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Optimizing Mechanized Dosage Systems for Enhanced Nitrogen Removal Efficiency in Industrial Wastewater Treatment

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ABSTRACT

This study investigates the effectiveness of bio-waste, specifically cassava and plantain peels, as absorbents for industrial wastewater treatment.. Given the environmental and health risks associated with nitrogen pollution,. Therefore, treating wastewater with environmentally friendly bioagents is essential before its release. This research aims to develop a sustainable, efficient, and economically viable wastewater treatment approach that minimizes nitrogen pollution and supports environmental conservation efforts .To prepare the absorbents, the peels were sun-dried, cleaned and pulverized into a fine powder using a sterilized industrial electric food mill. The pulverized peels were soaked in a 50% concentrated sulfuric acid and sodium hydroxide solution for two hours to ensure complete saturation respectively. A 250 mL wastewater sample was inoculated with the prepared bio-absorbents, and the rate of absorbance was measured using a UV spectrophotometer. The statistical analysis of absorbent dosing effects on nitrogen removal was done using response surface methodology (RSM) in Design Expert (version 13). The generated models identified the optimal process parameters. Functional groups were analyzed using infrared (IR) spectroscopy. The results demonstrated the efficacy of the bio-absorbents in enhancing nitrogen removal from wastewater. Numerical optimization revealed that acid-impregnated plantain peels achieved the highest nitrogen removal efficiency of 92% under optimal conditions, with a dosage of 1.011 g. Analysis of variance (ANOVA) yielded a high coefficient of determination (R^2 = 99.9%), validating the model's reliability. This study demonstrates a cost-effective and sustainable alternative to expensive commercial chemical absorbents while promoting waste recycling for environmental sustainability.

Keywords: Wastewater; dosage loading; biodegradable; denitrogenation; optimization.

1. Introduction

Water is a natural resource needed for the survival of all living organisms (Halder *et al.*, 2015; Bibi *et al.,* 2016). According to Wang et al. (2020), industrial wastewater often contains large concentrations of nitrogenous chemicals, which can cause major environmental problems such eutrophication, oxygen depletion, and toxicity in aquatic environments if they are not properly handled. Excessive nitrogen emissions from industrial operations contribute to groundwater contamination and pose serious health risks (Galloway et al., 2018).

Effluents from hospitals and abattoirs eventually infiltrate the aquifer (Elemile et al., 2019). Abattoir waste contains a mixture of organic and mineral materials, including blood, oil, salts, and chemicals introduced during processing (Akange, 2016). This waste is often disposed of in gullies, where rainwater carries it downhill, contaminating groundwater and nearby water bodies. The situation worsens when abattoirs are located near residential areas, as many residents remain unaware of the health risks, assuming the water is safe for consumption. Runoff from municipal wastewater introduces nutrients such as nitrates and phosphates, which promote excessive aquatic plant growth, leading to eutrophication. The presence of heavy metals and nitrogen-rich wastewater poses a significant threat to water resources and environmental sustainability (Xianxin et al., 2021).

Research has shown that nitrate contamination in groundwater contributes to blue baby syndrome in infants (Chaudhry & Malik, 2017; Jennyfer et al., 2014; Buitenkamp & Stintzing, 2008). Reports indicate that drinking water should not exceed a nitrate concentration of 50 mg/L or 11 mg/L as nitrate-nitrogen, as levels beyond this threshold increase the risk of blue baby syndrome (Abascal et al., 2021; Yu et al., 2020; Lin et al., 2023). Contaminants in wastewater are a major contributor to immune suppression, reproductive disorders, and acute poisoning (Haseena et al., 2017). Exposure to polluted water has been linked to the spread of infectious diseases and kidney-related health issues (Khan & Ghouri, 2011; Juneja & Chauhdary, 2013; Halder & Islam, 2015). Environmental regulations now mandate and enforce the treatment of effluents before their release into the environment. If left untreated, these effluents can lead to the transmission of infectious diseases, water contamination, and even radioactive pollution (Grégorio & Eric, 2019).

The increasing demand for water, driven by rapid population growth and urbanization, has led to the release of harmful substances into water bodies (Ossai et al., 2023). These water bodies often contain various organic and inorganic impurities, which can be hazardous, pathogenic, or toxic, posing serious health risks, especially when their concentrations exceed permissible limits (Rim-Rukeh, 2009). Water resource policies must be regularly updated as water pollution has become a significant global environmental concern. Countries worldwide are facing challenges related to water contamination (USEPA, 2009). According to an environmental study by Chaudhry and Malik (2017), various factors influence water quality, including human agricultural activities and point source pollution from industries and municipalities. Verma and Dwivedi (2013) further emphasized that environmental contamination can occur at all stages of industrial production.

To reduce water pollution and prevent the eutrophication of water

bodies, the removal of nitrogen and phosphorus from industrial and municipal wastewater has become increasingly important (Khalaf, 2016; Rathoure & Dhatwalia, 2016). The environmental impact of pollutants becomes more evident over time as their concentration exceeds the natural absorption capacity of the ecosystem (Tietenberg, 2006). Several studies have highlighted the widespread use of adsorption processes for heavy metal removal on a global scale (Ahmed et al., 2006; Aloko & Afolabi, 2007; Cheng & Chung, 2006; Amin et al., 2006; Khaled, 2006). According to Mulu (2013), adsorption sites remain unsaturated throughout the adsorption process. Findings from various studies indicate a linear relationship between adsorbent dosage and the removal efficiency of heavy metals, dyes, and nitrates through bio-adsorption (Hou et al., 2016; Vahdat et al., 2019; Bensalah et al., 2020).

Conventional nitrogen removal techniques, including biological nitrification-denitrification and chemical precipitation, often encounter challenges such as high operational costs, complex maintenance, and variable removal efficiency (Zhou et al., 2019). Consequently, mechanized dosage systems have emerged as a promising solution for optimizing the application of absorbents and chemical reagents in wastewater treatment. These systems enable precise and controlled dosing, minimizing resource waste while improving nitrogen removal efficiency (Li et al., 2021).

Nitrogen compounds can be adsorbed onto a surface through chemical or physical interactions. In chemical adsorption, a bond forms between the adsorbent and the substance, leading to changes in the compound's electronic structure (WHO, 2009). The adsorption capacity of modified laterite is significantly higher than that of natural laterite, primarily due to the enhanced pore structure, which stimulates rapid mass transfer mechanisms (Sarma et al., 2020). Building on the findings of Hameed et al. (2007), the adsorption process remains constant once the active adsorbent surface nears saturation. When all active sites are fully occupied, equilibrium is reached at the maximum dosage. At lower dosages, the percentage of removal is lower due to the limited availability of active sites. Equilibrium is reached when the pores and surface area of the bio-adsorbent are fully saturated, preventing any further adsorption of nitrates onto the adsorbent (Wang et al., 2013).

Recent advancements in process optimization techniques, including response surface methodology (RSM) and machine learning algorithms, have enhanced mechanized dosage systems by enabling real-time monitoring and adaptive control of wastewater treatment processes (Huang et al., 2022). Furthermore, the incorporation of bio-based absorbents derived from agricultural waste provides a cost-effective and environmentally friendly alternative to traditional chemical treatments, helping to minimize the ecological impact of wastewater treatment operations (Adeleye et al., 2020).

This study aims to optimize dosage systems to improve nitrogen removal efficiency in industrial wastewater treatment. It investigates the effects of dosage variation, process parameters, and absorbent performance to identify the optimal conditions for maximum nitrogen removal. Additionally, the research assesses the viability of bio-based absorbents as a cost-effective and environmentally sustainable alternative to traditional chemical treatments.

2. Materials and Methods

2.1 Materials Sourcing

This study utilized untreated wastewater discharged from Central Hospital and Central Abattoir, both of which share the same drainage system for wastewater disposal. The sample was collected in a clean plastic pet bottle at the discharge point where the wastewater enters the Orogodo River in Agbor, (5°10′-6°20′ N, 6°10′- 6°6′ E), Nigeria. Samples were preserved in ice chest chiller and were taken to Chemical Engineering laboratory, Faculty of Engineering, University of Delta, Agbor. The fresh peels of cassava and ripe plantains used as bio-waste were collected from an agricultural produce market at Abavo, Nigeria .

2.2 Pre-treatment of Raw Materials

The peels were rinsed thoroughly with clean water to remove debris and other impurities, and then sun-dried for a period of 7 days to obtain a constant weight. Thereafter, the clean peels were pulverized into fine powder using a sterilized industrial electric food mill. Using a sieve of 500 microns pore size the powdered peels were sieved to obtained the desire particle size. The pulverized powders were stored in well labelled air-tight plastic pet bottles at room temperature for further processing and treatment.

2.3 Preparation of Adsorbents

Three different forms of the pulverized cassava peels were used. They are the raw pulverized cassava peel without any form of modification or impregnation (CU). Pulverized peels impregnated with acid (CA). This was prepared by soaking the pulverized cassava powder with 50% concentrated sulphuric acid for 2 hours, followed by washing it with distilled water until all traces of the acid is removed which was confirmed by litmus paper indicator test. The filtrate was recovered by filtering through a whatman No. 1 filter paper. The filtrate was then oven-dried at 120°C for 5 hours to remove all traces of water. The dried untreated and treated cassava peels were then stored in a dried plastic pet bottles at room temperature.

The third form of the pulverized cassava powder impregnated with base (CB) was prepared by soaking with 50% Sodium hydroxide solution and same procedures above were repeated.

Three different forms of the pulverized plantain peels were also used. They are the raw pulverized plantain peel without any form of treatment or impregnation (PU), pulverized peels impregnated with acid (PA) and pulverized peels impregnated with base (PB). Same laboratory procedures for cassava peels were strictly adhered to for the treatment process of the ripe plantain peels.

2.4 Determination of Functional group

The peels were subjected to infra-red spectroscopy to analyse the functional groups and structural changes as a result of treatment with acid and base. The chemical structure of the adsorbent is necessary to understand the adsorption process. The FTIR spectra ranges from 4000 cm^{-1} – 500cm^{-1}.

2.5 Experimental Determination of Nitrate ions from Wastewater sample

Nitrate ions present in wastewater was determined using the method reported by Ossai et al., (2023). The prepared mixture was heated for a few minutes in a boiling water bath after adding brucine-sulphanilic acid reagent. A UV spectrophotometer at a wavelength of 410nm was used. The solution concentration was determined using the regression equation from the calibration curve of the wastewater . Equation 1 was use to calculate the amount of adsorbed nitrate;

$$a = \frac{(co - ce)v}{m} \qquad (1)$$

where a is amount of nitrate adsorbed, Co is initial concentration of nitrate before adsorption (mg/l), Ce is concentration at equilibrium (mg/l), V is volume of solution used (ml) and m is mass of adsorbent used (g)

2.6 Determination of Adsorbent Dosage

In investigating the effects of adsorbent dosage, 0.2g of each of the adsorbents were weighed into their respective flasks containing 20ml each of wastewater. The mixtures were stirred mechanically for an hour. This was repeated by varying the dosages of adsorbents mixed with the wastewater (0.4g, 0.6g, 0.8g, and 1g). The contents were filtered and the filtrate analysed for nitrate using standard procedures. No adsorbent was added to the control flask. Equation 2 was used in the determination of the percentage removal of the nitrate present as

a result of the interaction of the adsorbents and the wastewater.

$$\% \text{ Removal} = \frac{(ci - ca)}{ci} \times 100 \quad (2)$$

where C_i and C_a are the initial nitrogen concentration in wastewater and the absorbed concentration of nitrogen after interaction with wastewater (Wang et.al., 2013).

3.7 Design of Experiment

One variable design approach was used as the independent variable, adsorbent dosage (X_1). The response variables such as removal rate using Cu (Y_1), CA (Y_2), CB (Y_3), PU (Y_4), PA(Y_5) and PB(Y_6). Equation 3 was use in estimating coefficients, predicting responses, and determining whether the resulting model is acceptable are all steps in system optimization.

$$Y = f \quad (X_1 \ldots Xn \pm \mathcal{E}) \quad (3)$$

where Y and f is the response and its function, X_1...Xn are independent variables, and is the experimental error.

One factor Design Matrix was used and response values for percentage removal were obtained experimentally using the bio-adsorbents. Equation 4 and 5 are the predicted responses. They are a function of an independent variable which depend largely on the interaction between the independent variable and the response variable using a second-order and third order polynomial equation

$$Y_i = b_o + \sum b_i X_i + \sum b_{ij} X_i X_{ij} + \sum b_{ii} X_i^2 + e_i \quad (4)$$

$$Y_i = b_o + \sum b_i X_i + \sum b_{ij} X_i X_{ij} + \sum b_{ii} X_i^2 + \sum b_{ii} X_i^3 + e_i \quad (5)$$

Y is the predicted response, $b_o$is the intercept, and $b_i b_{ii}$, b_{ij} are linear, quadratic, and interaction coefficients. X_i and X_j are coded values of the process variables and experimented error denoted as .

To choose the most appropriate polynomial model, statistical measures involving various polynomial models were examined. Through analysis of variance, a significant difference was identified by determining the F value at the probability function. Response plots were equally generated using Design Expert to examine the impact of contact time on the response variables. Coded and actual independent variables are shown in Table 1.

Table 1: Coded and actual levels of one factor design of Pulverised unmodified and modified (acid and base) peels of cassava and ripe plantains

Independent Variable	Symbols	Coded and Actual Levels		
		-1	0	+1
Adsorbent loading (g)	X_2	0.20	0.60	1.00

3.0 Results and Discussion

3.1 FTIR Analysis

3.1.1 Cassava Peels

Tables 2-4 showed the FTIR results of the various categories of cassava peels used in this study. Transmittance was plotted against wave number to analyze the functional groups present in the unmodified cassava peels. The FTIR results shown in Table 2, revealed a broad absorption band at 3277.54 cm^{-1}, which corresponds to O-H stretching vibrations, characteristic of alcohols and phenols (Silverstein et al., 2014; Coates, 2006). A sharp band observed at 2918.69 cm^{-1} is attributed to C-H stretching, typically associated with acids and carboxylic compounds (Pavia et al., 2013). Additionally, the absorption peak at 1629.49 cm^{-1} indicates the presence of C=C stretching vibrations, signifying the presence of alkene functional groups. This results obtained is in synergy with the works of Smith,(2011); Stuart, (2004) on fundamentals and applications of infrared microscopy.

The study by Colthup et al.(2012) on Introduction to Infrared and Raman Spectroscopy conforms with the FTIR of the acid modified cassava peels in Table 3, peaks at the bands 3325.35cm^{-1} and 3276.66 cm^{-1} were attributed to O-H stretch which indicates alcohols and phenols compounds. The band at 1724.64cm^{-1} region shows C=O stretch (aldehydes) at 1631.66cm^{-1} signifies the alkenes groups.

For the base modified cassava peels Table 4, the peak at 3300.65 cm^{-1} is an O-H stretch (alcohols and phenols) and the peak at region 2916.48cm^{-1} were attributed to O-H stretch (acids, carboxylic compounds) and 1593.26cm^{-1} confirms the C=C stretch of the alkenes functional group. The results here are in line with the works of Socrates, (2001).

Overall, acid-modified cassava peels demonstrated a potential for nitrogen removal, as indicated by the intensified C=O functional group, which plays a critical role in adsorption interactions. Base modification also improved adsorption efficiency compared to unmodified peels, likely due to increased hydroxyl functional groups and surface activation. The findings confirm that chemical modification significantly enhances the adsorption capacity of cassava peels, making them a viable and cost-effective alternative to conventional adsorbents for wastewater treatment. This is in tandem with the works of Xia et al.(2022)

3.1.2 Plantain PeelsFrom Table 5, the FTIR result of unmodified plantain peels exhibited a characteristic band at 3281.19 cm^{-1}, corresponding to O-H stretching vibrations, which is indicative of hydroxyl groups present in alcohols and phenols . Additionally, absorption bands at 2920.60 cm^{-1} and 2851.79 cm^{-1} were attributed to O-H stretching (acids, carboxylic compounds) and C-H stretching (alkyl groups), respectively. The 1735.23 cm^{-1} peak was assigned to C=O stretching, characteristic of esters and carboxyl functional groups. The 1628.43 cm^{-1} band was linked to N-H bending, indicating the presence of amine functional groups, while the 1376.34 cm^{-1} peak was associated with C-H bending, which corresponds to methyl ($-CH_3$) groups as was explained in the study by Yang et al.,(2020).

The FTIR result of acid-modified plantain peels as shown in Table 6 exhibited a broad absorption band at 3289.39 cm^{-1}, corresponding to O-H stretching vibrations, and characteristic of alcohol and phenol functional groups (Coates, 2006; Silverstein et al., 2014; Stuart, 2004). A sharp peak at 2920.44 cm^{-1} also indicates O-H stretching, but specifically from carboxylic acids (Kumar et al., 2021).

Additionally, the peak at 2852.29 cm^{-1} corresponds to C-H stretching, which is associated with alkyl groups. The absorption band at 1630.40 cm^{-1} is attributed to N-H bending, indicating the presence of amine functional groups, while the peak at 1441.81 cm^{-1} corresponds to C-H bending, characteristic of alkyl groups (Awoyemi et al., 2023).

The FTIR data of base-modified plantain peels is shown in Table 7. The spectra exhibited a distinct absorption band at 3325.66 cm^{-1}, corresponding to O-H stretching vibrations, which is characteristic of alcohols and phenols . Additionally, another O-H stretching band associated with carboxylic acids was observed at 2917.50 cm^{-1}, indicating the presence of acidic functional groups (Kizil et al., 2023). Furthermore, the absorption peak at 1630.57 cm^{-1} was attributed to N-H bending, signifying the presence of amine functional groups (Adeyi & Jumo, 2022)

In all, acid-modified plantain peels exhibited the most significant structural transformation, as indicated by stronger carbonyl (C=O) and hydroxyl (O-H) functional groups**,** which are known to enhance adsorption efficiency. Base modification also improved adsorption capacity but to a lesser extent than acid treatment**.** These findings

Table 2: Functional group of Unmodified Cassava peels.

Wavenumber	Functional group	Stretching band
3277.54 cm^{-1},	alcohols and phenols	O-H stretching
2918.69 cm^{-1}	acids and carboxylic compounds	C-H stretching,
1629.49 cm^{-1}	alkene	C=C stretching

Table 3: Functional group of acid modified Cassava peels.

Wavenumber	Functional group	Stretching band
3325.35cm^{-1}	alcohols and phenols	O-H stretching
3276.66 cm^{-1}	,,	,,
1724.64cm^{-1}	aldehydes	C=O stretch
1631.66cm^{-1}	alkenes	C=C stretching

Table 4: Functional group of base modified Cassava peels.

Wavenumber	Functional group	Stretching band
3300.65 cm^{-1}	alcohols and phenols	O-H stretching
2916.48cm	acids, carboxylic compounds	O-H stretch
1593.26cm^{-1}	alkenes	C=C stretch

confirm that chemical modification enhances the adsorption potential of plantain peels, making them a viable and cost-effective alternative to commercial adsorbents for wastewater treatment (Yang et al., 2020) Comparatively, both acid-modified peels showed enhanced adsorption capacity, but since the specific pollutants targeted is nitrogenous compound, acid-modified plantain peels exhibited more amine functional groups, suggesting a potential advantage in binding nitrogen-based pollutants

3.2 Effect of absorbent dosage

To determine the effectiveness of the absorbents in removing nitrogenous compounds from wastewater, the concentration of nitrogen before and after treatment was measured using Equation 1. This data was then used to calculate the percentage removal efficiency (%R) of the absorbents using Equation 2 as seen in Table 8.

The results of adsorbent dosage and nitrate removal efficiency are presented in Table 8. The control sample refers to the wastewater without any adsorbent. The adsorption process was conducted at varying adsorbent dosages, ranging from 0.2 g to 1.0 g. The findings revealed that nitrate removal efficiency increased with increasing adsorbent dosage, with the highest efficiency recorded at 1.0 g for all adsorbents, regardless of the modification type. This trend can be attributed to the greater availability of active binding sites on the adsorbents, allowing for higher nitrate uptake. However, once the adsorbent's pores and surface area become fully saturated, no further nitrate adsorption occurs, indicating that the system has reached adsorption equilibrium. (Wang et al, 2013). Based on the study by Hameed et al. (2007), the adsorption process stabilizes once the active sites on the adsorbent surface reach saturation.The unmodified plantain peel demonstrated a higher nitrate removal efficiency (64%) compared to the unmodified cassava peel (52%). When modified with a base treatment, plantain peel exhibited an 85% removal efficiency, whereas base-modified cassava peel achieved 60%.

Similarly, acid-modified cassava peel recorded an 80% removal efficiency, while acid-modified plantain peel achieved the highest efficiency at 92%, making it the most effective adsorbent.

The increase in adsorption efficiency observed in this study can be attributed to the modification treatments, which enhanced the pore structure of the bio-adsorbents, thereby improving their adsorption capacity. The enlargement of pores facilitates a faster transfer mechanism between the bio-adsorbents and the nitrate contaminants in wastewater from hospital and abattoir sources. As a result, the modified adsorbents outperformed their unmodified counterparts in nitrate removal (Sarma et al., 2020; Akange et al., 2016; Gautam et al., 2007).

3.3 Percentage Removal of Nitrates from Wastewater Using Response Surface Methodology Statistical Analysis Equations (5–10) were generated using Response Surface Methodology (RSM) in Design Expert software to predict the responses as earlier stated in equation 5 for the cassava and plantain peels. The generated model equations are as follows:

Table 5: Functional group of Unmodified Plantain peels.

Wavenumber	Functional group	Stretching band
3281.19 cm^{-1},	hydroxyl groups present in alcohols and phenols	O-H stretching vibrations,
2920.60 cm^{-1}	acids and carboxylic	,,
2851.79 cm^{-1}	alkyl	C-H stretching
1735.23 cm^{-1}	esters and carboxyl	C=O stretching,
1628.43 cm^{-1}	amine	N-H bending,
1376.34 cm^{-1}	methyl ($-CH_3$)	C-H bending

Table 6: Functional group of acid- modified Plantain peels.

Wavenumber	Functional group	Stretching band
3289.39 cm^{-1},	alcohols and phenols	O-H stretching vibrations
2920.44 cm^{-1}	carboxylic acids	O-H stretching,
2852.29 cm^{-1}	alkyl	C-H stretching,
1630.40 cm^{-1}	amine	N-H bending,
1441.81 cm^{-1}	alkyl	C-H bending

Table7 : Functional group of base -modified Cassava peels

Wavenumber	Functional group	Stretching band
3325.66 cm^{-1},	alcohols and phenols	O-H stretching
2917.50 cm^{-1},	carboxylic acid compounds	O-H stretch
1630.57 cm^{-1}	amine	N-H bending,

Table 8: Concentration and percentage removal of nitrates for effect of loading

Weight(g)	Control	CU		CA		CB		PU		PA		PB	
	mg/l	mg/l	%R	mg/l	%R	mg/l	%R	mg/l	%R	mg/l	%R	mg/l	%R
0.2	273.12	199.92	27	193.11	29	194.06	29	187.80	31	174.09	36	179.07	34
0.4	273.12	185.05	32	159.48	42	179.60	34	175.52	36	127.04	53	125.48	54
0.6	273.12	163.44	40	107.71	61	152.51	44	158.51	42	69.18	75	77.00	72
0.8	273.12	138.93	49	86.68	68	126.51	54	132.81	51	53.16	81	55.95	80
1.0	273.12	131.48	52	55.71	80	109.21	60	98.66	64	21.69	92	40.19	85

$$Y_1 = 40.22 + 18.50X_1 - 0.67X_1^2 - 6.00X_1^3 \quad (6)$$
$$Y_2 = 59.44 + 25.56X_1 - 5.33X_1^2 \quad (7)$$
$$Y_3 = 43.96 + 21.50X_1 + 0.53X_1^2 - 6.00X_1^3 \quad (8)$$
$$Y_4 = 42.04 + 14.50X_1 + 5.47X_1^2 + 2.00X_1^3 \quad (9)$$
$$Y_5 = 73.13 + 28.00X_1 - 9.60X_1^2 \quad (10)$$

Where Equations (Y_1-Y_6) represent the predicted responses for CU, CA, CB, PU, PA, and PB, respectively. X_1 denotes the coded levels of adsorbent dosage.

The predicted values of $y_1, y_2..y_6$ as determined by Equations (5–10), are presented in Tables 9 and 10 for cassava and plantain peels respectively. The actual and predicted response values are almost the same as can seen from tables 4 and 5. This implies that the developed model is highly accurate, well-fitted to the experimental data, and capable of making reliable predictions for process optimization. This enhances confidence in using the model for decision-making in experimental studies and industrial applications.

Statistical information for ANOVA

The analysis of variance shown in Table 11 was performed to determine the coefficient of determination. ANOVA was performed to ascertain the level of significance. The results in Table 11 shows models for CU, CA,CB,PU,PA and PB were statistically significant with p values of <0.0001. CU, CA, CB,PU,PA and PB models have high coefficient of determination (R^2) as seen from Table 11. This shows that the models were able to adequately represented the relationship between the independent variable (adsorbent dosage) and responses (CU, CA, CB, PU, PA, and PB). R^2 values of 0.999,0.991,0.997,0.999 ,0.989 and 0.999 signifies that the models were able to explain 99.9%, 99.1%, 99.7%, 99.9%, 98.9% and 99.8% respectively. From Table 5, there is reasonable agreement between the predicted R square value and the adjusted R squared value. Hence the model can be used to navigate the design space.

3.4 Solutions for optimum conditions

The optimal conditions for the independent variable (adsorbent dosage) and the responses (percentage removal of CU, CA, CB, PU, PA, and PB) were obtained through numerical optimization of the statistical models. The optimized results are presented in Table 12.

The highest adsorption efficiencies for CU, CA, CB, PU, PA, and PB were achieved at an optimal adsorbent dosage of 1.011 g as seen in Table 6. Under these conditions, the percentage removal efficiencies were recorded as 52.032%R (CU), 80.063%R (CA), 60.099%R (CB), 68.865%R (PU), 91.763%R (PA), and 84.922%R (PB).The modification and impregnation of the adsorbents led to a significant increase in the number of active adsorption sites, enhancing pore size and pore volume (Mulu, 2013). This structural enhancement, achieved through acid and base treatments, contributed to the improved adsorption performance of CA, CB, PA, and PB, as the larger pore size and increased surface area facilitated better contaminant uptake and interaction with nitrogenous compounds.

Table 9: Predicted response for cassava peels and was calculated using Equations 6 -11.

Run No	Variable	adsorbent Dosage(g)	Responses					
	Coded level	Actual Value	CU (%R)		CA (%R)		CB (%R)	
	X_1	X_1	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	0. 0	0.6	40	40	61	59	44	43
2	1. 0	1.0	52	64	80	79	60	59
3	0. 0	0.6	40	39	61	59	44	43
4	-1. 0	0.2	27	15	29	29	29	28
5	-1. 0	0.2	27	15	29	29	29	28
6	-0. 0	0.4	32	30	42	45	34	34
7	1. 0	1.0	52	64	80	79	60	59
8	0.0	0.6	40	39	61	59	44	43
9	0.5	0.8	49	50	68	71	54	54

Table 10: Predicted response for plantain peels and was calculated using Equations 6-11.

Run No	Variable (adsorbent dosage) (g)		Responses					
	Coded level	Actual Value	PU (%R)		PA (%R)		PB (%R)	
	X_1	$_1$ X	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	0.0	0.6	42	42	75	73	72	71
2	1.0	1.0	64	60	92	92	85	87
3	0.0	0.6	42	42	75	73	72	71
4	-1.0	0.2	31	35	36	36	34	36
5	-1.0	0.2	31	35	36	36	34	36
6	-0.5	0.4	36	36	53	56	54	56
7	1.0	1.0	64	60	92	92	85	87
8	0.0	0.6	42	42	75	73	72	71
9	0.5	0.8	51	50	81	84	80	81

Table 11: Analysis of Variance

Parameter	Responses					
	CU	CA	CB	PU	PA	PB
R-Squared	0.999	0.991	0.997	0.999	0.9895	0.9984
Mean	39.89	56.78	44.22	44.78	68.33	65.33
Standard Deviation	0.33	2.13	0.067	0.067	2.56	0.92
C.V%	0.84	3.76	0.15	0.15	3.74	1.41
Adeq. Precision	112.500	41.477	697.500	742.500	37.947	95.917
Adjusted R-Square	0.9988	0.9879	0.997	0.998	0.9860	0.9979
Pred. R-Squared	0.9955	0.9850	0.9999	0.999	0.9826	0.9974

Table 12: Optimum Absorption Performance

Solution Number	Adsorbent dosage(g)	CU(%R)	CA(%R)	CB(%R)	PU(%R)	PA(%R)	PB(%R)	Desirability
1	1.011	52.032	80.063	60.099	64.865	91.763	84.922	0.908
2	1.009	52.027	80.000	60.083	64.726	91.727	84.918	0.908
3	1.008	52.020	79.958	60.072	64.635	91.703	84.915	0.908

4. Conclusion

This study investigated the potential of cassava and plantain peels as bio-adsorbents for nitrogen removal from industrial wastewater. FTIR analysis confirmed that acid and base modifications significantly altered the adsorbents' surface chemistry, increasing pore size, surface area, and the number of active functional groups (O-H, C=O, and N-H), which enhanced their adsorption capacity. Experimental results showed that acid-modified plantain peels exhibited the highest

nitrogen removal efficiency (92%)**,** followed by acid-modified cassava peels (80%) and base-modified plantain peels (85%)**.** Unmodified adsorbents displayed lower efficiencies, with plantain peels (64%) outperforming cassava peels (52%)**.** The improved adsorption performance in modified adsorbents is attributed to their enhanced surface reactivity and better interaction with nitrogenous compounds. Using Response Surface Methodology (RSM) for optimization, the optimal adsorbent dosage was determined to be 1.011 g**,** achieving maximum nitrogen removal efficiencies of 91.76% (PA), 84.92% (PB), 80.06% (CA), 68.86% (PU), 60.09% (CB), and 52.03% (CU**)**. These findings confirm that chemical modifications enhance bio-waste adsorption efficiency**,** making them effective alternatives to synthetic adsorbents. In summary, this study demonstrates that **c**hemically modified agricultural waste can serve as a cost-effective and environmentally friendly solution for wastewater treatment**.** The results suggest strong potential for **s**caling up these bio-adsorbents for industrial applications. Future research should explore adsorption kinetics, regeneration potential, and real-world application in wastewater treatment systems to further validate and optimize this approach.

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