

Original Article

Efficacy of Adsorption of Congo Red Dyes from an Aqueous Media using Silicon Nitride (Si_3N_4) Adsorbent Derived from Sand and Coffee Husk Wastes

Samuel N. Ndung'u^{1,*} | Ruth N. Wanjau¹ | Esther W. Nthiga²

¹Department of Chemistry, Kenyatta University, P.O Box 43844-00100, Nairobi, Kenya

²Department of Chemistry, Dedan Kimathi University of Technology, P.O Box 657-10100, Nyeri, Kenya



Citation S.N. Ndung'u, R.N. Wanjau, E.W. Nthiga, Efficacy of Adsorption of Congo Red Dyes from an Aqueous Media using Silicon Nitride (Si_3N_4) Adsorbent Derived from Sand and Coffee Husk Wastes. *Eurasian J. Sci. Technol.*, 2024, 4(3), 253-263.

<https://doi.org/10.48309/EJST.2024.433646.1121>



Article info:

Received: 2024-01-02

Accepted: 2024-01-28

Available Online: 2024-02-13

ID: EJST-2401-1121

Checked for Plagiarism: Yes

Checked Language: Yes

Keywords:

Silicon Nitride (Si_3N_4), Hydroxylation, Congo Red (CR), Efficacy, Kinetic, Chemisorption.

ABSTRACT

The current study utilizes Silicon Nitride (Si_3N_4) as a novel adsorbent in evaluating its adsorptive ability for Congo red dyes from an aqueous solution. The adsorbent was prepared using extracted silica from sand and coffee husk biochar in an ammonia environment. The Si_3N_4 adsorbent was characterized using a Field Emission Scanning Electron Microscope (FEI ESEM) which showed rod-like and fiber-like structures for α - Si_3N_4 and β - Si_3N_4 , respectively. The SEM results also showed pores on the adsorbent surface before adsorption and a more rigid and restrained surface after adsorption. The adsorbent surface is hydroxylated in water to give important adsorption sites of silanolate ions (Si-O^-) and silazane groups ($\text{Si}_2=\text{NH}_2^+$) responsible for congo red (CR) dye removal. The adsorption process was investigated by batch mode. The maximum adsorption capacity (28.87 mg/g) was obtained at an optimal pH=1.00, agitation time (50 minutes), adsorbent dosage (25 mg), and initial concentration (50 mg/L). The Langmuir isotherm model was best fitted with equilibrium data with $R^2 > 0.9$, showing that the adsorption was chemisorption in nature. The results revealed Si_3N_4 adsorbent as a potential adsorbent in textile dye wastewater treatment.

Introduction

Safe water is essential for domestic use, agriculture, economy's growth and peoples' health [1]. Due to the essential role that water plays, its demand and scarcity has remained a global problem [2]. The available water reserves are contaminated by industrial effluents, and this affect the quality of life [3]. In Kenya alone, 27% of the population obtains drinking water from these sources water and additional burden for water treatment. The global challenge of the twenty-

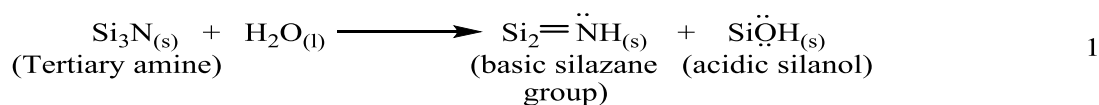
resulting to water-related diseases [4]. Majority are unable to afford the expensive chemicals needed to treat water from these available water reserves and therefore are forced to drink as it is or source water from the nearby water vendors whose quality is not guaranteed [5]. With the issue of housing being one of the agendas of Kenya kwanza government, this will definitely have an effect on demand for clean first century is therefore to overcome the lack of clean water and to provide safe water for a

*Corresponding Author: Samuel N. Ndung'u. samuelndungu530@gmail.com

healthier ecosystem [2]. Many industries such as textiles, leather, food, plastics, and pharmaceutical play a crucial role in the global economy, but is also a significant contributor to environmental pollution due to the discharge of dye-containing effluents [6]. Globally, it is estimated that more than 100,000 types of commercially accessible dyes exist and an annual worldwide production of 700,000 tons has been reported [7]. These dyes are used to colour products [8]. Due to this, a considerable amount of coloured wastewater is therefore generated due to large consumption of water at different steps of dyeing and finishing processes [9]. In fact, processing one ton of a dyestuff product consumes between 200-270 tons of water with majority of it going to waste [10]. Approximately, 20% of these lost dyes enter in the nearby water bodies as an industrial wastewater without treatment causing potential damage to the environment [7]. The presence of the dye in water even in small amounts (1 mg/L) is highly visible [11]. The dye synthetic origin, complex aromatic structure and non-biodegradability nature make them stable making it difficult to treat such wastewater [12].

Congo red (CR) dye, a benzidine-based anionic diazo dye is one of the most harmful contaminants that is toxic, mutagenic, and carcinogenic [8]. The dye is irritant to the skin,

gastrointestinal tract and eyes [13]. Long term ingestion of the wastewater containing the dye has health hazards such as destroying the human body's blood system, liver, and hematopoiesis and various symptoms such as breathing difficulties, diarrhea, vomiting, and nausea [14]. Therefore, an innovative, cost effective and sustainable treatment methods are essential in mitigating the impacts. Conventional methods for the dye removal such as nanotechnology [15] and electrochemical process [16] often involve chemical treatments or physical processes that are energy-intensive, costly, and may produce large volumes of sludge containing harmful by-products [17]. Adsorption technology has however remained the most effective method for dye removal because of its low cost, environmentally friendly and high efficiency [18]. Low-cost adsorbents such as pine bark [8], banana peel [19] and Silica gel [20] among others have been reported in removal of Congo red dye from wastewater. Silicon nitride (Si_3N_4) adsorbent is reported to adsorb pollutants such as fluoride ions [21] and tetracycline [22]. This is due to hydroxylation of Si_3N_4 surface structure in aqueous phase to yield acidic silanol ($\text{Si}-\text{OH}$) and basic silazane ($\text{Si}_2=\text{NH}$) groups which then make the surface charged [23]. This is as shown in Equation 1 and Figure 1 [24].



The present work, a continuation of the previous study by [25] sought to synthesize Si_3N_4 adsorbent using extracted silica from sand and coffee husk biochar to assess the efficacy and kinetics of batch adsorption of Congo red dye from an aqueous solution.

Materials and Methods

All the chemicals used were of anal grade. Ammonium solution (NH_4OH), Congo red dye ($\text{C}_{32}\text{H}_{22}\text{N}_6\text{Na}_2\text{O}_6\text{S}_2$), Hydrochloric acid (HCl),

Ammonia acetate ($\text{C}_2\text{H}_7\text{O}_2\text{N}$), and Sodium hydroxide (NaOH) were all sourced from Sigma Aldrich (Kobian, Nairobi Kenya). Distilled water obtained from Kenyatta University chemistry laboratory was used throughout the study.

Si₃N₄ Adsorbent Preparation

The silicon nitride adsorbent was carried out first by carbothermal reduction followed by nitridation. The biochar powder was mixed with the extracted silica in the ratio of 3 to 2 for

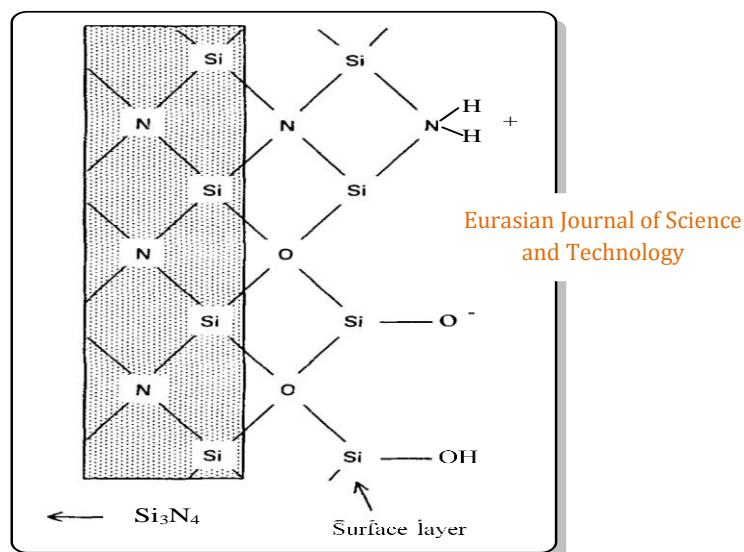


Figure 1 Hydroxylated Si_3N_4 surface structure

two hours and then placed in a digestion bomb. The bomb was tightly closed and placed in a thermostat-controlled muffle furnace and heated at 300 °C for 12 hours and the final product allowed to cool. Approximately 200 mL of NH_4OH solution (28% v/v) was then added, bomb tightly closed and heating continued at 300 °C for another 12 hours. The final product was then allowed to cool, ground and stored in an airtight container.

Dye Solutions

The stock solutions (1000 mg/L) was made by dissolving 1.00 g of the anal grade Congo red azo dye in an ammonium acetate ($\text{C}_2\text{H}_7\text{O}_2\text{N}$) buffer media to maintain a constant ionic strength, and then serial dilutions followed to obtain working solutions. 0.1 M NaOH or 0.1 M HCl solutions were used for pH adjustments. The fresh dilutions were used in each adsorption experiment.

Instrumentation

The used instruments and equipment were Field Emission Scanning Electron Microscope (FEI ESEM, Vega3 Tescan LMH), pH meter (PHS-3C), Thermostat-controlled muffle

furnace (MC5-12 Biobase), double beam UV-Visible Spectrophotometer (Specord 200, Analytik Jena), Distiller (WSB 14), Lab-line mechanical reciprocating shaker (SSL₂ Harrogate, UK), and Analytical weighing balance (ATX224 Shimadzu).

Adsorption Experiments

Batch Studies

The effect of pH, agitation time, dosage, and initial concentration on Congo red sorption onto Si_3N_4 adsorbent was optimized by batch method using plastic screw cap bottles (100 mL). The process parameters of pH (1.0-13.0), agitation time (10-130 minutes), adsorbent dosage (5.00-40.00 mg) and initial concentration (10-150 mg/L) were varied in 20 mL of the test solution. This was done by adjusting a single parameter while keeping the other parameters constant. The experiments were done thrice at an agitation speed of 150 rpm. The dye concentration was analyzed using a double beam UV-Visible spectrophotometer at an absorbance wavelength (λ_{max}) of 500 nm. The amount of dye ions adsorbed per unit mass of the adsorbent was determined using Equation 2.

$$q_e = \frac{(C_i - C_e)V}{M} \quad (2)$$

Where, q_e is the amount adsorbed (mg/g) at equilibrium, C_i indicates the initial concentration (mg/L), C_e is the final concentration (mg/L), V is the solution volume (mL), and M denotes the adsorbent dosage (g).

Isotherm Studies

The Langmuir, Freundlich and Dubinin-Radushkevich models are employed for fitting of equilibrium data. The Langmuir assumes a monolayer interaction which is chemisorption in nature [26]. Its linearized form is given by Equation 3.

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{K_L q_m} \quad (3)$$

Where, q_e (mg/g) is the adsorbed dye ions at equilibrium, q_m (mg/g) is the maximum amount of dye ions, and C_e (mg/L) is the concentration of dye ions adsorbed at equilibrium. K_L (L/g) is a Langmuir constant. The Freundlich isotherm describes a multilayer adsorption on a heterogeneous surface and assumes an exclusively physisorption [27]. Its linearized equation is shown by Equation 4.

$$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e \quad (4)$$

Where, K_F and n correspond to adsorption capacity (mg/g) and adsorption intensity constants, respectively. The Dubinin-Radushkevich is based on the assumption that the adsorption process is by micropore filling mechanisms onto both homogenous and heterogeneous surfaces [28]. Its linearized expression is given by Equation 5.

$$\ln q_e = \ln q_m - K_{D-R} \varepsilon^2 \quad (5)$$

Where, q_e is the amount of dye molecules adsorbed at equilibrium (mg g⁻¹), q_m is the theoretical isotherm saturation capacity (mg/g), K_{D-R} is the Dubinin-Radushkevich

isotherm constant (mol²/kJ²), and ε is the Polanyi potential. The model is usually applied to distinguish the physisorption and chemisorption processes [29]. The mean free energy (E) computed by Equation 6.

$$E = \frac{1}{\sqrt{-2K_{D-R}}} \quad (6)$$

The Polanyi potential value (ε) can be calculated by Equation 7.

$$\varepsilon = RT \ln \left(1 + \frac{1}{C_e} \right) \quad (7)$$

Where, R is molar gas constant (8.314 J/mol/K), T is absolute temperature (K) and C_e is the dyes equilibrium concentration (mg/L).

Results and Discussion

Hydroxylation Mechanism

The hydroxylation mechanism of silicon nitride (Si₃N₄) adsorbent surface is displayed in [Figure 2](#).

The presence of charged silazane and silanolate adsorption sites makes the material suitable for Congo red dyes adsorption from water.

Scanning Electron Microscope (SEM) analysis

The SEM micrographs for Si₃N₄ adsorbent before and after adsorption was obtained at an accelerating voltage (20.0 kV) and magnification (Mg = 6.50 K X). The results are presented in [Figure 3](#).

The results in [Figure 3](#) showed the presence of rod-like and fiber-like micrographs. These are attributed to α -Si₃N₄ and β -Si₃N₄ structures [30,31]. Before adsorption (A), the adsorbent surface evidenced pores of different shapes and sizes. The dye-loaded adsorbent surface (B) is more rigid and restrained which is contributed to dyes having occupied the pores.

Optimization

The results on effect of pH on mean uptake of the dye are demonstrated in Figure 4.

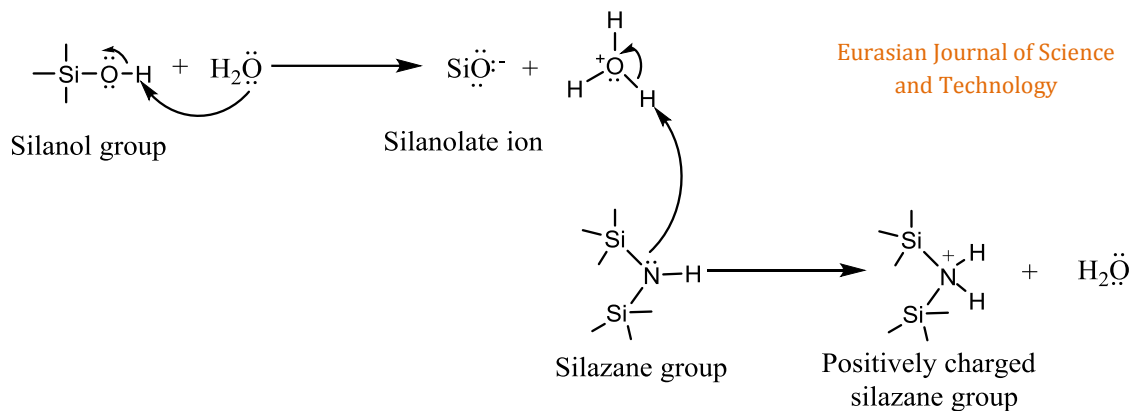


Figure 2 Silicon nitride surface hydroxylation mechanism

Eurasian Journal of Science and Technology

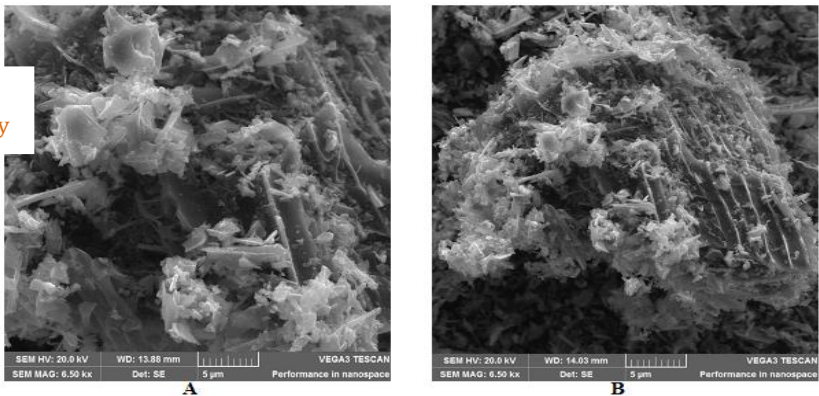
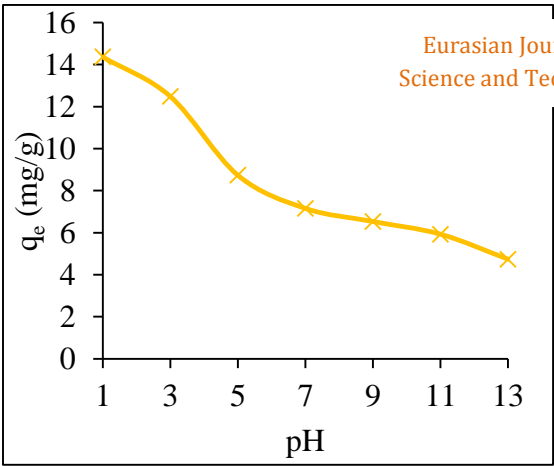


Figure 3 The SEM micrographs before (A) and after (B) adsorption

The mean uptake was maximum (14.37 ± 0.08 mg/g) at optimum pH (1). This was followed by a significant decrease in removal capacity with increased in solution pH. The positively charged silazane groups of Si_3N_4 adsorbent were enhanced in strongly acidic dye solution favoring the adsorption process. At $\text{pH } 1.00 \leq \text{pH}_{\text{pzc}} 5.10$, the H^+ ions concentration in the dye solution is increased. This causes electrostatic repulsion between the H^+ ions and the positively charged silazane groups of Si_3N_4 adsorbent. These H^+ ions get attracted by the negatively charged silanolate ions and are neutralized [21]. This leaves more silazane active sites readily available for CR dye adsorption by electrostatic attraction. At $\text{pH } 1.00 \geq \text{pH}_{\text{pzc}} 5.10$, the dye solution continues to become more alkaline due to the presence of excess OH^- ions which destabilizes the CR dyes

by competing with the $-\text{SO}_3^-$ ions for silazane binding sites in a basic dye solution. This consequently weakens its adsorption effect [34]. The adsorption mechanism is shown in Figure 5.



Eurasian Journal of Science and Technology

Figure 4 Effect of pH on CR dyes removal onto Si_3N_4 adsorbent

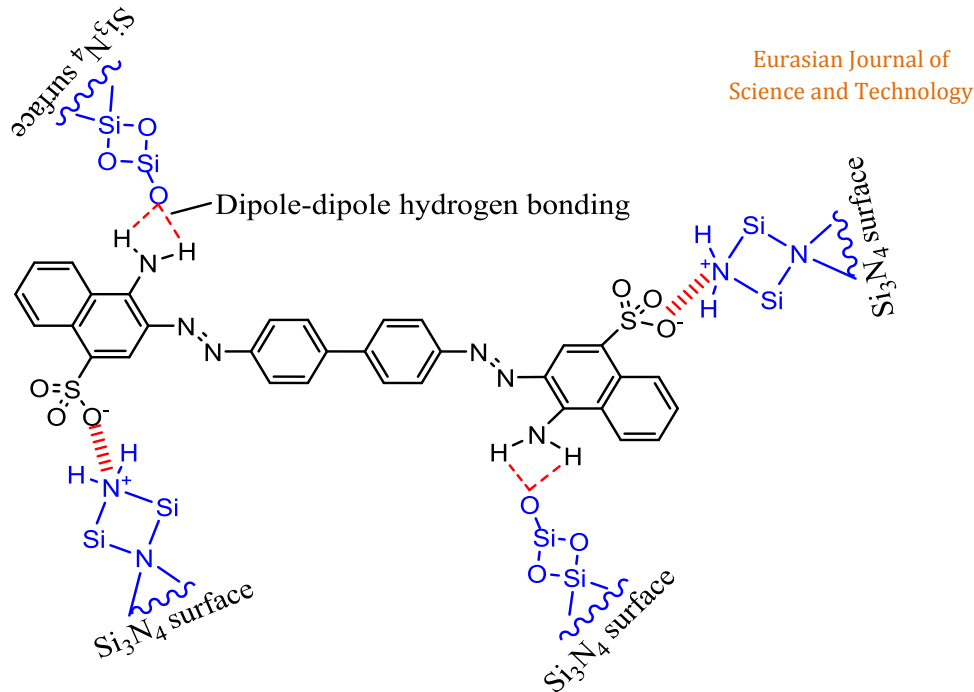
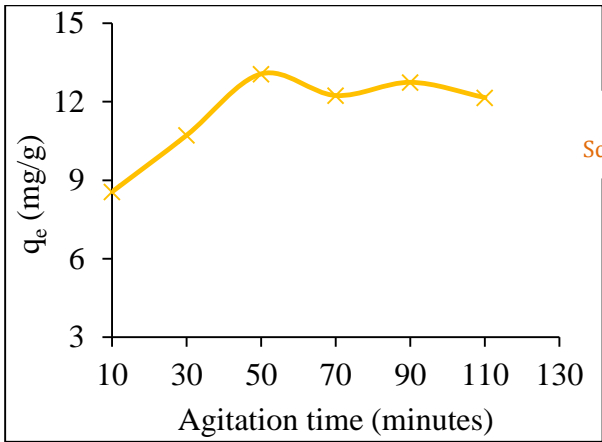


Figure 5 Adsorption mechanism of CR dye onto Si_3N_4 adsorbent

Effect of Agitation Time

The effect of agitation time on sorption of CR dyes was investigated and the results are presented in the [Figure 6](#). The optimal agitation time 50 minutes with a maximum uptake of 13.06 ± 0.02 mg/g. The uptake increased with increasing agitation time during the initial stages of adsorption to

optimal then became constant or lower beyond equilibrium. The rapid adsorption was due to the fact that, at the initial stages of adsorption, vacant adsorption sites are available for maximum uptake [32]. Subsequently, the lower adsorption rate beyond the optimum time is due to a decrease in the number of vacant sites of adsorbent [33].



Eurasian Journal of Science and Technology

Figure 6 Effect of agitation time on CR dyes removal onto Si_3N_4 adsorbent

Effect of Adsorbent Dosage

The dosage effect on CR adsorption was evaluated by changing the dose from 5 - 40 mg. The results are presented by Figure 7.

From the results in Figure 7, the uptake of CR dyes was maximum at optimal dosage of 25 mg. The uptake was low at low dosages but increased with increase in dosage to optimum then a slight decrease. The number of the active and empty sites for adsorption increased when the adsorption dosage increased in the dye solution [34,35]. A decrease in dye removal capacity beyond optimal dosages could be attributed to the overlapping of the adsorption sites as a result of overcrowding adsorbent particles [36,37].

Effect of Initial Concentration

The influence of initial concentration (10-130 mg/L) was investigated and results are presented in Figure 8.

The sorption of CR dyes increased to maximum of 28.87 ± 0.07 mg/g at an optimal concentration of 50 mg/L followed by a steady state. The trend can be explained by the fact that at low concentration values, there are available adsorbent sites on the adsorbent surface with less available dye molecules in the solution [38]. Increasing the dye concentration with unchanging amount of adsorbent sites led to increase in their removal capacity to optimal concentration [39]. The decrease in dye removal at concentration values beyond optimal is due to the saturation of active sites at high dye concentration conditions leaving more unadsorbed in the solution [40,41].

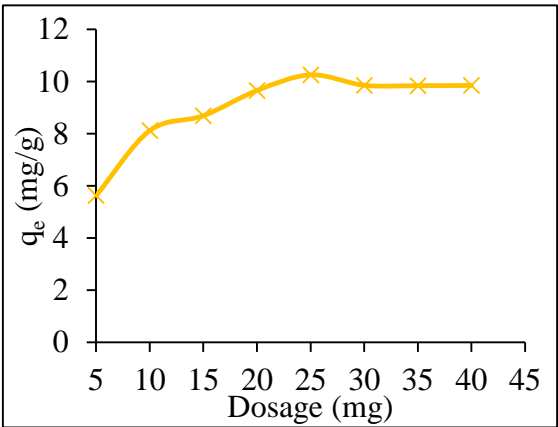


Figure 7 Effect of adsorbent dose on adsorption of CR on Si₃N₄ adsorbent

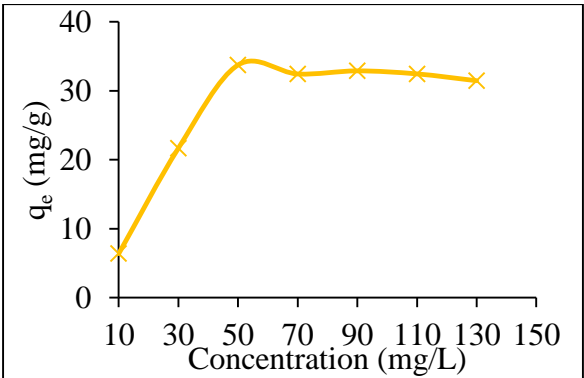


Figure 8 Effect of initial concentration on adsorption of CR on Si₃N₄ adsorbent

Eurasian Journal of
Science and Technology

Eurasian Journal of
Science and Technology

Adsorption Isotherm Studies

The Langmuir, Freundlich, and Dubinin-Radushkevich parameters are indicated in Table 1.

The results show that Langmuir gave better regression coefficient ($R^2 > 0.95$) than those of

Freundlich and Dubinin-Radushkevich. This suggested a monolayer interaction between the dye molecules and the adsorbent sites which are chemisorption in nature [18]. The comparison of adsorption capacity of Si_3N_4 adsorbent with previously reported adsorbents is presented in Table 2.

Table 1 Langmuir, Freundlich, and Dubinin-Radushkevich parameters for CR dyes adsorption onto Si_3N_4 adsorbent

Langmuir				Freundlich			Dubinin-Radushkevich			
Q_m , exp mg/g	Q_m , cal mg/g	K_L (L/g)	R^2	$1/n$	K_F mg/g	R^2	Q_m , cal mg/g	K_{D-R} (mol ² /kJ ²)	E kJ/mol	R^2
28.87	33.90	9.42×10^{-2}	0.954	4.32×10^{-1}	5.83	0.595	57.22	4.56×10^{-2}	3.31	0.865

Table 2 Adsorption capacity of different adsorbents for the adsorption of CR dyes

Adsorbent	Adsorption capacity (mg/g)	Ref.
Banana peel	1.73	[19]
Jujube seeds (Activated carbon)	19.73	[42]
Commercial zeolite catalyst	21.11	[43]
Pine bark	1.60	[8]
Silica gel (amino-functionalized)	5.37	[20]
Silicon nitride (Si_3N_4)	28.87	This study

Conclusion

In this study, the silicon nitride (Si_3N_4) adsorbent was successfully synthesized and this was confirmed by SEM micrographs. The interactions between CR dyes and the adsorbent surface were also confirmed by the micrographs. The adsorption process was greatly influenced by batch study parameters of pH, agitation time, adsorbent dosage, and initial concentration. The optimum values were pH=1.00, 50 minutes, 25 mg and 50 mg/L. The CR dyes adsorption onto Si_3N_4 adsorbent followed Langmuir isotherm model explaining that the CR dye removal was chemisorption.

Acknowledgements

The authors are grateful to technical staff of Kenyatta University (KU) and Dedan Kimathi University of Technology (DeKUT) from Chemistry laboratories for their assistance during data collection. Furthermore, to my

colleagues, family, and friends for their constant support, wise counsel and critiques.

References

[1] López-Cervantes J., Sánchez-Machado D.I., Sánchez-Duarte R.G., Correa-Murrieta M.A., Study of a fixed-bed column in the adsorption of an azo dye from an aqueous medium using a chitosan–glutaraldehyde biosorbent, *Adsorption Science & Technology*, 2018, **36**:215. [Crossref], [Google Scholar], [Publisher]
[2] Goutam S.P., Saxena G., Roy D., Yadav A.K. Bharagava R.N., Green synthesis of nanoparticles and their applications in water and wastewater treatment, *Bioremediation of Industrial Waste for Environmental Safety: Volume 1: Industrial Waste and Its Management*, 2020, 349. [Crossref], [Google Scholar], [Publisher]

- [3] Ndung'u S.N., Wanjau R.N., Nthiga E.W., Fixed Bed Column Adsorption Studies of selected Phenols and Dyes using Low-cost adsorbents, A mini Review, 2022 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [4] Boateng G.O., Collins S.M., Mbullo P., Wekesa P., Onono M., Neilands T.B., Young S.L., A novel household water insecurity scale: Procedures and psychometric analysis among postpartum women in western Kenya, *PLoS one*, 2018, **13**:198591 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [5] Gurung A., Adhikari S., Chauhan R., Thakuri S., Nakarmi S., Ghale S., Dongol B.S., Rijal D., Water crises in a water-rich country: case studies from rural watersheds of Nepal's mid-hills, *Water Policy*, 2019, **21**:826 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [6] Hoseini Dastgerdi Z., Meshkat S.S., Jalili H., Investigation of an Adsorptive Indigo Carmine Dye Removal via Packed Bed Column: Experiments and Computational Fluid Dynamics Simulation, *AUT Journal of Mechanical Engineering*, 2020, **4**:315 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [7] Mani S., Chowdhary P., Bharagava R.N., Textile wastewater dyes: toxicity profile and treatment approaches, *emerging and eco-friendly approaches for waste management*, 2019, 219 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [8] Litefti K., Freire M.S., Stitou M., González-Álvarez J., Adsorption of an anionic dye (Congo red) from aqueous solutions by pine bark, *Scientific Reports*, 2019, **9**:16530 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [9] Gadekar M.R., Ahammed M.M., Coagulation/flocculation process for dye removal using water treatment residuals: modelling through artificial neural networks, *Desalination and Water Treatment*, 2016, **57**:26392 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [10] Kloster M., de Almeida A.A., Muraca D., Marcovich N.E., Mosiewicki M.A., Chitosan-based Magnetic Particles as Adsorbents for Anionic Contaminants, *Engineered Science*, 2023, **22**:851 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [11] Ali H.Q., Mohammed A.A., Removal of Congo Red from Aqueous Solution by Circulating Fluidized Bed (CFB), *Association of Arab Universities Journal of Engineering Sciences*, 2021, **28**:1 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [12] Jain S.N., Tamboli S.R., Sutar D.S., Jadhav S.R., Marathe J.V., Shaikh A.A., Prajapati A.A., Batch and continuous studies for adsorption of anionic dye onto waste tea residue: kinetic, equilibrium, breakthrough and reusability studies, *Journal of Cleaner Production*, 2020, **252**:119778 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [13] Dovi E., Aryee A.A., Kani A.N., Mpatani F.M., Li J., Li Z., Qu L., Han R., Functionalization of walnut shell by grafting amine groups to enhance the adsorption of Congo red from water in batch and fixed-bed column modes, *Journal of Environmental Chemical Engineering*, 2021, **9**:106301 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [14] Zhang Z., Li Y., Du Q., Li Q., Adsorption of Congo red from aqueous solutions by porous soybean curd xerogels, *Polish Journal of Chemical Technology*, 2018, **20**:95 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [15] Mittal H., Kumar A., Khanuja M., In-situ oxidative polymerization of aniline on hydrothermally synthesized MoSe₂ for enhanced photocatalytic degradation of organic dyes, *Journal of Saudi Chemical Society*, 2019, **23**:836 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [16] Nandi B., Patel S., Effects of operational parameters on the removal of brilliant green dye from aqueous solutions by

electrocoagulation, *Arabian Journal of Chemistry*, 2013, **10**:2961. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[17] Kumar P., Joshiba G., Femina C., Varshini P., Priyadharshini S., Karthick M., Jothirani R., A critical review on recent developments in the low-cost adsorption of dyes from wastewater, *Desalination and Water Treatment*, 2019, **172**:395 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[18] Rosanti A., Kusumawati Y., Hidayat F., Fadlan A., Wardani A., Anggraeni H., Adsorption of methylene blue and methyl orange from aqueous solution using orange peel and CTAB-modified orange peel, *Journal of the Turkish Chemical Society*, 2022, **9**:237 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[19] Mondal N., Kar S., Potentiality of banana peel for removal of congo red dye from aqueous solution: Isotherm, kinetics and thermodynamics studies, *Applied Water Science*, 2018, **8**:157 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[20] Farias R., Buarque H., Cruz M., Cardoso L., Gondim T., Paulo, V., Adsorption of congo red dye from aqueous solution onto amino-functionalized silica gel, *Sanitary Engineering Journal*, 2018, **23**:1053 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[21] Adamu A., Mbuvi H., Evans O., Removal of fluoride ion by silicon nitride powder, *International Journal of Water and Wastewater Treatment*, 2017, **3**:1 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[22] Sharma G., Bhogal S., Kumar A., Naushad M., Sharma S., Ahamad T., Stadler F., AgO/MgO/FeO@Si₃N₄ nanocomposite with robust adsorption capacity for tetracycline antibiotic removal from aqueous system, *Advanced Powder Technology*, 2020, **31**:4310 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[23] Shi C., Zhu Y., Qian H., Lu L., Fabrication of silicon nitride fiber-PMMA composite through free radical polymerization in batch, *Materials*

Research Bulletin, 2014, **51**:161 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[24] Hackley V., Malghan S., The surface chemistry of silicon nitride powder in the presence of dissolved ions, *Journal of Materials Science*, 1994, **29**:4420 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[25] Ndung'u S., Nthiga E., Wanjau, R., Characterization of amorphous silicon nitride prepared from sand and coffee husk wastes by carbothermal reduction-nitridation. *African Journal of Pure and Applied Sciences*, 2023, **4**:24 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]65735336

[26] Njeri J., Nthiga E., Muthakia G., The efficacy of coffee husks biochar in the adsorption of methyl red from textile dyeing wastewater, *International Journal of Scientific Research in Chemical Sciences*, 2023, **10**:1 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[27] Ndung'u S.N., Wanjau R.N., Nthiga E.W., Ndiritu, J., Mbugua, G.W., Complexation equilibrium studies of Cu²⁺, Cd²⁺ and Pb²⁺ ions onto ethylenediamine quaternised Artocarpus heterophyllus L, seeds from aqueous solution. *IOSR Journal of Applied Chemistry*, 2020, **13**:1 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[28] Saadi R., Saadi Z., Fazaali R., Fard N. E., Monolayer and multilayer adsorption isotherm models for sorption from aqueous media, *Korean Journal of Chemical Engineering*, 2015, **32**:787 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[29] Elwakeel K., Elgarahy A., Elshoubaky G., Mohammad, S., Microwave assist sorption of crystal violet and congo red dyes onto amphoteric sorbent based on upcycled Sepia shells, *Journal of Environmental Health Science and Engineering*, 2020, **18**:35 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

[30] Ji H., Huang Z., Chen K., Li W., Gao Y., Fang M., Liu Y., Wu X., Synthesis of Si₃N₄ powder with tunable α/β -Si₃N₄ content from waste silica

fume using carbothermal reduction nitridation, *Powder Technology*, 2014, **252**:51 [Crossref], [Google Scholar], [Publisher] [31] Mahmut S., Mustafa G., Ali Ç., Gülsüm T., Silicon nitride ceramic for all-ceramic dental restorations, *Dental Materials Journal*, 2020, **39**:1080 [Crossref], [Google Scholar], [Publisher] [32] Song J., Wang Y., Qiu J., High adsorption performance of methyl blue from aqueous solution using hyper-branched polyethyleneimine grafted MWCNTs as an adsorbent, *ES Materials & Manufacturing*, 2018, **3**:29 [Crossref], [Google Scholar], [Publisher] [33] Maia L., Da Silva A., Carneiro E., Monticelli F., Pinhati F., Mulinari D., Activated carbon from palm fibres used as an adsorbent for methylene blue removal, *Journal of Polymers and the Environment*, 2021, **29**:1162 [Crossref], [Google Scholar], [Publisher] [34] Tuli F.J., Hossain A., Fazle Kibria A., Tareq A., Mamun S., Atique Ullah A., Removal of methylene blue from water by low-cost activated carbon prepared from tea waste: A study of adsorption isotherm and kinetics, *Environmental Nanotechnology, Monitoring & Management*, 2020, **14**:1 [Crossref], [Google Scholar], [Publisher] [35] Unugul T., Nigiz F.U., Preparation and characterization an active carbon adsorbent from waste mandarin peel and determination of adsorption behavior on removal of synthetic dye solutions, *Water, Air, & Soil Pollution*, 2020, **231**:538 [Crossref], [Google Scholar], [Publisher] [36] Qu W., He D., Huang H., Guo Y., Tang Y., Song R. Characterization of amino-crosslinked hypromellose and its adsorption characteristics for methyl orange from water, *Journal of Materials Science*, 2020, **55**:7268 [Crossref], [Google Scholar], [Publisher] [37] Jiang R., Zhu H.Y., Fu Y.Q., Zong E.M., Jiang S.T., Li J.B., Zhu J.Q., Zhu Y.Y., Magnetic NiFe₂O₄/MWCNTs functionalized cellulose bioadsorbent with enhanced adsorption

property and rapid separation, *Carbohydrate Polymers*, 2021, **252**:1. [Crossref], [Google Scholar], [Publisher] [38] Youcef L., Belaroui L., López-Galindo A., Adsorption of a cationic methylene blue dye on an Algerian palygorskite, *Applied Clay Science*, 2019, **179**:1 [Crossref], [Google Scholar], [Publisher] [39] Khan A., Naeem A., Mahmood T., Ahmad B., Ahmad Z., Farooq M., Saeed T. Mechanistic study on methyl orange and congo red adsorption onto polyvinyl pyrrolidone modified magnesium oxide, *International Journal of Environmental Science and Technology*, 2022, **19**:2515 [Crossref], [Google Scholar], [Publisher] [40] Rondina D., Ymbong D.V., Cadutdut M., Nalasa J., Paradero J., Mabayo V., Arazo, R., Utilization of a novel activated carbon adsorbent from press mud of sugarcane industry for the optimized removal of methyl orange dye in aqueous solution, *Applied Water Science*, 2019, **9**:181 [Crossref], [Google Scholar], [Publisher] [41] Radoor S., Karayil J., Parameswaranpillai J., Siengchin, S., Removal of anionic dye congo red from aqueous environment using polyvinyl alcohol/sodium alginate/ZSM-5 zeolite membrane, *Scientific Reports*, 2020, **10**:1 [Crossref], [Google Scholar], [Publisher] [42] Aminu I., Gumel S.M., Ahmad W.A., Idris, A.A., Adsorption isotherms and kinetic studies of congo-red removal from waste water using activated carbon prepared from jujube seed, *American Journal of Analytical Chemistry*, 2020, **11**:47 [Crossref], [Google Scholar], [Publisher] [43] Khalaf I., Al-Sudani, F., AbdulRazak A., Aldahri T., Rohani S., Optimization of Congo red dye adsorption from wastewater by a modified commercial zeolite catalyst using response surface modeling approach, *Water Science & Technology*, 2021, **83**:1369 [Crossref], [Google Scholar], [Publisher]