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Synthesis, characterization of novel protein-modified rice husk biochar and their applications for highly adsorptive removal azo dye in water

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Abstract

This study investigates the removal of anionic dye New Coccine (NCC) using a new bio-based adsorbent protein lysozyme-modified rice husk biochar (Lys-RHB). Rice husk biochar (RHB) which was synthesized through a simple pyrolysis process, was characterized structurally and chemically using XRD, FT-IR, SEM, EDX, BET and ζ potential. The RHB was modified with lysozyme at pH 11 to increase the positive surface charge, enhancing electrostatic attraction to negatively charged pollutants. The major breakthrough of our study is optimization of conditions for the removal of NCC were obtained at pH 3, contact time 120 min and adsorbent dosage of 1.5 mg/mL; achieving the maximum adsorption capacity of 32.15 mg/g and the highest NCC removal efficiency of 97.3%. Our findings reveal that the adsorption mechanisms of lysozyme on RHB and NCC on Lys-RHB were dominated by electrostatic forces, facilitating strong interactions between oppositely charged molecules. The adsorption of NCC on Lys-RHB was most accurately fitted by Freundlich isotherm, while the adsorption kinetics corresponded to the feature of pseudo-second-order model. Significantly, the Lys-RHB demonstrates as highly effective in removal of dyes, highlighting its potential as a sustainable and eco-friendly solution for wastewater treatment applications. These results present groundbreaking advancements in environmental science by providing an economical and effective method for dye pollution. Moreover, this study paves the way for future research on utilizing biochar for various environmental purposes.

Keywords:

Rice husk biochar, Protein, Adsorption, NCC, Water treatment

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1. Introduction

Bio-based materials have attracted great attention in recent years because of their adaptability and environmentally friendly nature and their potential applications in replacing traditional synthetic materials in many industrial applications (Vigneshwaran et al., 2021). Among those materials, biochar which is a carbon-rich resource fabricated from the pyrolysis of organic waste, is a potent material with a wide range of uses, from remediation of soils (Guo, 2020; Kabir et al., 2023) to use as an active agent in catalysis (Wang et al., 2020) as well as utilization as an effective adsorbent. Derived from agricultural waste such as rice husk, aquatic grasses, bamboo, or sewage sludge, biochar not only provides efficient utilization of waste but also possesses unique physico-chemical properties that make various advantages and applications, especially in environmental remediation (Li et al., 2023). Biochar fabricated from rice husk has great prospects for removing various contaminants from the water environment. Rice husk is abundant in rice-growing areas and offer a high silica and carbon contents (Dinh et al., 2022), making them an especially attractive and cost-effective feedstock for biochar production. Additionally, transforming rice husk into biochar plays a vital role in advancing the circular economy by converting agricultural waste into valuable, reusable resources. Rice husk-derived biochar (RHB) has many novelties such as high specific surface area, porous structure and diverse functional groups, that contribute to its superior adsorption capacity (Aziz et al., 2023; Herrera et al., 2022).

Since many organic pollutants in water are hydrophilic with different charged properties while the RHB has low charge density. Therefore, surface modification of RHB is needed to enhance the charging behaviour and adsorption capacity. Some modification techniques have been studies such as acid-base treatment (Jaber et al., 2024; Sharma et al., 2022), metal impregnation (Jaber et al., 2024), or using active chemicals but these method are the high-cost, limiting their application in sustainable wastewater treatment (Díaz et al., 2024; Younas et al., 2021). Recently, amino acids or proteins were effectively used to modify nanomaterial surfaces and apply to removal of different pharmaceutical products (Pham et al., 2024; Vu et al., 2022; Vu et al., 2023). Nevertheless, coating protein Lysozyme on RHB surface to modify the surface charge and enhance adsorption of organic dyes have not been investigated. Recently, many studies have used biochar, both before and after surface modification as a high adsorbent for for various pollutants. KOH-modified biochar was applied to remove methylene blue and congo red in wastewater, with the maximum adsorption capacity up to 1112.35 mg/g and 3472.22 mg/g, respectively (Zhang et al., 2024). Morover, Fe-modified biochar pose a great potential in the adsorption of azithromycin and ciprofloxacin, which removal efficiency reach 88% and 90% (Aziz et al., 2024). On the other hand, biochar establishes its position as a novel adsorbent with effective application for heavy metals and inorganic salt removal in wastewater (Gizaw et al., 2021; Veni et al., 2017; Yi et al., 2022; Yılmaz & Güzel, 2022).

New Coccine (NCC) is a widely used anionic azo dye in the food, textile, and cosmetic industries but this dye is an emerging organic pollutants due to very low self-degradation and toxic to human (Wang et al., 1998). Different techniques were developed to remove azo dye including NCC (Dutta et al., 2021) in which adsorption is eco-friendly technique for dye and pollutants removal by using different adsorbents including biochar (Dąbrowski, 2001; Doan et al., 2021; Yılmaz et al., 2021). Many scientific researches indicated the high performance and effectiveness of biochar in eliminating synthetic dyes (Dwivedi & Dey, 2023), antibiotics (Pham et al., 2023) or pesticides (Mojiri et al., 2020). However, few studies have been investigated on protein-modified biochar and their applications in removal of organic dye. With the enhancement of surface charge density, RHB with Lysozyme modification shows a promising adsorbent for ionic dye removal.

In this work, for the first time, we fabricate RHB with surface modification by Lysozyme adsorption to investigate the adsorptive removal of NCC in water. To assess the effectiveness of the NCC removal under various circumstances, including changing pH, dye concentrations, and contact time, we carried out the tests including protein modification and dye adsorption. Adsorption isotherms and adsorption kinetics were used to model the adsorption behaviour and determine the underlying mechanisms involved in the removal process.

2. Mateials and methods

2.1. Materials

New Coccine (NCC), an anionic azo dye (purity>85%), was sourced from TCI (Japan) and used as a polluted adsorbate in adsorption experiments. Lysozyme, a protein derived from egg whites, was provided by Sigma, while biochar was produced from rice husk collected in Bac Ninh, Vietnam. Other high purity chemicals were purchased from Merck while Millipore water was used to prepare all solutions.

2.2. Synthesis and characterization of rice husk-biochar

First, rice husk was washed by ionized water and dried at 105^{o}C. To achieve sample homogeneity, the powder was sieved with a size of less than 500 µm. After that, approximately 1.0 gam sample was put on a ceramic boat in an electric furnace under N_2 gas at 500^{o}C for 2h. After heating, temperature was cooled down at room temperature.

The structure of adsorbent was determined by X-ray Diffraction (Bruker D8 Advance Diffractometer). The surface morphology and size distribution were measured by scanning electron microscopy (SEM, Hitachi). The FTIR spectra was conducted by Affinity-1S spectrophotometer (Shimadzu, Japan) from 400 to 4000 cm^{-1} with a resolution of 4 cm^{-1}. Total specific surface area and average pore size using N_2 adsorption and desorption following by BET theory were carried out by BELsorp miniII, MicrotracBEL, Japan.

2.3. Adsorption studies

The RHB surface was modified by pre-adsorption of Lysozyme in 120 min under different pHs and ionic strengths. Then, the Lysozyme was separated using centrifugation. Finally, the concentration of remaining Lysozyme was measured by using UV-Vis spectroscopy.

After being modified with Lysozyme under ideal conditions, RHB nanoparticles were used to remove NCC. Different parameters affecting to NCC removal were tested to find the optimal conditions for NCC adsorption by Lys-RHB. After shaking, the solution was separated from the sample by centrifugation. The remaining NCC concentration in the sample was determined by UV-Vis technique (UV-1650PC, Shimadzu, Japan) at 506 nm wavelength.

The removal of NCC was calculated according to Equation (1).

$$\%Removal = \frac{C_i - C_e}{C_i} \times 100\% \quad (1)$$

By using Equation (2), the adsorption capacity Γ(mg/g) of Lysozyme on RHB and NCC on Lys-RHB can be calculated.

$$\Gamma = \frac{C_i - C_e}{m} \times 1000 \quad (2)$$

where Ci (g/L) and Ce (g/L) are the initial and equilibrium concentrations; m (mg/mL) is the adsorbent dosage.

The isothermal adsorption was investigated under optimal conditions with different initial concentrations of Lysozyme and NCC, ranging from 5 to 1400 mg/L. The adsorption isotherms for Lysozyme on RHB and NCC on Lys-RHB were fitted by Langmuir and Freundlich models. The Langmuir model, which assumes monolayer adsorption, is represented by Langmuir's equation (3) (Langmuir, 1916). The adsorption isotherms which assumes multilayer was fitted by the Freundlich's equation (F., 1906).

For the adsorption kinetics, pseudo-first and pseudo-second-orders models were employed to assess the pathways and mechanisms of NCC adsorption at 20 and 200 mg/L.

The pseudo-first and pseudo-second-orders were used to analyze the adsorption kinetics of NCC Lys-RHB (Zuorro et al., 2017):

3. Results and discussion

3.1. Charaterization of synthesized rice husk biochar (RHB)

The synthesized biochar fabricated from rice husk was characterized by XRD, FT-IR, SEM, EDX and BET methods.

A large broading peak at 2θ with degrees of 20-22° and a small peak at 43° at the XRD pattern (Figure 1A) indicate the presence of amorphous carbon in RHB prepared from organic compounds by pyrolysis technique to (002) and (001) of turbostractic structure (Wu et al., 2017). The FTIR spectrum in Figure 1B shows the functional group is -OH hydroxyl group, appearing from 3000 to 3600 cm^{-1}. The second functional group is C=O, which appeared at the peak of 1604 cm^{-1}, resulting from the decomposition of organic compounds during the pyrolysis of rice husk. The third functional assigned for the C-OH bending at 1106 cm^{-1} (Keiluweit et al., 2010). The band at 799 and 466 cm^{-1} corresponded to symmetric vibration of the Si-O bonding in the silicon-oxygen tetrahedron (SiO_4) and Si-O-Si bending vibrations, which belongs to the cristobalite type, a structural form of silica (de Cordoba et al., 2019; Uzunov et al., 2012).

The SEM image in Figure 1C indicates that RHB has porous and honeycomb-like structure which has many cylindrical hollows connected together by large pores forming the fractured surface. The RHB size was found around 50 μm. Based on result of EDX in Figure 1D, the elemental C, O and Si with the weight percentages of 46.2, 32.1 and 21.7 %, respectively were calculated.

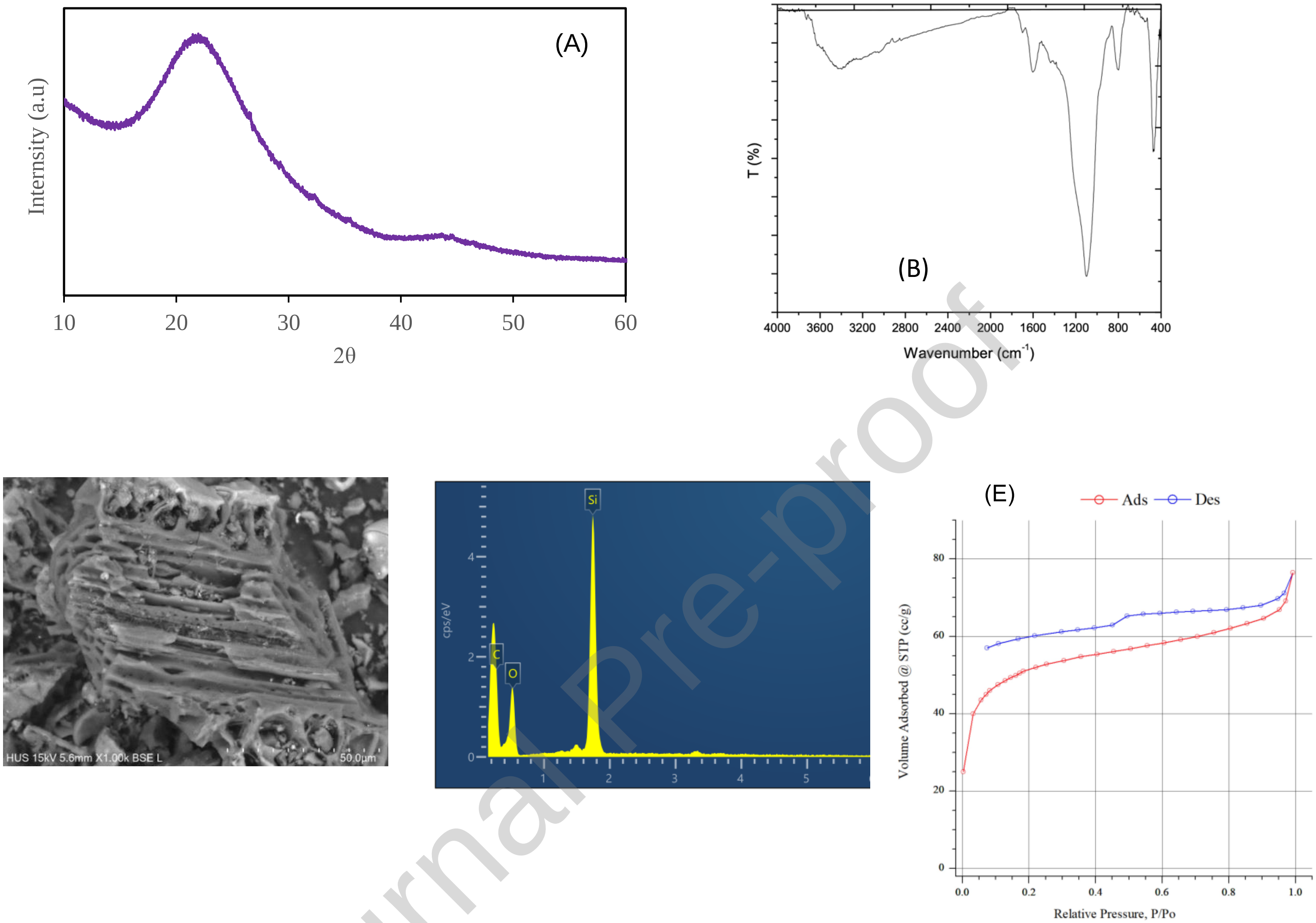


Figure 1. Characterization of synthesized rice husk biochar by different physicochemical techniques: XRD (A), FT-IR (B), SEM (C), EDX (D), N_2 adsorption-desorption (E).

Based on the N_2 adsorption-desorption isotherms at 77K (Figure 1E), the specific surface area and pore size were obtained. The N_2 adsorption isotherm exhibited low pressure hysteresis of IUPAC type I, related to the ultra-micropore structure present in RHB. BET results confirmed the porous structure of biochar. The specific surface area was measured to be 189.22 m^2/g while the pore size and pore volume were calculated using the method BJH (Barrett et al., 1951) were about 2.5 nm and 0.1183 cm^3/g, respectively.

Based on the results of XRD, FT-IR, SEM, EDX, BET, we confirm that RHB was successfully fabricated by a simple and green pyrolysis procedure without any chemicals.

3.2. Modification of RHB by adsorption of protein Lysozyme

The solution pH is one of the key factors influencing the adsorption of proteins onto RHB because pH affects to RHB surface charge. Figure 2 illustrates that the adsorption capacity of Lysozyme gradually increases as the pH increases. The surface charge of RHB becomes more negative when pH rises from 4 to 11 (Sadegh-Zadeh & Seh-Bardan, 2013; Samsuri et al., 2014) while Lysozyme is always positive at pH <12. This occurs because surface functional groups on biochar, such as hydroxyl (-OH) and carboxyl (-COOH), become deprotonated at high pH, making the biochar surface more negatively charged (Samsuri et al., 2014). According to the results, Lysozyme adsorption reached its highest capacity at pH 11 thus pH 11 was selected as the modification condition.

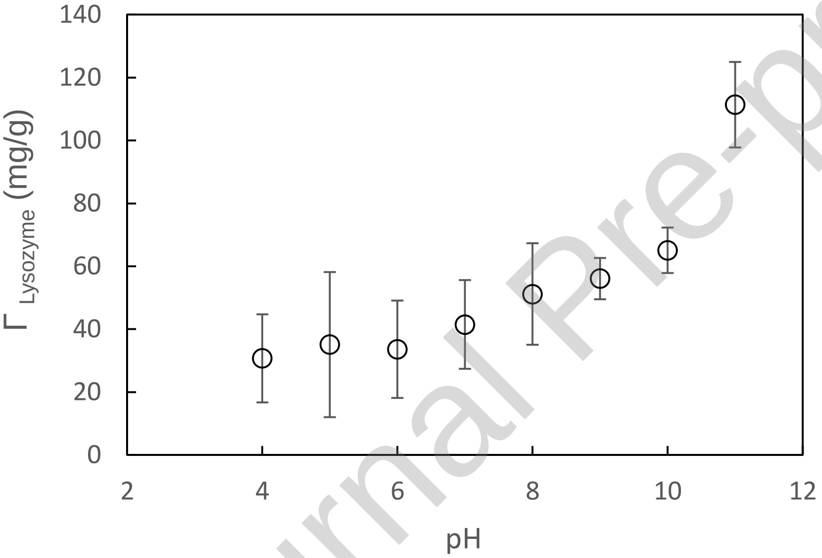


Figure 2. Adsorption capacity of Lysozyme of RHB as a function of solution pH.

The adsorption isotherms at different ionic strengths can be used to evalaute effect of electrostatic interaction (Guzmán et al., 2009). Table 1 shows that at all three KCl concentrations, the $R^2_{\text{F, Lys}}$ of the Freundlich model is higher than that of the Langmuir model ($R^2_{\text{L, Lys}}$), suggesting that heterogeneous and multilayer adsorption mechanisms dominate the adsorption of lysozyme on RHB. The relatively high n_F value decreased from 2.638 at 1 mM to 1.899 at 10 mM and 2.382 at 100 mM, indicating that lysozyme adsorption is more favorable at low KCl concentrations.

Figure S2 shows that adsorption capacity of lysozyme on RHB depends on the ionic strength. As the ionic strength increases, the protein adsorption capacity decreases sharply that is close to the Lysozyme adsorption on nanosilica at pH 10 (Vu et al., 2023). As the ionic strength increases, the number of countercations increases around the positive Lysozyme molecular and negative RHB surface. As the electrostatic force decreases, other interactions such as Van der Waals forces and hydrogen bonding may increase, leading to an overall increase in adsorption (Mészáros et al., 2002). This indicates that while electrostatic forces play an important role, non-electrostatic interactions also contribute to the adsorption mechanism.

Table 1. Parameters of Lysozyme adsorption isotherms on RHB at different KCl concentrations by Langmuir and Freundlich models.

Model	**Parameters**	**KCl concentration (mmol/L)**		
		1	10	100
Langmuir	$\Gamma_{\text{max, Lys}}$ (mg/g)	99.00	52.08	75.75
	$K_{\text{L, Lys}}$ (L/g)	0.0093	0.0039	0.0021
	$R^2_{\text{L, Lys}}$	0.9738	0.8716	0.7870
Freundlich	$K_{\text{F, Lys}}$	6.824	1.333	2.203
	$n_{\text{F,Lys}}$	2.638	1.899	2.382
	$R^2_{\text{F, Lys}}$	0.9886	0.9882	0.9483

3.3. Adsorptive removal of NCC using RHB and Lys-RHB

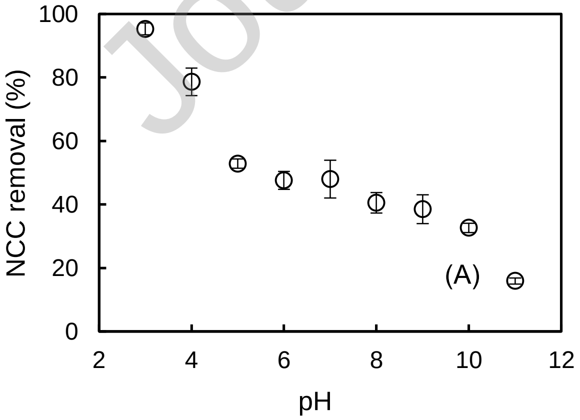
The adsorptive removal of NCC using RHB and Lys-RHB was compared to evaluate the importance of protein presence.

Figure S3 shows that the NCC removal efficiency using raw RHB is markedly low across the pH range of 3-11 due to the negligible interaction between anionic NCC and negatively charged RHB surface, resulting from the strong electrical repulsion force. At the optimal pH, the NCC removal efficiency increased from 10.5 to 97.3% by the modification of biochar with Lysozyme. Since the raw RHB charged surfaces are negative (Liu et al., 2012), the immobilization of protein Lysozyme with positive charge change the surface charge properties of the raw RHB, which could facilitate the removal of negatively charged contaminant such as NCC. In other word, RHB needs a modification with Lysozyme for NCC removal enhancement. Some important parameters influence to NCC removal using Lysozyme- modified RHB (Lys-RHB) are discussed in details bellows.

This study examined the NCC removal in the pH range from 3 to 11. Figure 3A shows that the removal of NCC decreased from 97.3% to 15.9% with increasing pH from 3 to 11. At low pH (pH 3), the surface of the modified biochar is positively charged due to the protonation of functional groups such as the amino group (–NH_2) on lysozyme while NCC is an anionic dye, thus the Coulombic force between the negative NCC ions and positive Lys-RHB surface is enhanced. Due to this strong attraction, the removal reached 97.3% at pH 3. As the pH increases, the solution becomes less acidic resulting in reducing the protonation degree of the functional groups on the modified biochar, and making the Lys-RHB surface less positively charged (Russell, 2017), leading to a weakening of the electrostatic attraction between NCC and the Lys-RHB surface. Therefore, the removal gradually decreased to about 60% when the pH increases to 6. In alkaline environment, the removal decreased sharply due to the desorption of Lysozyme and competition between the OH^- group and NCC. Therefore, the optimal pH 3 for NCC adsorption was fixed for further studies.

Figure 3B indicates that the NCC removal was further enhanced with increasing Lys-RHB dosage from 0.25 to 1.5 mg/mL due to the increased overall charge density. However, when the dosage was above 1.5 mg/mL, the removal efficiency of the NCC was slightly reduced because of the coagulation of Lys-RHB leading to adsorption site saturation. Thus, 1.5 mg/mL Lys-RHB was kept as optimum dosage for NCC removal.

The results shown in Figure 3C indicate that NCC removal gradually improved when contact time increased from 0 to 120 min. Nevertheless, after 120 min, the adsorptive removal of NCC using Lys-RHB changed insignificantly because the adsorption process reached equilibrium. Thus, the contact time at 120 min was kept for subsequent experiment.



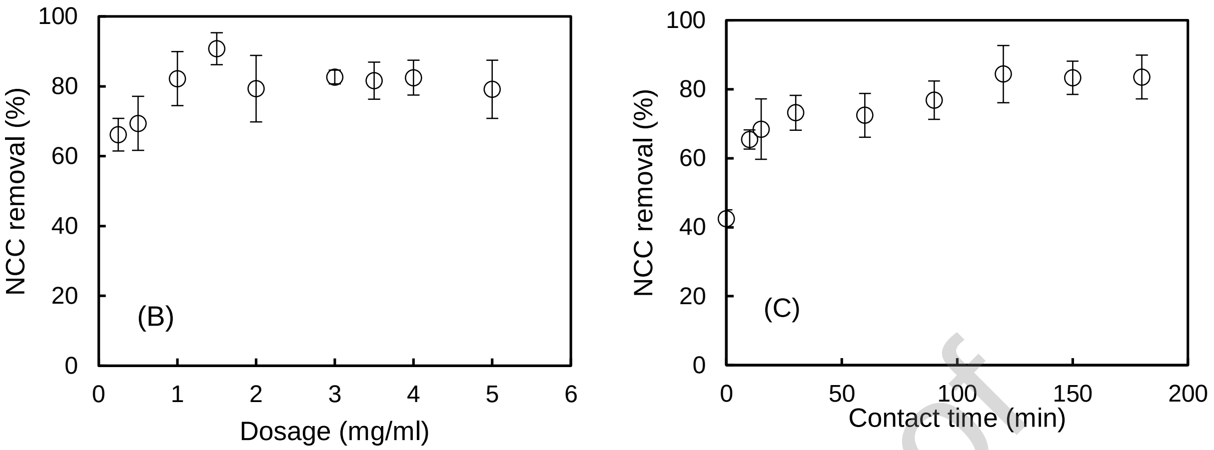


Figure 3. Effect of pH (A), adsorbent dosage (B) and contact time (C) on NCC removal using lysozyme modified RHB (C_i, NCC= 20 mg/L).

3.4.Adsorption isotherms and kinetics of NCC on Lys-RHB

Adsorption isotherms of NCC on Lys-RHB with NCC concentrations in the range 5-1000 mg/L at three ionic strengths under above optimum conditions were investigated.

Table 2: The fit parameters for NCC adsorption on Lys-RHB at different ionic strengths

Model	**Parameter**	**KCl concentration (mmol/L)**		
		1	10	100
Langmuir	$\Gamma_{\text{max, NCC}}$ (mg/g)	16.26	19.34	32.15
	$K_{L,NCC}$ (L/g)	0.026	0.019	0.009
	$R_{L,NCC}^2$	0.9464	0.9381	0.8628
Freundlich	$K_{F,\ NCC}$	5.563	6.544	2.874
	n_{NCC}	0.715	7.027	3.018
	$R_{F,NCC}^{\ 2}$	0.9622	0.9317	0.9443

Table 2 indicates that the adsorption capability of NCC using Lys-RHB increase following the growth of KCl concentration. The plateau adsorption at 100mM is two times higher than that at 1mM. The highest NCC adsorption capacity increased from 16.26 to 32.15 mg/g when ionic strengths increase from 1 to 100 mM. It can be explained that the increase of the ionic strength lead to the reduction of the electrostatic repulsion between charged species on the Lys-RHB surface and NCC molecules, that enhances NCC molecules occur more easily onto Lys-RHB surface by overcoming potential electrostatic barriers. Table 2 also shows that NCC adsorption on Lys-RHB fitted by Frendlich model better than Langmuir model with higher value of $R_{F,NCC}^2$ (>0.9), proving that the adsorption of NCC on Lys-RHB followed a multi-layer process. Our results in this case are similar to that of NCC on nanocrystalline granular ferric hydroxide (GFH) (Hamidi et al., 2022). There are differences between the value of n_{NCC} at thre KCl concentration, the value of n_{NCC} at 1mM less than 1 proves that the adsorption of NCC on to material surface is unfavorable and the interaction between adsorbate and adsorbent is weak. On the contrary, the values of n_{NCC} at two remaining KCl concentrations are more than 1, indicates a favorable NCC adsorption process onto Lys-RHB and the adsorption intensity decreases when the initial NCC concentration increases.

As can be seen in Table S1, the pseudo-second had higher R^2_{NCC} than that of pseudo-fisrt order for NCC adsorption. Our results are similar to kinetic adsorption of NCC on Chitosan 4B, where pseudo-second order matched better than other kinetic models (Islam et al., 2021). In addition, the higher value of $k_{2,K,NCC}$ at 200mg/L NCC initial concentration indicates that the adsorption equilibrium take longer at lower concentration than that at lower concentration, which results from the activation of more adsorption sites at high NCC concentration.

3.5. Adsorption mechanisms of NCC on Lys-RHB

In this study, we employed ζ potential and FT-IR for characterizing Lysozyme adsorption on RHB and NCC on Lys-RHB.

As described in Figure S4, the surface charge of RHB was altered after the protein adsorption, which gave rise to the charge reversal effect. When RHB was modified with lysozyme the surface potential changed from negative (ζ = -27.6 mV) to become positive surface (16.4 mV) resulting in Lys-RHB. The adsorption of lysozyme on RHB resulted in a positively charged bio-adsorbent, as indicated by charge reversal effect in the presence of protein (Yamaguchi & Kobayashi, 2016). The NCC adsorption caused a decrease in the zeta potential values from 16.4 to 6.71 mV after the process. This result is similar trends of the NCC adsorption onto PDADMAC-modified nanosilica (Pham et al., 2021) and also follows the finding of the pH on the removal of NCC.

Figure S4 shows the differences in the active groups RHB after Lysozyme modification. The intensity of the 3200-3600 cm^{-1} band due to the increase of hydrogen bonds between the -OH group of biochar and the -NH_2 or -OH groups of lysozyme protein. This effect may be attributed to the contribution of amine and hydroxyl groups in the structure of lysozyme (Luo et al., 2018) to this absorption spectrum. The peak at 1621 cm^{-1} became more obvious and had increased intensity compared to RHB. This is the characteristic position of the amide I group in the protein, which is related to the C=O stretching vibration of the peptide bond in Lysozyme.

Compared with Lys-RHB, the intensities of -OH at the 3200-3600 cm^{-1} band and -NH at the peak at 1621 cm^{-1}, 1115 cm^{-1} were reduced after NCC adsorption. This reduction is probably due to NCC adsorption on the Lys-RHB surface, which seems to have masked or even replaced over the hydrogen-bonding hydroxyl and amine functions.

The results of XRD patterns and EDX spectra shown in Figure S5 once again confirm the adsorption mechanism of NCC on Lys-RHB. The XRD patterns show that the phase structures with amorphous carbon of the material were unchanged compared to RHB and Lys-RHB. The intensity tends to be slightly less intense at the peak position than RHB, possibly due to the Lysozyme coating and NCC adsorption. The EDX spectra show the new presence of sulphur element in the Lys-RHB sample after NCC adsorption, which reflects the presence of sulfonate groups from NCC. Based on these results, we confirm that the NCC adsorption on Lys-RHB was controlled by both Coulombic and non-Coulombic including hydrophobic, π-π interactions but electrostatic attraction between anionic NCC and positively charged Lys-RHB surface was dominated.

3.6. Effectiveness of Lys-RHB for NCC removal

The new bio-adsorbent Lys-RHB is high performance for NCC removal with high efficiency and reusability. Figure 4 shows that NCC removal efficiencies changed insignificantly and still reached greater than 92 % after 5 reused times, demonstrating that Lys-RHB is a highly reusable and novel adsorbent in NCC removal. Recently, many studies focused on adsorptive removal of NCC using different adsorbents. However, not any study about NCC adsorption using Lys-RHB was published. Table 3 shows the NCC adsorption ability between Lys-RHB and other investigated adsorbents. The Lys-RHB indicated the best NCC adsorption capacity of 32.15 mg/g, confirming again that Lys-RHB is a great bio-adsorbent for NCC removal.

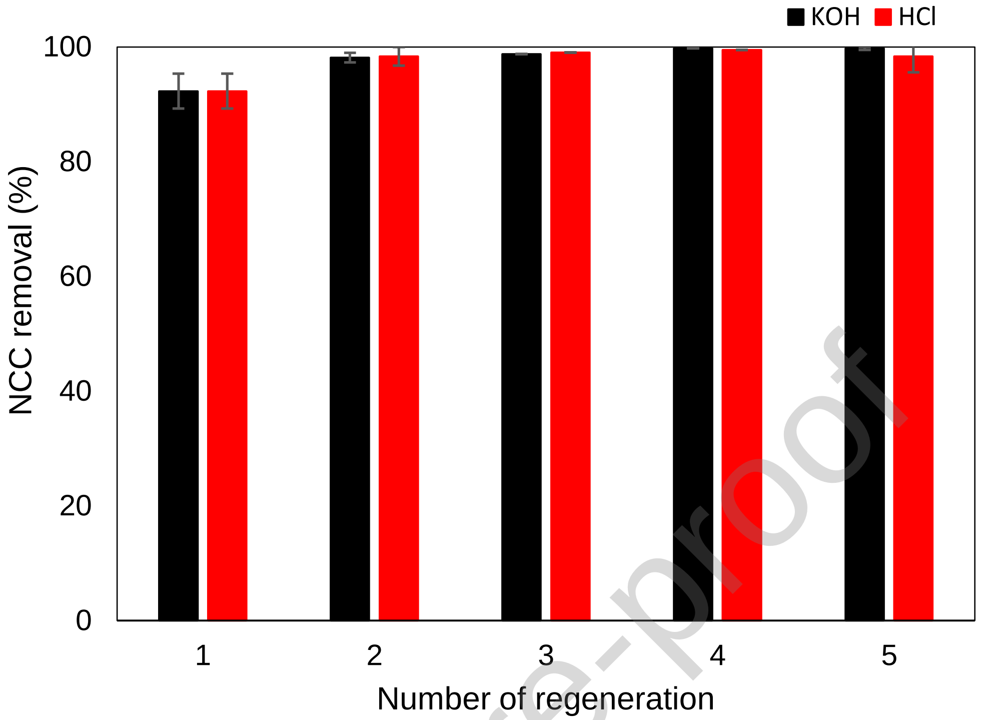


Figure 4. The removal efficiencies of NCC using Lys-RhB after 5 regenerations

Table 3. Adsorption capacities of NCC on Lys-RHB and other adsorbents

Adsorbent	Adsorption capacity (mg/g)	References
Yeast	10.13	(Borysiak & Gabruś, 2020)
Polypyrrole / Chitosan / Graphene oxide	5.400	(Salahuddin et al., 2018)
Cationic surfactant modified Zeolite	15.47	(Kieu et al., 2024)
Granular ferric hydroxide (GFH)	29.13	(Hamidi et al., 2022)
Cordierite honeycomb ceramics treated with oxalic acid (CORA)	7.350	(Yang et al., 2023)
Hexadecyl-trimethyl ammonium chloride modified Nano-pumice (HMNP)	12.84	(Kasraee et al., 2023)
PVBTAC-modified α-Al_2O_3	12.50	(Doan et al., 2022)
Lys-RHB	**32.15**	**This study**

4. Conclusions

We have studied the batch adsorption of NCC on the Lysozyme-modified rice husk biochar (Lys-RHB) surface. Biochar was successfully prepared from rice husk with high carbon amount, containing C=O, -OH functional groups, and large specific surface area of 189.2 m^2/g. Modifying RHB with Lysozyme enhanced the positive surface charge density for the adsorption of negatively charged organic compounds. Optimal conditions for removing NCC were pH 3, 120 min of contact time, and 1.5 mg/mL of adsorbent dosage, which resulted in a maximum adsorption capacity of 32.15 mg/g and a removal efficiency of 97.3%. After 5 regenerations, NCC removal efficiencies remained above 92 %. The adsorption isotherm suggested the multilayer adsorption following the Freundlich isotherm and the kinetic study was consistent with the second-pseudo-order, suggesting a chemical adsorption mechanism. The prevailing adsorption force was electrostatic , with the contribution of hydrogen bonding and lateral interactions. These results highlight that Lys-RHB is an efficient and eco-friendly bio-adsorbent for the elimination of anionic dyes in water.

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Author contributions

Thi Kim Chi Tran: Formal Analysis, Investigation, Data Curation, Writing-Original Draft Preparation; Thi Thuy Trang Truong: Software, Formal Analysis, Investigation, Data Curation, Writing-Original Draft Preparation; An Luong Le: Formal Analysis, Data Curation, Investigation; Duc Anh Minh Do:, Formal Analysis, Data Curation, Investigation; Thu Giang Nguyen: Formal Analysis, Data Curation, Investigation; Thi Duyen Tran: Resources, Validation, Formal Analysis, Investigation; Tien Duc Pham: Conceptualization, Methodology, Investigation, Visualization Writing-Original Draft Preparation, Writing-Review & Editing, Supervision, Project Administration, Funding acquisition. All authors reviewed and approved the manuscript.

Conflicts of Interest

The authors declare no competing financial interests.

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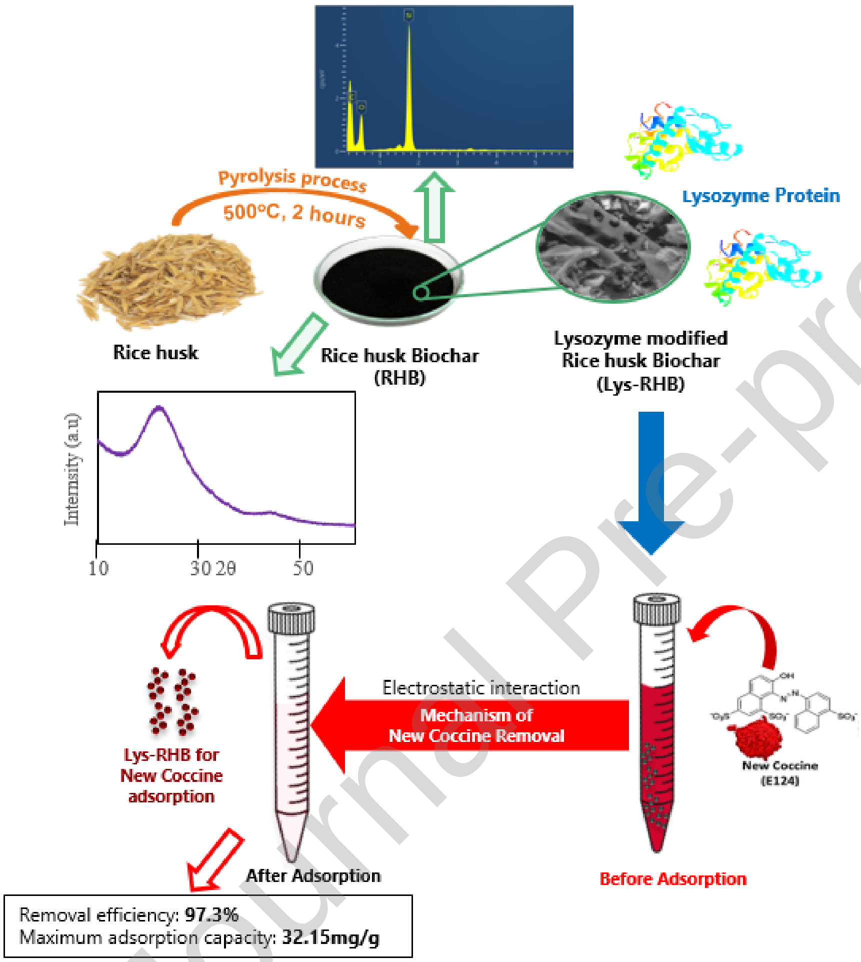
Declaration of Competing Interest

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Graphical abstract



Highlights

- The Lysozyme coating synthesized rice husk biochar was successfully fabricated.
- The Lys-RHB was an excellent adsorbent for removal of anionic azo dye New Coccine.
- Adsorption was fitted well with Freundlich isotherm and pseudo-second kinetic models.
- High removal efficiency of 92% retained after 5 regenerations.