Adsorption and Release Kinetics, Equilibrium, and Thermodynamic Studies of Hymexazol onto Diatomite

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ABSTRACT: Pesticide sustained-release agents have advantages of low toxicity, high efficiency, and long duration. However, the sustained-release effects were not ideal, such as short release time and low release rate. The physical and chemical properties of diatomite are high stability, high porosity, and good sustained-release and controlled-release abilities. A series of diatomite-based pesticide sustained-release agents were prepared by adsorbing hymexazol onto diatomite. Kinetics, equilibrium, and thermodynamic studies for adsorption were carried out as well. It was found that the modified diatomite has a better adsorption effect for hymexazol, and the adsorption rate reached 16.64%. The equilibrium data followed with the Langmuir isotherm model, and the adsorption process was an endothermic process. Release results showed that the diatomite-based pesticide has a significant sustained-release effect. The sustained-release time reached more than 25 days, and the maximum release rate was above 70%. The experimental data was fitted into the Ritger–Peppas equation, and it was found that the release was controlled by the Fick diffusion mechanism. This confirmed the applicability of the modified diatomite as an efficient adsorption carrier for pesticide release.

1. INTRODUCTION

China is a large agricultural country with a large demand for pesticides.1 Due to the open policy; the large amount of pesticide used; and the improper processing, dosage form, and use mode, environmental pollution has been caused.2,3 As a new application method, use of pesticide sustained-release agents has advantages of low toxicity, high efficiency, long-lasting effects, sustained and stable release, safety, and economy.4−7 For hymexazol, the most commonly used carrier materials are lignin derivatives and activated carbon materials.8−11 The release time is short. Therefore, the selection of a carrier is key to the preparation of pesticide sustained-release agents.

Diatomite has the characteristics of low density, small bulk density, high porosity, and strong adsorption.12−14 The surface hydroxyl groups of diatomite can form hydrogen bonds with the hydroxyl groups, amino groups, ketone groups, and carboxyl groups of some organic molecules, which allows them to adsorb on the surface. Diatomite can be positively or negatively charged in different pH media, so the charged ions with the opposite sign can be adsorbed by electrical action.15 The adsorption process is mainly physical adsorption and minimal chemical adsorption. It can carry out single-molecule adsorption and multimolecular layer adsorption as well.16 Diatomite can be widely used in metal ion adsorption17−19 and dye adsorption20−22 and can also function as a carrier for high content powder,23 especially suitable for processing liquid pesticides into a carrier of high content powder. Therefore, diatomite as a carrier of pesticides has high research value.

As a broad-spectrum pesticide, hymexazol has the characteristics of low toxicity, high efficiency, and safety, but it also has the disadvantages of easy loss and short duration. Therefore, the preparation of a sustained-release agent would not only prolong the period of validity but also have environmental protection significance.

In this regard, to develop more efficient sustained-release pesticide agents, the present work selected diatomite as the adsorption carrier to adsorb hymexazol and focused on the investigation of the adsorption and release kinetics, equilibrium, and thermodynamics. It provides a low-cost, readily available, and environmentally friendly method for pesticide utilization.
2. RESULTS AND DISCUSSION

2.1. Effects of Diatomite Samples on Hymexazol Adsorption. Diatomite samples were used to adsorb the pesticide. The maximum adsorption of the diatomite sample was optimized to be as a carrier for pesticide. The adsorption effects of the diatomite material mentioned above are shown in Figure 1.

![Figure 1. Adsorption effects of different diatomite materials.](https://dx.doi.org/10.1021/acsomega.0c04449)

Compared with the raw diatomite, the diatomite treated with acid or high temperature had a better adsorption capacity. This indicated that the treatment process can remove impurities effectively from the raw diatomite, which improved the adsorption effect. It was shown that the hymexazol adsorption effect of the modified diatomite was better than that of the calcined diatomite. The adsorption rate reached 16.64%.

2.2. Characterization of Different Diatomite Samples. The adsorption effects of different diatomite samples are different. The properties of the diatomite sample determined the adsorption effect directly. The properties of the different diatomite samples were characterized by Fourier transform infrared (FT-IR), Brunauer−Emmett−Teller (BET), and scanning electron microscopy (SEM) analyses.

2.2.1. FT-IR Analysis. For the three kinds of samples, the characteristic peaks were 3449, 1635, 1400, 1100, and 795 cm$^{-1}$ (Figure 2). The peaks at 3449 and 1635 cm$^{-1}$ corresponded to the vibration absorption peak of Si−OH. However, the peak strength of calcined diatomite was obviously weak, which was due to the destruction of Si−OH.$^{24,25}$ The peak at 1400 cm$^{-1}$ was attributed to some organic substances. However, the peak strength of the calcined sample was weak. This was due to the decomposition of organic components after calcination of diatomite.$^{26}$ The peak at 1000−1200 cm$^{-1}$ was identified as the asymmetric shoulder-

like broad and strong absorption peak, which belonged to the Si−O−Si antisymmetric stretching vibration.$^{27−29}$ The peak at 795 cm$^{-1}$ belonged to the vibration adsorption peak of Si−OH. The peak at 620 cm$^{-1}$ was attributed to the structural vibration of the Si−O tetrahedral six-membered ring in crystalline quartz. The peak near 470 cm$^{-1}$ corresponded to the antisymmetric bending vibration of Si−O−Si in [SiO$_4$] tetrahedron. Its strength increased obviously in the modified diatomite and calcined diatomite due to the decrease of impurities after modification and calcination of raw diatomite, as the silicon content increased. The impurities in the raw diatomite can be removed by calcination and acid modification, resulting in the lower adsorption properties of the raw diatomite than those of the calcined diatomite and modified diatomite. However, the calcination process can destroy Si−OH to a certain extent and acid modification not only has less damage to Si−OH but also dissolved some metals and metal oxides. Thus, acid modification was the best method to treat the raw diatomite in this work.

2.2.2. BET Analysis. The specific surface area, pore volume, and pore diameter are the key factors affecting adsorption. The pore structure parameters of the three kinds of diatomite materials are listed in Table 1.

![Figure 2. IR analysis of different diatomite materials.](https://dx.doi.org/10.1021/acsomega.0c04449)

|                  | specific surface area, m$^2$ g$^{-1}$ | pore volume, cm$^3$ g$^{-1}$ | pore diameter, nm |
|------------------|--------------------------------------|-----------------------------|-------------------|
| Raw diatomite    | 21.794                               | 0.030                       | 5.498             |
| Modified diatomite | 29.282                             | 0.062                       | 10.903            |
| Calcined diatomite | 4.0196                            | 0.0056                      | 5.578             |

It can be seen from Table 1 that the pore structure parameters of the modified diatomite are larger than those of the raw diatomite and the calcined diatomite. Because the impurities covered in the micropores on the surface of diatomite were effectively washed out in the acid treatment process and some new micropores were exposed, it increased the porosity, specific surface area, pore volume, and pore size. However, the surface area of the calcined diatomite decreased greatly after calcination. Through literature review,$^{30}$ it was known that after calcination, some of the complete diatomite were destroyed, resulting in a decrease in the surface area greatly. The pore volume of the modified diatomite increased with the decrease of diatomite impurities and some metals and metal oxides after acid modification. However, the pore volume of the calcined diatomite decreased due to the collapse of micropores caused by high-temperature calcination. Thus, the hymexazol adsorption performance of the modified diatomite was better than that of the other two diatomite materials.

2.2.3. SEM Analysis. The SEM micrographs of the raw diatomite, calcined diatomite, and modified diatomite are presented in Figure 3. It can be observed that the microstructure of the three kinds of diatomite materials was a circular sieve structure. Among the three diatomite materials,
the cleanness of the modified diatomite was obviously better than that of the raw diatomite and the calcined diatomite. Furthermore, the disc sieve structure of the calcined diatomite collapsed and the melting corrosion was severe at the high temperature. It was found that the modified diatomite has a relatively complete structure and less impurity.

Figure 4 shows clearly that diatomite round sieve particles had a large number of pores arranged in order, which can provide more adsorption sites and a larger adsorption area. There were many impurities on the surface of raw diatomite, which blocked a lot of micropores. Impurities on the calcined diatomite were less, but the micropores collapsed and corroded severely, which decreased the integrity. The micropores of the modified diatomite were regular in size and arranged in order. In addition, due to the acid treatment, some metals and oxides in the diatomite micropores were removed, resulting in the increase of micropores. The more the micropores of diatomite exposed, the stronger the adsorption capacity. The micropores of raw diatomite and calcined diatomite were obviously smaller than those of the modified diatomite. Therefore, the modified diatomite was selected as a carrier material for hymexazol.

The results of FT-IR, BET, and SEM analyses showed that compared with the raw diatomite and calcined diatomite, in the modified diatomite, the impurities were reduced, the Si–OH functional groups affecting the adsorption were less destroyed, the pore structure parameters were significantly improved, and the surface micropores became larger and more, which led to the enhancement of adsorption capacity. This concluded that the modified diatomite is a kind of good sustained-release pesticide carrier.

2.3. Adsorption Kinetics. 2.3.1. Adsorption Isotherm. The adsorption of hymexazol solution with different initial concentrations on the modified diatomite at 298, 308, and 318 K was investigated (Figure 5).

Results showed that the ultimate adsorption capacity of the modified diatomite increased with the increase of the equilibrium concentration of the hymexazol solution and finally tended to equilibrium. This showed that the increase of temperature made the thermal movement of the molecules in the solution more intense, and it was easier for the molecules...
to contact diatomite. Therefore, it easily adsorbed into the pores of the diatomite, and it was also found that the appropriate temperature rise was conducive to the adsorption reaction.

2.3.2. Adsorption Isotherm Model. The adsorption of hymexazol onto diatomite belongs to the adsorption on the solid surface at a constant temperature, which is explained by Langmuir and Freundlich models. The Langmuir adsorption model shows that each adsorption site has the same adsorption capacity, which shows single-molecule adsorption. The Freundlich adsorption model shows that the adsorption is multimolecular and the surface of the adsorbent is not uniform.

According to the experimental data, using formulas 2 and 3, respectively, for \( C_e/Q_e - C_e \) and \( \ln Q_e - \ln C_e \), the results of Langmuir and Freundlich adsorption isotherms for the adsorption of hymexazol solution by the modified diatomite are shown in Figures 6 and 7, respectively.

![Figure 6. Langmuir equilibrium isotherm for hymexazol adsorbed by diatomite.](image)

![Figure 7. Freundlich equilibrium isotherm for hymexazol adsorbed by diatomite.](image)

Through the comparison of \( R^2 \), it was found that the Langmuir model can simulate the isothermal adsorption characteristics of hymexazol on the modified diatomite. By fitting the data equation, it can be seen that the adsorption effect was closely related to temperature. Results showed that the modified diatomite had a good adsorption effect on hymexazol at different temperatures. However, the change of temperature affected the adsorption capacity. The adsorption capacity of the modified diatomite improved with the increase of temperature.

The Freundlich model was used to describe the adsorption mechanism of hymexazol onto the modified diatomite as well. The fitting equation indicated that the temperature affected the adsorption capacity and adsorption efficiency. With the increase of temperature, the adsorption performance and capacity improved obviously.

Based on the adsorption isotherm equation of hymexazol onto diatomite, the regression analysis data of isotherms are listed in Table 2.

| T (K) | \( Q_{max} \) (mg g\(^{-1}\)) | \( K_L \) | \( R^2 \) | \( K_F \) | \( 1/n \) | \( R^2 \) |
|-------|------------------|--------|--------|--------|-------|--------|
| 298   | 18.25            | 0.0004 | 0.9091 | 0.2491 | 0.4543 | 0.9391 |
| 308   | 18.18            | 0.0006 | 0.9942 | 0.4190 | 0.4119 | 0.9715 |
| 318   | 20.07            | 0.0008 | 0.9983 | 0.6805 | 0.3724 | 0.9627 |

The correlation between the two isotherms at different temperatures was good. However, on comparing \( R^2 \) values, it was observed that the correlation coefficient of the Langmuir adsorption isotherm was significantly higher than that of the Freundlich adsorption isotherm. Results showed that the adsorption of hymexazol onto the modified diatomite fitted to the Langmuir isotherm adsorption model. \(^{31}\) The adsorption process was mainly physical adsorption, which was consistent with FT-IR and BET analyses. 1/\( n \) is related to adsorption strength. When \( 0.1 < 1/n \leq 0.5 \), it is easy to carry out adsorption. When \( 0.5 < 1/n \leq 1 \), it is easy to carry out adsorption. When \( 1/n > 1 \), adsorption is comparatively difficult. 1/\( n \) gained in this work was between 0.3724 and 0.4543, indicating that the adsorption of hymexazol onto the modified diatomite was very easy, and the adsorption process involved single-molecular layer adsorption. Moreover, the trend of \( K_L \) and \( K_F \) increased with the increase of temperature showed that the adsorption capacity of diatomite was stronger with the increase of temperature. It was considered that higher temperature was beneficial to the adsorption of hymexazol onto the modified diatomite material.

2.3.3. Adsorption Thermodynamics. When the temperature was 298, 308 and 318 K, respectively, the equilibrium adsorption capacity of hymexazol onto the modified diatomite was measured. The Gibbs equation was used to analyze the adsorption thermodynamics. The linear regression for \( -1/T \) was made, and \( \Delta S \) and \( \Delta H \) were calculated according to the slope and intercept. Linear regression \( \ln K_f - T^{-1} \) is shown in Figure 8. \( \Delta S \) and \( \Delta H \) are shown in Table 3.

The adsorption process can be judged as an endothermic process by the fitting equation, and the adsorption capacity of hymexazol on diatomite can be improved by increasing the temperature. \( \Delta S \) and \( \Delta H \) can be calculated by fitting the slope and intercept of the equation.

\( \Delta H \) was greater than zero, indicating that the process of adsorption of hymexazol solution on diatomite was an endothermic process. The total energy of the reactant was lower than the total energy of the product. Moreover, the
increase of the temperature made the adsorption easier, which was consistent with the trend of adsorption isotherm.

2.4. Study on the Performance of the Release.

As shown in Figure 9, the pesticide hymexazol sustained-release agent is gray-white, granular, and with good formability; the particles are small and dispersed; and the morphology is regular. Moreover, it has high bulk density and is easy to be preserved. According to different needs, the effect of sustained-release will be different, and the exploration of the conditions required in the process of sustained release becomes extremely important. It was found that pH and temperature have significant effects on sustained release. The best release conditions can be achieved by discussing the influence of pH and temperature.

2.4.1. Effects of pH on Release.

Figure 10 shows that the release effect was perfect under different pH (6, 7, 8) conditions. The sudden release of hymexazol under alkaline conditions was relatively obvious, reaching 53.54% on the first day and 83.28% at the limit. Compared with that in the alkaline condition, the release amount was slightly lower on the first day when the pH was 6 and 7. However, the subsequent changes in the release were relatively mild. Under the different pH conditions, the prepared release agent achieved a better sustained-release persistence.

2.4.2. Effect of Temperature on Release.

The whole release process can be divided into three stages: linear sudden release stage, curved slow release stage, and uniform release stage. In the sudden release stage, they all reached about 50%. In the slow release and uniform release stages, the release rate increased slowly and stably. The release amount at 35 °C was higher than that at 15 and 25 °C. The release rate of the drug-loaded system increased with the increase of temperature. One of the reasons may be that the increase of the temperature resulted in the acceleration of Brownian motion and thus the release of hymexazol. In addition, similar to the influence of pH conditions mentioned above, the sustained-release persistence of the prepared release agents at different temperatures was very good. Therefore, temperature selection is one of the key factors of release control. Higher temperatures are more suitable for the requirements of a high sustained-release amount of pesticides (Figure 11).

Table 3. Thermodynamics Parameters for Hymexazol Adsorption onto Diatomite

| T (K) | $\Delta H$ (kJ mol$^{-1}$) | $\Delta S$ (kJ mol$^{-1}$) |
|-------|-----------------|-----------------|
| 298   | 14.44           | 0.0253          |
| 308   |                  |                 |
| 318   |                  |                 |

Figure 8. ln $K_c$ = $1/T$ of hymexazol adsorption onto diatomite.

Figure 9. Diatomite-based pesticide sustained-release granule.

Figure 10. Effect of pH on cumulative release of hymexazol granules.

Figure 11. Effect of temperature on cumulative release of hymexazol granules.
In sum, temperature and pH influenced the sustained-release effect of hymexazol. Results showed that the sustained-release amount reached more than 60% and the sustained-release time was more than 25 days.

2.4.3. Kinetic Equation of Release. 2.4.3.1. Release Kinetics Equation for Different pH Conditions. Figure 12 shows that the release of hymexazol, so that the release amount increased (Table 4).

![Figure 12. Kinetics fitting curve of Ritger–Peppas for different pH conditions.](image)

with the increase of pH and release time, the cumulative release of the drug gradually increased. Compared with the acidic and neutral conditions, the cumulative release was more effective under the alkaline conditions, indicating that the alkaline conditions had a greater impact on the release of hymexazol, which was consistent with the results shown in Figure 10.

The fitting correlation coefficient $R^2$ showed that the release process under alkaline conditions was better in accordance with the Ritger–Peppas model than that under neutral and acidic conditions. The fitting index $n$ was between 0.0645 and 0.1578, less than 0.5, indicating that the release of hymexazol was controlled by the Fick diffusion mechanism. The release rate constant $K$ increased with the increase of pH, which indicated that the increase of pH accelerated the diffusion of hymexazol, so that the release amount increased (Table 4).

![Figure 13. Kinetics fitting curve of Ritger–Peppas for different temperatures.](image)

molecules, resulting in the improvement of sustained-release properties (Table 5).

![Table 4. Ritger–Peppas Release Model Fitting Results for Different pH Conditions](image)

| pH  | $K$     | $n$     | $R^2$ |
|-----|---------|---------|-------|
| 6   | 44.5964 | 0.0757  | 0.8325|
| 7   | 50.0611 | 0.0645  | 0.8498|
| 8   | 48.8427 | 0.1578  | 0.9344|

2.4.3.2. Release Kinetics Equation for Different Temperatures. Figure 13 clearly shows that drug cumulative release increased with the increase of temperature. As mentioned above, higher temperature is good for release of hymexazol. A higher sustained-release amount can be achieved by increasing the temperature and pH appropriately in application.

The fitting correlation coefficient $R^2$ showed that the fitting degree was high, and the release process was in accordance with the Ritger–Peppas model. The fitting index $n$ was between 0.0243 and 0.0979, less than 0.5, indicating that the release of hymexazol was controlled by the Fick diffusion mechanism. At high temperature, the release rate constant $K$ was larger. High temperature accelerated the movement of

3. CONCLUSIONS

Three kinds of diatomite materials were selected as the adsorption carrier of hymexazol to investigate their adsorption performance. It was confirmed that the adsorption effect of the modified diatomite was better than that of the raw diatomite and the calcined diatomite. Its adsorption rate reached 16.64%. The Langmuir isotherm adsorption model was more suitable for elucidating the adsorption behavior of hymexazol onto the modified diatomite. The adsorption process involved single-molecular layer adsorption, was physical adsorption, and was an endothermic process. Furthermore, the release properties of the modified diatomite-based hymexazol sustained-release agent were studied. Results showed that it had a good sustained-release effect, and the sustained-release time can reach more than 25 days. The maximum release rate of hymexazol was about 70%. The research found that the release rate and the amount of the pesticide were related to temperature and pH. The sustained-release agent of hymexazol was more suitable for neutral and acidic soil environments. The release rule of the pesticide can be described by the Ritger–Peppas equation and controlled by the Fick diffusion mechanism. This concluded that the modified diatomite was a highly efficient and stable carrier of hymexazol to prepare pesticide sustained-release agents.

4. EXPERIMENTAL SECTION

4.1. Materials and Reagents. The raw diatomite (100 mesh) and calcined diatomite (calcined at 1000 °C for 4 h) samples were supplied by Jilin Lulin Novel Materials Co., Ltd., Baishan, Jilin Province, China. Hymexazol (97%) was purchased from Hubei Dixin Chemical Manufacturing Co., Ltd. Hydrochloric acid (analytically pure) was supplied by Tianjin Tianhe Chemical Reagent Factory. Talcum powder
was supplied by Tianjin Yongda Chemical Reagent Co., Ltd. Sodium polyacrylate was provided by Tianjin Kemeo Chemical Reagent Development Center.

### 4.2. Experimental Methods. 4.2.1. Modified Diatomite.
To obtain a cost-effective pesticide sustained-release carrier by a simple method, the raw diatomite was modified by acid. HCl (100 mL; 10%) was put into conical bottles containing 10 g of diatomite. At 30 °C, the mixed solution was placed in a table concentrator and shaken at 120 rpm for 1 h. Then, the diatomite was filtered, washed, and dried for use. The BET parameters of the diatomite before and after modification were determined by a full-automatic specific surface area and mesoporous analyzer. The morphology of the diatomite was analyzed by scanning electron microscopy (JEOL JSM-6460LV SEM). The infrared spectrum of the diatomite was determined by Fourier-transformed infrared (FT-IR) spectroscopy.

### 4.2.2. Adsorption of Hymexazol.
The standard curve of hymexazol was established by a UV spectrophotometer with different absorbance concentrations (the maximum absorption wavelength was 205 nm). The hymexazol standard curve was \( Y = 0.06358x + 0.01147 \). The diatomite sample (0.25 g) was weighed as an adsorbent for adsorption in 25 mL of 100 ppm hymexazol solution for a certain time and kept in a shaking table. The adsorption capability was determined according to eq. 1.

\[
Q_t = \frac{(C_0 - C_t)V}{m}
\]

where \( C_0 \) and \( C_t \) (mg mL\(^{-1}\)) are the concentrations of hymexazol solution at the initial time and time \( t \) (h), respectively. \( V \) (mL) is the volume of the hymexazol solution used, and \( m \) (g) is the weight of the carrier.

### 4.2.2.1. Adsorption Kinetics.
The weighed (0.25 g) diatomite sample adsorbed a series of 25 mL of hymexazol solutions (1–6 mg mL\(^{-1}\)) at 25, 35, and 45 °C, and the absorbance was measured at \( \lambda = 205 \text{ nm} \) after 3 h. According to the adsorption of hymexazol on diatomite, the adsorption isotherm was achieved.

Langmuir equation (eq 2) and Freundlich equation (eq 3) were used to describe the adsorption model of diatomite.

\[
\frac{C_e}{Q_e} = \frac{1}{K_LQ_m} + \frac{C_e}{Q_m}
\]

\[
\ln Q_e = \ln K_f + \frac{1}{n} \ln C_e
\]

where \( Q_e \) (mg g\(^{-1}\)) and \( Q_m \) (mg g\(^{-1}\)) are the equilibrium adsorption capacity and the maximum adsorption capacity, respectively. \( C_e \) (mg L\(^{-1}\)) is the adsorption equilibrium concentration. \( K_L \) (L mg\(^{-1}\)) is a Langmuir constant related to the affinity of the binding sites. \( K_f \) and \( n \) are the Freundlich constants related to the adsorption capacity and surface heterogeneity of adsorbents, respectively.

The adsorption thermodynamics of hymexazol on diatomite was studied. The adsorption enthalpy (\( \Delta H \)) and entropy (\( \Delta S \)) were calculated by the following equations:

\[
\ln K_c = \frac{\Delta H}{RT} - \frac{\Delta S}{R}
\]

\[
\Delta G = \Delta H - T\Delta S
\]

where \( K_c \) is the adsorption equilibrium constant; \( C_{\text{ad}} \) is the drug concentration on the adsorbent at equilibrium; \( C_e \) is the equilibrium concentration of the solution; \( R \) is the universal gas constant (8.314 J K\(^{-1}\) mol\(^{-1}\)); and \( T \) (K) is the absolute temperature.

### 4.2.3. Preparation of Diatomite-Based Pesticide Sustained-Release Agents.
Modified diatomite (1 g) was added into a 250 mL conical flask containing hymexazol solution with an initial mass concentration of 6 mg mL\(^{-1}\), and the mixed solution was placed in a water-bathing constant temperature vibrator and stirred at 150 rpm at 45 °C for 2 h. After the sorption, it was filtered, washed, and dried to a constant weight at 40 °C. Talcum powder and 1% sodium polyacrylate solution were added to the moderate sample, squeezed granulation after mixing, and drying at 40 °C, 0.1% hymexazol sustained-release agent was obtained.

### 4.2.4. Release of Hymexazol.
The effects of pH (6, 7, 8) and temperature (15, 25, 35 °C) on the release of hymexazol were studied. The drug release rate was calculated as follows

\[
W_t = \frac{C_t}{C_r} \times 100\%
\]

where \( W_t \) is the release rate at time \( t \), \( C_t \) is the concentration of the drug in solution at time \( t \), and \( C_r \) is the concentration of the drug that should theoretically be released completely.

### 4.2.5. Release Kinetics.
The release curve was fitted with the Ritger–Peppas empirical equation.

\[
\frac{M_t}{M_\infty} = Kt^n
\]

where \( M_t/M_\infty \) is the drug accumulation–release ratio. \( t \) is the drug release time. \( K \) is the release rate constant. \( n \) is the diffusion index.

For the convenience of investigation, the logarithm of both sides of formula 9 was taken at the same time, and the equation was as follows

\[
\log \frac{M_t}{M_\infty} = n \log t + C
\]

When \( n < 0.5 \), release is controlled by Fick’s diffusion; when \( 0.5 < n < 1 \), the release process is anomalous diffusion, which is a combination of Fick’s and non-Fick’s diffusion; and when \( n > 1 \), the release process involves two kinds of diffusion.

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Notes
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