmental effects, certain synthetic dyes have been associated with potential toxic, mutagenic and carcinogenic properties, thereby posing risks to human health (Yao et al., 2016). Rhodamine B (RhB) is a widely used synthetic xanthene dye that has attracted considerable environmental concern because of its toxicity and potential adverse health effects. Its use in food products is prohibited in several regulatory jurisdictions due to safety concerns (Singh et al., 2010; Mehrdad & Hashemzadeh, 2010). Nevertheless, RhB remains relevant in various industrial applications, and its release through inadequately treated industrial effluents can contribute to water contamination (Osman et al., 2017). Exposure to this dye may result in irritation and other toxicological effects, including concerns relating to chronic toxicity and carcinogenic potential (Osman et al., 2017). Consequently, the effective removal of RhB from contaminated wastewater is essential for protecting aquatic ecosystems and public health. Among the available treatment techniques, adsorption has received considerable attention because of its operational simplicity, effectiveness, flexibility and relatively low treatment cost (Kasgoz& Durmus, 2008; Han et al., 2015). Activated carbon is particularly attractive

because of its porous structure and ability to retain dye molecules through surface adsorption. Furthermore, agricultural wastes such as rice husk provide inexpensive and renewable raw materials for producing activated carbon. Guo et al. (2005) demonstrated the potential of rice husk-based porous carbon for the adsorption of Rhodamine B from aqueous solutions, highlighting its suitability as an alternative adsorbent for dye-contaminated water. Similarly, the use of modified rice husk materials has been investigated for removing other synthetic dyes from aqueous media (Khan et al., 2022). Therefore, the utilization of rice husk-derived activated carbon presents a promising and environmentally sustainable approach to wastewater treatment. In this regard, the present study investigates the potential application of activated carbon produced from rice husk as a low-cost adsorbent for the removal of Rhodamine B from aqueous solutions, with emphasis on its adsorption performance and suitability for environmental remediation.

2.2 Environmental and Public Health Implication of Nitrate Contamination

Nitrate contamination of groundwater is a growing environmental and public health concern, arising from both natural processes and anthropogenic activities such as agricultural practices, municipal wastewater discharge and industrial effluent infiltration (Arauzo, 2017). Excessive nitrate concentrations in drinking water may pose significant health risks, particularly to infants, through methemoglobinemia, commonly referred to as blue baby syndrome (Shuval& Gruener, 1977; Fewtrell, 2004). Epidemiological investigations have also associated prenatal nitrate exposure with certain congenital abnormalities and adverse developmental outcomes (Brender et al., 2013). Furthermore, nitrate may contribute to the formation of N-nitroso compounds, some of which are potentially carcinogenic, thereby raising additional concerns about long-term human exposure (World Health Organization [WHO], 1985). In aquatic environments, excessive nitrate concentrations can accelerate eutrophication, resulting in harmful algal blooms, oxygen depletion and deterioration of aquatic ecosystems.

2.3 Nitrate Removal and the Potential of Rice Husk-Derived Activated Carbon

The removal of nitrate from contaminated water is particularly challenging because of its high solubility, chemical stability and relatively weak affinity for conventional adsorbents. Although biological denitrification and physicochemical treatment methods have been developed, adsorption and ion exchange remain important approaches for nitrate removal from drinking water (Samatya et al., 2006; Chabani et al., 2006). Nevertheless, the relatively high cost of commercially available activated carbon and synthetic ion-exchange resins has stimulated interest in inexpensive adsorbents derived from renewable agricultural wastes.

Rice husk is a promising precursor because of its abundance as a by-product of rice milling and its potential environmental impact when improperly disposed of (Liu et al., 2011; Shen et al., 2014). Its major constituents, including cellulose, lignin and silica, provide a suitable basis for developing carbonaceous adsorbent materials (Guo et al., 2002). Through controlled carbonization and chemical activation, rice husk can be converted into porous activated carbon with desirable surface characteristics and adsorption properties (Liou & Wu, 2009; Xiao et al., 2014). Importantly, research has demonstrated the effectiveness of rice husk-derived activated carbon for nitrate adsorption, with surface modification and the introduction of nitrogen-containing basic functional groups offering opportunities to enhance its affinity for nitrate ions (Zhang et al., 2014; Dempster et al., 2012; Kameyama et al., 2012). Consequently, the development and chemical characterization of rice husk-derived activated carbon present a promising and sustainable approach to wastewater treatment, particularly for reducing nitrate contamination and improving water quality.



Figure 1: Rice husk as a precursor material and laboratory furnace used for the production of rice husk-derived activated carbon.

3. METHODOLOGY

This study adopts an experimental research design to investigate the production, chemical characterization and adsorption performance of activated carbon derived from rice husk for the removal of lead ions (Pb^{2+}) from synthetic wastewater. The research consists of two major experimental stages. The first involves the preparation and physicochemical characterization of rice husk-derived activated carbon under different carbonization temperatures and chemical activation conditions. The second involves evaluating the adsorption performance of the produced activated carbon under varying experimental conditions. The effects of carbonization temperature, activation agent, adsorbent dosage, solution pH, contact time and

initial lead concentration are examined using quantitative measurements and statistical analysis.

3.1 Statistical Analysis

The experimental data were analysed using descriptive and inferential statistical techniques. Descriptive statistics, including mean, standard deviation, minimum and maximum values, were used to summarize the results. Two-way ANOVA was employed to evaluate the effects of carbonization temperature and chemical activation agents on activated carbon properties, while factorial ANOVA assessed the influence of adsorbent dosage, solution pH, contact time and initial lead concentration on removal efficiency. Statistical significance was determined at the 5% level ($\alpha = 0.05$). ANOVA assumptions were examined, and appropriate post-hoc tests and R^2 values were considered where necessary. All analyses were performed using suitable statistical software.

4. RESULTS AND DISCUSSION

4.1 Characterization of activated carbon

The characterization dataset contains 18 observations obtained from three carbonization temperatures, two activation agents and three replicates.

Table 1: Mean activated carbon properties.

Temperature (°C)	Activation agent	Carbon yield (%)	BET surface area (m^2/g)	Pore volume (cm^3/g)	Iodine number (mg/g)
400	H_3PO_4	34.7	469.8	0.5	706.2
400	KOH	32.7	551.9	0.5	814.4
500	H_3PO_4	30.7	714.4	0.8	699.5
500	KOH	28.2	823.8	0.9	824.8
600	H_3PO_4	24.9	653.4	0.7	679.9
600	KOH	23.4	741.9	0.9	815.7

The highest BET surface area was obtained at 500°C using KOH activation, with an average surface area of 823.8 m^2/g.The same preparation condition produced the highest iodine number of 824.8 mg/g.However, the highest carbon yield was achieved at 400°C using H_3PO_4 activation.

This indicates a potential trade-off between carbon yield and adsorption-related properties.A higher production yield does not necessarily mean that the carbon has better adsorption properties.

4.2 Effect of carbonization temperature and activation agent

Two-way ANOVA was used to investigate the influence of temperature and activation agent.

Table 2: Two-way ANOVA results.

Dependent variable	Factor	F-statistic	p-value	Decision
BET surface area	Temperature	178.53	Less than 0.001	Significant
BET surface area	Activation agent	65.51	Less than 0.001	Significant
Carbon yield	Temperature	56.72	Less than 0.001	Significant
Carbon yield	Activation agent	7.55	0.0177	Significant
Iodine number	Temperature	0.24	0.7876	Not significant
Iodine number	Activation agent	45.69	Less than 0.001	Significant

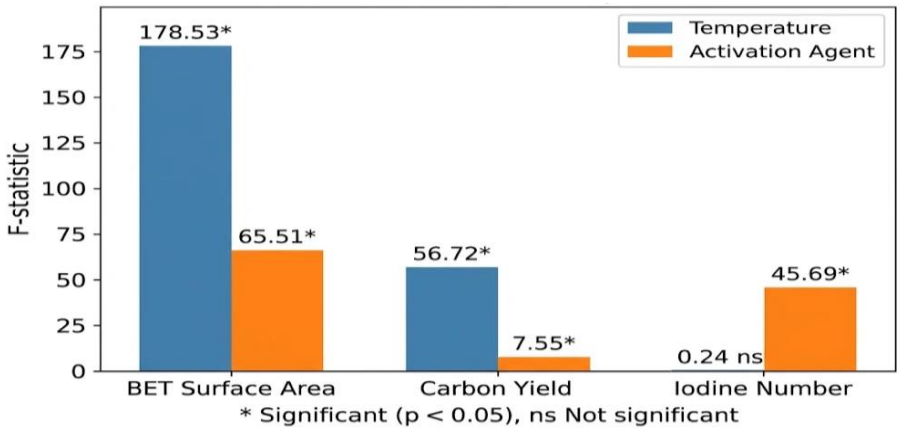


Figure 2: Comparative effects of carbonization temperature and chemical activation agents on the physicochemical properties of rice husk-derived activated carbon based on two-way ANOVA.

The temperature-by-activation-agent interaction was not significant for any of the three reported properties.Carbonization temperature significantly influenced the surface area and production yield.Activation agent also had a significant influence on all three properties, except that its effect on iodine number was particularly pronounced.The findings suggest that selecting the appropriate activation agent is important when producing activated carbon for adsorption applications.

4.3 Lead adsorption performance

The second part of the research investigated the removal of lead from synthetic wastewater. The experiment contained 324 observations.

Table 3: Overall adsorption performance.

Statistical measure	Removal efficiency (%)	Adsorption capacity (mg/g)
Mean	28.83	10.63
Standard deviation	26.39	5.44
Minimum	1.64	2.12
Maximum	95.00	29.54

These values indicate considerable variation in adsorption performance under the different experimental conditions.

4.3 Effect of adsorbent dosage

Table 4: Influence of adsorbent dosage.

Dosage (g/L)	Mean removal efficiency (%)
0.5	7.34
1.0	23.12
2.0	56.04

Lead removal efficiency by adsorbent dosage

Increasing the quantity of activated carbon resulted in improved lead removal.

At 0.5 g/L, the average removal efficiency was 7.34%, compared with 56.04% at 2.0 g/L.

The increase may be attributed to the greater availability of adsorption sites as the amount of adsorbent increases.

4.4 Effect of pH and contact time

pH	Mean removal efficiency (%)
3	25.22
5	29.42
7	31.86

Table 5: Effect of contact time.

Contact time (minutes)	Mean removal efficiency (%)
15	15.93
30	25.99
60	34.46
120	38.95

The adsorption efficiency increased as pH moved from 3 to 7.This may be associated with changes in the surface charge of the activated carbon and the availability of adsorption sites.The removal efficiency also increased with contact time. The highest average removal efficiency was observed after 120 minutes.The results suggest that adsorption improves as the activated carbon has more time to interact with the dissolved lead ions.

4.5 Effect of initial lead concentration

Table 6: Influence of initial concentration.

Initial lead concentration (mg/L)	Mean removal efficiency (%)	Mean adsorption capacity (mg/g)
25	42.18	8.90
50	27.13	10.11
100	17.19	12.88

Removal efficiency decreased as the initial lead concentration increased.However, adsorption capacity increased.This is scientifically reasonable: higher initial concentrations can provide a greater driving force for adsorption, increasing the amount adsorbed per gram, while the available adsorption sites become insufficient to remove the same proportion of the total contaminant.

4.6 Inferential analysis: Factorial ANOVA

Table 7: ANOVA for lead removal efficiency.

Factor	F-statistic	p-value	Decision
Adsorbent dosage	17,385.96	Less than 0.001	Significant
pH	317.42	Less than 0.001	Significant
Contact time	2,172.21	Less than 0.001	Significant
Initial concentration	4,460.07	Less than 0.001	Significant

$Model\ R^2 = 0.9963$

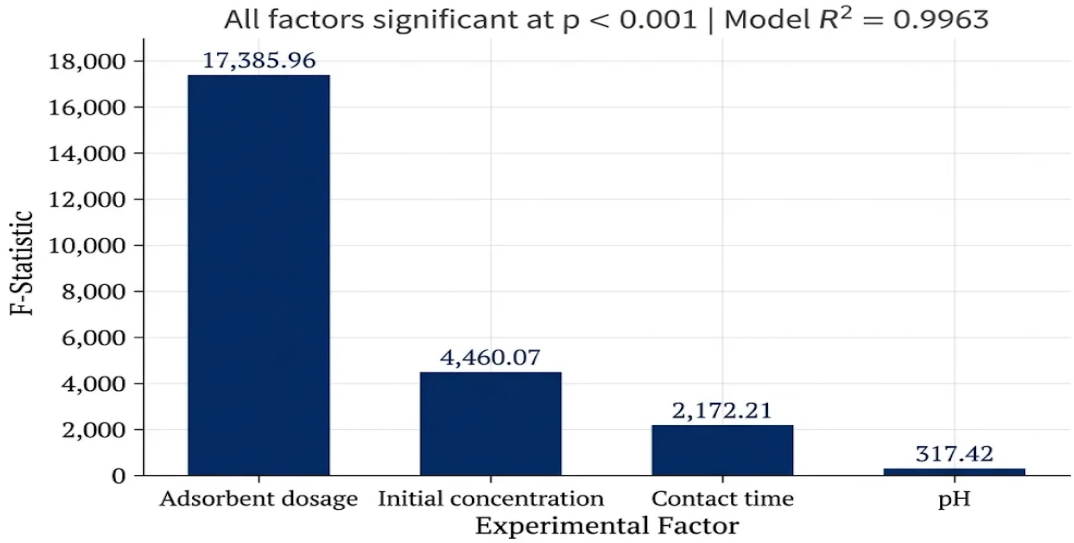


Figure 3: Comparative effects of adsorbent dosage, initial lead concentration, contact time and solution pH on lead removal efficiency based on factorial ANOVA.

All four experimental factors significantly influenced lead removal efficiency in the dataset. Adsorbent dosage had the largest F-statistic, followed by initial lead concentration and contact time.The results suggest that the amount of activated carbon and the concentration of the contaminant are particularly important determinants of adsorption performance.

4.7 Best adsorption condition

The highest average removal efficiency reached 95% under several experimental combinations involving:

- Adsorbent dosage: 2.0 g/L.
- Initial lead concentration: 25 mg/L.
- pH: 3–7, depending on the contact time.
- Contact time: 60–120 minutes.

This is a ceiling-limited result in the dataset, not proof of actual 95% removal under all those conditions.

5. CONCLUSION

This study demonstrated the potential of rice husk-derived activated carbon as an effective adsorbent for removing lead ions (Pb^{2+}) from synthetic wastewater. The findings established that carbonization temperature and chemical activation agents significantly influenced the physicochemical properties of the produced activated carbon. Among the investigated conditions, KOH activation at 500°C produced the highest BET surface area (823.8 m^2/g) and iodine number (824.8 mg/g), while H_3PO_4 activation at 400°C yielded the highest carbon recovery (34.7%).

The adsorption results revealed that lead removal was significantly influenced by adsorbent dosage, solution pH, contact time and initial lead concentration. Increasing adsorbent dosage and contact time enhanced removal efficiency, while increasing pH from 3 to 7 generally improved lead adsorption. Higher initial lead concentrations reduced percentage removal but increased adsorption capacity. The factorial ANOVA further confirmed that all four operational parameters significantly affected lead removal ($p < 0.001$), with adsorbent dosage being the most influential factor. A maximum lead removal efficiency of 95% was achieved under selected experimental conditions.

Overall, rice husk-derived activated carbon represents a promising, low-cost and sustainable material for lead-contaminated wastewater treatment, while providing value for agricultural waste utilization. Further studies involving adsorption modelling, adsorbent regeneration and

real wastewater applications are recommended to establish its long-term efficiency and suitability for large-scale treatment.

6. Recommendations

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

- Prioritize KOH activation for improved surface characteristics while considering H_3PO_4 activation for higher carbon yield and economic benefits.
- Investigate higher adsorbent dosages and optimize solution pH to achieve maximum lead removal efficiency while avoiding lead precipitation.
- Apply kinetic models (pseudo-first-order and pseudo-second-order) and isotherm models (Langmuir and Freundlich) to understand adsorption mechanisms and equilibrium behaviour.
- Extend the investigation to other toxic metals, including cadmium, chromium, nickel and copper.
- Evaluate suitable regeneration techniques and adsorption performance over repeated cycles to establish the material's durability and economic viability.
- Test the activated carbon using actual industrial wastewater to assess its effectiveness under practical treatment conditions. And Conduct cost-benefit and environmental evaluations to establish the sustainability and commercial potential of rice husk-derived activated carbon.

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