

Sorption kinetics of chromium(VI) in synergetic biochar derived from *Saccharum officinarum* and *Prosopis juliflora*

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This study presents an investigation into the effectiveness of utilizing biomass derived from *Prosopis juliflora* (Mesquite) and bagasse for the removal of hexavalent chromium [Cr(VI)] from water sources. The experimental analysis includes examining the impact of various factors such as adsorbent type, concentration, and temperature on the removal efficiency of Cr(VI). The obtained data reveal that both Mesquite and bagasse exhibit varying degrees of removal efficiency under different experimental conditions. Mesquite demonstrates higher removal percentages for specific Cr(VI) concentrations, particularly at 100 ppm and a temperature of 60°C. On the other hand, bagasse showcases better removal efficiency for certain concentrations. The comparative analysis of the two adsorbents indicates the influence of their distinct properties on the removal process. The results emphasize the importance of carefully selecting the appropriate adsorbent and optimizing operating conditions to achieve efficient Cr(VI) removal. The findings of this study contribute to the understanding of the potential of Mesquite and bagasse as adsorbents for hexavalent chromium removal and underscore the need for tailored strategies to address diverse water contamination scenarios.

Keywords: Adsorption, Bagasse, Biochar, Biomass, Chemical kinetics, Equilibrium uptake, *Prosopis juliflora*

Introduction

Metals play a pivotal role in modern society's progress. Some metals possess higher densities and can be toxic even at trace concentrations¹. These are referred to as heavy metals, a category that includes elements like lead, mercury, cadmium, and chromium. Chromium, with its characteristic properties, occupies a significant place in various industrial processes and applications². Chromium exists primarily in two forms: trivalent chromium Cr(III) and hexavalent chromium Cr(VI). While Cr(III) is an essential nutrient, Cr(VI) has garnered attention due to its potential toxicity. This dual nature of chromium underscores the need for a comprehensive assessment of its applications and impacts. Cr(VI) is of particular concern due to its environmental impact. The wide-ranging use of Cr(VI) compounds in industries has led to its discharge into water bodies, contributing to water pollution³. The potential for Cr(VI) to accumulate in aquatic ecosystems and its associated health risks have raised alarms globally. The unique characteristic of Cr(VI) to transform into a range of oxidation states further complicates its behaviour in the environment. Chromium contamination has prompted research into

effective removal strategies to mitigate its adverse effects on ecosystems and human health⁴. One approach gaining attraction is adsorption, a process where contaminants adhere to the surface of solid materials known as adsorbents. Agricultural waste materials, such as rice husk, coconut shells, and sugarcane bagasse, have demonstrated promising results as efficient adsorbents for chromium removal⁵. These abundant and readily available materials offer a sustainable solution to the chromium pollution predicament.

In recent years, innovative methods and technologies have emerged to address the challenges of Cr removal from water and wastewater. Adsorption, driven by its cost-effectiveness and efficiency, has garnered significant attention. Advances in material science have led to the development of tailored adsorbents with enhanced chromium adsorption capacities⁶. Nanotechnology, for instance, has facilitated the fabrication of nanostructured materials with high surface areas, providing more active sites for chromium binding. In the pursuit of sustainable remediation strategies, bioadsorbents have gained prominence. Utilizing the inherent adsorption

capabilities of biological materials, such as algae, bacteria, and fungi, researchers are exploring eco-friendly alternatives for Cr removal. These bioadsorbents not only offer efficient Cr removal but also contribute to minimizing waste generation and promoting a circular economy approach⁷. Activated carbon, a versatile and widely used adsorbent, has emerged as a powerful tool in addressing heavy metal contamination, including the removal of Cr from water and wastewater. Activated carbon's exceptional adsorption properties, coupled with its diverse applications, make it a pivotal component in environmental remediation efforts. Activated carbon, often referred to as activated charcoal, is a carbonaceous material characterized by its high surface area and intricate pore structure⁸. This remarkable structural arrangement enhances its adsorption capabilities by providing an extensive network of sites where contaminants can physically adhere. The adsorption process occurs through van der Waals forces, electrostatic interactions, and chemical bonding between the contaminant molecules and the carbon surface. Activated carbon comes in various forms, each tailored to specific applications. The two most common types are powdered activated carbon (PAC) and granular activated carbon (GAC). PAC, with its fine particle size, offers a large external surface area but can be challenging to separate from treated water. GAC, on the other hand, consists of larger granules, making it more suitable for fixed-bed adsorption systems⁹.

The process of producing activated carbon involves the controlled thermal decomposition of carbon-rich precursors, such as wood, coconut shells, peat, and even agricultural wastes like rice husks. Bagasse, a by-product from sugarcane processing, has been increasingly recognized for its potential as a precursor to biochar. Biochar, a carbon-rich material produced through the pyrolysis of biomass, has gained attention for its utility in environmental applications, particularly as an adsorbent. The adsorption capacity of bagasse biochar can be attributed to its porous structure, high specific surface area, and the presence of functional groups on its surface. The biochar's surface may contain carboxyl, hydroxyl, and other functional groups that can interact with nitrates and phosphates, facilitating their adsorption. The ion exchange mechanism, where calcium or magnesium ions present in biochar exchange with nitrate or phosphate ions, also plays a role. Several factors play a pivotal role in influencing the adsorption

capabilities of bagasse biochar for nitrates and phosphates. The particle size of the biochar is paramount, as it directly affects its surface area. Generally, finer particles possess a larger surface area, which typically correlates with enhanced adsorption capability. The pH of the solution is another crucial determinant, shaping both the surface charge of the biochar and the speciation of the contaminants.

For nitrates and phosphates, optimal removal is often observed within slightly acidic to neutral pH ranges. Temperature also exerts an influence on the adsorption process. While an increase in temperature can invigorate the kinetics and equilibrium of adsorption, there might be a threshold beyond which the adsorption capacity dwindles. Additionally, contact time, or the duration for which contaminants interact with the biochar, plays a role in achieving adsorption equilibrium. Extended contact times often result in heightened removal efficiencies, at least until an equilibrium state is attained. When juxtaposed with other biochar materials, bagasse biochar frequently showcases competitive, if not superior, adsorption capacities for nitrates and phosphates. Its allure is further magnified considering its abundance, cost-efficiency, and the sustainable manner of its production, making it a compelling choice for water and wastewater treatment endeavors. However, challenges do arise, especially concerning the regeneration of biochar post-saturation. Though various regeneration methods have been explored, including solvent washing and heating, the adsorption capacity of bagasse biochar might witness a decline after multiple regeneration cycles. The broader implications of employing bagasse biochar extend beyond its adsorption capabilities. From an environmental perspective, leveraging bagasse, an otherwise agricultural waste, in the creation of biochar presents an opportunity to mitigate environmental pollution. Economically, the transformation of this waste into a valuable resource for wastewater treatment offers a sustainable and cost-effective solution, further emphasizing the potential of bagasse biochar in environmental applications.

Once the adsorbent becomes saturated with contaminants, it can be regenerated through thermal or chemical treatment. Regeneration involves desorbing the contaminants from the carbon surface, restoring its adsorption capacity^{10,11}. This characteristic makes activated carbon a cost-effective and environmentally friendly option for water treatment. While activated

carbon holds immense promise in Cr removal and environmental remediation, challenges persist. The variability in feedwater composition, potential fouling, and competing adsorbates can impact its performance. Overcoming these challenges requires a comprehensive understanding of the adsorption process and continuous research to optimize treatment protocols.

The urgency to address chromium contamination is particularly relevant in developing nations like India. Rapid industrialization and inadequate waste management have contributed to chromium contamination, posing risks to public health and the environment. Challenges related to chromium contamination are multifaceted and require multidisciplinary solutions that encompass environmental science, policy, and engineering¹². Efforts to combat chromium pollution are further underscored by its detrimental effects on human health. Long-term exposure to hexavalent chromium has been linked to respiratory problems, weakened immune systems, kidney and liver damage, and even lung cancer. The widespread occurrence of chromium in drinking water sources and its bioaccumulation potential emphasize the need for stringent regulations and effective removal strategies. The environmental and human health risks associated with hexavalent chromium have prompted governments and regulatory bodies worldwide to establish guidelines and standards for its permissible concentrations in water sources. Organizations like the World Health Organization and the Environmental Protection Agency have defined limits for chromium levels in drinking water to safeguard public health¹³.

In the quest for sustainable solutions to Cr contamination and other environmental challenges, activated carbon stands as a beacon of hope. Its unique structural attributes, exceptional adsorption capacity, and versatility have positioned it as a go-to adsorbent in water and wastewater treatment. As technological advancements continue to refine activated carbon's properties and applications, its role in safeguarding water resources and ecosystems becomes increasingly vital. The present study explores the use of biomass derived from bagasse and *Prosopis juliflora* as adsorbents for the removal of hexavalent chromium from water^{14,15}. The maximum equilibrium uptake capacities and kinetics are studied in order to determine their operational applicability and feasibility in large scale industrial treatment systems¹⁶.

Experimental Section

Bagasse, the fibrous residue left post sugarcane juice extraction, and Mesquite, are taken for the adsorbent preparation. This process encompasses a series of structured steps including material collection, washing, chopping, and subsequent oven drying at 100°C. Following this, carbonization is executed at 600°C within a muffle furnace, followed by grinding and sieving through a 425 μ IS sieve. Particles passing through the sieve are stored in airtight containers, ensuring the uniformity and suitability of the adsorbents for subsequent analysis.

A standard Cr(VI) solution a concentration of 500 ppm was prepared by dissolving potassium dichromate in distilled water. The requisite apparatuses involve 50 mL centrifuge vials, a micro balance, an orbital shaker for ensuring effective adsorbate-adsorbent interaction, and a UV-visible spectrophotometer (Labman, LMSP-UV1200, Single beam, 190-1100 mm), for accurate chromium analysis.

The investigation's methodology is grounded in the systematic variation of crucial parameters, designed to offer a comprehensive grasp of adsorption kinetics. These parameters encompass the concentration of the adsorbate, the dosage of the adsorbent, and the temperature of the system. The study adopts two potential end conditions: the complete adsorption of chromium and the achievement of a saturation state. The variation of adsorbate concentration retains a fixed adsorbent dosage of 0.5 g, exploring three concentrations (100 ppm, 200 ppm, and 500 ppm) while adhering to a pH below 2. The investigation of adsorbent dosage variation employs a fixed concentration of 500 ppm while altering the dosage to 0.5 g, 2 g, and 5 g, maintaining a pH below 2. Additionally, the study on temperature variation considers a consistent concentration of 500 ppm, a 0.5 g adsorbent dosage, and explores temperatures set at 27°C and 60°C, with a pH below 2.

Results and Discussion

The adsorption capacity of activated carbon depends on factors such as pore structure, surface chemistry, and the nature of the adsorbate^{17,18}. The equilibrium capacity indicates the maximum adsorption that can be achieved under specific conditions. Activated carbon's versatility extends beyond water treatment. It finds application in diverse fields, from air purification to medical uses. In the realm of water treatment, activated

carbon is employed to remove a wide range of contaminants, including organic pollutants, volatile organic compounds (VOCs), and heavy metals like chromium. Its effectiveness in adsorbing a variety of substances has led to its integration into filtration systems, such as activated carbon filters in households¹⁹. Table 1 presents the sorption efficiency of chromium on Mesquite, the interplay between key variables, including initial chromium concentration, exposure time, and the adsorbent's mass. These findings offer valuable information for optimizing chromium removal processes using Mesquite and understanding the underlying adsorption mechanisms. The time-dependent nature of adsorption becomes evident through the data, showcasing that increased exposure time correlate with higher chromium adsorption onto Mesquite. For instance, at 5 min, the adsorption of chromium from a 100 ppm solution onto 0.5 g of Mesquite is 4.035 mg/g, which progressively increases to 10.100 mg/g at 360 min. This aligns with adsorption kinetics, where prolonged contact between the adsorbent and adsorbate enhances binding opportunities. Long exposure time is thus essential for achieving efficient chromium removal using Mesquite. Moreover, the influence of initial chromium concentration is apparent, as higher initial concentrations result in greater chromium adsorption for a given exposure time^{20,21}. At 60 min of exposure, the adsorption capacities for 100 ppm, 200 ppm, and 500 ppm chromium solutions onto 0.5g of Mesquite are 5.053 mg/g, 6.803 mg/g, and 22.5 mg/g, respectively. This phenomenon is attributed to the concentration gradient between the solution and adsorbent, driving mass transfer.

Consequently, higher initial chromium concentrations boost overall adsorption efficacy. The role of the

initial mass of Mesquite emerges as a significant factor affecting adsorption efficiency. Increased Mesquite mass leads to higher chromium adsorption, which is emphasizing the importance of adsorption site availability. Larger masses of Mesquite provide more binding sites, enhancing the overall adsorption capacity and efficiency²². For instance, at 60 min of exposure, the adsorption capacities for 500 ppm chromium solutions onto 0.5 g, 2g, and 5g of Mesquite are 22.5 mg/g, 3.125 mg/g, and 2.76 mg/g, respectively. The data also unveils instances of adsorption saturation, where further increases in exposure time or initial concentration yield diminishing returns in adsorption efficiency. This saturation effect highlights the equilibrium point, where active sites become saturated. Beyond this point, additional exposure or higher initial concentrations do not lead to proportional increases in adsorption^{23,24}. For example, at 480 min of exposure, the adsorption capacities for 500 ppm chromium solutions onto 0.5 g of Mesquite remain constant at 10.100 mg/g, indicating saturation. Furthermore, the data's temperature dependence section showcases that elevated temperatures, such as those observed at 60°C, can enhance adsorption efficiency. This suggests that temperature influences the mobility of molecules, facilitating interactions between the adsorbate and active sites on the adsorbent's surface. At 60 min of exposure, the adsorption capacity for a 500 ppm chromium solution onto 0.5 g of Mesquite at 60°C is 10.154 mg/g, compared to 2.76 mg/g at room temperature.

Similarly, the adsorption of chromium on to bagasse is presented in Table 2. The time-dependent nature of chromium adsorption is evident from the data, revealing that as exposure time increases, the

Table 1 — Optimization of operational parameters for the adsorption of Cr(VI) on Mesquite

Time (min)	100 ppm (0.5 g) (mg/g)	200 ppm (0.5 g) (mg/g)	500 ppm (0.5 g) (mg/g)	500 ppm (2 g) (mg/g)	500 ppm (5 g) (mg/g)	500 ppm (0.5 g) (60C) (mg/g)
5	4.035	0.5377	4.4	0.375	0.35	1.0312
10	4.035	0.966	4.4	0.675	1.088	1.375
15	4.035	1.854	11.3	1.05	2.76	1.6875
30	4.035	3.834	13.6	2.525	2.76	4.1818
60	5.053	6.803	22.5	3.125	2.76	10.154
120	6.0729	9.405	25.7	3.4	2.76	22.353
180	7.0369	10.329	32.46	5.775	2.76	24.411
240	8.0414	10.329	32.46	5.925	2.76	28.472
300	8.0027	10.329	32.46	6.425	2.76	28.472
360	10.100	10.329	32.46	8.525	2.76	28.472
420	10.100	10.329	32.46	8.525	2.76	28.472
480	10.100	10.329	32.46	8.525	2.76	28.472

Table 2 — Optimization of operational parameters for the adsorption of Cr(VI) on Bagasse

Time (min)	100 ppm(0.5 g) (mg/g)	200 ppm(0.5 g) (mg/g)	500 ppm(0.5 g) (mg/g)	500 ppm(2 g) (mg/g)	500 ppm(5 g) (mg/g)	500 ppm(0.5 g)(60°C) (mg/g)
5	1.803	3.7	14.19	0	2.9	0
10	2.983	4.2	17.142	4.3	2.93	0
15	2.983	4.3	24.333	4.325	3.43	6.182
30	2.983	4.4	31.047	4.975	4.53	6.182
60	3.243	4.7	31.047	6.225	4.61	9.000
120	4.143	4.8	31.047	7.4	4.86	12.076
180	4.713	6.8	31.047	8.2	5	13.923
240	4.713	6.8	31.047	9.65	5	18.095
300	4.713	6.8	31.047	9.65	5	18.809
360	4.713	6.8	31.047	9.65	5	21.588
420	4.713	6.8	31.047	9.65	5	21.588
480	4.713	6.8	31.047	9.65	5	21.588

adsorption of chromium onto bagasse also increases. For instance, at 5 min of exposure, the adsorption of chromium from a 100 ppm solution onto 0.5 g of bagasse is 1.803 mg/g, which progressively increases to 4.713 mg/g at 360 min. This trend aligns with adsorption kinetics, where prolonged contact between the adsorbent and adsorbate leads to enhanced binding opportunities, resulting in increased adsorption over time²⁵. The impact of initial chromium concentration on the adsorption process is clearly observed, indicating that higher initial concentrations lead to higher chromium adsorption for a given exposure time. At 60 min of exposure, the adsorption capacities for 100 ppm, 200 ppm, and 500 ppm chromium solutions onto 0.5 g of bagasse are 3.243 mg/g, 4.7 mg/g, and 31.047 mg/g, respectively. This phenomenon is consistent with the concept of concentration gradient-driven mass transfer, where higher initial concentrations facilitate higher adsorption capacities due to a greater driving force.

The data also illustrates the influence of the adsorbent mass on chromium adsorption efficiency. Larger masses of bagasse lead to higher chromium adsorption, indicating the significance of the availability of adsorption sites. For instance, at 60 min of exposure, the adsorption capacities for 500 ppm chromium solutions onto 0.5 g, 2 g, and 5 g of bagasse are 31.047 mg/g, 6.225 mg/g, and 4.61 mg/g, respectively. This underscores the importance of surface area and available binding sites in dictating the overall adsorption capacity¹². Moreover, the dataset highlights instances of adsorption saturation, where further increases in exposure time or initial concentration result in diminishing incremental adsorption efficiency. This saturation effect indicates

the equilibrium point at which active sites on the adsorbent's surface become saturated. Beyond this point, additional exposure time or higher initial concentrations do not lead to commensurate increases in adsorption efficiency. For instance, at 480 min of exposure, the adsorption capacities for 500 ppm chromium solutions onto 0.5 g of bagasse remain constant at 21.588 mg/g. Furthermore, the influence of temperature on the adsorption process is apparent in the dataset. Elevated temperatures, such as those observed at 60°C, can enhance chromium adsorption efficiency. This is evident in the increased adsorption capacities observed at elevated temperatures compared to room temperature. For example, at 60 min of exposure, the adsorption capacity for a 500 ppm chromium solution onto 0.5 g of bagasse at 60°C is 9.000 mg/g, compared to 4.61 mg/g at room temperature.

Considering the initial exposure time of 5 minutes, the adsorption efficiency for a 100 ppm chromium solution onto Mesquite is calculated to be 4.035 mg/g, whereas the efficiency onto bagasse is notably lower at 1.803 mg/g. As the exposure time progresses, the adsorption efficiencies on both materials show an increasing trend. However, the efficiencies for Mesquite consistently surpass those for bagasse. For instance, at 240 min of exposure, the efficiency for a 100 ppm chromium solution onto Mesquite reaches 8.0414 mg/g, surpassing the corresponding efficiency onto bagasse at 4.713 mg/g. This trend holds true across different initial concentrations and adsorbent masses. Notably, at 60 min of exposure, the efficiency for a 500 ppm chromium solution onto 0.5 g of Mesquite stands at 6.803 mg/g, while the efficiency onto bagasse is recorded at 4.7 mg/g.

Table 3 — Consolidated results derived from kinetics plots of sorption on biomass derived from Mesquite and Bagasse

Adsorbents	Saturation value (A)	Rate constant (B)	Regression coefficient (r^2)
Mesquite 100 ppm (0.5 g)	8.95	0.012	0.93
Mesquite 200 ppm (0.5 g)	10.63	0.0159	0.99
Mesquite 500 ppm (0.5 g)	32.26	0.03621	0.99
Mesquite 500 ppm (2 g)	9.47	0.00484	0.96
Mesquite 500 ppm (5 g)	2.79	0.0812	0.902
Mesquite 500 ppm (0.5 g) (60°C)	31.9	0.007817	0.98
Bagasse 100 ppm (0.5 g)	4.275	0.08712	0.859
Bagasse 200 ppm (0.5 g)	5.87	0.126	0.777
Bagasse 500 ppm (0.5 g)	31.19	0.09892	0.988
Bagasse 500 ppm (2 g)	9.213	0.05337	0.907
Bagasse 500 ppm (5 g)	4.726	0.1163	0.943
Bagasse 500 ppm (0.5 g) (60°C)	20.58	0.01476	0.949

Table 3 provides saturation values (a), rate constants (b), and regression coefficients (r^2) for different adsorbents and conditions, derived from the kinetic plot equation $y = a * [1 - e^{-(bx)}]$. Upon scrutinizing the Table 3, it's evident that the saturation values (a) represent the maximum adsorption capacity for each adsorbent and concentration. Higher saturation values typically indicate a greater adsorption capacity. For instance, Mesquite demonstrates varying saturation values across different concentrations. At 500 ppm (0.5 g), the saturation value is 32.26, suggesting a higher adsorption capacity compared to 100 ppm (0.5 g), where the saturation value is 8.95. The rate constant (b) signifies the rate of adsorption. Smaller rate constants generally imply slower adsorption kinetics. It's interesting to observe that different concentrations of the same adsorbent can exhibit different rate constants. At 100 ppm (0.5 g), Mesquite has a rate constant (b) of 0.012, while at 500 ppm (0.5 g), the rate constant increases to 0.03621, indicating faster kinetics.

Moving on to the regression coefficient (r^2), it reflects the degree of fit between the experimental data and the kinetic plot equation. Higher r^2 values imply a better fit of the data to the equation. Notably, most of the r^2 values in the table are relatively high, indicating a strong agreement between the experimental data and the kinetic model. For instance, the r^2 value for Mesquite at 500 ppm (0.5 g) is 0.99, showcasing a robust correlation between the two. Comparing the adsorption performances of Mesquite and Bagasse, it's clear that Mesquite generally exhibits higher saturation values and lower rate constants than Bagasse. This suggests that Mesquite has a higher adsorption potential and a slower rate of adsorption. Moreover, the higher r^2 values for Mesquite signify an excellent fit of the experimental data to the kinetic model.

The efficiency of Cr(VI) removal across 12 different experimental conditions is elucidated in the provided data as presented in Table 4. The results are summarized in the subsequent table, detailing the percentage removal for each adsorbent and concentration. Upon inspecting the data in Table 4, it's evident that the percentage removal of Cr(VI) varies significantly across different conditions. For instance, with Mesquite (0.5 g) at 100 ppm concentration, the removal is 100%, implying complete elimination of the contaminant. Conversely, when the concentration increases to 200 ppm, the removal percentage drops to 51.645%, indicating a decrease in efficiency as the concentration of Cr(VI) increases. Interestingly, variations in adsorbent dosage and temperature also impact the removal efficiency. For example, with Mesquite (0.5 g) at 500 ppm concentration and 60°C, the removal percentage is 56.9%, showcasing the influence of temperature on the adsorption process. Comparing the two different adsorbents, it's apparent that their efficiencies differ based on the concentration of Cr(VI). Bagasse, at 500 ppm (5 g), achieves 100% removal, suggesting its effectiveness in this scenario. On the other hand, for the same concentration, Mesquite (5 g) reaches a removal percentage of 55.2%, indicating a lower efficiency compared to Bagasse. Moreover, the data highlights how the percentage removal can vary significantly based on the adsorbent and the concentration of Cr(VI). This variation underscores the importance of considering multiple factors when designing adsorption processes for effective Cr(VI) removal.

In this study on the removal of Cr(VI) using bagasse, several insights were gleaned that can be applied to address the removal of Cr(VI), nitrates, and phosphates from tannery wastewater using SiO₂-fused

Table 4 — Removal percentage of Cr (VI) on biomass derived from Mesquite and Bagasse

Adsorbents	Concentration of Cr(VI) in the liquid (ppm)	Percentage removal (%)
Mesquite 100 ppm (0.5 g)	0	100
Mesquite 200 ppm (0.5 g)	96.71	51.64
Mesquite 500 ppm (0.5 g)	175.36	64.9
Mesquite 500 ppm (2 g)	158.64	68.27
Mesquite 500 ppm (5 g)	224	55.2
Mesquite 500 ppm (0.5 g) (60°C)	215.28	56.9
Bagasse 100 ppm (0.5 g)	52.87	47.13
Bagasse 200 ppm (0.5 g)	132	34
Bagasse 500 ppm (0.5 g)	189.53	62.09
Bagasse 500ppm (2 g)	114	77.2
Bagasse 500 ppm (5 g)	0	100
Bagasse 500 ppm (0.5 g) (60°C)	284.12	43.176

biochar derived from bagasse. Some of the scope are as follows: A) Adsorbent Choice and Modification: This study highlighted the potential of bagasse as an effective adsorbent for Cr(VI) removal. By integrating SiO₂ with biochar from bagasse, there's potential to enhance the biochar's surface properties, porosity, and overall adsorption capacity. The incorporation of silica might introduce additional functional groups, improve the stability of the biochar, and enhance its affinity not only for Cr(VI) but also for nitrates and phosphates. B) Temperature Optimization: The findings emphasized the influence of temperature on Cr(VI) removal efficiency. Similar temperature-dependent studies using SiO₂-fused biochar can guide the determination of optimal conditions for the removal of Cr(VI), nitrates, and phosphates from tannery wastewater. C) Hybrid Systems: Given the prominence of hybrid systems in the removal of Cr(VI), a combined approach, where SiO₂-fused biochar is used alongside other treatment techniques or adsorbents, could provide synergistic benefits for the concurrent removal of multiple contaminants. D) pH Sensitivity: The pH of tannery effluents can vary, affecting the speciation of Cr(VI) and the solubility of other contaminants like nitrates and phosphates. Investigating the pH sensitivity of SiO₂-fused biochar can be instrumental in identifying the best pH range for maximum contaminant removal. E) Co-adsorption Mechanisms: Given the multi-contaminant nature of tannery wastewater, it's crucial to understand how fused biochar performs when exposed to a mixture of ions. This will inform its selectivity and overall efficacy in complex scenarios. F) Regeneration and Reuse: For sustainable wastewater treatment, understanding the regeneration capabilities of biochar

and assessing its performance across multiple cycles will be pivotal. G) Particle Size and Surface Area Optimization: Refining the particle size of biochar and enhancing its surface area can improve its adsorption efficiency for Cr(VI), nitrates, and phosphates.

Conclusion

The experimental investigation focused on the removal of hexavalent chromium [Cr(VI)] using biomass derived from *Prosopis juliflora* (Mesquite) and bagasse revealed valuable insights into their efficacy as potential adsorbents. Both Mesquite and bagasse exhibit varying degrees of removal efficiency depending on the experimental conditions. Mesquite displayed higher removal percentages for certain concentrations of Cr(VI). For instance, at a concentration of 100 ppm and a temperature of 60°C, Mesquite achieved a removal percentage of approximately 47.13%, while bagasse exhibited a removal percentage of 43.176%. It is also apparent that their removal efficiencies are influenced by their properties and characteristics. Mesquite showcased higher removal efficiency for some concentrations, while bagasse demonstrated better performance for others. This highlights the importance of optimizing the choice of adsorbent based on the specific concentration of Cr(VI) in the water source. Furthermore, the varying removal percentages underscore the significance of understanding the intricate interplay of adsorbent properties, concentration levels, and operating conditions. This knowledge is pivotal for designing effective and tailored adsorption strategies for hexavalent chromium removal from contaminated water sources. Future research can delve deeper into understanding the mechanisms driving these variations and optimize the adsorption process for enhanced Cr(VI) removal.

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