

Removal of ceftriaxone using modified layered double hydroxide MgAl-LDH with *Hylocereus costaricensis* extract

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Abstract

The use of pharmaceutical products, especially the antibiotic ceftriaxone (CTX), is increasingly widespread and raises serious concerns due to its waste residues that pollute the environment. In this study, a layered double hydroxide (MgAl-LDH) material was modified using dragon fruit peel extract (*Hylocereus costaricensis*) to develop an adsorbent (MgAl-HC) for removing CTX antibiotic effluent from the aquatic environment. LDH was synthesized using the co-precipitation method and dragon fruit extract was obtained through maceration. Material characterization was performed using X-Ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Brunauer-Emmett-Teller (BET) analysis, and showed that modification with dragon fruit peel extract increased the specific surface area from 18.471 m²/g to 28.035 m²/g. The adsorption kinetics study revealed that the adsorption process followed the pseudo-second-order model and the isotherm analysis followed the Freundlich isotherm model with the maximum adsorption capacity ($Q_{\max}$) reaching 322.580 mg/g. Regeneration tests showed that the MgAl-HC composite material could be reused for up to three cycles without any significant decrease in its adsorption capacity. These findings suggest that MgAl-HC composites have great potential as effective adsorbents for removing antibiotic effluents from aquatic environments.

Key findings

- Modification of MgAl-LDH with dragon fruit peel extract enhances the adsorption capacity for ceftriaxone.
- The surface of the modified material becomes wider and more porous, as evidenced by BET data in the adsorption process.
- The material's regeneration ability remains effective up to three cycles, indicating good stability.

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1. Introduction

In the past decade, the production level of medical chemicals reached 100,000 to 200,000 tons, most of which are antibiotics that are widely used for the treatment of humans, animals, and poultry [1]. Contaminants caused by in-

dustrial wastewater, including antibiotics, have been detected in surface water and groundwater, posing serious risks to human health, marine ecosystem life, and the environment [2]. One of the most common antibiotics found as a contaminant is ceftriaxone (CTX), which is a third-generation antibiotic of the cephalosporin family that is effective

against a variety of bacteria, including strains resistant to other antibiotics [3] with a chemical structure as shown in Figure 1. CTX is known to have advantages in terms of high antibacterial potency, good tolerance to β -lactamase, wide clinical effectiveness, and relatively low allergy rate [4]. In the human body, CTX is eliminated through urine by 34–63% and through feces by about 30% [5]. However, CTX residues discharged into the environment remain active due to their degradation-resistant structure, posing significant ecological and health risks [6]. Therefore, the development of effective and sustainable pharmaceutical waste treatment technologies is urgently needed to minimize the negative impact on public health and the environment [7].

Some of the technologies that can be used to treat pharmaceutical waste include ozonation, nanofiltration, osmosis, photocatalysis, and adsorption [8]. Among these methods, adsorption-based treatments hold the greatest potential due to several advantages [9] such as simple design and operation low energy requirements [10], the absence of toxic byproducts [11], ease of use, high efficiency [9], and user-friendly operation [10]. Adsorption is a process that occurs at the surface, where pollutants move and adhere to the adsorbent surface [14]. The efficiency of this process is influenced by various factors, such as the chemical and physical properties of the adsorbent and adsorbate, solution pH, temperature, contact time, pollutant concentration, and adsorbent particle size [15]. Adsorbents commonly used for the treatment of waste pollutants in the environment can be classified into two types, namely organic and inorganic adsorbents [16]. Widely used organic adsorbents include activated carbon [17], chitosan [18], and biochar [19]. Meanwhile, commonly used inorganic adsorbents include zeolites [20], alumina [21], silica [22], and layered double hydroxide [23].

Of the various types of adsorbents, layered double hydroxide (LDH) is known as a type of anionic hydrocalcite compound consisting of a stack of positive layers separated by an interlayer of anions and water with M^{2+} as the divalent metal and M^{3+} as the trivalent metal [24]. LDH originates from the brucite mineral structure, causing a positive charge to remain on the surface of the layer, which is then balanced by anions and water in the interlayer [25]. However, LDH has a disadvantage in terms of mechanical durability, especially when used repeatedly or undergoing a regeneration process, because the coating structure is prone to peeling. Therefore, the use of LDH will be more effective if it is supported by materials with larger particle sizes [26]. The adsorption capacity and structural resistance of LDH can be significantly improved through modification. The modification has been shown to increase the surface area and improve the adsorption performance for various adsorbates [27].

According to the study conducted by Ahmad et al. [28], the modification of MgAl-layered double hydroxide (LDH) with activated carbon resulted in a significant increase in

adsorption capacity from 71.429 mg/g for activated carbon and 101.010 mg/g for pristine LDH to 133.333 mg/g for the MgAl-activated carbon composite. Meanwhile, Wibiyan et al. [29] modified ZnAl-LDH with *Eucheuma cottonii* and showed that stable regeneration performance with adsorption capacity remaining significant until the seventh cycle. Zhang et al. [30] reported that modification of MgFe LDH with biochar increased the specific surface area from 12.56 m²/g to 90.12 m²/g which influenced the improvement of adsorption performance. The research by Amri et al. [31] showed that the modification of Ni/Al-LDH with graphene oxide (Ni/Al-GO) provided a maximum adsorption capacity of 61.35 mg/g and a high regeneration rate reaching 93.49% in the fifth cycle. Furthermore, Jefri et al. [32] reported that modification of NiFe-LDH using *Uncaria gambir* leaf extract accelerated the adsorption kinetics and increased the adsorption efficiency to 96.420%, compared to 92.085% for the unmodified NiFe-LDH.

Layered double hydroxide (LDH) materials modified with carbon-based support materials show significant improvements in characteristics, such as increased specific surface area, higher adsorption capacity, and better structural stability [33]. In addition, the utilization of natural extracts as supporting materials in LDH modification has become an interesting research topic in recent years [34]. One example is red dragon fruit peel extract (*Hylocereus costaricensis*) because it has a distinctive color, high nutritional content, and antioxidant properties [35] with high nutritional components such as carbohydrates, polyphenols, and fatty acids [36]. Red dragon fruit peel is also rich in antioxidant compounds such as vitamins, flavonoids, tannins, phenolics, betacyanin, and other substances that have functional groups such as OH, C=O, C-O, C=C, and NH which can help the adsorption process and show its potential as a bioreduction in the process of synthesizing nanotechnology-based materials [37].

The purpose of this study is to modify layered double hydroxide with dragon fruit peel extract into a material with a more stable structure and high adsorption capacity so that it can be used repeatedly to remove ceftriaxone in wastewater. Factors affecting the adsorption process were studied and analyzed through the influence of pH, contact time, temperature, and initial concentration of ceftriaxone using kinetics, isotherm, and thermodynamic model approaches, with an illustrative scheme as shown in Figure 2.

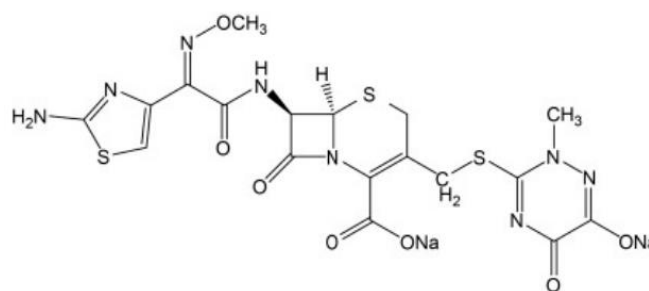


Figure 1 Chemical structure of ceftriaxone [4].

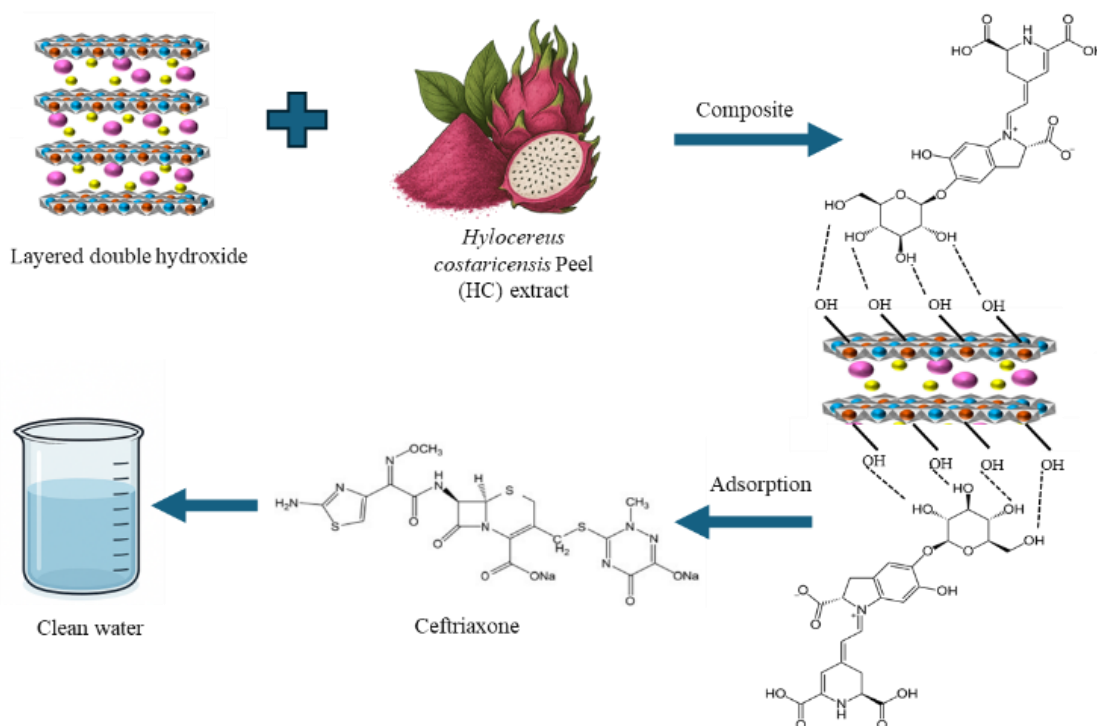


Figure 2 Schematic illustration procedure of ceftriaxone adsorption with MgAl-HC adsorbent.

2. Experimental Section

2.1. Chemical and Instrumental

Materials used include magnesium nitrate hexahydrate ($\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, CAS No. 1344618-9), aluminum nitrate nonahydrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, CAS No. 778427-2) purchased from Sigma-Aldrich, sodium hydroxide (NaOH , CAS No. 131073-2), ethanol (96%, CAS No. 6417-5) purchased from Merck. Hydrochloric acid (HCl , 37%, CAS No. 764701-0) was purchased from MallinckrodtAR. Distilled water (H_2O) was purchased from Brataco, as were red dragon fruit peel (*Hylocereus costaricensis*) and a ceftriaxone commercial antibiotic sample. Material characterization was performed by X-ray diffraction (XRD) analysis using a Rigaku Miniflex-6000 instrument with $\text{Cu K}\alpha$ radiation, which produced XRD patterns simulated with JCPDS. Fourier transform infrared (FTIR) spectrophotometry using a Shimadzu Prestige-21 instrument covering a wavelength range of 500 to 4000 cm^{-1} was performed with KBr. Quantachrome type NovaWin Brunauer-Emmett-Teller (BET) and adsorption measurements were performed with a UV-visible spectrophotometer using Biobase BK-UV 1800 PC at room temperature.

2.2. Synthesis of MgAL-LDH

A total of 100 mL of 0.75 M $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ solution was mixed with 100 mL of 0.25 M $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, then stirred for 30 min, and the pH was adjusted by dripping 2 M NaOH solution to reach pH 10. The mixture was stirred at 80°C for 24 h to form a precipitate. The precipitate was filtered then washed using distilled water and dried using an oven at 100°C .

2.3. Extraction of Dragon Fruit Peel [38]

The peel of red dragon fruit *Hylocereus costaricensis* (HC) was washed, cut, and then dried. The dried dragon fruit skin was pulverized, and 96% ethanol was added at a ratio of 1:10 into a closed container and precipitated for seven days until it completely settled. The precipitate was then filtered to obtain a clear filtrate. The resulting filtrate was evaporated using a rotary evaporator at 50°C .

2.4. Preparation of Composite LDH-HC

A total of 10 g of HC extract was added to a solution containing 0.75 M $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 0.25 M $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ dissolved in 100 mL of distilled water, and then stirred for 30 min. Next, the pH was adjusted by adding 2 M NaOH until it reached pH 10. The mixture was maintained at 80°C for 24 h until a precipitate was produced. The precipitate was filtered, then washed with distilled water and dried using an oven at 100°C .

2.5. Adsorption Study

To evaluate the adsorbent of MgAl-LDH and MgAl-HC composites for the efficiency of ceftriaxone adsorption. The adsorption process carried out includes variations in pH, adsorption time, the effect of concentration, and adsorption temperature using 20 mg of adsorbent in 20 mL of adsorbate. The pH variation was carried out in the range of pH 2–11. The adsorption process was stirred with time variations from 5 to 150 min (at optimal pH). Adsorbate concentration was varied between 50 mg/L, 75 mg/L, 100 mg/L and 125 mg/L and temperature was adjusted in the range of 30 – 60°C . After all the steps were carried out, the residue and

filtrate were separated using centrifugation, and the adsorption ratio was recorded through a UV-visible spectrophotometer at 301 nm.

2.6. Desorption and regeneration

The desorption process of ceftriaxone was carried out using an ultrasonic device. The adsorbent that had been dried and inserted into 20 mL of water solvent was desorbed in 70 min for MgAl-HC and 80 min for MgAl-LDH; then the absorbance was measured using a UV-Vis spectrophotometer. Regeneration was carried out by adding adsorbents that went through the desorption process, was mixed with 20 mg/L of ceftriaxone solution and then stirred for 2 h; after that, the residual concentration was measured using a UV-vis spectrophotometer.

3. Result and Discussion

3.1. Characterization

X-Ray powder diffraction (XRD) in Figure 3 (a) shows the pattern of MgAl-LDH with typical peaks at 2θ angles of $11.32^\circ(003)$, $22.47^\circ(006)$, $34.22^\circ(012)$, $38.64^\circ(015)$ and $60.49^\circ(113)$, which correspond to JCPDS 14-0191 [39], and the pattern of MgAl-HC shows minor changes with lower

peak intensity and an additional peak at 17.9° region indicating the interaction of LDH and HC extract. The IR technique is used to determine functional groups, as shown in Figure 3(b). Figure 3(b) shows broadened vibrations at wavelength $3100\text{--}3600\text{ cm}^{-1}$ indicating the presence of -OH groups of water molecules, those at wavelength 1381 cm^{-1} indicating the presence of NO_3^- groups, and the vibrational peaks at wavelength 594 cm^{-1} indicating the presence of bonds between metals and oxides [40]. MgAl-HC demonstrated absorbances at a wavelength of 3400 cm^{-1} indicating the presence of -OH , at 2975 cm^{-1} indicating the presence of alkane C-H groups, and at 1644 cm^{-1} and 1086 cm^{-1} indicating the presence of C=O and C-O carboxylic acid vibrations which are characteristic of dragon fruit peel extract. Tan and Zhou [41] conducted FTIR analysis on dragon fruit peel detecting two peaks around 2940 cm^{-1} and 2855 cm^{-1} which are associated with C-H vibrations, and those at 1635 cm^{-1} and 1060 cm^{-1} peaks signaling C=O and C-O bond vibrations.

The nitrogen (N_2) adsorption-desorption isotherm plot of the MgAl-LDH material in Figure 4(a) shows a curve with type IV hysteresis and H3 hysteresis (based on IUPAC classification) which indicates the material has a mesopore structure with a pore network that is not fully open.

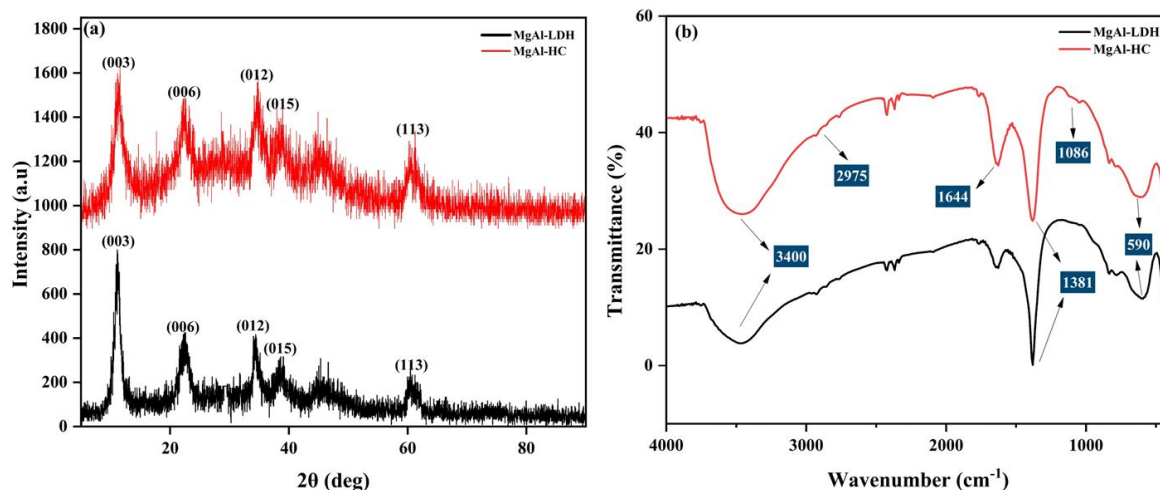


Figure 3 X-Ray diffraction of MgAl-LDH and MgAl-HC (a), FTIR Spectrum of MgAl-LDH and MgAl-HC (b).

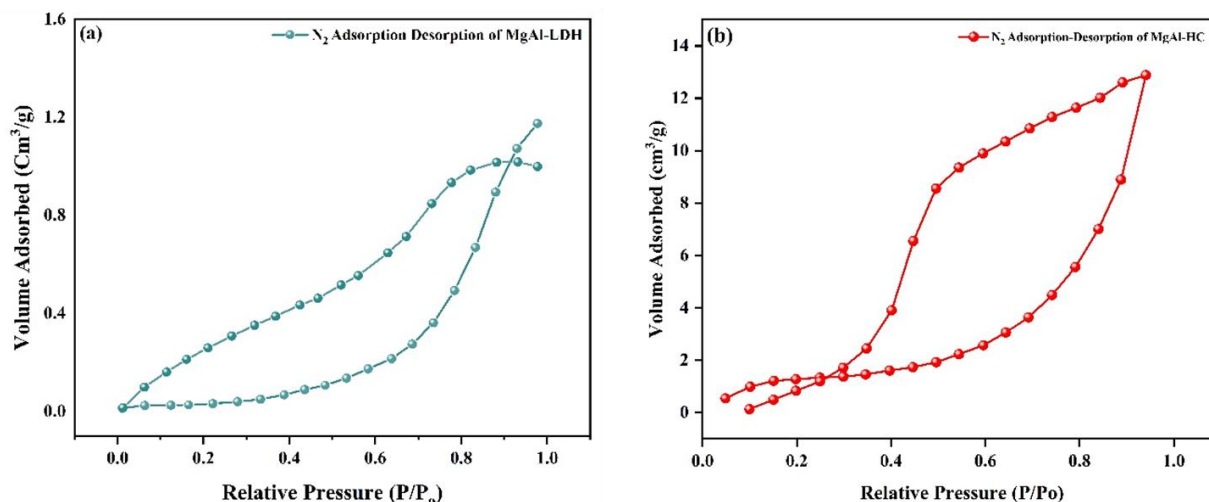


Figure 4 N_2 adsorption-desorption of material (a) MgAl-LDH (b) MgAl-HC.

Figure 4(b) also shows the nitrogen (N_2) adsorption-desorption isotherm curve for the MgAl-HC material with a type IV curve shape with a much wider H3-type hysteresis than the MgAl-LDH material, indicating a significant increase in the mesopore structure. Active compounds in dragon fruit peel, such as betacyanin, polyphenols, flavonoids, and aromatic carbon compounds, interact with the LDH surface and produce pores through the intercalation process. Type IV curve is observed in adsorbents with cylindrical and conical mesopores with pore widths less than 4 nm showing full reversibility with narrowed pore ends, so that adsorption occurs in monolayer to multilayer. The hysteresis process is caused by pore condensation where gas condenses into a liquid phase [42]. This indicates that the MgAl-HC material has more dominant mesopore characteristics and a more open pore structure, especially in the <0.4 region, which indicates an increase in specific surface area.

A more precise pore size distribution was obtained using the Barret, Joyner and Halenda (BJH) method. The BET-BJH method was used to identify the physical properties of the surface and structure of the material [43]. The results are shown in Table 1 indicating an increase in surface area, pore size, and pore volume from pure to modified LDH. The surface area of MgAl-LDH of 18.471 m^2/g is lower than that of MgAl-HC, 28.035 m^2/g .

3.2. Adsorption Study of Ceftriaxone

The optimal pH in CTX adsorption, as shown in Figure 5, using MgAl-LDH and MgAl-HC is at pH 5 with an adsorbed concentration of 16.110 mg/L with MgAl-LDH and 65 mg/L with MgAl-HC. The increase in adsorbed concentration in the MgAl-HC material explains that the synthesis of the material into a composite is able to increase the adsorption capacity of CTX. CTX has three dissociation constants at $pK_1 = 3$, $pK_2 = 3.2$, and $pK_3 = 4.1$. As the pH increases above the pK_a values, CTF becomes negatively charged [44] and can interact with positively charged material through electrostatic attraction [1]. However, a further increase in pH above 7 may lead to a decrease in the adsorption capacity due to the competitive effect between ions $-OH$ in the alkaline conditions and CTX molecules during the adsorption process [45].

Figure 6 shows the adsorption performance of CTX with time. The optimal adsorption time for MgAl-HC was 70 min with an adsorption capacity that increased to 30 mg/L and then showed minimal increase. For MgAl-LDH, the optimal adsorption time was 80 min with an adsorption capacity of 17.300 mg/L which then increased minimally. The adsorption kinetics model study based on Table 2 shows that the

MgAl-LDH and MgAl-HC materials follow a pseudo-second-order model, which is supported by the correlation coefficient (R^2) value in this model which is closer to 1. The adsorption kinetics model is determined based on the correlation coefficient and experimental data in accordance with the calculated data [46].

Table 1 BET-BJH study of MgAl-LDH and MgAl-HC materials.

Material	SBET (m^2/g)	Average pore size (nm)	Average pore volume (cm^3/g)
MgAl-LDH	18.471	1.523	0.023
MgAl-HC	28.035	1.705	0.028

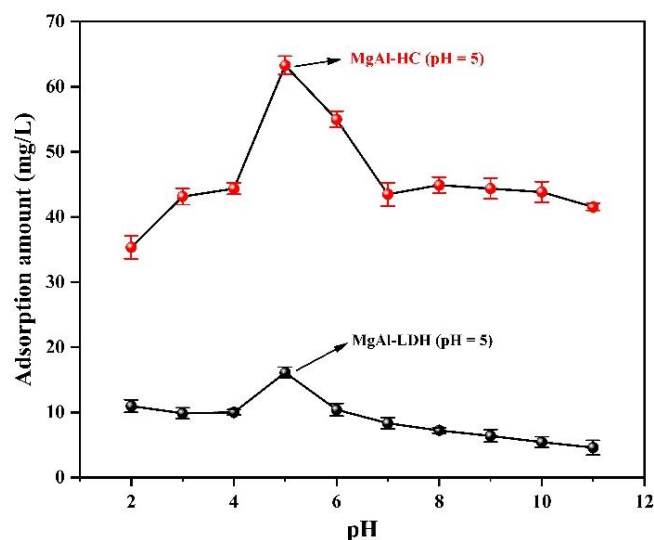


Figure 5 Effect of pH on CTX adsorption by MgAl-LDH and MgAl-HC.

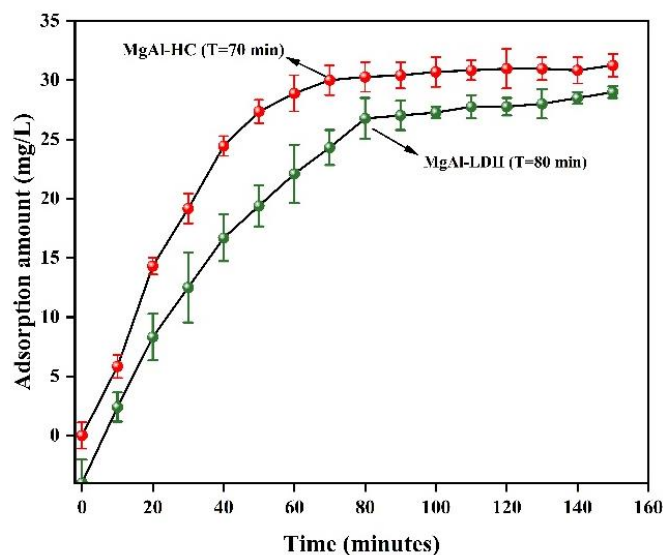


Figure 6 Effect of contact time on CTX adsorption with MgAl-LDH and MgAl-HC material.

Table 2 Kinetic parameters of pseudo-first-order and pseudo-second-order models.

Material	$Q_{e,exp}$ (mg/g)	Pseudo-first-order			Pseudo-second-order		
		$Q_{e,calc}$ (mg/g)	K_1 (min^{-1})	R^2	$Q_{e,calc}$ (mg/g)	K_2 ($g \cdot mg^{-1} \cdot min^{-1}$)	R^2
MgAl-LDH	17.360	31.120	0.009	0.984	14.313	0.030	0.987
MgAl-HC	30.000	41.200	0.055	0.959	39.370	0.001	0.992

The adsorption rate of a material, which describes the equilibrium function and the amount of substance adsorbed at a constant temperature, can be analyzed using adsorption isotherms. Adsorption isotherms can provide information about the adsorption mechanism and the interaction between the adsorbent and the adsorbate [47]. The Langmuir and Freundlich isotherm models are widely used in adsorption studies to describe the interaction between the concentration of the adsorbate in solution and the amount of substance adsorbed on the adsorbent surface. The Langmuir isotherm shows that adsorption occurs uniformly (homogeneously) on the surface in a single layer (monolayer). The Freundlich isotherm shows that adsorption occurs heterogeneously with the concept of multilayers. The suitability of the isotherm is indicated by a higher R^2 value approaching 1 [48].

The adsorption isotherm analysis on both MgAl-LDH and MgAl-HC materials shown in Table 3 follows the Freundlich isotherm model based on the coefficient of determination (R^2) value reaching 0.995 on MgAl-LDH and 0.999 on MgAl-HC, which means that the adsorption process is physical and takes place heterogeneously on the surface. The maximum adsorption capacity increased significantly from 52.630 mg/g on MgAl-LDH to 322.580 mg/g on MgAl-HC.

The thermodynamic parameters of adsorption can be studied because the adsorption process is temperature-dependent to determine if a process is spontaneous and feasible. The thermodynamics of adsorption in Table 4 shows that the adsorption process of MgAl-LDH shows a ΔH value of 6.706 kJ/mol, a ΔS value of 0.029 kJ/mol·K, and a negative ΔG value at all temperatures which indicates the reaction occurs spontaneously and is endothermic. In the MgAl-HC material, the ΔH value is 9.272 kJ/mol, the ΔS value is 0.029 kJ/mol·K, but the ΔG value at low temperatures is positive and only becomes negative at higher temperatures (333 K), which indicates that the adsorption process of the MgAl-HC material is spontaneous at higher temperatures.

Several previous studies examined the adsorption process of ceftriaxone using various types of adsorbents, with maximum adsorption capacity (Q_{max}) values summarized in

Table 5. Unmodified layered double hydroxide (LDH) based adsorbents generally show relatively low adsorption capacity compared to various modified adsorbents, such as N-Bent-NTiO₂-chitosan nanocomposite, chitosan/graphene oxide nanocomposite modified with zirconium, magnetized activated carbon (PAC-Fe₃O₄), *Pseudomonas putida* biomass, mixed metal oxide ZnCoFe, and mesoporous copper oxide nanosphere. In contrast, the modified adsorbent developed in this study showed superior performance with a Q_{max} value of 322.58 mg/g in the ceftriaxone adsorption process, surpassing the performance of other adsorbents based on currently available data. These findings suggest that MgAl-LDH modified with dragon fruit peel extract has great potential as a new candidate in adsorption applications, particularly for water treatment and purification in the environment.

The possible adsorption mechanism of ceftriaxone with MgAl-HC as adsorbent is illustrated in Figure 7. The layered structure of MgAl-HC is composed of Mg²⁺ and Al³⁺ surrounded by -OH. The presence of betasianin, which is one of the active compounds derived from dragon fruit peel extract, plays a role in increasing the surface activity of the adsorbent. CTX adsorption is thought to be realized through two main mechanisms. The first mechanism that may occur is the interaction between positively charged cations from the adsorbent with CTX atoms that have free electron pairs. In the second mechanism, hydrogen bonds can be formed between hydrogen atoms from OH groups on the adsorbent surface and oxygen atoms on the CTX structure [56].

Figure 8 shows the regeneration process performed for six cycles, to determine the adsorption performance of MgAl-LDH and MgAl-HC materials. Desorption was carried out using H₂O as a solvent with the help of an ultrasonic device for 30 min to remove the adsorbed CTX from the adsorbent surface. The results show that the MgAl-HC material can be effectively reused up to the third cycle without experiencing a significant decrease in adsorption capacity. In the first cycle, the regeneration efficiency of MgAl-HC was higher at 22.361% than that of MgAl-LDH at 15.509%.

Table 3 Langmuir and Freundlich parameters.

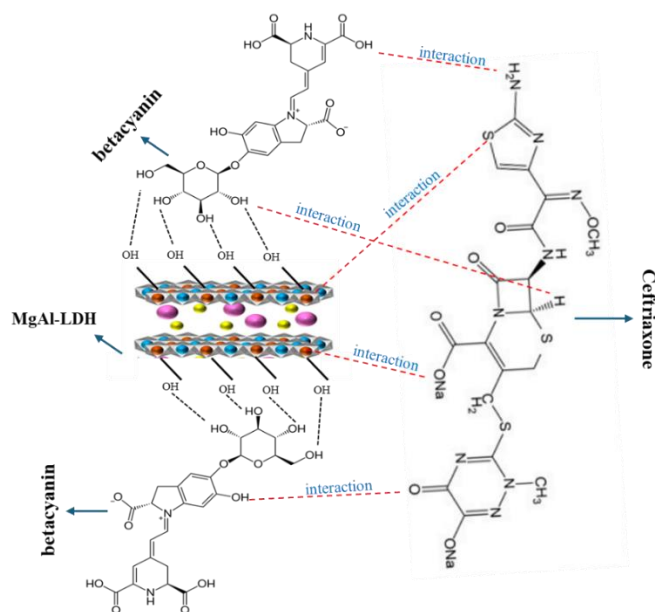
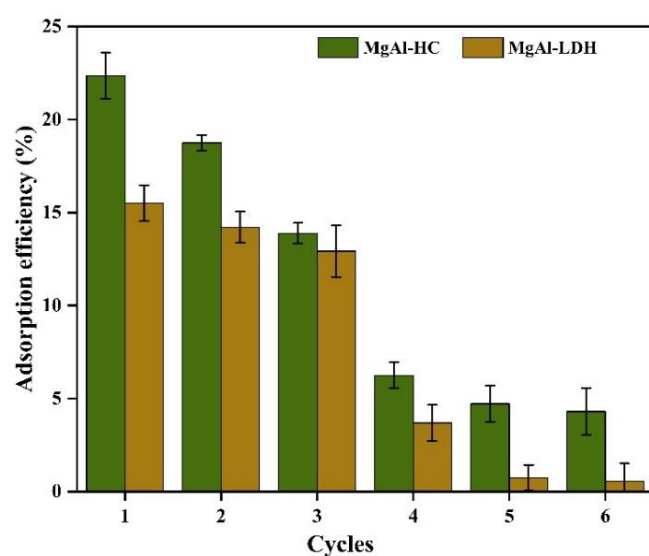
Material	Temperature (°C)	Adsorption isotherm model					
		Langmuir			Freundlich		
		Q_m	K_L	R^2	n	K_F	R^2
MgAl-LDH	30	52.632	0.003	0.957	0.810	14.873	0.995
MgAl-HC	30	322.580	0.001	0.841	0.951	4.553	0.999

Table 4 Thermodynamics adsorption of MgAl and MgAl-HC.

Material	ΔH (kJ/mol)	ΔS (kJ/mol·K)	ΔG (kJ/mol)			
			303 K	313 K	323 K	333 K
MgAl-LDH	6.706	0.029	-2.095	-2.386	-2.676	-2.967
MgAl-HC	9.272	0.029	0.596	0.309	0.023	-0.263

Table 5 Some references for the adsorption of ceftriaxone with different types of adsorbents.

Adsorbent	Maximum adsorption capacity (mg/g)	Ref.
Graphene oxide from corn cob	3.02	[51]
Thermally treated red mud with $[\text{FeOx}(\text{OH})_y]$	29 g/g	[52]
Mesoporous iron oxide	58	[53]
Nbent-NTiO ₂ -Chitosan nanocomposite	90.91	[3]
Chitosan/graphene oxide nanocomposite functionalized with zirconium	91.7	[54]
Magnetized powdered activated carbon (PAC-Fe ₃ O ₄)	100	[6]
<i>Pseudomonas putida</i> biomass	109.5	[55]
ZnCoFe mixed metal oxide	118.45	[44]
Mesoporous copper oxide nanosphere	127	[1]
MgAl-LDH	52.630	(This work)
Composite MgAl-HC	322.580	(This work)

**Figure 7** Possible adsorption mechanisms of ceftriaxone on MgAl-HC adsorbent.**Figure 8** Regeneration of MgAl-LDH and MgAl-HC.

A drastic decrease occurred in the fourth cycle where the efficiency of MgAl-HC dropped to 6.250%, while that of MgAl-LDH decreased to 3.690%. However, in the sixth cycle MgAl-HC still maintained a slight regeneration efficiency, while MgAl-LDH almost lost its regeneration ability. The decrease in the adsorption ability of the material is likely due to damage to the active surface area and weakening of the electrostatic force between ions and the adsorbent surface [57]. This suggests that MgAl-HC has a more stable structure and is more resistant to degradation due to repeated adsorption-desorption processes.

4. Limitations

The MgAl-HC composite has shown excellent performance in adsorbing ceftriaxone (CTX), but this study still has limitations in the regeneration ability of the material where the adsorption efficiency significantly decreases after the third cycle, which indicates that this material is not fully stable for long-term use. Further analysis is needed to identify the material structure to make it more stable. This study also only focused on the removal of ceftriaxone antibiotics without evaluating the adsorption performance of other pharmaceutical compounds or mixtures of other contaminants that are often found in waste in aqueous environments.

5. Conclusions

In this study we successfully modified layered double hydroxide MgAl-LDH with dragon fruit peel extract *Hylocereus costaricensis* (HC), producing MgAl-HC composite material, which showed excellent adsorption performance towards ceftriaxone. The material was analyzed by using XRD, FTIR, and BET methods, and showed an increase in specific surface area. The ceftriaxone adsorption kinetics model study showed that the adsorbent material followed a pseudo-second-order model, while the adsorption isotherm analysis of MgAl-HC followed the Freundlich isotherm model with a maximum adsorption capacity of 322.580 mg/g.

Thermodynamic parameters show that the adsorption process is spontaneous at higher temperatures (333 K). The MgAl-HC material can be used repeatedly for the three cycles, which indicates that this material possesses better cyclability compared to the MgAl-LDH material. Overall, the modification of LDH using dragon fruit peel extract can increase the surface area, adsorption capacity, and structural stability of the material, thus making it a promising adsorbent for application in the purification of wastewater.

Supplementary materials

No supplementary materials are available.

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Author contributions

Conceptualization: A.L.
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Funding acquisition: R.J.S., A.L.
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Writing – original draft: R.J.S.
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Conflict of interest

The authors declare no conflict of interest.

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