

Article

Nanocrystalline Zinc–Manganese Ferrite Carbonate Sorbent: A High-Performance Material for Sustainable and Efficient Removal of Anthraquinone Dye from Wastewater

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Abstract

Threatening environmental resources such as water, air and soil, and thus indirectly threatening biodiversity, through rapid, uncontrolled and non-ecological industrial production systems must be prevented through appropriate purification methods. In this research, the sorption of Reactive blue 19 anthraquinone dye from aqueous solution was carried out in a batch system using nano zinc–manganese ferrite carbonate ($\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$) synthesized by the co-precipitation method. Various factors affecting the sorption activity of the material were examined, and the most suitable conditions were determined to be pH 2 and $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ concentration of 0.25 g/L, whereby an equilibrium sorption capacity of 1463.10 mg/g was achieved. The $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ removal efficiency was found to be 88.48% in effluent from a textile manufacturing industry. Utilizing FTIR, SEM, EDS, XRD, TGA and BET methods, the material's morphological and structural characteristics were thoroughly investigated and reported. Regarding the kinetic and isotherm models that were analyzed, the Langmuir and pseudo-second-order (PSO) models provided the best fit to the aforementioned sorption system. Thermodynamic data confirmed the spontaneity of the sorption reaction and the exothermic nature of the process. An extensive study of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ demonstrated its high efficiency in removing RB19 dye, as well as the safety and simplicity of the synthesis, the cost-effectiveness of the sorption process, and the possibility of regeneration and reuse over multiple cycles. These findings highlight the potential of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ for advanced water and wastewater purification technologies targeting anthraquinone dyes.

Keywords: nanosorbent; ferrites; wastewater; reactive blue 19; sorption; thermodynamics; real water



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1. Introduction

Many industries release unused dyes through wastewater, which has a negative impact on the ecosystem and biodiversity [1]. Harmful compounds released during the production and use of dyes contaminate abiotic factors of habitats (soil, water and air) and contribute to the release of greenhouse gases [2]. The removal of synthetic dyes is becoming

a more prominent research topic in the realms of material application and environmental protection because of their severe toxic effects and the risk of accumulation [2]. Therefore, it is important to find an adequate treatment method that is the most cost effective, easy to handle, sustainable, reusable and does not produce toxic byproducts [3].

Reactive blue 19 (RB19) belongs to the class of anthraquinone dyes and is renowned in textile manufacturing because of its vibrant color, affordability, and good solubility. It can have carcinogenic and mutagenic effects on living organisms because of its ability to incorporate part of its structure into a DNA molecule [4]. Numerous techniques for eliminating dyes and organic molecules, including ozonation [5], photocatalysis [6–8], mediated electrochemical oxidation [9], electrocoagulation [10], the Fenton process [11], membrane separation [12], biological treatment [13] and sorption [14], are documented in the literature. Although numerous techniques have been reported for RB19 removal, including advanced oxidation, membrane separation, ozonation and the Fenton process, these approaches often suffer from high operational costs, energy demand, or secondary waste generation. In contrast, the sorption process offers a simpler and more cost-effective route, with easier handling and regeneration potential. Considering its accessibility, ease of use, reliability and notable removal efficiency, sorption is characterized as an extremely competitive method [15]. Research on the removal of RB19 dye from water has been carried out using the various types of sorbents, such as biochar [16], graphene oxide [17], silica gel [18], magnetic nanocomposites [19], waste biosorbents [20], starch-based polymers [21], ash [22], carbon nanotubes [23], layered double hydroxides [24], activated carbon [25], biomass [26], biochar-caged zirconium ferrite [27], etc.

Ferrites are a class of materials that are ferrimagnetic. On the basis of their magnetic features, ferrite nanoparticles can be characterized as soft or hard depending on their coercivity. Owing to their structure, they are classified as ortho-ferrites, garnets, spinels, or hexagonal ferrites [28]. $M^{2+}Fe_2^{3+}O_4$ is a typical ferrite formula, where M^{2+} represents a divalent metal ion (Co^{2+} , Ba^{2+} , Sr^{2+} , Mg^{2+} , Cd^{2+} , Bi^{2+} , Cu^{2+} , Ni^{2+} , Zn^{2+} , Mn^{2+} , or Fe^{2+}) [29]. Mixed ferrites are compounds that include at least two different types of divalent metal ions. Their physical characteristics might differ according to their composition [30]. The most prevalent type of ferrite is the spinel, where Fe^{3+} ions and divalent metal ions are grouped octahedrally or tetrahedrally, depending on the form of ferrite, and are connected to oxygen ions [31]. The arrangement of metal ions and the type of synthesis procedure, including the reaction conditions, pH value and temperature, affect the material characteristics [32]. Many properties of ferrites, such as their ease of synthesis, resistance to high temperatures and corrosion, ability to regenerate the material, cost-effectiveness, and catalytic, optical, and magnetic features, ensure their application in the fields of medical treatment, electronics, biosensors, catalysis, water purification and others [33].

There are scarce studies on the preparation of ferrites using carbonates. The synthesis of the novel and effective nano zinc–manganese ferrite carbonate material ($ZnMn-Fe_2O_4-CO_3$) was carried out through a co-precipitation process. Ensuring the safe treatment of textile wastewater and achieving successful material regeneration are the primary goals, with a focus on process simplicity and financial viability in terms of a sustainable circular economy. Experiments investigating the effects of temperature, pH, initial concentration of RB19 dye, contact time and sorbent dose on the RB19 sorption performance of the material were performed in a batch system. Analysis of the material's structural features was performed via X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), thermogravimetric analysis (TGA), Brunauer–Emmett–Teller (BET) and Fourier transform infrared spectroscopy (FTIR) techniques. To investigate the mechanism of the sorption process, the experimental data were analyzed via pseudo-first-order, pseudo-second-order and intraparticle diffusion kinetic models, as well as Langmuir,

Freundlich, Brouers–Sotolongo and Sips isotherm models, with additional examination of thermodynamic variables. The impact of real wastewater conditions on the sorption process, as well as the regenerative ability of the material for further reuse, was investigated.

2. Materials and Methods

2.1. Reagents

The reagents used in the experiments were of ACS purity ($\geq 95\%$), and no additional depuration was performed. Sigma–Aldrich (St. Louis, MO, USA) supplied iron(III) chloride hexahydrate, zinc chloride, sodium carbonate, sodium hydroxide and manganese(II) chloride tetrahydrate, while Merck (Darmstadt, Germany) supplied RB19 dye. All solution preparations were performed with deionized water ($18\text{ M}\Omega\text{ cm}^{-1}$).

2.2. Synthesis

The co-precipitation process was used for the synthesis of the sorbent, during which the pH of the solution was maintained at 10. Three solutions were made by individually dissolving 2.0 g of iron(III) chloride hexahydrate, 0.25 g of zinc chloride, and 0.75 g of manganese(II) chloride tetrahydrate in 30 mL of deionized water. Then, all three solutions were mixed together in an Erlenmeyer flask with the addition of a reflux condenser, heated and stirred ($80\text{ }^{\circ}\text{C}$ and 400 rpm). Then, slow precipitation was started by dropping 2.0 M NaOH and 1 M Na_2CO_3 , until a pH of 10 was reached. When the precipitation was finished, stirring and heating were continued for the next two hours. After that, the suspension was stirred for 12 h without heating, and then centrifuged at 4000 rpm. Afterwards, the precipitate was repeatedly eluted with heated deionized water and left to dry for 6 h at $80\text{ }^{\circ}\text{C}$. The obtained material from this synthesis process was abbreviated as $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$.

2.3. Characterization of the Material

UV–vis spectra were acquired using a Shimadzu 1800 UV–vis PC (Kyoto, Japan) following filtration through a $0.45\text{ }\mu\text{m}$ membrane filter (Agilent Technologies, Waldbronn, Germany). Carbon tabs Leit-C were used to attach the samples for EDS and SEM to stubs made of aluminum. SEM analysis was performed on a field-emission gun SEM Hitachi SU8030 (Tokyo, Japan) with X-ray detection using a Thermo NORAN (Madison, WI, USA) system 7 for EDS analysis. Thermogravimetric examination was conducted on a TG analyzer (TA Instruments Q5000, New Castle, DE, USA). A Hartmann and Braun spectrometer (Québec, QC, Canada) type Bomem MB 100 was employed for recording Fourier transform infrared (FTIR) spectra in the frequency range of $4000\text{--}400\text{ cm}^{-1}$. The BET surface area was ascertained via a Gemini 5 BET analyzer from Micrometrics (Norcross, GA, USA). XRD was carried out on a Bruker D8 Advance diffractometer (Karlsruhe, Germany) with the following setup: theta–theta geometry, reflecting mode, and Cu K–alpha radiation. The results were collected from 2° to $80^{\circ} 2\theta$, applying a 0.02° step size and a one-second measurement interval for every step.

2.4. Batch Sorption Experiments and Determination of pH_{PZC}

To carry out the batch experiments, working solutions were created by diluting a 1000 mg/L RB19 stock solution. The experiments were conducted three times for each investigated parameter. During the analysis of individual variables, other conditions were sustained at constant values. The effect of pH on RB19 sorption was tested in the pH range of 2–7 at a temperature of $25\text{ }^{\circ}\text{C}$, a sorbent dose of 0.25 g/L and an RB19 concentration of 300 mg/L. The pH was maintained at ± 0.1 pH units throughout the experiments. The effect of contact time was analyzed from 0 to 300 min, and the subsequent parameters were

applied: pH 2, sorbent dose of 0.25 g/L, 25 °C, and 300 mg/L of RB19. The influence of temperature was tested at 10, 25 and 50 °C. The effect of sorbent dose was investigated in a range of 0.1 to 0.5 g/L. The study was conducted at pH 2, a 300 mg/L starting concentration of RB19, 200 rpm stirring speed and 25 °C. The effect of the initial RB19 concentration was investigated in a range of 200–700 g/L, while the temperature was maintained at 25 °C, the sorbent dose was 0.25 g/L, and the pH was 2. A Julabo Refrigerated and heating circulator F12-ED (Seelbach, Germany) was used to control the sample temperature during the analytical process.

In the experiment with real wastewater from the textile industry, a temperature of 25 °C and a sorbent dosage of 0.25 g/L were the optimal parameters for conducting the experiment. RB19 dye was added to deionized water and textile wastewater to a total concentration of 300 mg/L. The pH value of the wastewater sample and the deionized water sample was adjusted to 2.0, using 1 mol/L HCl.

The point of zero charge (pH_{PZC}) of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ was determined using the drift technique in a 0.1 mol/L NaNO_3 electrolyte solution. The initial pH value of the electrolyte solution was varied between 2 and 9.

2.5. Reusability and Desorption Experiment

Five consecutive cycles of sorption and desorption of RB19 molecules were used to examine the removal efficiency and reusability of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$. Each cycle of the experiment was carried out under constant temperature conditions of 25 °C, with a $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ sorbent concentration of 0.25 g/L, where the RB19 concentration was 300 mg/L, and the total solution volume was 0.25 L. The mixing speed was set to 200 rpm, while the duration of the sorption process was 180 min. The sorption process was followed by centrifugation and further filtration with rinsing with deionized water. The concentration of RB19 in the filtrate after the sorption process was determined by the UV-Vis method. To desorb RB19 molecules and regenerate the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ sorbent, 0.25 L of 1 mol/L NaOH solution was used. After mixing the material in the provided solution for an hour, the material was filtered to complete the desorption and regeneration process. The residual RB19 concentration in the obtained filtrate was measured.

2.6. Sorption Isotherm, Kinetic and Thermodynamic Theoretical Background

Sorption isotherms indicate a correlation between the number of RB19 molecules sorbed on the ferrite surface at equilibrium and the amount of material remaining in the solution after reaching equilibrium. For equilibrium examination, isotherm models such as the Langmuir (Equation (1)) [34], Freundlich (Equation (2)) [35], Sips (Equation (3)) [36], Brouers–Sotolongo (Equation (4)) [37], and Temkin (Equation (5)) [38] were utilized.

$$q_e = q_m \frac{K_L c_e}{1 + K_L c_e} \quad (1)$$

$$q_e = K_F c_e^{\frac{1}{n}} \quad (2)$$

$$q_e = \frac{q_m (\beta_S c_e)^n}{1 + (\beta_S c_e)^n} \quad (3)$$

$$q_e = q_m (1 - e(-K_W c_e^\alpha)) \quad (4)$$

$$q_e = \frac{RT}{b} \ln(K_T c_e) \quad (5)$$

where c_e (mg/L) represents the equilibrium concentration of adsorbate, q_m (mg/g) denotes the maximum sorption capacity, q_e (mg/g) denotes the sorption capacity at equilibrium, K_L (L/mg) is a Langmuir constant associated with the sorption energy, n and α stand for

the Freundlich and Brouers–Sotolongo exponents, K_F (mg/g) (L/mg)^{1/n} and β_S (L/mg) correspond to the Freundlich sorption capacity constant and Sips constant of sorption affinity, the Brouers–Sotolongo constant of the isotherm is denoted by K_W (L/mg), and b (kJ/mol) and K_T (L/g) correspond, respectively, to the Temkin sorption constants attributed to the heat and binding energy.

The characterization of the Langmuir isotherm is largely influenced by the parameter R_L , which refers to the separation factor. Its value describes the favorability of the sorption process, and it can be represented by Equation (6).

$$R_L = \frac{1}{1 + K_L c_i} \quad (6)$$

where c_i (mg/L) is the initial concentration of adsorbate.

The kinetic research for establishing the mechanism governing the sorption process involves the use of pseudo-first-order (PFO) (Equation (7)) [39], pseudo-second-order (PSO) (Equation (8)) [40] and the Chrastil model (Equation (9)) [41] (nonlinear forms) and the intraparticle diffusion model (IPD) (Equation (10)) [42] (linear form). The models stated above are explained by the following equations:

$$q_t = q_{e,cal} \left(1 - e^{-k_1 t}\right) \quad (7)$$

$$q_t = \frac{k_2 q_{e,cal}^2 t}{1 + k_2 q_{e,cal} t} \quad (8)$$

$$q_t = q_{e,cal} \left(1 - e^{-k_c A_0 t}\right)^n \quad (9)$$

$$q_t = K_{id} t^{\frac{1}{2}} + C \quad (10)$$

where the sorption capacity at a certain time t (min) and at the equilibrium state time are denoted by q_t and $q_{e,cal}$ (mg/g), respectively; k_c (L/g min), k_1 (1/min) and k_2 (g/mg min), respectively, correspond to the sorption rate constants in the Chrastil model and the sorption rate constants for the PFO and PSO models; A_0 (g/L) represents the amount of sorbent; n is a constant representing heterogeneous structural diffusion resistance; K_{ID1} and K_{ID2} (mg/g min^{1/2}) represent the equilibrium IPD coefficient; and C_1 and C_2 (mg/g) are constants connected to the external mass transfer.

Thermodynamic analysis, which provides a more thorough description of the nature of sorption, was conducted by determining the enthalpy (ΔH°) (kJ/mol), entropy (ΔS°) (J/mol), and free Gibbs energy changes (ΔG°) (kJ/mol) via the following formulas (Equations (11)–(13)):

$$\Delta G^\circ = -RT \ln K \quad (11)$$

$$\ln K = -\frac{\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R} \quad (12)$$

$$\Delta G^\circ = \Delta H^\circ - T \Delta S^\circ \quad (13)$$

where R (8.314 J/mol K) is the gas constant, T (K) is the temperature, and K is the Langmuir constant K_L , converted using the molecular weight of RB19 and the standard concentration.

The van't Hoff plot ($\ln K$ vs. $1/T$) was used to determine the values ΔG° , ΔH° and ΔS° .

The capacity of ferrite sorption q_t (mg/g) at time t , the RB19 removal efficiency RE (%), and the mean relative deviation MRD (%) were estimated via the following formulas (Equations (14)–(16)):

$$q_t = \frac{(c_0 - c_t) \cdot V}{m} \quad (14)$$

$$RE = \frac{c_0 - c_t}{c_0} \cdot 100\% \quad (15)$$

$$MRD = \frac{\sum_{i=1}^{i=n} |q_{t,exp} - q_{t,cal}|}{\bar{q}_{e,exp} \cdot n} \cdot 100\% \quad (16)$$

where n is number of data points.

3. Results and Discussion

3.1. ZnMn-Fe₂O₄-CO₃ Characterization

3.1.1. Spectral FTIR Analysis

The FTIR spectra before and after RB19 sorption by ZnMn-Fe₂O₄-CO₃ are shown in Figure 1a,b. FTIR sorption band analysis (400–4000 cm^{−1}) verified the presence of distinctive groups originating from the spinel ferrite structure. The pronounced characteristic bands in the region around 3483 and 1617 cm^{−1} for the pre-sorption spectrum and 3463 and 1600 cm^{−1} for the post-sorption spectrum are attributed to stretching and bending vibrations of the hydroxyl group and water molecules embedded in the ferrite structure or present in the free state [43]. In the FTIR spectrum of ZnMn-Fe₂O₄-CO₃ before RB19 sorption, the broad band at 1487 cm^{−1} and the sharp band at 863 cm^{−1} can be assigned to the carbonate ion. The valence stretching vibrations of M–O ions situated in the tetrahedral and octahedral surroundings are characterized by a high-intensity band at 611 cm^{−1} and a medium-intensity band at 507 cm^{−1}, respectively [44]. After sorption, three more peaks at wavelengths of 1222, 1123 and 1038 cm^{−1} were observed. These peaks are roughly identical in intensity and are thought to be the result of asymmetric-type stretching vibrations of S=O that originate from the SO₃ group of the RB19 molecule [45]. By comparing the spectra before and after RB19 sorption, it is evident that the sorption of RB19 molecules by ZnMn-Fe₂O₄-CO₃ has resulted in a modest drop in the peak intensity and a minor movement of the bands towards lower wavenumbers.

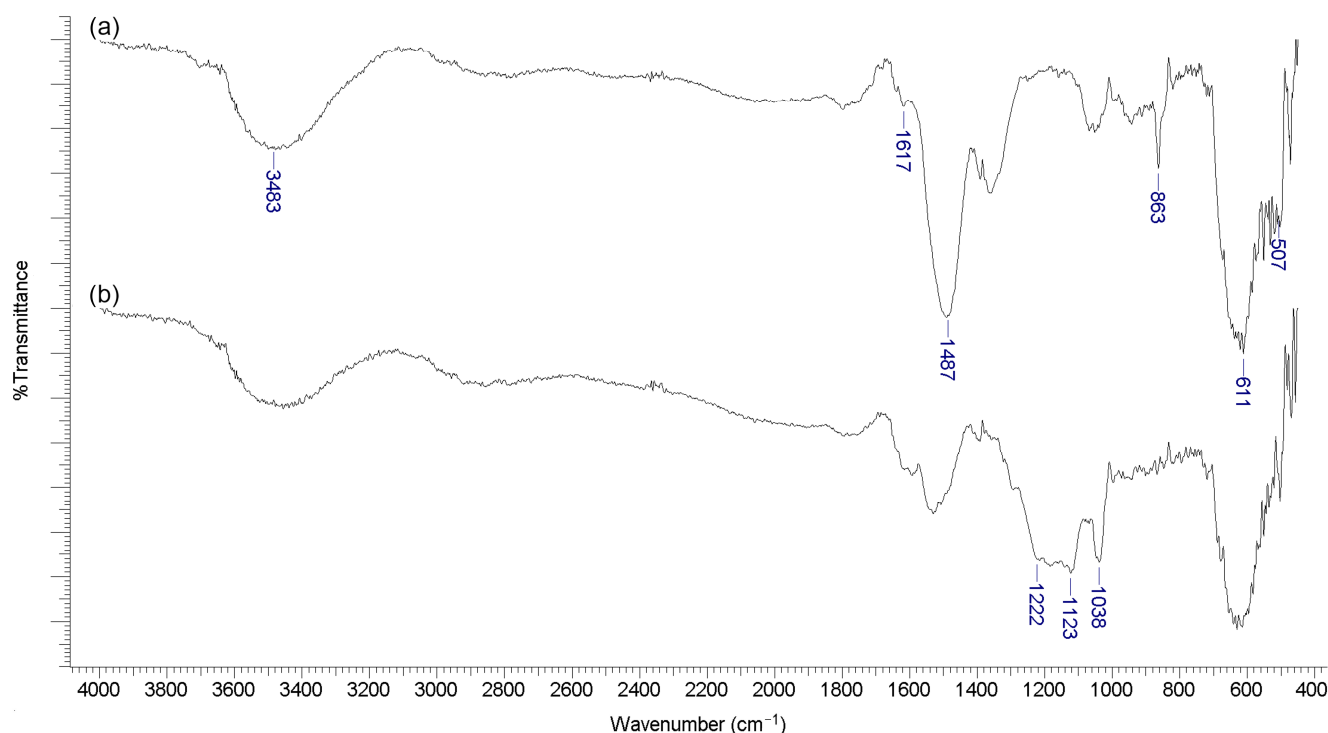


Figure 1. FTIR spectra (a) before and (b) after sorption processes.

3.1.2. Thermogravimetric Analysis

Thermogravimetric analysis was performed over the temperature range from 25 °C to 600 °C, and the results are shown in Figure 2. An overall percentage of mass loss of 11.36% was determined. A mass loss of approximately 4.7% was observed at temperatures up to 100 °C, which is the consequence of the evaporation of unbound or bound water molecules on the material's surface [46]. The mass of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ drops by around 3.9% when the temperature is raised from 100 °C to 250 °C. This might be owing to the loss of internal water molecules, the breakdown of the ferrite structure, and the probable formation of metal oxides [47]. Decomposition of the carbonate structure starts at temperatures between 250 and 350 °C. At the end of the carbonate decomposition, a cation-deficient ferrite with cation vacancies (nonstoichiometric ferrite) is formed. Further heating forms a ferrite a stoichiometric structure. This change in stoichiometry is accompanied by a mass loss of 0.9%.

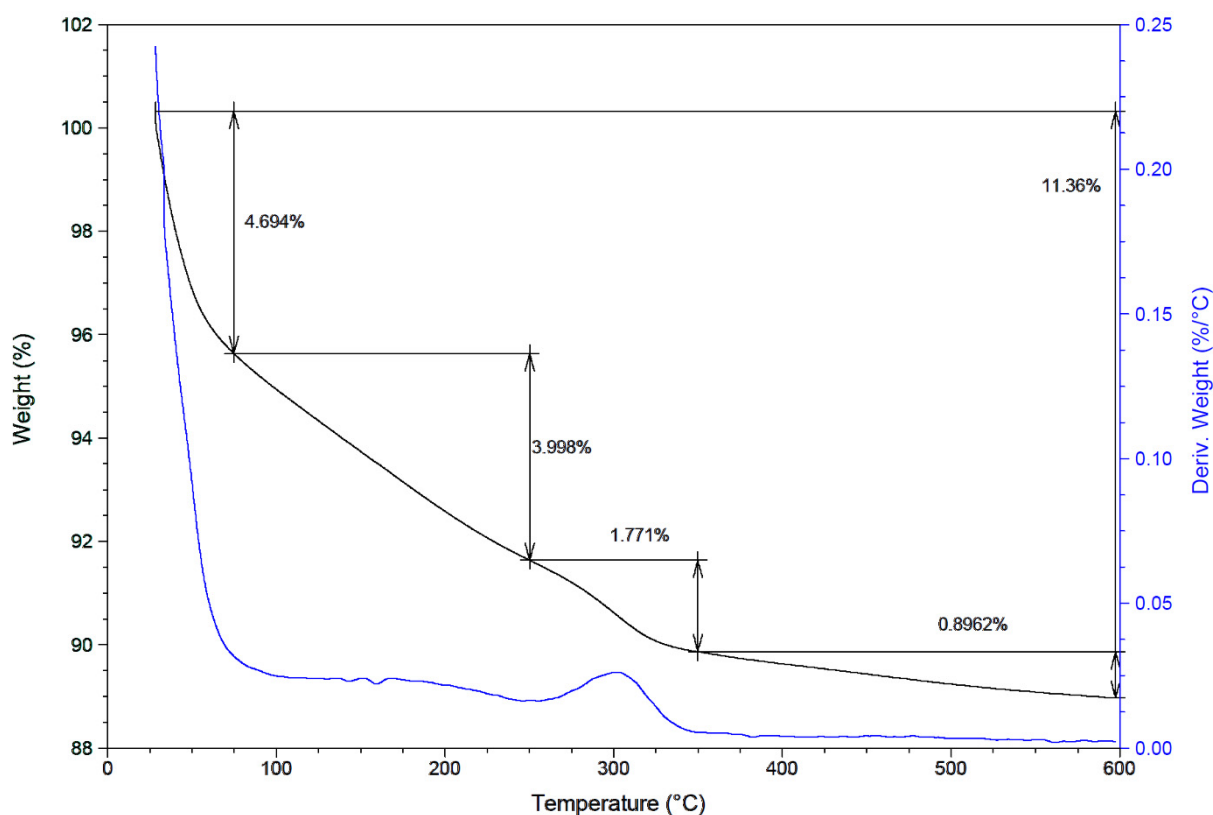


Figure 2. Thermogravimetric diagram of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$.

3.1.3. XRD Analysis

The crystal composition and structure of the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ sample were examined using XRD analysis before and after RB19 sorption, and the outcomes have been displayed in Figure 3a,b. The XRD analysis of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ reveals distinct, expressive, and sharp peaks, indicating very high crystallinity, and the width of the peaks verifies that the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ particles are of nanoscale diameter. The structure of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ is confirmed by the agreement between the acquired XRD results and the number 01-088-4373 in the JCPDS (ICDD/PDF) database. Moreover, the diffraction data confirmed $(\text{Fe}_{0.279}\text{Mn}_{0.494}\text{Zn}_{0.227})(\text{Mn}_{0.182}\text{Fe}_{0.097}\text{Fe}_{1.721})\text{O}_4$ as the dominant crystalline compound. The characteristic peak (311) shows that the nanoparticles have a spinel structure having the Fd-3m space group. Additional components of the sample prior to sorption showed a negligible amount of ZnO (01-070-2551), NaCl (01-076-3452), and MnCO_3 (01-084-6999), which is probably the result of ions being lost

during the synthesis process. After the sorption procedure of RB19, no peaks of other phases were visible in the XRD patterns, probably because of the leaching of Zn and Mn at low pH values. Additionally, the XRD spectra confirm that the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ structure remains stable after the treatment.

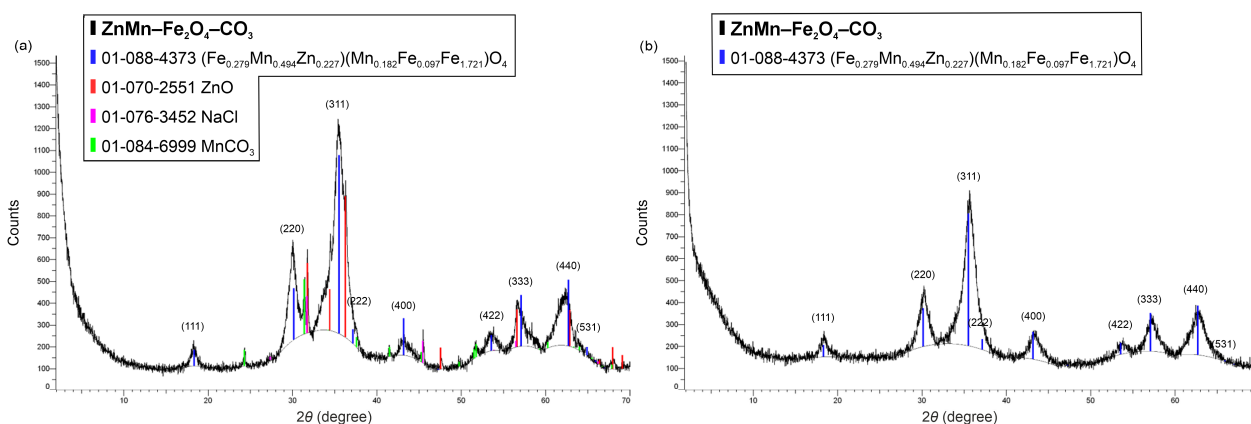


Figure 3. XRD spectra (a) before and (b) after sorption of RB19.

3.1.4. BET

The assessment of the total specific surface area, volume and pore diameter of the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ was carried out using the Brunauer–Emmett–Teller (BET) method of nitrogen adsorption and desorption. Ferrite adsorption and desorption isotherm curves followed an analogous pattern, and the isotherm's form referring to the IUPAC classification is the most comparable to type IV Langmuir isotherm with an H1 hysteresis loop. According to the BET method, the specific surface area was $73.47 \text{ m}^2/\text{g}$. Barrett–Joyner–Halenda (BJH) total pore volume and average size of pores for adsorption were $0.12 \text{ cm}^3/\text{g}$ and 5.98 nm , respectively, whereas BJH diameter cumulative surface area for adsorption was $78.03 \text{ m}^2/\text{g}$. The ferrite sample's BET tests demonstrated its mesoporous structure and high specific surface, which allowed for a considerable number of accessible sorption sites. The pore size is large enough to allow ions to diffuse rapidly, reducing diffusion resistance. Also, mesopores prevent pore blocking and allow ions to penetrate deeply into the material, ensuring that the bulk of the sorbent participates in the process rather than just the surface.

3.1.5. SEM and EDS

Figure 4a,b show the outcomes of the SEM and EDS testing, respectively. The SEM picture displays uniform and nanometer-sized particles in a homogenous layout. The estimated particle diameter was around 23 nm (SEM measurement statistics) which validated the nanomaterial characteristics of the produced material. SEM micrographs taken before and after the RB19 sorption process reveal that the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ sample's particles were unaltered. This proves that the synthesis method was adequate for producing a stable sorbent with a consistent composition. Investigating the element content and its percentage in $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ was done at seven various points. In the EDS diagram, the peaks proving the presence of Mn, Zn and Fe are clearly expressed and exhibit the existence of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$. Since manganese was added in an amount exceeding the stoichiometric ratio in the obtained ferrite, an impurity in the form of MnCO_3 was formed (detected by XRD analysis), and EDS showed an excess of manganese. After the sorption of RB19, the occurrence of S in the EDS spectrum is noticeable, which can be related to the sorption of RB19 molecules onto the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ surface through the sulfo group.

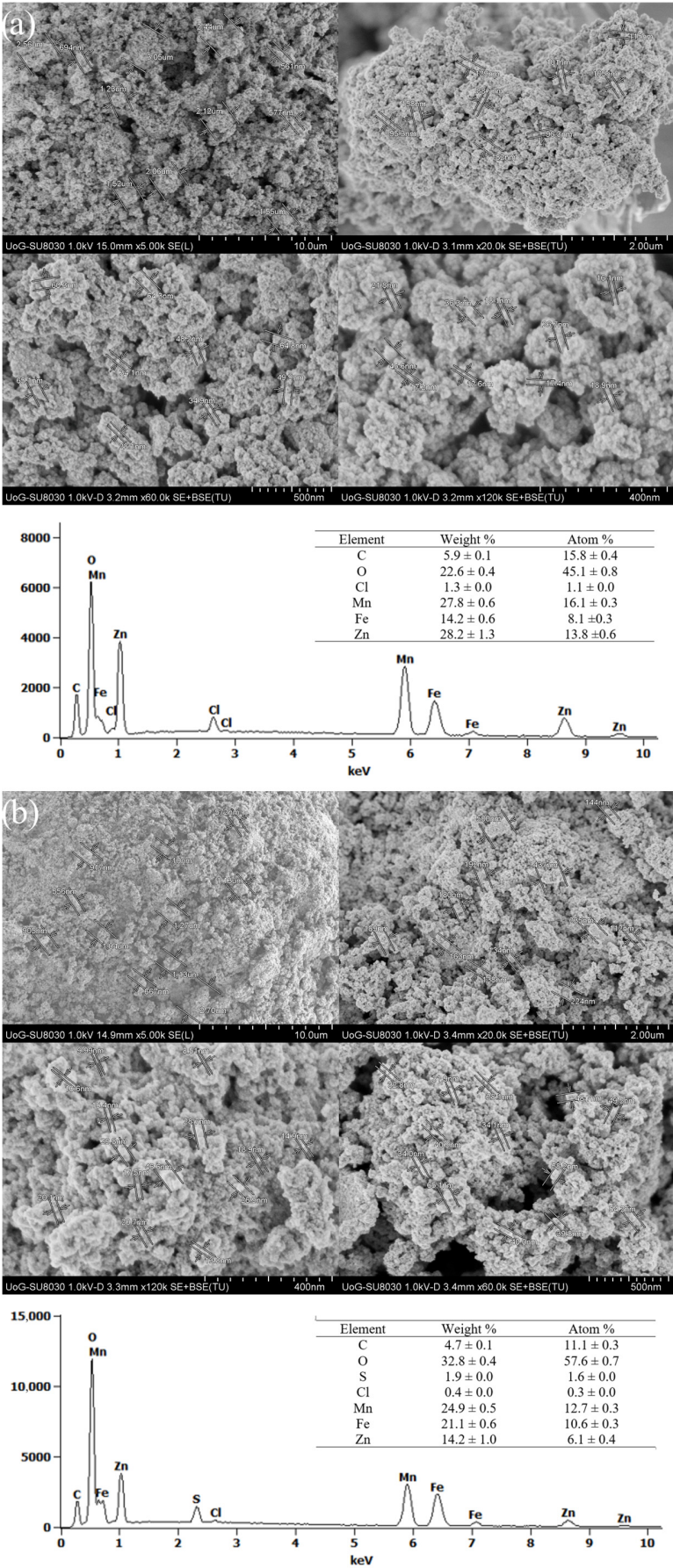


Figure 4. SEM and EDS outcomes for ZnMn-Fe₂O₄-CO₃ (a) before and (b) after sorption process.

3.2. Sorption Study

3.2.1. Effect of ZnMn-Fe₂O₄-CO₃ Dosage

Figure 5a depicts the outcomes of an examination of ZnMn-Fe₂O₄-CO₃ dosage on RB19 uptake. Varying the sorbent dose from 0.1 g/L to 0.25 g/L led to a slight increase in sorption capacity from 1188.20 to 1194.65 mg/g and then a sharp decrease in sorption capacity to 600.0 mg/g at a sorbent dose of 0.5 g/L. The reason behind this outcome is that at sorbent dose of 0.5 g/L, many sorption sites remain unoccupied, which reduces the sorption capacity. Nevertheless, the removal efficiency changed from 39.6% to 100.0%. The explanation for this is that a higher ZnMn-Fe₂O₄-CO₃ dose resulted in greater RB19 removal because more sorption sites became available, which amplified the efficiency of RB19 removal. Ultimately, the findings of this research revealed 0.25 g/L as the most suitable ZnMn-Fe₂O₄-CO₃ dosage.

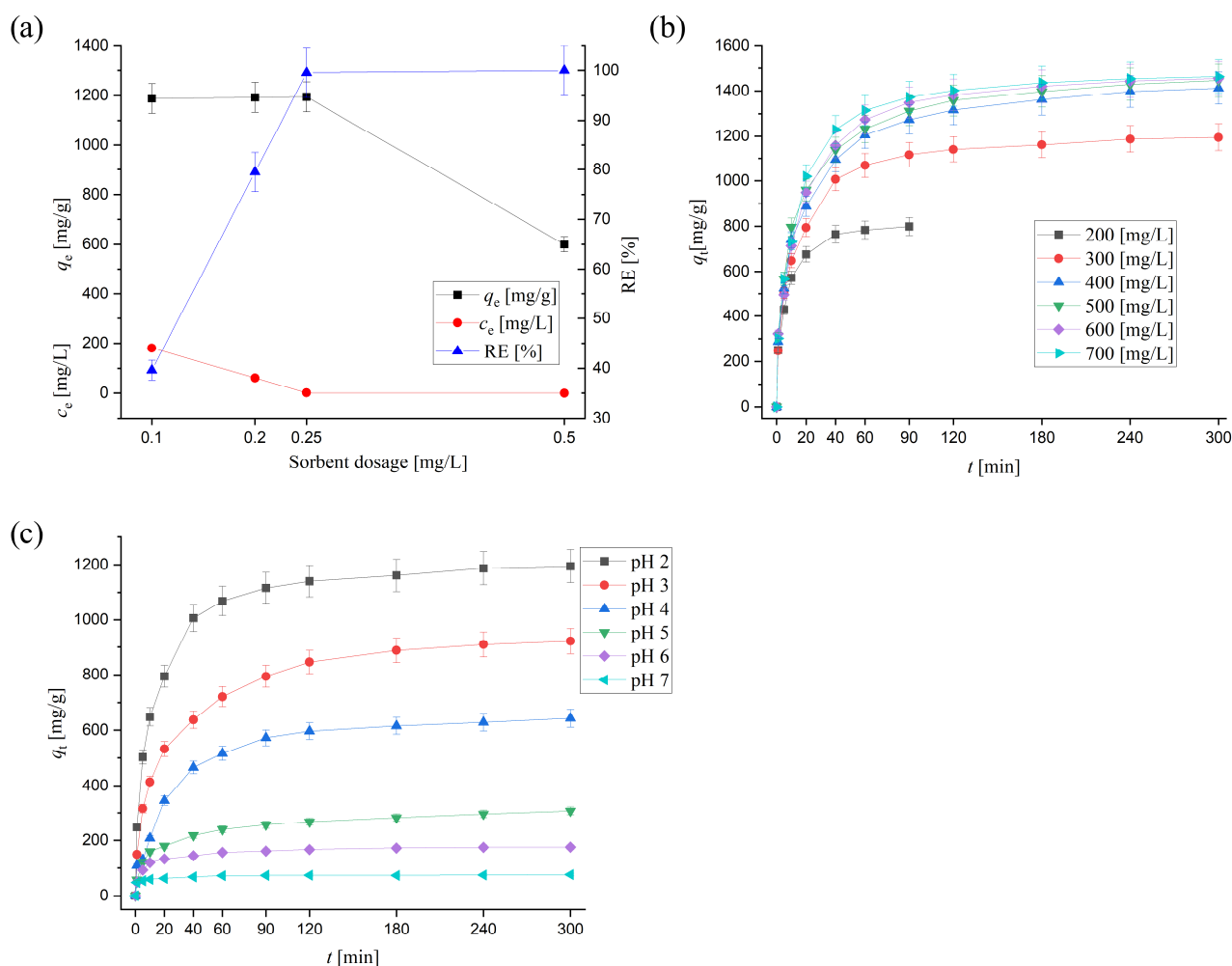


Figure 5. Graphical representation of (a) effect of sorbent dosage (b) initial concentration of RB19 and contact time effect on ZnMn-Fe₂O₄-CO₃ sorption and (c) effect of pH value on RB19 uptake onto ZnMn-Fe₂O₄-CO₃.

3.2.2. Effect of Contact Time

In order to investigate the way contact time affects the sorption properties, the removal of RB19 by ZnMn-Fe₂O₄-CO₃ was examined (Figure 5b). Three distinct stages of the sorption process can be identified based on the examination of the contact time at 0, 1, 5, 10, 20, 40, 60, 90, 120, 180, 240, and 300 min. In the first 20 min, sorption takes place very quickly, which is understandable considering that at the beginning of the process, the

largest number of active sites is unoccupied. Furthermore, in the second stage from 20 to 90 min, the difference in chemical potentials between the two phases decreases, and the sorption capacity has a stable, moderate but slight growth until the moment of reaching equilibrium [48,49]. The third stage after 90 min can be explained by the establishment of equilibrium, and further, there are no significant variations in the values of sorption capacities because all active sorption sites have already been filled.

3.2.3. Effect of Initial RB19 Concentration

Defining the most optimal value of the initial RB19 concentration was done in the range of 200–700 mg/L. The presentation of the obtained findings in Figure 5b illustrates that the equilibrium sorption capacity increases proportionally (from 798.6 to 1463.1 mg/g) as the concentration of RB19 gets higher. Thus, the concentration gradient's pushing power increases as well, exceeding the obstacle to RB19 mass transfer, which leads to enhanced mutual interaction [50].

3.2.4. Effect of pH Value

The effect of pH on the amount of sorbed RB19 is reflected in its influence on the structure and ionization of surface characteristic groups of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ and RB19 molecules. Figure 5c illustrates the correlation between the sorption capacity of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ and the exposure period to RB19 dye. $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ exhibited the highest sorption capacity of 1194.6 mg/g in the solution with the lowest pH value of 2. Further, the sorption capacity gradually and moderately decreased with increasing solution pH, reaching a minimum of 76.1 mg/g at pH 7. This occurrence can be associated with the pH_{PZC} , which in the case of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ was estimated to be 7.8. Active ferrite groups are positively charged in an acidic environment (pH lower than pH_{PZC}), whereas RB19 molecules possess a negative charge. Apart from $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ deprotonating at rising pH values, a competition for binding to ferrite active sites is also present between the hydroxyl ions and the negatively charged sulfonic groups of RB19. The sorption capacity of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ decreases even further, beyond pH_{PZC} where its negative charge drives it to behave as a cation exchanger.

3.2.5. Kinetic Study

The study of the sorption kinetics of RB19 on $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ by interpreting the kinetic parameters was performed using PFO, PSO, Chrastil model and IPD model. Table 1 provides a summary of all kinetic parameters. By analyzing the key parameters obtained using the PFO and PSO, coefficients of determination (R^2) and mean relative deviation, which are the best indicators of good agreement of experimental data with the corresponding model, it can be concluded that the PSO kinetic model has higher values of R^2 (0.984–0.989) and lower values for MRD (2.7–4.34). This indicates a better fit of the PSO model to the experimental data and further indicates that chemical sorption is the leading process that regulates the reaction rate. On the other hand, the PFO model could not demonstrate a satisfactory match since it gave larger values for MRD (6.32–8.85) and lower values for R^2 (0.944–0.966), making it inappropriate for kinetics prediction in the present case. The Chrastil kinetic model gave the minimum MRD values (1.04–1.64) for all applied initial concentrations, and in addition, the highest values for R^2 (0.997–0.999). Resistance of diffusion related to a Chrastil coefficient n (0.37–0.455) has been demonstrated to substantially restrict the sorption process. By comparative analysis of experimentally obtained sorption capacities with applied kinetic models, good agreement was achieved by PSO with approximately similar values, and the closest values were achieved by Chrastil's model.

Table 1. Parameters of all applied kinetic models for RB19 sorption onto ZnMn-Fe₂O₄-CO₃.

Parameters	200.0 [mg/L]	300.0 [mg/L]	400.0 [mg/L]	500.0 [mg/L]	600.0 [mg/L]	700.0 [mg/L]
$q_{e,exp}$	798.60	1194.65	1412.50	1446.02	1454.49	1463.10
Pseudo-first order						
$q_{e,cal}$	761.07	1127.05	1307.80	1335.85	1374.88	1392.18
k_1	0.163	0.083	0.073	0.084	0.067	0.077
R^2	0.950	0.956	0.946	0.944	0.958	0.966
MRD	6.99	7.20	8.85	8.69	7.25	6.32
Pseudo-second order						
$q_{e,cal}$	823.02	1210.35	1418.26	1441.88	1493.49	1501.73
$k_2 \times 10^{-4}$	3.15	1.04	0.74	0.84	0.65	0.75
R^2	0.982	0.987	0.984	0.984	0.984	0.989
MRD	4.34	2.89	3.85	3.81	2.77	2.35
Chrastil model						
$q_{e,cal}$	800.30	1177.08	1394.21	1424.15	1441.70	1444.07
k_c	0.216	0.105	0.075	0.079	0.09	0.114
n	0.407	0.415	0.387	0.37	0.43	0.455
R^2	0.999	0.999	0.998	0.998	0.997	0.998
MRD	1.04	1.38	1.40	1.64	1.60	1.53
Intraparticle diffusion model						
K_{ID1}	149.84	178.47	199.38	215.05	205.36	222.12
C_1	59.47	50.47	54.43	59.45	49.47	41.23
R^2	0.951	0.967	0.970	0.971	0.980	0.990
K_{ID2}	10.67	28.71	46.85	47.27	47.53	36.81
C_2	698.38	835.19	817.98	852.25	881.11	1011.96
R^2	0.973	0.945	0.929	0.967	0.912	0.952

The applied IPD model provides data on the sorption mechanism, taking into account the fact that mass transfer during the sorption process can be controlled by one step or a combination of steps. The sequence of consecutive phases implies the transport of sorbate particles from the fluid to the surface of the boundary layer, which includes sorbent particles (film diffusion), the transfer of particles over the surface of the sorbent (surface diffusion), and intraparticle diffusion into the pores (particle diffusion) and the connection of sorbate molecules with the active sites of the sorbent [51,52]. IPD studies several processes through the various phases of sorption in order to further investigate the mechanism through the reaction rate [53]. The IPD curve depicts two linear segments at a concentration of 200 mg/L (caused by fast sorption) and three linear segments for all other tested concentrations on the graph showing the dependency of q_t on $t^{1/2}$. The first, most pronounced phase corresponds to surface diffusion, which occurs quickly due to the large concentration gradient. The next phase is somewhat slower, and refers to the diffusion of RB19 molecules into the sorbent and lasts until 120 min, while after that the third phase occurs and involves the establishment of equilibrium of the sorption reaction. Comparison of K_{ID1} and K_{ID2} values shows that K_{ID1} has values higher than K_{ID2} , which supports the fact that the second step of sorption, i.e., interparticle diffusion, is the step that controls the speed rate of the sorption reaction. The values of the constant C , which is related to mass transfer, indicate a greater thickness of the boundary layer in the second phase than in the first phase of the sorption process ($C_2 > C_1$). IPD is not the sole mechanism governing the sorption process in this case, as indicated by the fact that the IPD curve does not pass through the origin. An additional

graphical representation describing the PFO, PSO, Chrastil, and IPD models is provided in the Supplementary data (Figure S1).

3.2.6. Equilibrium Study

Isotherm models clarify the nature of the sorbent and provide insight into the sorbent composition, surface properties, and the interface mechanism among the sorbent and sorbate molecules at the point of equilibrium, while determining the sorption capacity according to the applied model [54–56]. Nonlinear forms of models, including Langmuir, Freundlich, Sips, Temkin, and Brouers–Sotolongo have been used. To validate the experimental data, the model that best fits and provides the most accurate description of the sorption process was evaluated. Figure 6a displays the curves corresponding to the studied models, while Table 2 summarizes the variables and constants of the related models. It can be concluded from the R^2 and MRD parameters that the Langmuir model has the lowest MRD value of all tested isotherm models and the highest R^2 (nearest to 1). This confirms the best agreement of the Langmuir isotherm with the given sorption process of RB19 molecules using $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$. This isotherm model reveals the energy equality of the specified sorption sites, as well as the homogeneity of the sorbent surface, which is in line with the findings of BET study [57]. In the initial concentration range of 200–700 mg/L, the Langmuir isotherm model yields an R_L value between $14.2 \cdot 10^{-4}$ and $4.06 \cdot 10^{-4}$, suggesting a favorable sorption at higher RB19 starting concentrations. The R^2 and MRD results for the Freundlich model indicate that this model is not relevant for this sorption system. Furthermore, the Sips model, which combines the Freundlich and Langmuir models, indicates agreement with the associated features of the Freundlich model at low initial concentrations of sorbate. At high starting concentrations, it resembles the Langmuir model. Since the value of the Sips heterogeneity parameter is close to 1 ($n_s = 0.987$), the homogeneous character of the sorbent surface can be assumed. Conversely, the Brouers–Sotolongo exponent α , which is a measure of energy heterogeneity, gives a value less than 1, indicating the heterogeneous sorbent's surface nature. Comparing the q_e values computed using isothermal models with the q_e value derived by experimental treatment, it appears that the Langmuir model has the closest agreement. Therefore, without dismissing the potential for heterogeneous surface characteristics, a thorough examination of the sorption system for the sorption of RB19 molecules from solution could conclude that its sorption occurs likely but not solely on a homogeneous surface in a monolayer.

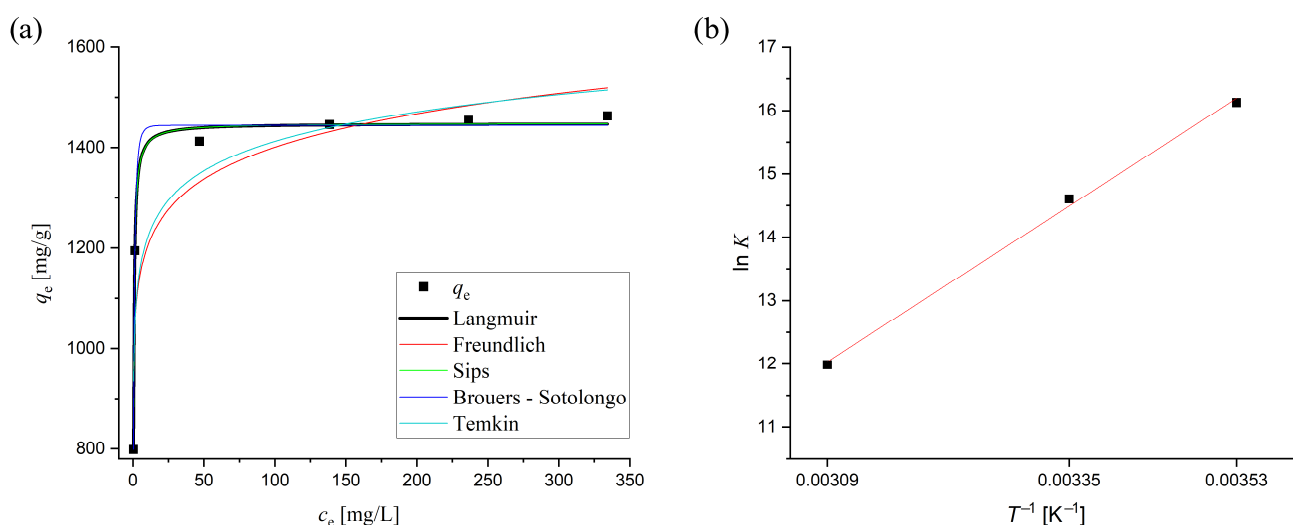


Figure 6. (a) Nonlinear isotherms for sorption of RB19 by $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$, (b) The linear plot applied for establishing ΔH° and ΔS° .

Table 2. Summarized isotherm and thermodynamic parameters for RB19 sorption onto ZnMn-Fe₂O₄-CO₃.

Isotherm Parameters									
	$q_{e,exp}$	1463.10							
Langmuir	q_m	1447.92	K_L	3.51			0.996		0.69
Freundlich	K_F	1029.11	n	14.94			0.792		6.26
Sips	q_m	1448.48	β_S	3.53	n_s	0.987		0.995	0.72
Brouers–Sotolongo	q_m	1444.03	K_W	1.48	α	0.582	R^2	0.993	MRD 0.81
Temkin	b	84.48	K_t	1.82×10^5				0.828	5.60
Thermodynamic Parameters									
Temperature of 283 K		1488.51		16.1266		−37.96			
Temperature of 298 K	q_m	1447.92	$\ln K$	14.6047	ΔG°	−36.20	ΔS°	−142.8	ΔH° −78.60
Temperature of 323 K		1297.66		11.9873		−32.21		R^2	0.996

3.2.7. Thermodynamic Study

The crucial factors to comprehending the thermodynamics of the sorption process of RB19 onto ZnMn-Fe₂O₄-CO₃ are shown in Table 2, providing deeper insight into energy fluctuations and their indirect influences on process efficiency. Figure 6b presents the corresponding graphical depiction. The sorption reaction is spontaneous, meaning that the energy inside the system is what drives its development, reflected by the negative values of the free Gibbs energy. Since the ΔG° values become less negative with increasing temperature, the sorption process is more favorable at lower temperatures. This is further supported by the decrease in the q_m value, which is associated with weaker sorbent–sorbate interaction at higher temperature. The negative entropy value suggests reduced disorder as the mobility of molecules on the sorbent surface becomes restricted after sorption [58,59]. The exothermic nature of the sorption process is confirmed by the enthalpy value of −78.60 kJ/mol. This magnitude lies close to the upper boundary of the physisorption/chemisorption range (40–80 kJ/mol), implying that the mechanism is predominantly chemisorption, but may also involve strong electrostatic interactions, as discussed in Section 3.3. The confirmation of the thermodynamic analysis is further supported by the high value of the determination coefficient ($R^2 = 0.996$).

3.3. Sorption Mechanism

A thorough explanation of the interaction mechanism between ZnMn-Fe₂O₄-CO₃ and RB19 can be provided by considering thermodynamics, isotherms, and kinetics analyses as well as the influence of the pH_{Hzc} value on the sorption efficiency. The results showed that under acidic conditions, electrostatic attractive forces occur between the positively charged active sites of ZnMn-Fe₂O₄-CO₃ and the negatively charged sulfonic group of the RB19 molecule, which ensured the initial attraction to the material surface, after which short range Van der Waals forces also contribute to the sorption process. In addition to the physical interactions that take place, the sorption process adheres to the PSO kinetic model confirming chemical sorption as one of the factors controlling the reaction rate. The equilibrium study demonstrates that the Langmuir isotherm, in the particular case, appropriately characterizes the sorption system and indicates the predominant homogeneity of the sorption surface and the specificity of the active sites, which is also confirmed by the BET analysis. A large surface area and mesoporosity provide numerous accessible sites for physisorption, while sufficiently wide mesopores enable rapid ion diffusion and prevent pore blocking, ensuring that the bulk of the sorbent actively participates in the process. In terms of thermodynamic parameters, the sorption reaction showed an exothermic nature, and the enthalpy value also indicated chemisorption. These integrated facts established that

chemisorption with the inevitable influence of electrostatic interactions, and the possible presence of physisorption, are most likely the mechanisms leading to this sorption process.

3.4. Comparison of Sorbents Properties

Table 3 provides an overview of materials that can sorb RB19 molecules with a broad range of maximum starting RB19 concentration. The following list includes materials with various compositions and origins that demonstrate diversity in sorption efficiency. Comparative results indicate that the applied ZnMn-Fe₂O₄-CO₃ material was effective in the removal of RB19 dye, whereas the other materials exhibited lower sorption capacity. The only material that surpasses the sorption capacity of ZnMn-Fe₂O₄-CO₃ is Poly (*N,N'*-methylene-bis (1-3-vinylimidazolium)) with an exceptional value of 2605 mg/g. Most high-capacity sorbents achieve maximal performance only under acidic conditions. This limits direct application to real textile effluents, which are typically alkaline, and requires acidification prior to treatment. In contrast, Chitosan film and G-ZnO-Cs show activity closer to neutral pH, but with lower capacities. Materials with very high capacities often require relatively low dosages, whereas biochar and composite sorbents demand higher dosages, which may increase operational cost and sludge generation. Activated carbon and biochar derived from agricultural waste (coconut shell, *Ulva reticula*) are inexpensive and widely available, but their sorption capacities are significantly lower. The time required to establish equilibrium reveals notable differences among sorbents. Fast sorption was achieved with Chitin hydrogels and activated carbon, while chitosan-based materials required much longer times. ZnMn-Fe₂O₄-CO₃ reached equilibrium in 90 min, representing a compromise between capacity and sorption rate. Overall, sorbents with extremely high capacities often exhibit moderate to long equilibrium time. Advanced polymeric or nanocomposite sorbents show high performance but involve higher synthesis cost and complex preparation routes. These comparisons highlight that ZnMn-Fe₂O₄-CO₃ occupies a significant place among materials capable of successfully removing RB19 molecules, with the added advantage of regeneration potential.

Table 3. Comparative overview of different materials for RB19 sorption.

Sorption Material	Maximal Sorption Capacity [mg/g]	pH	Sorbent Dosage [g/L]	Equilibrium Time [min]	Initial RB19 Concentration [mg/L]	Reference
Poly (<i>N,N'</i> -methylene-bis(1-3-vinylimidazolium))	2605.00	2.0	0.137	60	100.0	[60]
ZnMn-Fe ₂ O ₄ -CO ₃	1463.10	2.0	0.25	90	700.0	[this study]
Chitin nonfiber-/nanowhisker-based hydrogels	1331.00	1.0	0.5	20	1000.0	[61]
Chitosan film	822.40	6.8	0.007	150	800	[62]
Activated carbon	488.46	/	/	25	300	[63]
Magnetic chitosan/benzoin Schiff's base/fly ash	303.2	4.0	1.0	180	300	[64]
G-ZnO-Cs	219.6	5.0	1.0	90	100.0	[65]
<i>Ulva reticula</i> derived biochar	204.5	2.0	2.0	60	500.0	[14]
N ¹ -(3-trimethoxysilylpropyl)diethylenetriamine	178.8	2.0	1.5	About 100	300.0	[66]
Biochar derived from coconut shell	57.06	2.0	1.0	120	15.0	[67]

3.5. Real Water Sample Removal of RB19

A comparative analysis of four experiments on the removal of RB19 molecules using $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ in deionized water and under real wastewater from the textile industry conditions was performed, and the results of the *RE* versus sorption time are shown in Figure 7. Table S1 in the Supplementary lists the wastewater matrix's chemical content and its concentrations. The wastewater from the textile industry had a pH of 7.72, an RB19 initial concentration of 18.23 mg/L, a brown color, total dissolved solids of 376 mg/L, dissolved oxygen of 7.11 mg/L and BOD₅ of 6.08 mg/L. In the deionized water experiment, the highest removal efficiency of RB19 was 99.55% (concentration of RB19 was 300 mg/L, pH 2), but in the wastewater treatment (RB19 dye was added to textile wastewater to a total concentration of 300 mg/L, pH 2), it was 88.48%. The presence of different ions and molecules of inorganic and organic origin, which compete with RB19 molecules for binding at the sorption sites, is the reason for the 11% reduction in removal efficiency in the wastewater sorption system. In particular, nitrate (79.5 mg/L) and nitrite (3.6 mg/L) concentrations exceed the WHO reference values, and these oxyanions may compete with RB19 for sorption onto $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$. Such competitive interactions could further reduce the overall dye removal efficiency. The sorption systems equilibrium and kinetics were comparable, which further opens the possibility of broader use for the purification of wastewater that has been contaminated by the textile industry. Dye removal from textile wastewater (RB19 dye was added to a total concentration of 300 mg/L) at a native pH (7.72) resulted in a removal efficiency of about 6%. Finally, the removal of RB19 from wastewater in which no additional RB19 was added (the concentration was 18.23 mg/L) at native pH of 7.72 using $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ resulted in complete sorption. Based on this finding and the effect of pH value, it can be concluded that effective water purification using $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ can be achieved only within the acidic pH range up to 4, particularly when treating wastewater containing high dye concentrations.

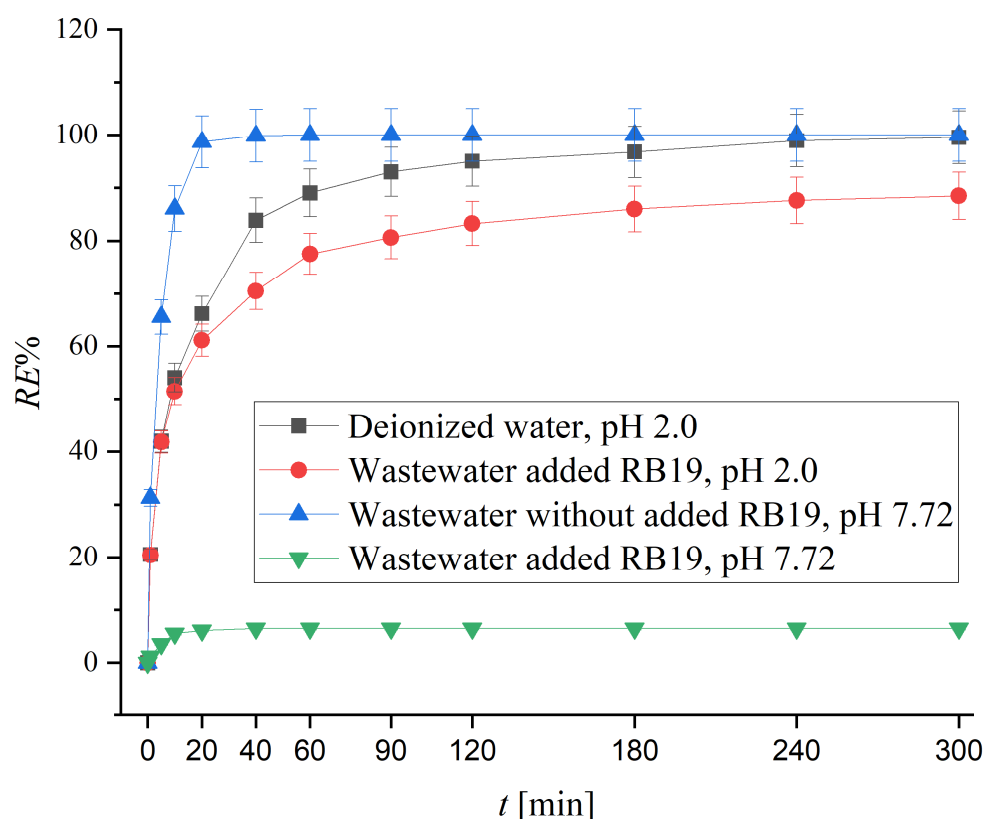


Figure 7. Removal efficiency comparison for deionized water and real wastewater.

3.6. Regeneration Study of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$

From an environmental protection perspective, a significant segment of quality of materials used in wastewater treatment processes is reflected in their ability to regenerate after a sorption cycle followed by desorption of pollutants under appropriate conditions. Following each cycle, a decline in removal efficiency was noted. After the first cycle, the overall removal efficiency was 99.55%, and after the second and third cycles, it was 93.42% and 90.76%, respectively. After the fourth cycle, the acquired RE was 89.21%, ending with the fifth cycle, after which the obtained RE was 86.98%. After five completed sorption–desorption cycles, the overall sorption efficiency dropped by around 12.60%. The desorption and regeneration of the material in basic conditions are explained by the rejection of the negatively charged $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ and the anionic dye RB19. The irreversible occupancy of the sorption sites and material shedding are the most likely causes of the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ declining sorption capability with each cycle. The observed mass loss was less than 7%, which can be attributed to physical loss during handling. Also, this mass loss could be partially due to leaching of Zn and Mn from impurities in the material detected by XRD in the form of ZnO and MnCO_3 which are soluble at pH 2.0 at which the sorption was performed (Figure 3). Ferrite is insoluble at pH 2.0 and in 1.0 M NaOH (Figure S2 in the Supplementary data). This percentage of mass loss is not considered significant in terms of sorbent stability and efficiency. XRD analysis after five completed sorption–desorption cycles confirmed the stability of the $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ structure (Figure S2 in the Supplementary data), except for the dissolution of impurities present in the form of ZnO and MnCO_3 (Figure 3a). No diffraction peaks corresponding to ZnO and MnCO_3 were observed in the XRD spectra after five cycles. All facts considered, $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ fulfills reproducibility requirements and maintains good efficiency even after several cycles, which might result in a considerable reduction in raw material consumption, energy costs, and environmental contamination.

4. Conclusions

Nano $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ sorbent was produced to purify water contaminated by anthraquinone dye RB19. $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ was thoroughly characterized, and its characteristics were described using FTIR, XRD, TGA, BET, SEM and EDS techniques. Sorption bands from the FTIR spectrum confirm the presence of the corresponding groups characteristic of $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$, as well as the confirmation of the successful sorption of RB19 molecules. XRD examination verified that the material sample consisted of the cubic Fd-3m group of crystals. The BET technique identified a type IV Langmuir isotherm with an H1 hysteresis loop, a mesoporous structure, and a specific surface area of $73.45 \text{ m}^2/\text{g}$. The particle size determined by the SEM examination was about 23 nm, while the EDS analysis confirms the corresponding elemental composition of the material both before and after sorption. The optimal parameters of the sorption process were achieved at pH 2, RB19 concentration of 300 mg/L and $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ dose of 0.25 g/L. Thermodynamic study showed that the given sorption system had an exothermic character, and the assumed type of sorption was chemisorption. According to the information gathered on the material's regenerative properties, thermal stability, and very high maximum sorption capacity, as well as the ease of use and affordability of the procedure, $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$, can be effectively employed in wastewater treatment procedures, possibly even in big plants. The proposed sorption system using $\text{ZnMn-Fe}_2\text{O}_4\text{-CO}_3$ material complies with the regenerative model of the circular economy, which is reflected in the reduction in waste, the improvement of resource efficiency, and the reuse of raw materials, with an emphasis on ecosystem restoration and environmental protection.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16157709/s1>, Table S1: Physicochemical properties of wastewater; Figure S1: Graphical representation of q_t vs. t for pseudo-first-order, pseudo-second-order and Chrastil model, and plot of q_t vs. $t^{1/2}$ for the intraparticle diffusion model for initial dye concentrations from 200.0 mg/L to 700.0 mg/L; Figure S2. XRD spectra after five completed sorption–desorption cycles.

Author Contributions: Conceptualization, M.M.K.; methodology, M.M.K.; software, K.N.F., S.M.N., M.D.R.V., N.D.V.G., S.A.R. and M.M.K.; validation, M.M.K.; formal analysis, K.N.F., S.M.N., N.D.V.G., M.D.R.V., S.A.R. and M.M.K.; investigation, K.N.F., M.M.K., S.M.N., M.D.R.V., N.D.V.G. and S.A.R.; data curation, K.N.F., S.M.N., M.D.R.V., N.D.V.G., S.A.R. and M.M.K.; writing—original draft preparation, M.M.K. and K.N.F.; writing—review and editing, M.M.K., N.D.V.G. and S.M.N.; visualization, M.M.K.; supervision, M.M.K. and A.L.B.; project administration, M.M.K. and A.L.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ZnMn–Fe ₂ O ₄ –CO ₃	nano zinc–manganese ferrite carbonate
XRD	X-ray diffraction
SEM	Scanning electron microscopy
EDS	Energy dispersive X-ray spectroscopy
TGA	Thermogravimetric analysis
BET	Brunauer–Emmett–Teller
FTIR	Fourier transform infrared spectroscopy
pH _{PZC}	Point of zero charge
PFO	Pseudo-first order
PSO	Pseudo-second order
IPD	Intraparticle diffusion model
MRD	Mean relative deviation

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