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RESEARCH ARTICLE

Chromium Removal from Contaminated Water Using Thiourea-Modified Biochar and Zinc Nanoparticle-Enhanced Biochar

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ABSTRACT

Chromium (Cr) is a heavy metal that is one of the most dangerous and is a Group A carcinogen as determined by the U.S Environmental Protection Agency (EPA) because it is highly toxic and carcinogenic. Its hexavalent Cr (VI) is much more toxic than trivalent Cr (III) due to its high solubility, mobility and bioavailability. The primary sources of chromium pollution are anthropogenic activities, e.g., steel production, leather tanning, electroplating, and inappropriate disposal of industrial waste. The paper compares the applicability of thiourea-modified biochar and zinc nanoparticle-modified biochar as effective adsorbents in the removal of Cr (VI) in contaminated water. Experiments in batch were aimed to test the impact of pH, contact time, initial concentration and sorbent dosage. The adsorption behaviour was explained by adsorption kinetics and isotherm models (Langmuir, Freundlich, pseudo-first-order, and pseudo-second-order). The surface functionalization of the modified biochar shown to have an increased redox interactions and active-site availability suggested that surface functionalization enhances the sorption capacity of the modified biocarbon. The research suggests a green, inexpensive, and affordable remedial strategy in chromium waters.

Key words: Chromium, biochar, zinc nanoparticle, Langmuir, sorption capacity.

INTRODUCTION

The problem of water pollution is one of the significant issues at the international level because of the rapid industrialization, urbanization, and agricultural intensification that have considerably reduced the quality of freshwater (Almeida et al., 2019). One of the most intractable and poisonous pollutants is heavy metals which accumulate in nature and cause severe ecological and public-health hazards (Arain et al., 2009). Chromium (Cr) is especially dangerous, being one of the most common metals of the crust of the Earth and commonly found in the metallurgical industry, electroplating, leather tanning, and pigment (Shahid et al., 2017). Cr is typically found in two oxidation states in the environment, namely, Cr (III) and Cr (VI), where the latter is extremely toxic because of its solubility and ability to enter the biological membrane (Jin et al., 2016; Yu et al., 2018). Cr (VI) is a Group 1 carcinogen that is classified as such by the International Agency to Research on Cancer (IARC) due to its mutagenicity and carcinogenicity in human and animal cells. Its existence in the aquatic environments disrupts the development of the plant life, damages aquatic animals, and accumulates in food chains, causing chronic exposure risks (Jobby et al., 2018).

Chromium contamination is mostly caused by industrial effluents and especially by electroplating, textile dyeing, and tanning industries that discharge millions of tons of chromium-containing wastewater each year (Protsenko, 2024). Cr(VI) levels in industrial effluents are usually 30 to 200 mg/L, which is hundreds of times the acceptable concentration of 0.05mg/L of Cr(VI) in drinking water recommended by the World Health Organization (WHO) (Zhou et al., 2016). Outside of point sources, runoff of agricultural activities and urban trash also lead to the non-point spread of chromium and make it even harder to clean up (Arnold, 2024). This form of pollution does not only worsen the quality of water but also endangers biodiversity, food security as well as socioeconomic stability of the areas that experience pollution (Radu et al., 2011; Velusamy et al., 2025). Hence the need to come up with effective, cheap, and sustainable remediation techniques has been an area of research interest.

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A broad assortment of technologies such as ion exchange, reverse osmosis, ultrafiltration, precipitation and redox treatments have been considered in terms of chromium removal. Nonetheless, these methods can be costly, energy-consuming and they produce secondary waste, which would need further management. Contrary to this, adsorption has become one of the most useful and cost-effective procedures to remove heavy-metals because it is simple, selective, and can be regenerated (Zhou et al., 2016). Biochar, a carbon-based adsorbent material, is one of the adsorbents that have been reported to receive considerable attention as an environmental application. Biochar is a good adsorbent of heavy metals, including Pb, Cu, Zn, Ni, and Cr, due to its size (large surface area), porosity, and the number of functional groups (Ahmed et al., 2021; Khalil et al., 2020; Laishram et al., 2025). In addition, the biochar manufacturing of waste materials including the rice husk and sugarcane bagasse is in line with the principles of the circular-bioeconomy and carbon-neutral technologies (Dunnigan et al., 2018).

Recent research has been concerned with surface modification of biochar to enhance its performance in adsorption. Thiourea-containing biochar provides the advantages of adding sulfur and nitrogen functional groups, which chelate chromium ions intensely and convert toxic Cr(VI) into Cr(III) (Deng et al., 2022; Ashraf et al., 2017; Hassan & Su, 2026). Similarly, zinc nanoparticle (ZnNP) surface modification increases redox potential, and electron-transfer efficiency, which generates synergistic effects to immobilize chromium (Jehan et al., 2024). The combination of these changes enhances the density of the active sites and surface reactivity, which enhances adsorption and detoxification. Thus, the paper defines the use of thiourea-modified biochar and ZnNP-modified biochar prepared of sugarcane bagasse as efficient and cost-effective sorbents to remove chromium in water.

MATERIALS AND METHODS

Biochar Preparation and Modification

Mixed pyrolysis of rice husk was done in a furnace with a limited oxygen supply to ensure that it did not burn down to become biochar. First, the feedstock was washed using distilled water followed by 48 hours of air drying and then crushed into particles with a particle size of less than 3 cm to provide uniform heating. Its moisture content was kept under 15 percent in order to maximize carbonization. Pyrolysis was conducted under a slow heating rate of 57 0 C/min and temperature of 350 0 C to 400 0 C at 3 hours in order to prevent any thermal shock. It was a process consisting of drying, pre-carbonization, carbonization and calcination. Once the furnace was cooled, it was put under nitrogen atmosphere to avoid oxidation. The biochar that was derived was ground and sieved using a 100 mesh sieve then stored in airtight desiccators awaiting further modification.

To enhance the chemical properties, thiourea was used to modify the biochar to add both nitrogen and sulfur functional groups which enhance the binding of metal ions. A 1 gram of prepared biochar was combined with 20 mL of 1 N thiourea, and incubated at 40 0 C in a water bath with constant stirring. This response made it possible to graft the carbon surface with the NH 2 and C = S groups (Zhu et al., 2016; Tang et al., 2016). It was filtered (Whatman No. 42), washed with deionized water and dried in the oven at 70 0 C overnight. Dried material was then broken into fine powder and put in airtight containers to avoid contamination (Li et al., 2017).

Synthesis of Zinc Nanoparticles

Nano zero-valent zinc (nZVZn) particles were produced through chemical reduction using sodium borohydride ($NaBH_4$). A solution containing 1.5 g $ZnCl_2$ was prepared in a 25 mL ethanol–deionized water mixture (5:1 v/v), while a separate $NaBH_4$ solution (1.5 g in 40 mL water) acted as the reducing agent. The reductant was added dropwise to the zinc solution under constant stirring for 30 minutes, following the reaction:

$$Zn^{2+} + 2BH_4^- + 6H_2O \rightarrow Zn^0 + 2B(OH)_3 + 7H_2$$

A color change confirmed nanoparticle formation. The solution was stirred for another hour, then centrifuged at 10,000 rpm for 15 min. The resulting nanoparticles were washed with trichloroethanol to prevent oxidation, dried at 60 °C for 6 hours, and preserved in a vacuum desiccator.

Batch Sorption Studies

Contact tests to determine the adsorption of modified biochar and Zn nanoparticles were conducted using batch tests by changing the pH, chromium concentration, contact time, and adsorbent dosage.

pH effect: 0.1 M HCl or 0.1 M NaOH was placed in chromium solutions (10 mg/L) until the pH became 39. The flasks were loaded with 1 g sorbent in 50 mL solution, and swirled at 150 rpm in 25 ± 2 0 C. Chromium concentration was determined following centrifugation and filtration with the help of AAS (Escudero et al., 2017).

Effect of Starting Concentration: Solutions of 1-20 mg/L Cr (IV) were made, and a constant dose of the sorbent (1 g / 50 mL) was placed in the solution. The level of chromium that remained in the shaking solution after 2 hours was assayed and the adsorption capacity was determined by calculating the difference between the initial and equilibrium concentration.

Effect of Contact Time and Sorbent Dose: At constant Cr(VI) concentration (10 mg/L) and sorbent loading (4 g/L), contact time studies were conducted. The samples were taken at repetitive intervals of 10180 minutes, centrifuged, filtered, and analyzed as the remaining chromium (Montoya et al., 2018). In a similar manner, adsorption was analyzed at different doses (1–8 g/L) with the same conditions to find out the ideal dose at which maximum Cr(VI) had been eliminated (Sansuk et al., 2018).

Isotherm and Kinetic Modeling

The equilibrium data were analyzed using Langmuir and Freundlich isotherm models to describe chromium adsorption behavior. Langmuir model was:

$$\boldsymbol{Qe = \frac{QmKLCe}{(1 + KLCe)}}$$

where Q_e (mg/g) is the equilibrium adsorption capacity, Q_m is maximum monolayer capacity, C_e (mg/L) is equilibrium concentration, and K_L (L/mg) is the Langmuir constant.

Kinetic data were interpreted using pseudo-first-order and pseudo-second-order models to determine rate constants and understand adsorption mechanisms.

Chromium Determination

Chromium concentrations were determined using an Atomic Absorption Spectrophotometer (Hitachi Z-8200, Japan) following the AOAC (1990) protocol. Calibration was performed using standard chromium solutions, and absorbance values were recorded at the element's characteristic wavelength to quantify residual metal in filtrates.

Statistical Analysis

All experiments were conducted in triplicate, and data were expressed as mean ± standard deviation. Statistical analysis was performed using Microsoft Excel and Statistical Software v8.1. One-way ANOVA, followed by Tukey's post-hoc test, was used to determine significant differences between treatments at a 95% confidence level (P<0.05).

RESULTS

SEM Characterization of Adsorbents

SEM was used to analyze the surface morphology of the prepared materials as in Figure 1. The biochar (RH-BC) obtained through the rice husk was rough and irregular in texture, having a large quantity of pores and cracks, which are characteristics of pyrolyzed agricultural waste. These micro- mesopores seriously augment surface area, and furnish large quantities of active sites in which metal can be absorbed, with residual oxygen-containing groups including hydroxyl and carboxyl providing metal ion binding.

Biochar after thiourea modification was more compact and denser, but still had smaller but chemically active sites. Having nitrogen- and sulfur-based groups of functionality (–NH 2, -SH, -C=S) that were added to thiourea also improved the affinity of the material with chromium through complexation and electrostatic interaction, therefore, suggesting that adsorption in the context of TMBC relies more on chemical interactions than on physical porosity.

The SEM picture of nZVZn- biochar composite was bright with uniformly distributed, zinc nanoparticles (20 100 nm) attached to the biochar. This even distribution increased surface reactivity and redox potential allowing the removal of chromium through adsorption and reduction processes. Pure nZVZn particles, conversely, had a smooth, spherical morphology (20-80nm) with low aggregation, which proved that they have been successfully synthesized and they are highly surface active to be used in wastewater treatment.

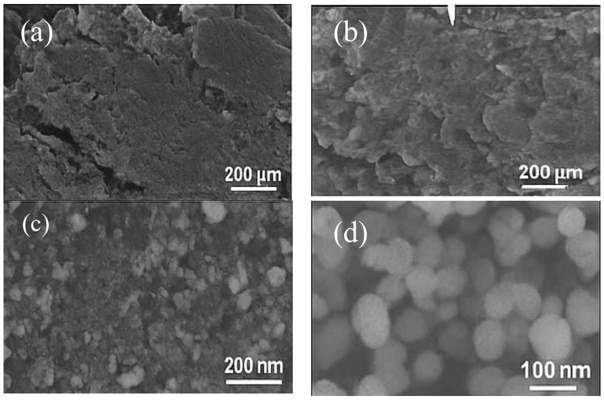

Fig. 1: SEM images showing (a) rice husk-derived biochar (RH-BC) with porous surface, (b) thiourea-modified biochar (TMBC) with enhanced pore structure, (c) nZVZn-BC composite with well-dispersed zinc nanoparticles, and (d) spherical nZVZn particles (20–80 nm) confirming successful synthesis.

Effect of Sorbent Dose on Chromium Removal

All the adsorbents were tested on the effect of sorbent dosage on the removal efficiency, and the findings are summarized in Figure 2. Adding more sorbent in the 1 g L -1 to the 8 g L -1 dose resulted in an increasing rate of chromium removal with all the materials, even though the rate of increase leveled off at the higher doses owing to the limited supply of Cr ions in the solution as most of the binding sites were already taken. As the case of rice husk biochar (RH-BC) shows, chromium adsorption rose continuously with dose meaning that the higher the surface area and active site a greater the capture of the ion. But beyond 4 g L -1, the efficiency gain was insignificant indicating particle aggregation or saturation at the site in the higher concentrations.

The thiourea-functionalized biochar (TMBC) showed more vivid increments of sorption between 4 g L -1 and 8 g L -1 which is attributed to the presence of nitrogen and sulfur-based functional groups (-NH 2 -SH) in providing the biochar with more coordination sites to reduce and bind Cr(VI). TMBC had the best and most repetitive elimination of 8 g L -1, which validated the benefit of chemical modification. In the case of nano zero-valent zinc particles (nZVZn), adsorption performance increased with dose which exhibited a sharp increase at 8 g L -1. This improvement has been credited to the increase in the surface reactivity and availability of reductive Zn o sites that reduce the toxic Cr(VI) to the less harmful Cr(III). The standard error and stability at high doses are greater, a fact that reflects consistency in the performance of nZVZn at the ideal loading conditions. The same was true with the biochar-based zinc composite (nZVZn-BC). At lower concentrations (14 g L -1 and 4 g L -1), the removal efficiency varied, which may have been caused by the non-dispersion of nanoparticles on the biochar surface. The material was more efficient and with a lower variation at 8 g L -1, indicating an improved particle interaction and reliable adsorption.

In general, all sorbents were found to have a better ability to remove the chromium with a rise in dose, with an 8 g L -1 as the most effective and consistent concentration to be used in practice to treat water (Figure 2).

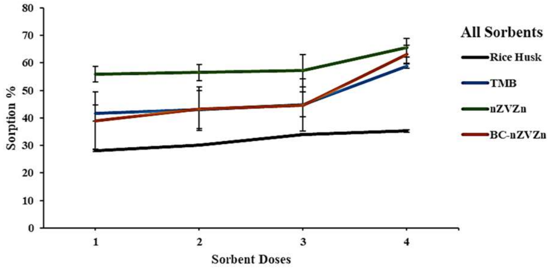

Fig. 2: Effect of sorbent dose on chromium removal efficiency for RH-BC, TMBC, nZVZn, and nZVZn-BC adsorbents.

Effect of pH on Chromium Removal by Different Sorbents

The effect of the pH on the adsorption of chromium was examined on the all the sorbents and the findings are shown in Figure 3. The efficiency of chromium removal showed a significant rise with the pH between 3 and 5 and it was at its optimum at mildly acidic pH conditions. In the case of rice-husk biochar (RH-BC), adsorption rose to approximately 51 o-60 o in pH 3, and approximately 89 o-60 in pH 5-6, thereafter, adsorption dropped at neutral and alkaline pH, presumably because of reversal of the surface charge of the sorbent and a decrease of electrostatic attraction between Cr species and the sorbent. This trend was similar in the case of biochar- zinc composite (nZVZn -BC) with moderate uptake at low pH (≈45%) and maximal uptake at near pH 5 (≈60%) where the balancing of surface charges and chromium speciation favored sorption. The nanoscale zero-valent zinc (nZVZn) particles were the most pH-sensitive with adsorption increasing steadily to 55 (pH 3) to about 75 (pH 5) with increasing pH as the particles became more negatively charged and developed electrostatic repulsion. In all materials, the best removal of chromium was at pH 5 ± 0.5 which showed that mildly acidic conditions are the most effective in ensuring the stage of effective adsorption of chromium (Cr(VI)) by the materials through positive surface interactions and speciation of chromium.

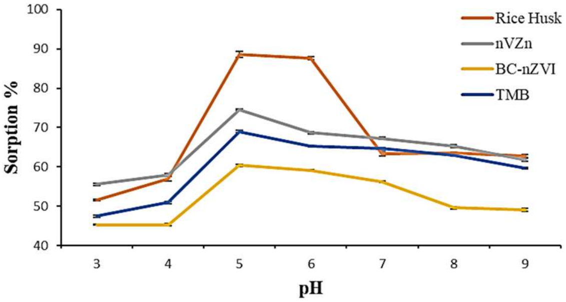

Fig. 3: Effect of pH on chromium removal efficiency for RH-BC, TMBC, nZVZn, and nZVZn-BC adsorbents.

Effect of Contact Time on Chromium Removal

Figure 4 shows the relationship that exists between contact time and chromium adsorption efficiency of various sorbents. An initial rapid absorption of Cr ions by all the materials was followed by a slow increment to the state of equilibrium. In the case of rice husk biochar (RH-BC), the removal of chromium increased gradually between approximately 40 and almost 70 percent within 1440 minutes and this shows that the kinetics of adsorption is moderate. The thiourea-modified biochar (TMBC) had the best overall performance which was around 75% removal during the same time. The improved adsorption of TMBC is explained by thiourea-based nitrogen and sulfur functional groups, which add more binding points to the material and enhance the process of reducing Cr(VI) to Cr(III), which increases adsorption on the sorbent surface. Nano zero-valent zinc (nZVZn) also has good performance with a sorption efficiency of approximately 50 percent to 75 percent compared with TMBC and slightly low because of minimal surface functionalization. The biochar-zinc composite (nZVZn-BC), though, had lower kinetics, and removal success only increased to 45% and approximately 55% indicating that it was more saturated and contained fewer active sites. As a whole, all adsorbents exhibited improved contact time-dependent chromium removal with the most effective and sustained adsorption being observed with TMBC and nZVZn (Figure 4).

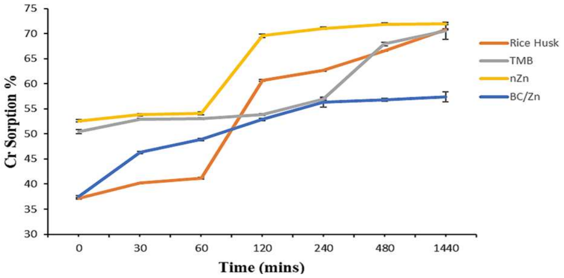

Fig. 4: Effect of contact time on chromium removal efficiency for RH-BC, TMBC, nZVZn, and nZVZn-BC adsorbents.

Effect of Initial Chromium Concentration on Sorption Efficiency

Figure 5 provides the impact of different initial chromium concentration on adsorption efficiency with different sorbents. In the case of rice husk biochar (RH-BC), the concentration of chromium removed steadily with the concentration. At low concentrations (0.52 mg L -1 -2mg L +1), adsorption was moderate (approximately 55-65 per cent), which means that the active functional sites of the untreated biomass were not very numerous. When the concentration was further raised to 8-15 mg L -1, the sorption performance was observed to increase to more than 75 percentage indicating increased use of the surface sites with high levels of the contaminant.

The thiourea-modified biochar (TMBC) was much superior to all concentrations with an almost 90 percent removal at 815 mg L -1. This is enhanced by the availability of groups of amine (–NH 2) and thiocarbonyl (–C= S) that were added during modification that facilitate the formation of a strong complex, electrostatic attraction and partial reduction of Cr(VI) to Cr(III).

High and reproducible removal up to over 85 percent was also observed with nano zero-valent zinc (nZVZn). It has a wide reactive surface area due to its size on a nanoscale and strong reducing potential which converts Cr(VI) to the less toxic Cr(III), which plays a role in adsorption as well as redox removal.

The most effective in general was the biochar-based zinc composite (nZVZn-BC) which retained 6070% removal at low concentrations and was found to exceed 90% at high concentrations. Such an excellent performance is due to the synergistic effect of porous properties of biochar and reactive zinc nanoparticles that balance stability, avoid aggregation of the particles, and maintain a high level of reactivity. All sorbents performed better with increase in initial concentration with nZVZn-BC being the most effective and stable material in remedial of chromium over a broad range (Figure 5).

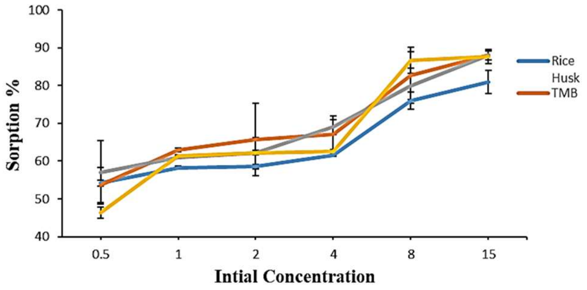

Fig. 5: Effect of initial chromium concentration on removal efficiency using RH-BC, TMBC, nZVZn, and nZVZn-BC sorbents.

Sorption Kinetic and Isotherm Modeling

Kinetic and equilibrium adsorption models were applied to better understand the mechanisms controlling chromium removal by different sorbents. The experimental data were evaluated using pseudo-first-order and pseudo-second-order kinetic equations, along with the Langmuir and Freundlich isotherm models.

The pseudo-first-order model, represented as

$$qt = qe(1 - e^{-k1t})$$

describes the rate of adsorption based on the difference between equilibrium and time-dependent sorption capacities. The parameters obtained from the model are presented in Table 2. All sorbents exhibited good conformity with this model, suggesting that chromium adsorption was primarily governed by physisorption mechanisms at the early stages. The apparent rate constant (k_1) remained consistent (0.5 min^{-1}) for all sorbents, while the equilibrium capacities (q_e) varied. Among them, nZVZn displayed the highest q_e value (2.51 mg g^{-1}), indicating the strongest affinity for chromium, followed by TMB (2.31 mg g^{-1}) and rice husk biochar (2.03 mg g^{-1}). The biochar–zinc composite (BC/Zn) recorded the lowest q_e (1.83 mg g^{-1}), reflecting comparatively reduced adsorption efficiency. These results confirm that chromium uptake was rapid at the beginning and gradually approached equilibrium as surface sites became occupied.

The equilibrium data were further analyzed using the Langmuir and Freundlich isotherm models to evaluate surface behavior. The Langmuir isotherm, expressed as

$$\frac{Ce}{qe} = \frac{1}{qmax}.b + \frac{Ce}{qmax} \qquad \dots\dots\dots 1$$

assumes monolayer adsorption on a homogeneous surface, where *qmax* represents the maximum adsorption capacity and *b* is the binding affinity constant. In contrast, the Freundlich isotherm is an empirical model describing heterogeneous surface adsorption. Its constants, *Kf* and *n*, indicate adsorption capacity and intensity, respectively. The obtained parameters are listed in Table 1**.**

As shown in Table 1**,** higher *Kf* values correspond to greater adsorption capacity, while *1/n* values between 0 and 1 indicate favorable adsorption conditions. The BC/Zn composite exhibited the highest *Kf* (4.48) and *n* (3.10×10^7), confirming its superior adsorption potential and strong interaction with chromium ions. The nZVZn and TMB sorbents also showed excellent performance, reflecting enhanced surface activity and functional group interactions. The rice husk biochar**,** though less efficient, demonstrated satisfactory adsorption at higher pollutant concentrations, supporting its potential for low-cost treatment applications.

Table 1: Freundlich isotherm constants (*Kf* and *n*) for different sorbents

Sorbent	Kf	n
Rice Husk	6.97×10^{-7}	0.102
BC/Zn	4.48	3.10×10^7
Zn	2.75	9.91×10^6
TMB	3.53	7.94×10^6

Overall, the combined kinetic and isotherm analysis indicates that chromium removal followed pseudo-first-order kinetics and exhibited favorable adsorption behavior under both Langmuir and Freundlich models. The BC/Zn and nZVZn materials emerged as the most effective sorbents, offering strong adsorption capacity and rapid uptake dynamics suitable for practical water-treatment applications.

Table 2: Pseudo-first-order kinetic parameters (q_e and k_1) for different sorbents

Sorbent	q_e (mg g^{-1})	k_1 (1/min)
Rice Husk	2.03	0.500
BC/Zn	1.83	0.500
nZVZn	2.51	0.500
TMB	2.31	0.500

DISCUSSION

The efficiency of chromium removal was highly dependent on the sorbent dose with an increasing mass loading performing adsorption to nearly saturating surface sites (Eroglu et al., 2017). As in the case of Figure 2, all sorbents exhibited a growing curve to a point of 8 g L -1, at which point increases were only marginal in value, most probably a result of particle aggregation and overlapping sites. The biochar that was most increased in removal at higher dosage was thiourea-modified biochar (TMBC) due to the presence of other nitrogen and sulfur functional groups to facilitate complexation and electrostatic attraction. Nano zero-valent zinc (nZVZn) and biochar-supported zinc (nZVZn-BC) were also found to be effective and this is the contribution of active zinc surfaces which effectively promote both reduction and adsorption of Cr(VI) (Ertani et al., 2017; Shoukat et al., 2024).

The pH of the solution had a strong influence on the uptake of chromium, as observed in Figure 3. All sorbents were removed optimally under mild acidic conditions (pH 5 + 0.5) in which protonated surfaces were preferentially electrostatically attracted to negatively charged Cr species (HCrO 4 -). The presence of excess H + at low PH values competed with chromium on active sites but at alkaline PH, deprotonation of the surfaces and the formation of Cr (OH) 3 reduced efficiency. The same trend was observed in materials: RH-BC was almost 89% at pH 5, TMBC and nZVZn had exceeded 70 and 70 percent respectively, and nZVZn-BC was stable with moderate efficacy. It is necessary to maintain a slightly acidic medium hence critical to optimum performance (Jennings, 2013).

Figure 4 presents time-dependent studies that gradually demonstrated that chromium adsorption improved with increase in duration of contact and this demonstrated the progressively filling of the available sites until equilibrium. The kinetics of rice-husk biochar was slower, with the obtainable percent removal of about 70 after 1440 min, compared to TMBC and nZVZn which reached about 75 percent after the same duration, suggesting faster surface reaction and potential Cr(VI) x Cr(III) reduction. The plateauing (around 55 percent) of the nZVZn-BC composite was earlier so indicating that diffusion or accessibility to the active-site is limited. Long-term kinetics improved with longer contact time against all materials but TMBC and nZVZn showed better long-term kinetics because of redox-active and functionalized surfaces (Economou-Eliopoulos et al., 2012).

These observations were supported by kinetic modeling. Pseudo-first-order and pseudo-second-order (PSO) models were both tested, as the latter gave a greater goodness of fit (higher R 2 values) in most cases, suggesting that the predominant process is chemisorption (Asgari et al., 2013). This was particularly true with TMBC where experimental and calculated capacities were close and with nZVZn that possessed redox behavior as well as chemisorptive behavior. BC/Zn composite had less conformity to either of the models, probably because of heterogeneous surface diffusion (Khan et al., 2013).

All in all, the combined findings are that TMBC and nZVZn are the best sorbents in all parameters dose, pH and contact time. The ideal elimination was at 8 g L -1, pH 5-6, and contact time > 240 minutes. Chemisorption was the most common process, and it was controlled by the surface complexation and redox reactions. These results highlight the possibilities of using thiourea modified biochar and nano zero-valent zinc as affordable and sustainable products in the remediation of chromium polluted water systems.

Conclusions

This study demonstrated that chromium removal efficiency depends strongly on sorbent characteristics, pH, dose, and contact time. Among all materials tested, thiourea-modified biochar (TMBC) and nano zero-valent zinc (nZVZn) showed the highest adsorption capacities and fastest kinetics under optimal conditions (pH 5–6, 8 g L^{-1}, contact > 240 min). The adsorption followed pseudo-second-order kinetics**,** indicating a chemisorption-dominated mechanism involving surface complexation and redox reactions. These results highlight TMBC and nZVZn as efficient, low-cost, and environmentally sustainable sorbents for the remediation of chromium-contaminated water.

Declarations

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Conflicts of Interest: All authors declare that they have no conflicts of interest.

Data Availability: The data collected for this article are included in the article.

Ethics Statement: Not applicable

Author's Contributions: MA and ZAS designed and conducted the experiment. AS wrote the initial draft. Review and editing were performed by AZ, and ZAS. All authors approved the final version of the manuscript.

Generative AI Statements: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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