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Marine-derived adsorption biomaterials for water treatment: Efficiency and kinetics of textile dye removal using functionalized fish bone adsorbents

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A B S T R A C T

This study provides a low-cost, environmentally friendly, and biologically derived adsorbent alternative for the removal of toxic dyes commonly found in industrial wastewater. The modification of waste materials such as fish bones contributes to sustainable resource utilization while achieving effective results in reducing dye pollution originating from the textile, food, and chemical industries. The adsorption mechanism was investigated by kinetic and diffusion models, since, they provide important data for the design and optimization of such materials. The surface of fish bone particles was modified in two steps. Firstly, the particles (H) were silanized with 3-aminopropyltriethoxysilane (S). In the second step, modification was made by shift base reaction between the amine on the surface and 2-Ethyl-2H-pyrazole-3-carbaldehyde (A). Adsorption experiments were conducted using fuchsine solution at different initial concentrations (6.76, 3.38, 1.69, and 0.676 mg/L) and adsorption capacity (q_e), removal efficiency (%), and kinetic parameters were comprehensively investigated. The results showed a noticeable increase in adsorption capacity (0.08–0.94 mg/g) with increasing initial concentration, while kinetic analyses indicated that the adsorption process followed the pseudo-second-order kinetic model with a high degree of correlation, suggesting that chemical interactions may play a dominant role in the adsorption mechanism.

INTRODUCTION

Globally, industrial activities lead to serious pollution of water resources, a problem that becomes especially pronounced due to dye waste originating from the textile, food, leather, and chemical industries (Markandeya and Shukla, 2022; Negi, 2025). Dyes possess high chemical stability and complex molecular structures, making them resistant to natural degradation processes and resulting in persistent pollution within aquatic ecosystems. Some dyes, in particular, exhibit toxic, mutagenic, and carcinogenic properties, posing significant risks to both human health and the environment. Therefore, the effective and economical treatment of dye-containing wastewater has become a priority research topic in environmental engineering and sustainable development policies (Lellis et al., 2019; Tkaczyk et al., 2020; Karabulut and Gürkan, 2023; Ambade et al., 2024; Dutta et al., 2025). Although conventional wastewater treatment methods such as chemical precipitation, ozonation, membrane filtration, and biological processes are commonly used, these methods often face limitations such as high operational costs, secondary waste generation, and low efficiency (Matesun et al., 2024; Sravan et al., 2024). Therefore, in recent years, there has been growing interest toward environmentally friendly, low-cost, and sustainable alternative treatment technologies. Among these technologies, adsorption has gained prominence due to its ease of application, high efficiency, and flexibility, making it a widely preferred method, particularly for dye removal applications (Moosavi et al., 2020; Zhang et al., 2025). Traditional adsorbents used in adsorption processes include activated carbon, silica, alumina, and various synthetic polymers; however, the high production costs and environmental impacts of these materials limit their widespread use. Therefore, developing low-cost, biodegradable adsorbents derived from renewable resources has become highly important (Satyam and Patra, 2024; Akhtar et al., 2024).

In recent years, there has been a growing focus on developing low-cost and environmentally friendly adsorbent materials. Agricultural and industrial wastes as adsorbents offers a sustainable approach for both waste management and water treatment (Mo et al., 2018; Ahmad, 2023; Alvez-Tovar et al., 2025). Marine-derived biomaterials, particularly the valorization of fish industry wastes, present remarkable potential in this field. Marine-origin biomaterials stand out as innovative and eco-friendly solutions in wastewater treatment applications (Uranga et al., 2019; Rudovica et al., 2021; Chellapandian et al., 2025). With the development of aquaculture and the parallel growth of the aquaculture processing sector, the availability of fish waste has also increased (Bayraklı and Duyar, 2019; Bayraklı et al., 2019; Bayraklı, 2023). Fish bones, shells of marine organisms, and other residues from the seafood processing industry are considered suitable raw materials for the production of functional adsorbents due to their rich mineral content and porous structures. Fish bones, a significant by-product of the seafood processing industry, represent a potential raw material for adsorption applications due to their high calcium carbonate content and porous structure (Kizilkaya et al., 2010). Fish bones are natural materials with high active surface areas that are amenable to various surface modifications and can be chemically stabilized. The utilization of such waste contributes both to the production of environmentally friendly materials and to marine waste management policies (Bayraklı et al., 2019, 2024; Duyar and Bayraklı, 2023). In this study, fish bone particles were functionalized through surface modifications, and their adsorption properties were thoroughly investigated for the removal of the anionic dye fuchsine, which originates from the textile industry. The results aim to highlight the potential use of marine-derived materials in wastewater treatment technologies and to contribute to the existing literature in this field.

MATERIALS AND METHODS

Functionalization of Bone Surfaces

In this study, the surface modification of fish bone particles (H) with 2-Ethyl-2H-pyrazole-3-carbaldehyde (A) was performed according to our previous studies (Kizilkaya et al., 2016, 2018). In summary, the surface modification was carried out in two steps. In the first step, the bone particle surfaces were silanized with 3-aminopropyltriethoxysilane (S). The silanization process began by stirring the silane solution (ethanol/water 9:1) for 30 minutes. Then, 5 g of H was added and stirred at room temperature for 24 hours. The resulting suspension was centrifuged and washed five times with technical ethanol and dried at 45°C. The obtained product was named HS. Subsequently, aldehyde modification was performed on the surface using 2-Ethyl-2H-pyrazole-3-carbaldehyde. For the aldehyde modification, an aldehyde solution (in ethanol) was prepared, and HS was added; the mixture was refluxed at 70 °C for 6 hours. After cooling, the mixture was left to rest at room temperature for 12 hours. Then, the mixture was washed five times with technical ethanol by centrifugation and dried at 45°C. The final product was named HSA.

Adsorption and Removal Studies

The experiments were conducted at room temperature (23 ± 1°C). Using an adsorbent-to-solvent ratio of 1:200, after adsorption and interaction times of 30 and 24 hours, the liquid phase was taken from the solution, filtered through a 0.45 μm syringe filter, and analyzed instrumentally to complete the experiment. Fuchsine was used as the cationic dye. Measurements were performed with a PG Instruments T80-UV/VIS spectrophotometer available at our faculty. Adsorption studies in aqueous media were carried out by measuring the absorbance at the maximum wavelength (λ_{max}) of 550 nm using UV spectrophotometry. The adsorption of fuchsine dye was investigated for all obtained materials. The HSA product was treated with fuchsine solutions at concentrations of 6.76, 3.38, 1.69, and 0.676 mg/L. Experiments were completed by filtering the liquid phase from the solution through a 0.45 μm syringe filter after 24 hours of adsorption time at an adsorbent-to-solvent ratio of 1:200. The change in absorbance of the sorption solution was analyzed by UV spectrophotometry to determine the amount of adsorbed fuchsine.

RESULTS AND DISCUSSION

Fuchsine is a synthetic dye belonging to the triphenylmethane group, widely used in the textile industry, characterized by high water solubility and vibrant colors. Its chemical structure contains aromatic ring systems and amino groups, providing bright pink and magenta hues. (Degano et al., 2019; Tamburini et al., 2024). Due to its high chemical stability and solubility, fuchsine poses a risk of persistent pollution in wastewater. When discharged into aquatic environments, particularly from textile and dye industries, it remains dissolved for extended periods, adversely affecting ecosystems and human health. This underscores the environmental necessity of effectively removing fuchsine in wastewater treatment processes (Liu et al., 2022; Al-Qarhami et al., 2025). Studies on the adsorption-based removal of fuchsine demonstrate that biologically derived adsorbents with surface modifications can be especially effective. Fuchsine can form electrostatic interactions, hydrogen bonds, and π-π interactions with adsorbent surfaces, enhancing adsorption capacity (Rajumon et al., 2019; Mohammadzadeh Pakdel et al., 2022). Therefore, developing low-cost, sustainable, and eco-friendly adsorbents for the treatment of dyes like fuchsine is of great importance. Figure 1 shows the results of the amount adsorbed per gram (mg/g), mole (µmol/g) and percentage removal (%) of the fuchsin dye adsorption of the bone particle surface modified HSA product. When evaluating the adsorption experimental results of fuchsine dye using the surface-modified fish bone-based adsorbent, the effect of the initial concentration on adsorption capacity and removal efficiency was clearly observed. At an initial concentration (C_0) of 6.76 mg/L, the amount of dye adsorbed per gram of adsorbent (q_e) was calculated as 0.94 mg/g (2.792 µmol/g), and under these conditions, the removal efficiency reached 69.60%. When the initial concentration decreased to 3.38 mg/L, the q_e value was recorded as 0.47 mg/g (1.389 µmol/g) with a removal efficiency of 69.26%. At a further reduced concentration of 1.69 mg/L, q_e was 0.22 mg/g (0.652 µmol/g) and removal efficiency was 65.03%. At the lowest initial concentration of 0.676 mg/L, the adsorption capacity was measured as 0.08 mg/g (0.223 µmol/g) with a removal efficiency of 55.47%. These data indicate that adsorption capacity increases with rising initial dye concentration, while removal efficiency tends to decrease below a certain concentration threshold. This is particularly attributed to the limited interaction probability between dye molecules in solution and the abundant active sites on the adsorbent surface at low concentrations, leading to relatively lower removal efficiencies. It can be concluded that surface-modified fish bone-based adsorbents demonstrate a certain adsorption capacity toward anionic dyes like fuchsine and can be considered as low-cost, biologically sourced alternative adsorbents. They hold promising potential for dye removal in environmental applications.

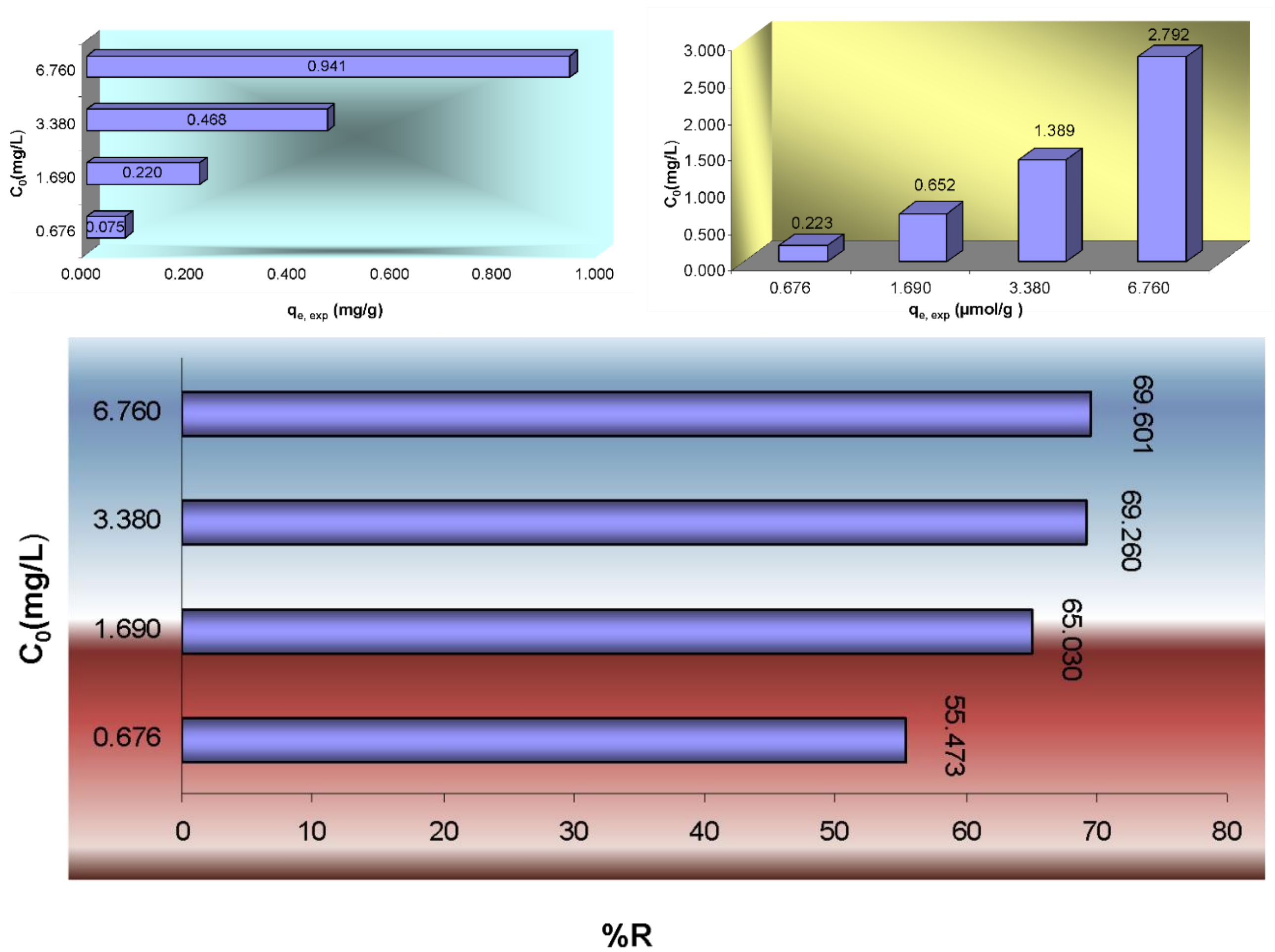

Figure 1. Results of the amount adsorbed per gram (mg/g), mole (µmol/g) and percentage removal (%) of the fuchsin dye adsorption of the bone particle surface modified HSA product

The adsorption capacities of fish bone were determined and expressed in terms of milligrams of adsorbed substance per gram of fish bone (mg/g), calculated using the relevant equation (1) (Kizilkaya et al., 2010; Kizilkaya and Tekinay, 2011):

$$q_t = \frac{(C_0 - C_t) \cdot V}{W} \quad (1)$$

In this equation, C_0 represents the initial concentration of metal ions (mg/L), while C_t indicates the metal ion concentration at time t after adsorption (mg/L). V refers to the volume of the metal ion solution (mL), and W denotes the weight of the fish bone adsorbent used in the process (g).

The kinetic behavior of the adsorption process was evaluated according to the pseudo-first-order model, applying the Lagergren equation as shown in equation (2) (El-Sikaily et al., 2007; Chairat et al., 2006; Cheung et al., 2000; Kizilkaya, 2012a):

$$\ln(q_e - q_t) = \ln q_{e,cal} - k_1 \cdot t \quad (2)$$

In the pseudo-first-order kinetic model, k_1 represents the rate constant of adsorption (h^{-1}), while q_e and q_t correspond to the amounts of metal adsorbed per gram of fish bone (mg/g) at equilibrium and at any given time t, respectively. A linear relationship was observed when plotting $ln(q_e - q_t)$ against t, confirming the applicability of the pseudo-first-order model to the adsorption process. The slope and intercept obtained from this linear plot were used to determine both the pseudo-first-order rate constant k_1 and the calculated equilibrium adsorption capacity $q_{e,cal}$.

Equation (3) was employed to represent the pseudo-second-order kinetic behavior of the adsorption process (Chiou and Li, 2003; Smičiklas et al., 2006; Kizilkaya, 2012b):

$$t/q_t = 1/k_{2}q_{e,cal}^{2} + t/q_{e,cal} \quad (3)$$

In the pseudo-second-order kinetic model, k_2 (g bone/mg·h) represents the rate constant of adsorption. A linear relationship was observed when plotting t/q_t against t, indicating that the adsorption process follows pseudo-second-order kinetics. The equilibrium adsorption capacity ($q_{e,cal}$) and the rate constant k_2) were determined from the slope and intercept of the t/q_t versus t plot.

The initial adsorption rate, h_i, was calculated using the rate constant k_2 derived from the pseudo-second-order kinetic model and is expressed by the following equation (4) (Chiou and Li, 2003; Chairat et al., 2006):

$$h_i = k_{2}q_{e,cal}^{2} \quad (4)$$

In this equation, the parameter h_i denotes the initial rate of metal adsorption, measured in milligrams of metal adsorbed per gram of bone per hour (mg/g bone·h). The constants k_2, $q_{e,cal}$ and h were calculated from the intercept and slope of the line obtained by plotting t/q_t against t.

The intraparticle diffusion (IPD) model developed by Weber and Morris is commonly used to analyze the kinetics of adsorption processes (Wu et al., 2009). Weber–Morris and Urano–Tachikawa models were employed to describe the diffusion behavior of fuchsine dye from aqueous solution. The Weber and Morris diffusion model is expressed by the following equation (5) (El-Sikaily et al., 2007; Hameed et al., 2008; Greluk and Hubicki, 2009; Kızılkaya et al., 2012b):

$$q_t = Kw.t^{0.5} + C \quad (5)$$

In this equation, Kw ($mg.g^{-1}\ h^{-0.5}$) represents the intraparticle diffusion rate constant according to Weber and Morris, while C is the intercept value of the plot, which provides insight into the boundary layer thickness (mg/g). The amount of adsorption at any time, q_t, is plotted against the square root of time ($t^{0.5}$) resulting in a linear relationship. The intraparticle diffusion constant (Kw) is determined from the slope of the q_t versus $t^{0.5}$ plot. The intraparticle diffusion coefficient (Dw) was calculated using the following equation (6) (Selatnia et al., 2004; Freitas et al., 2008; Kızılkaya et al., 2012a):

$$Dw = (\pi/8640)(dKw/q_e)^2 \quad (6)$$

In this equation, Dw ($m^2\ h^{-1}$) is the diffusion coefficient in the solid and d (m) is the mean particle diameter.

Equation (7) was employed to describe the intraparticle diffusion model developed by Urano and Tachikawa (1991) as applied by (Freitas et al., 2008; Kızılkaya et al., 2012b):

$$-\log\left[1 - (q_t/q_e)^2\right] = 4\pi^2\, D_i t/2.3d^2 \quad (7)$$

In this equation, D_i ($m^2\ min^{-1}$) is the diffusion coefficient in the solid. D_i was calculated from the slopes of $-log[1-(q_t/q_e)^2]$ versus t plots.

Based on the kinetic data presented in Table 1, the adsorption of fuchsine dye using the surface-modified fish bone-based adsorbent was evaluated according to the pseudo-first-order kinetic model. The experimentally obtained adsorption capacity values ($q_{e,exp}$) were compared with the adsorption capacities calculated from the model ($q_{e,cal}$) as well as the rate constant (k_1) values. At an initial concentration of 6.76 mg/L, the experimental adsorption capacity was measured as 0.94 mg/g, whereas the model-calculated value was 0.39 mg/g, with the corresponding rate constant 0.420 h^{-1} (k_1). Under these conditions, the correlation coefficient (R^2) was 0.869, indicating a limited fit to the model. Similarly, at an initial concentration of 3.38 mg/L, the experimental q_e was 0.47 mg/g, and the model value was calculated as 0.20 mg/g. The R^2 value of 0.948 indicated the best fit, suggesting that the pseudo-first-order kinetic model better represents the adsorption process within the mid-concentration range. At lower concentrations, such as 1.69 mg/L and 0.676 mg/L, a similar trend was observed. In both cases, the experimental q_e values differed from the model values, with R^2 values of 0.905 and 0.898, respectively. Overall, it can be concluded that the pseudo-first-order kinetic model shows a better fit in the mid-concentration range for fuchsine dye adsorption on surface-modified fish bone; however, a perfect fit across all concentration ranges was not achieved. This suggests that the adsorption mechanism is not limited to physical adsorption alone and that other processes such as chemical interactions or film diffusion may also play significant roles.

The kinetic data for fuchsine dye adsorption using the surface-modified fish bone-based adsorbent (Table 1) were evaluated according to the pseudo-second-order kinetic model. The results demonstrate that this model represents the adsorption process with high accuracy. Across all concentration ranges, the experimentally obtained adsorption capacities ($q_{e,exp}$) closely matched the model-calculated values ($q_{e,cal}$), with correlation coefficients (R^2) ranging from 0.9909 to 0.9980. An increase in adsorption capacity was observed with rising initial concentrations. For example, at an initial concentration of 6.76 mg/L, the calculated $q_{e,cal}$ was 0.95 mg/g, with a rate constant (k_2) of 3.43 g/mg·h and an initial adsorption rate (h_i) of 3.11 mg/g·h. Similarly, at 3.38 mg/L, $q_{e,cal}$ was 0.47 mg/g, k_2 was 6.37 g/mg·h, and h_i was 1.41 mg/g·h. At lower concentrations, such as 1.69 mg/L and 0.676 mg/L, $q_{e,cal}$ values were 0.22 mg/g and 0.08 mg/g, while k_2 values increased to 20.23 g/mg·h and 31.92 g/mg·h, respectively. Notably, as the initial concentration decreased, the rate constant (k_2) increased, whereas the initial adsorption rate (h_i) decreased. This indicates that adsorption occurs more rapidly at lower concentrations but with a more limited total adsorption capacity. These results reveal that the surface-modified fish bone adsorbent is effective in removing fuchsine dye and that the adsorption process follows the pseudo-second-order kinetic model. This suggests that adsorption is largely driven by chemical interactions, involving strong binding between the active sites on the adsorbent surface and the dye molecules. Considering the development of low-cost and environmentally friendly adsorbents, fish bone-based materials show promise as an alternative and sustainable option.

For the adsorption of fuchsine dye using the surface-modified fish bone-based adsorbent, both the pseudo-first-order and pseudo-second-order kinetic models were individually evaluated, and the obtained data were compared. Examination of the pseudo-first-order kinetic model revealed noticeable differences between the experimental adsorption capacity ($q_{e,exp}$) and the model-calculated adsorption capacity ($q_{e,cal}$), especially at high and low concentrations, with correlation coefficients (R^2) ranging from 0.869 to 0.948. This indicates that the pseudo-first-order model only partially represents the adsorption process of fuchsine dye. While this model is generally associated with physical adsorption processes, the results of this study suggest that physical adsorption alone cannot fully explain the mechanism. In contrast, the pseudo-second-order kinetic model results showed much closer agreement between experimental and calculated q_e values, with R^2 values ranging from 0.9909 to 0.9980. Furthermore, the rate constant (k_2) and initial adsorption rate (h_i) calculated in the pseudo-second-order model exhibited systematic changes depending on the initial concentration. This high degree of fit and systematic variation strongly indicates that the adsorption mechanism predominantly involves chemical adsorption (chemisorption), with strong bonds forming between the active groups on the adsorbent surface and the fuchsine dye molecules. In conclusion, based on the evaluation of both

Table 1. Pseudo first and second order kinetic constants of fuchsin adsorption of HSA product

$q_{e,exp}$ (mg/g)	Pseudo-first-order			Pseudo-second -order			
	$q_{e,cal}$ (mg/g)	k_1 (h^{-1})	R^2	$q_{e,cal}$ (mg/g)	k_2 (g/mg.h)	R^2	h_i (mg/g.h)
0.94	0.39	0.420	0.869	0.95	3.43	0.991	3.11
0.47	0.20	0.341	0.948	0.47	6.37	0.990	1.41
0.22	0.08	0.439	0.905	0.22	20.23	0.998	1.00
0.08	0.04	0.485	0.898	0.08	31.92	0.991	0.19

Table 2. Diffusion calculation results of fuchsin absorption of HSA product

Urano and Tachikawa		**Weber and Morris**		
D_i (m^2h^{-1})	**R^2**	**Kw (mg $g^{-1}h^{-0.5}$)**	**D_w (m^2h^{-1})**	**R^2**
9.762×10^{-11}	0.854	167.81×10^{-3}	1.1559×10^{-13}	0.972
7.706×10^{-11}	0.945	89.19×10^{-3}	1.3191×10^{-13}	0.969
1.013×10^{-10}	0.923	42.821×10^{-3}	1.3799×10^{-13}	0.831
5.57×10^{-11}	0.937	13.611×10^{-3}	1.1971×10^{-13}	0.943

kinetic models, the adsorption of fuchsine dye onto the surface-modified fish bone adsorbent better fits the pseudo-second-order kinetic model. The high correlation coefficients and the close agreement between calculated and experimental values serve as significant evidence that adsorption occurs mainly through chemical interactions in the system. In this context, the study results demonstrate that surface-modified fish bone-based adsorbents offer an effective and sustainable solution, particularly for environmental applications such as dye removal.

The Urano and Tachikawa model is a kinetic model commonly used to investigate the effect of film diffusion in adsorption processes. Film diffusion refers to the movement of solvent or dissolved substances through a thin liquid layer that exists between the bulk solution and the adsorbent surface before the adsorbate reaches the adsorbent. This thin film can create resistance to mass transfer and may act as a rate-limiting step in the overall adsorption process. The model enables the calculation of parameters such as the film diffusion coefficient (D_i), which quantifies the rate of mass transfer through the film layer. Thus, it allows evaluation of whether film diffusion acts as a limiting step in adsorption. The Urano and Tachikawa model serves as an important tool for understanding adsorption mechanisms by helping to distinguish different mass transfer steps. It is widely used in environmental engineering and chemical process applications to optimize adsorption by improving process conditions. In summary, the Urano and Tachikawa model mathematically describes the kinetic effect of film diffusion in adsorption and quantitatively determines the magnitude of this effect (Urano and Tachikawa, 1991; Freitas et al., 2008; Yao and Chen, 2017; Lopičić et al., 2019). The Urano and Tachikawa model as the role of film diffusion in the adsorption of fuchsine dye onto the surface-modified fish bone-based adsorbent was investigated in Table 2. The obtained film diffusion coefficient (D_i) values range between 5.57×10^{-11} m^2/h and 1.013×10^{-11} m^2/h. These values indicate that mass transfer through the film layer on the modified fish bone surface is relatively slow but cannot be neglected. Additionally, correlation coefficients (R^2) vary from 0.854 to 0.945, suggesting that while film diffusion contributes to the adsorption process, it does not solely control it. Particularly in concentration ranges where R^2 values exceed 0.9, film diffusion appears to play a more significant role as a rate-controlling step affecting adsorption speed. Overall, the results from the Urano and Tachikawa model suggest that fuchsine dye adsorption onto the surface-modified fish bone adsorbent is partially controlled by film diffusion, but the adsorption cannot be fully explained by this mechanism alone. The adsorption process occurs as a combined effect of surface interactions as well as film and intraparticle diffusion steps.

The Weber and Morris model is a widely used kinetic approach to investigate the role of intraparticle diffusion in adsorption processes. This model provides important parameters to evaluate the rate of mass transfer occurring within the internal structure of adsorbent particles and whether this step acts as a rate-limiting factor (El-Sikaily et al., 2007; Hameed et al., 2008; Greluk and Hubicki, 2009; Wu et al., 2009; Chu et al., 2025). The results presented in Table 2 include values for Kw (intraparticle diffusion rate constant), D_w (intraparticle diffusion coefficient), and R^2 (correlation coefficient). The Kw values range from 13.6 to 167.8×10^{-3} $mg\cdot g^{-1}\cdot h^{-0.5}$. As an indicator of the intraparticle diffusion rate, higher Kw values suggest faster intraparticle diffusion. These results indicate variations in diffusion rates depending on adsorption conditions. Specifically, higher Kw values reflect increased kinetic facilitation at this stage and highlight the significant role of diffusion. The Dw values range narrowly between 1.16×10^{-13} and 1.38×10^{-13} $m^2\cdot h^{-1}$, indicating generally slow intraparticle diffusion. Factors such as the pore structure of the adsorbent, particle size, and surface properties strongly influence these diffusion coefficients. The low Dw values suggest that intraparticle diffusion could be a rate-limiting step, potentially slowing down the overall kinetics. Correlation coefficients (R^2) vary between 0.831 and 0.972. High R^2 values (especially above 0.97) demonstrate strong agreement between the model and experimental data, indicating that intraparticle diffusion is an important mass transfer step in the adsorption kinetics and that the model accurately represents the process. Lower R^2 values suggest that other mechanisms such as film diffusion or chemical adsorption may also contribute. Overall, the data show that intraparticle diffusion plays a significant role in the adsorption of fuchsine dye onto the surface-modified fish bone adsorbent. However, the low intraparticle diffusion coefficients indicate that the process proceeds relatively slowly, pointing to the need for optimizing the adsorbent pore structure and surface properties to enhance adsorption rates. Therefore, strategies such as increasing pore volume, improving pore accessibility, and modifying surface chemistry could be pursued to enhance both adsorption capacity and kinetics. In conclusion, the Weber and Morris model parameters reveal that adsorption is partially controlled by intraparticle diffusion, which significantly influences adsorption performance. These insights can guide the design and application of modified fish bone-based adsorbents, contributing to the development of more effective and sustainable environmental solutions.

The kinetic and diffusion models related to the adsorption of fuchsine dye onto the surface-modified fish bone-based adsorbent were comprehensively evaluated, considering the mechanisms influencing the overall process. Within this scope, the results of the pseudo-first-order kinetic model, pseudo-second-order kinetic model, Urano and Tachikawa model, and Weber and Morris model were comparatively analyzed. The pseudo-first-order kinetic model showed limited agreement in describing the adsorption process. Deviations between experimentally obtained values and model calculations were observed, suggesting that physical adsorption alone does not sufficiently represent the adsorption mechanism. In contrast, the pseudo-second-order kinetic model exhibited very high correlation coefficients, indicating that the adsorption process is primarily chemical in nature and dominated by chemical interactions occurring on the adsorbent surface. The close agreement between experimental data and model calculations supports the dominant influence of this model on the process. The Urano and Tachikawa model, which evaluates the effect of diffusion, indicated that mass transfer from the solution to the adsorbent surface via film diffusion contributes to the adsorption process to a certain extent. However, film diffusion alone was not the rate-determining step, as reflected by lower correlation coefficients compared to the kinetic models. The Weber and Morris model highlighted the significance of intraparticle diffusion, showing that the adsorption process is partially controlled by diffusion within the adsorbent particles. The strong model fit especially points to the importance of the adsorbent pore structure and internal characteristics on the adsorption kinetics. However, the relatively low intraparticle diffusion coefficient suggests that this step could be rate-limiting. Overall, the evaluation demonstrates that the adsorption of fuchsine dye onto the surface-modified fish bone adsorbent is a multi-mechanistic process. In addition to chemical adsorption, film diffusion and intraparticle diffusion mechanisms also influence the process. The high conformity of the pseudo-second-order kinetic model underscores the dominance of chemical interactions, while diffusion models indicate that mass transfer steps cannot be neglected. This comprehensive analysis emphasizes the need to consider both surface chemistry and structural properties of the adsorbent to enhance its efficiency and performance in environmental applications.

CONCLUSION

This study holds significant importance as it offers a biologically sourced, low-cost, and environmentally friendly adsorbent alternative for the removal of toxic dyes commonly found in industrial wastewater. The modification and utilization of waste materials such as fish bones contribute to sustainable resource management while enabling the development of value-added products. Dye pollution, originating particularly from the textile, food, and chemical industries poses a serious threat to aquatic ecosystems. The effective removal of fuchsine dye in this study presents promising results for the treatment of other structurally similar anionic dyes. The findings shed light on the development of more economical and ecological solutions compared to conventional wastewater treatment methods. Moreover, the detailed investigation of adsorption mechanisms through kinetic and diffusion models provides critical information for the design and optimization of such materials. The multidisciplinary approach of this study serves as a valuable reference for researchers in environmental engineering, materials science, and chemistry. In this research, the efficacy of HSA adsorbent—obtained by chemically functionalizing fish bone waste was evaluated for the removal of fuchsine dye from aqueous solutions. Experimental results demonstrated that the modified fish bone adsorbent exhibited high adsorption capacity for fuchsine, with adsorption capacity increasing alongside initial dye concentration. Kinetic analyses revealed that the adsorption process followed a pseudo-second-order kinetic model, indicating that chemical adsorption is the dominant mechanism. Diffusion studies conducted using Weber-Morris and Urano-Tachikawa models showed that both intraparticle diffusion and film diffusion contribute to the adsorption process but neither acts as the sole rate-limiting step. Notably, a removal efficiency of 69.60% was achieved at the highest concentration tested (6.76 mg/L), proving the potential of this material as an alternative for industrial wastewater treatment. One of the key contributions of this study is providing an environmentally friendly and cost-effective solution to the waste management challenges faced by the seafood processing industry. The valorization of biological wastes such as fish bones serves as an important example in the development of sustainable water treatment technologies. While the results demonstrate the applicability of modified fish bone adsorbents particularly for treating textile and dye industry wastewater, future studies are recommended to test different dyes and real industrial wastewater samples. In conclusion, this research makes a significant contribution to the development of innovative and sustainable solutions in waste management and water treatment technologies, offering practical insights for industrial applications.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon request.

AI Disclosure

Generative AI (e.g., ChatGPT 4.0, DeepSeek) was used for grammatical review of the introduction and discussion sections. The author validated all outputs and assume full responsibility for the content.

REFERENCES

Ahmad, F. A. (2023). The use of agro-waste-based adsorbents as sustainable, renewable, and low-cost alternatives for the removal of ibuprofen and carbamazepine from water. *Heliyon*, *9*(6), e16449. https://doi.org/10.1016/j.heliyon.2023.e16449

Akhtar, M. S., Ali, S., & Zaman, W. (2024). Innovative adsorbents for pollutant removal: Exploring the latest research and applications. *Molecules*, *29*(18), 4317. https://doi.org/10.3390/molecules29184317

Al-Qarhami, F., Khalifa, M. E., Abdallah, A. B., & Awad, F. S. (2025). Remediation of wastewater containing methylene blue and acid fuchsin dyes using 2-aminothiazole chemically modified chitosan. *International Journal of Biological Macromolecules*, *303*, 140744. https://doi.org/10.1016/j.ijbiomac.2025.140744

Alvez-Tovar, B., Scalize, P. S., Angiolillo-Rodríguez, G., Albuquerque, A., Ebang, M. N., & de Oliveira, T. F. (2025). Agro-industrial waste upcycling into activated carbons: A sustainable approach for dye removal and wastewater treatment. *Sustainability*, *17*(5), 2036. https://doi.org/10.3390/su17052036

Ambade, K., Kumar, A., & Gautam, S. (2024). Sustainable solutions: Reviewing the future of textile dye contaminant removal with emerging biological treatments. *Limnological Review*, *24*(2), 126–149. https://doi.org/10.3390/limnolrev24020007

Bayraklı, B. (2023). Utilization of fish by-products for sustainable aquaculture: nutritional analysis of fishmeal derived from the by-products of *Oncorhynchus mykiss*. *Menba Journal of Fisheries Faculty*, *9*(2), 8–14. https://doi.org/10.58626/menba.1360875

Bayraklı, B., & Duyar, H. A. (2019). The effect of raw material freshness on fish oil quality produced in fish meal & oil plant. *Journal of Anatolian Environmental and Animal Sciences*, *4*(3), 473–479. https://doi.org/10.35229/jaes.636002

Bayraklı, B., Özdemir, S., & Duyar, H. A. (2019). A study on fishing and fish meal-oil processing technology of anchovy (*Engraulis encrasicolus*) and European sprat (*Sprattus sprattus*) in the Black Sea. *Menba Journal of Fisheries Faculty*, *5*(2), 9–16.

Bayraklı, B., Yiğit, M., Altuntaş, M., & Maita, M. (2024). Health risk assessment of metals via consumption of Rapa whelk (*Rapana venosa*) from the Black Sea. *Journal of Agricultural Sciences*, *30*(3), 546–561. https://doi.org/10.15832/ankutbd.1374919

Chairat, M., Rattanaphani, S., Bremner, J. B., & Rattanaphani, V. (2006). Adsorption kinetic study of lac dyeing on cotton. *Dyes and Pigments*, *76*(2), 435–439. https://doi.org/10.1016/j.dyepig.2006.09.008

Chellapandian, H., Jeyachandran, S., Park, K., & Kwak, I. (2025). Marine-derived functional biomaterials: Advancements in biomedicine and drug delivery applications. *Natural Product Communications*, *20*(6). https://doi.org/10.1177/1934578X241302009

Cheung, C., Porter, J., & McKay, G. (2000). Sorption kinetics for the removal of copper and zinc from effluents using bone char. *Separation and Purification Technology*, *19*(1–2), 55–64. https://doi.org/10.1016/s1383-5866(99)00073-8

Chiou, M. S., & Li, H. Y. (2003). Adsorption behavior of reactive dye in aqueous solution on chemical cross-linked chitosan beads. *Chemosphere*, *50*(8), 1095–1105. https://doi.org/10.1016/S0045-6535(02)00636-7

Chu, K. H., Hashim, M. A., Zawawi, M. H., & Bollinger, J.-C. (2025). The Weber–Morris model in water contaminant adsorption: Shattering long-standing misconceptions. *Journal of Environmental Chemical Engineering*, *13*(4), 117266. https://doi.org/10.1016/j.jece.2025.117266

Degano, I., Sabatini, F., Braccini, C., & Colombini, M. P. (2019). Triarylmethine dyes: Characterization of isomers using integrated mass spectrometry. *Dyes and Pigments*, *160*, 587–596. https://doi.org/10.1016/j.dyepig.2018.08.046

Dutta, S., Adhikary, S., Bhattacharya, S., Roy, D., Chatterjee, S., Chakraborty, A., Banerjee, D., Ganguly, A., Nanda, S., & Rajak, P. (2024). Contamination of textile dyes in aquatic environment: Adverse impacts on aquatic ecosystem and human health, and its management using bioremediation. Journal of Environmental Management, 353, 120103. https://doi.org/10.1016/j.jenvman.2024.120103

Duyar, H. A., & Bayraklı, B. (2023). Fatty acid profiles of fish oil derived by different techniques from by-products of cultured Black Sea salmon, *Oncorhynchus mykiss*. *Journal of Agricultural Sciences*, *29*(3), 833–841. https://doi.org/10.15832/ankutbd.1187017

El-Sikaily, A., Nemr, A. E., Khaled, A., & Abdelwehab, O. (2007). Removal of toxic chromium from wastewater using green alga *Ulva lactuca* and its activated carbon. *Journal of Hazardous Materials*, *148*(1–2), 216–228. https://doi.org/10.1016/j.jhazmat.2007.01.146

Freitas, O. M., Martins, R. J., Delerue-Matos, C. M., & Boaventura, R. A. (2008). Removal of Cd(II), Zn(II) and Pb(II) from aqueous solutions by brown marine macro algae: Kinetic modelling. *Journal of Hazardous Materials*, *153*(1–2), 493–501. https://doi.org/10.1016/j.jhazmat.2007.08.081

Greluk, M., & Hubicki, Z. (2009). Sorption of SPADNS azo dye on polystyrene anion exchangers: Equilibrium and kinetic studies. *Journal of Hazardous Materials*, *172*(1), 289–297. https://doi.org/10.1016/j.jhazmat.2009.07.007

Hameed, B., Salman, J., & Ahmad, A. (2008). Adsorption isotherm and kinetic modeling of 2,4-D pesticide on activated carbon derived from date stones. *Journal of Hazardous Materials*, *163*(1), 121–126. https://doi.org/10.1016/j.jhazmat.2008.06.069

Karabulut, Y. K., & Gürkan, Y. Y. (2023). Investigation of toxicological properties of some azo dyes by OECD QSAR method. *Kirklareli University Journal of Engineering and Science*, *9*(1), 1–22. https://doi.org/10.34186/klujes.1242876

Kizilkaya, B. (2012a). Removal of azure a dye from aqueous environment using different pretreated fish bones: equilibrium, kinetic, and diffusion study. *Journal of Dispersion Science and Technology*, *33*(10), 1429–1436. https://doi.org/10.1080/01932691.2011.620896

Kizilkaya, B. (2012b). Usage of biogenic apatite (fish bones) on removal of basic fuchsin dye from aqueous solution. *Journal of Dispersion Science and Technology*, *33*(11), 1596–1602. https://doi.org/10.1080/01932691.2011.629497

Kizilkaya, B., & Tekinay, A. A. (2011). Comparative study and removal of Co and Ni (II) ions from aqueous solutions using fish bones. *Science of Advanced Materials*, *3*(6), 949–961. https://doi.org/10.1166/sam.2011.1222

Kızılkaya, B., Türker, G., Akgül, R., & Doğan, F. (2012a). Comparative study of biosorption of heavy metals using living green algae *Scenedesmus quadricauda* and *Neochloris pseudoalveolaris*: Equilibrium and kinetics. *Journal of Dispersion Science and Technology*, *33*(3), 410–419. https://doi.org/10.1080/01932691.2011.567181

Kızılkaya, B., Doğan, F., Akgül, R., & Türker, G. (2012b). Biosorption of Co(II), Cr(III), Cd(II), and Pb(II) ions from aqueous solution using nonliving *Neochloris pseudoalveolaris* Deason & Bold: Equilibrium, thermodynamic, and kinetic study. *Journal of Dispersion Science and Technology*, *33*(7), 1055–1065. https://doi.org/10.1080/01932691.2011.599214

Kizilkaya, B., Tan, E., Bahceci, D., Ormanci, H. B., & Oztekin, A. (2018). An investigation on the conversion of functional materials of fish bones as waste products using surface modification methods. *Indian Journal of Biotechnology*, 17(1), 57-64.

Kizilkaya, B., Tekinay, A. A., & Dilgin, Y. (2010). Adsorption and removal of Cu (II) ions from aqueous solution using pretreated fish bones. *Desalination*, *264*(1–2), 37–47. https://doi.org/10.1016/j.desal.2010.06.076

Kizilkaya, B., Ucyol, N., & Tekinay, A. A. (2016). Surface modification of biogenic hydroxyapatite particles with 2-thiophenecarboxaldehyde. *Environmental Science: An Indian Journal*, *12*(7):102.

Lellis, B., Fávaro-Polonio, C. Z., Pamphile, J. A., & Polonio, J. C. (2019). Effects of textile dyes on health and the environment and bioremediation potential of living organisms. *Biotechnology Research and Innovation*, *3*(2), 275–290. https://doi.org/10.1016/j.biori.2019.09.001

Liu, J., Wei, S., Zhang, H., Deng, Y., Baeyens, J., Dewil, R., Sweygers, N., & Appels, L. (2022). Adsorption of acid fuchsine dye from wastewater by Mg-ferrite particles. *Journal of Environmental Management*, *317*, 115427. https://doi.org/10.1016/j.jenvman.2022.115427

Lopičić, Z. R., Stojanović, M. D., Marković, S. B., Milojković, J. V., Mihajlović, M. L., Kaluđerović Radoičić, T. S., & Kijevčanin, M. L. J. (2019). Effects of different mechanical treatments on structural changes of lignocellulosic waste biomass and subsequent Cu(II) removal kinetics. *Arabian Journal of Chemistry*, *12*(8), 4091–4103. https://doi.org/10.1016/j.arabjc.2016.04.005

Markandeya, D. M., & Shukla, S. P. (2022). Hazardous consequences of textile mill effluents on soil and their remediation approaches. *Cleaner Engineering and Technology*, *7*, 100434. https://doi.org/10.1016/j.clet.2022.100434

Matesun, J., Petrik, L., Musvoto, E., Ayinde, W., & Ikumi, D. (2024). Limitations of wastewater treatment plants in removing trace anthropogenic biomarkers and future directions: A review. *Ecotoxicology and Environmental Safety*, *281*, 116610. https://doi.org/10.1016/j.ecoenv.2024.116610

Mo, J., Yang, Q., Zhang, N., Zhang, W., Zheng, Y., & Zhang, Z. (2018). A review on agro-industrial waste (AIW) derived adsorbents for water and wastewater treatment. *Journal of Environmental Management*, *227*, 395–405. https://doi.org/10.1016/j.jenvman.2018.08.069

Mohammadzadeh Pakdel, P., Peighambardoust, S. J., Foroutan, R., Arsalani, N., & Aghdasinia, H. (2022). Decontamination of fuchsin dye by carboxymethyl cellulose-graft-poly(acrylic acid-co-itaconic acid)/carbon black nanocomposite hydrogel. *International Journal of Biological Macromolecules*, *222*(Part B), 2083–2097. https://doi.org/10.1016/j.ijbiomac.2022.10.007

Moosavi, S., Lai, C. W., Gan, S., Zamiri, G., Akbarzadeh Pivehzhani, O., & Johan, M. R. (2020). Application of efficient magnetic particles and activated carbon for dye removal from wastewater. *ACS Omega*, *5*(33), 20684–20697. https://doi.org/10.1021/acsomega.0c01905

Negi, A. (2025). Environmental impact of textile materials: Challenges in fiber–dye chemistry and implication of microbial biodegradation. *Polymers*, *17*(7), 871. https://doi.org/10.3390/polym17070871

Rajumon, R., Anand, J. C., Ealias, A. M., Desai, D. S., George, G., & Saravanakumar, M. P. (2019). Adsorption of textile dyes with ultrasonic assistance using green reduced graphene oxide: An in-depth investigation on sonochemical factors. *Journal of Environmental Chemical Engineering*, *7*(6), 103479. https://doi.org/10.1016/j.jece.2019.103479

Rudovica, V., Rotter, A., Gaudêncio, S. P., Novoveská, L., Akgül, F., Akslen-Hoel, L. K., Alexandrino, D. a. M., Anne, O., Arbidans, L., Atanassova, M., Bełdowska, M., Bełdowski, J., Bhatnagar, A., Bikovens, O., Bisters, V., Carvalho, M. F., Catalá, T. S., Dubnika, A., Erdoğan, A., . . . & Burlakovs, J. (2021). Valorization of marine waste: Use of industrial by-products and beach wrack towards the production of high added-value products. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.723333

Satyam, S., & Patra, S. (2024). Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. *Heliyon*, *10*(9), e29573. https://doi.org/10.1016/j.heliyon.2024.e29573

Selatnia, A., Bakhti, M., Madani, A., Kertous, L., & Mansouri, Y. (2004). Biosorption of Cd^{2+} from aqueous solution by a NaOH-treated bacterial dead *Streptomyces rimosus* biomass. *Hydrometallurgy*, *75*(1–4), 11–24. https://doi.org/10.1016/j.hydromet.2004.06.005

Smičiklas, I., Dimović, S., & Plećaš, I. (2006). Removal of Cs^{1+}, Sr^{2+} and Co^{2+} from aqueous solutions by adsorption on natural clinoptilolite. *Applied Clay Science*, *35*(1–2), 139–144. https://doi.org/10.1016/j.clay.2006.08.004

Sravan, J. S., Matsakas, L., & Sarkar, O. (2024). Advances in biological wastewater treatment processes: Focus on low-carbon energy and resource recovery in biorefinery context. *Bioengineering*, *11*(3), 281. https://doi.org/10.3390/bioengineering11030281

Tamburini, D., Sabatini, F., Berbers, S., van Bommel, M. R., & Degano, I. (2024). An introduction and recent advances in the analytical study of early synthetic dyes and organic pigments in cultural heritage. *Heritage*, *7*(4), 1969–2010. https://doi.org/10.3390/heritage7040094

Tkaczyk, A., Mitrowska, K., & Posyniak, A. (2020). Synthetic organic dyes as contaminants of the aquatic environment and their implications for ecosystems: A review. *Science of The Total Environment*, *717*, 137222. https://doi.org/10.1016/j.scitotenv.2020.137222

Uranga, J., Etxabide, A., Cabezudo, S., De La Caba, K., & Guerrero, P. (2019). Valorization of marine-derived biowaste to develop chitin/fish gelatin products as bioactive carriers and moisture scavengers. *The Science of the Total Environment*, *706*, 135747. https://doi.org/10.1016/j.scitotenv.2019.135747

Urano, K., & Tachikawa, H. (1991). Process development for removal and recovery of phosphorus from wastewater by a new adsorbent. II. Adsorption rates and breakthrough curves. *Industrial & Engineering Chemistry Research*, *30*(8), 1897–1899. https://doi.org/10.1021/ie00056a033

Wu, F., Tseng, R., & Juang, R. (2009). Initial behavior of intraparticle diffusion model used in the description of adsorption kinetics. *Chemical Engineering Journal*, *153*(1–3), 1–8. https://doi.org/10.1016/j.cej.2009.04.042

Yao, C., & Chen, T. (2017). A film-diffusion-based adsorption kinetic equation and its application. *Chemical Engineering Research and Design*, *119*, 87–92. https://doi.org/10.1016/j.cherd.2017.01.004

Zhang, Z., Lu, Y., Gao, S., & Wu, S. (2025). Sustainable and efficient wastewater treatment using cellulose-based hydrogels: A review of heavy metal, dye, and micropollutant removal applications. *Separations*, *12*(3), 72. https://doi.org/10.3390/separations12030072