Review of second-order models for adsorption systems

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Abstract

Applications of second-order kinetic models to adsorption systems were reviewed. An overview of second-order kinetic expressions is described in this paper based on the solid adsorption capacity. An early empirical second-order equation was applied in the adsorption of gases onto a solid. A similar second-order equation was applied to describe ion exchange reactions. In recent years, a pseudo-second-order rate expression has been widely applied to the adsorption of pollutants from aqueous solutions onto adsorbents. In addition, the earliest rate equation based on the solid adsorption capacity is also presented in detail.
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1. Introduction

Predicting the rate at which adsorption takes place for a given system is probably the most important factor in adsorption system design, with adsorbate residence time and the reactor dimensions controlled by the system's kinetics. A number of adsorption processes for pollutants have been studied in an attempt to find a suitable explanation for the mechanisms and kinetics for sorting out environment solutions. In order to investigate the mechanisms of adsorption, various kinetic models have been suggested. In recent years, adsorption mechanisms involving kinetics-based models have been reported. Numerous kinetic models have described the reaction order of adsorption systems based on solution concentration. These include first-order [1] and second-order [2] reversible ones, and first-order [3] and second-order [4] irreversible ones, pseudo-first-order [5] and pseudo-second-order ones [6] based on the solution concentration. On the other hand, reaction orders based on the capacity of the adsorbent have also been presented, such as Lagergren's first-order equation [7], Zeldowitsch's model [8], and Ho's second-order expression [9–12].

This paper describes an earlier adsorption rate equation based on the solid capacity for a system of liquids and solids [7], the Elovich equation for adsorption of gases onto a solid and apply-ing a second-order rate equation for gas/solid and solution/solid adsorption systems [8], a second-order rate expression for ion exchange reactions [13], and a pseudo-second-order expression [9].

2. Modeling

2.1. Second-order rate equation

A linear form of the typical second-order rate equation is

$$\frac{1}{C_t} = k_2 t + \frac{1}{C_0}, \tag{1}$$

where C_t is the equilibrium concentration (mg/dm^3), C_0 the initial concentration (mg/dm^3), t the time (min), and k_2 is the rate constant (dm^3/mg min).

Early applied second-order rate equations in solid/liquid systems described reactions between soil and soil minerals [14,15]. Others applied which the second-order rate equation included the adsorption of fluoride onto acid-treated spent bleaching earth [16]; and the adsorption of water using the dealumination of HZSM-5 zeolite by thermal treatment [17]. Moreover, Varshney et al. reported the kinetics of adsorption of the pesticide, phosphamidon, on beads of an antimony(V) phosphate cation exchanger during the first 15 min [18].

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2.2. Lagergren's equation

As early as 1898 [7], Lagergren described liquid–solid phase adsorption systems, which consisted of the adsorption of oxalic acid and malonic acid onto charcoal. Lagergren's first-order rate equation is the earliest known one describing the adsorption rate based on the adsorption capacity. It is summarised as follows:

$$\frac{dx}{dt} = k(X - x), \tag{2}$$

where X and x (mg/g) are the adsorption capacities at equilibrium and at time t (min), respectively, and k is the rate constant of the first-order adsorption (1/min).

Eq. (2) was integrated with the boundary conditions of $t = 0$ to $t = t$ and $x = 0$ to $x = x$ to yield

$$\ln\left(\frac{X}{X - x}\right) = kt \tag{3}$$

and

$$x = X(1 - e^{-kt}). \tag{4}$$

Eq. (3) may be rearranged to a linear form:

$$\log(X - x) = \log(X) - \frac{k}{2.303}t. \tag{5}$$

In order to distinguish kinetics equations based on concentrations of solution from adsorption capacities of solids, Lagergren's first-order rate equation has been called pseudo-first-order [10,19–22]. An early known application of Lagergren's kinetics equation to adsorption was undertaken by Trivedi et al. [23] for the adsorption of cellulose triacetate from chloroform onto calcium silicate. During the last four decades, the kinetics equation has been widely applied to the adsorption of pollutants from aqueous solutions [24].

2.3. Elovich's equation

Elovich's equation is another rate equation based on the adsorption capacity. In 1934 [8], the kinetic law of chemisorption was established though the work of Zeldowitsch. The rate of adsorption of carbon monoxide on manganese dioxide decreasing exponentially with an increase in the amount of gas adsorbed was described by Zeldowitsch [8]. It has commonly been called the Elovich equation in the following years:

$$\frac{dq}{dt} = a\, e^{-\alpha q}, \tag{6}$$

where q is the quantity of gas adsorbed during the time t, α the initial adsorption rate, and a is the desorption constant during any one experiment. The integrated form of Eq. (6) can be written in the form

$$q = \left(\frac{2.3}{\alpha}\right)\log(t + t_0) - \left(\frac{2.3}{\alpha}\right)\log t_0 \tag{7}$$

with

$$t_0 = \frac{1}{\alpha a}. \tag{8}$$

With a correctly chosen t_0, the plot of q as a function of $\log(t + t_0)$ should yield a straight line with a slope of $2.3/\alpha$; Eq. (8) then gives a which obviously represents the initial rate of adsorption for $q = 0$. The test thus involves one single disposable parameter, t_0, which is found by trial; if t_0 is too small, the curve is convex, and if t_0 is too large, it is concave to the axis of $\log(t + t_0)$ [25]. This Elovich equation is commonly used to determine the kinetics of chemisorption of gases onto heterogeneous solids, and is quite restricted, as it only describes a limiting property ultimately reached by the kinetic curve [26].

To simplify Elovich's equation, Chien and Clayton [27] assumed that $a\alpha t \gg 1$ and by applying the boundary conditions of $q = 0$ at $t = 0$ and $q = q$ at $t = t$, then Eq. (6) becomes [28]:

$$q = \alpha \ln(a\alpha) + \alpha \ln(t). \tag{9}$$

Thus, the constants can be obtained from the slope and the intercept of a straight line plot of q against $\ln(t)$. Recently, Rudzinski and Panczyk [29] published an exhaustive analysis of existing rationalizations for the Elovich equation found in the literature for the kinetics of adsorption onto heterogeneous surfaces.

In earlier years, numerous applications of Elovich's equation to the adsorption of gases onto solid systems were reported [30,31]. During the last three decades, the equation has been widely used to describe the kinetics of adsorption of gases onto solids [29,32–35]. The most frequently cited paper for the application of Elovich's equation to adsorption systems was an alternative to Elovich's equation for kinetics of adsorption of gases onto solids [33]. An earlier application of the rate equation of Elovich was the exchange of ^{32}P between the goethite (α-FeOOH) crystal surface and the solution phase [36]. The application of Elovich equation to the kinetics of phosphate release and adsorption in soils [27] is the most frequently cited paper on the adsorption in solution/solid systems. In addition, the Elovich equation has also been used to describe the adsorption of pollutants from aqueous solutions in recent years [19,37,38].

2.4. Ritchie's equation

In 1977 [33], Ritchie reported a model for the adsorption of gaseous systems. Assumptions were made as follows: θ is the fraction of surface sites which are occupied by an adsorbed gas, n the number of surface sites occupied by each molecule of the adsorbed gas, and α is the rate constant. Assuming that the rate of adsorption depends solely on the fraction of sites which are unoccupied at time t, then

$$\frac{d\theta}{dt} = \alpha(1 - \theta)^n. \tag{10}$$

Eq. (10) integrates to

$$\frac{1}{(1 - \theta)^{n-1}} = (n - 1)\alpha t + 1 \quad \text{for } n \neq 1 \tag{11}$$

or

$$\theta = 1 - e^{-\alpha t} \quad \text{for } n = 1. \tag{12}$$

It is assumed that no site is occupied at $t = 0$. When introducing the amount of adsorption, q, at time t, Eq. (11) becomes

$$\frac{q_\infty^{n-1}}{(q_\infty - q)^{n-1}} = (n-1)\alpha t + 1 \tag{13}$$

and similarly Eq. (12) becomes

$$q = q_\infty(1 - e^{-\alpha t}), \tag{14}$$

where q_∞ is the amount of adsorption after an infinite time.

In earlier years, Sobkowsk and Czerwiński [39] presented a rate equation for the reaction of carbon dioxide adsorption onto a platinum electrode:

$$\frac{d\theta}{dt} = k(1 - \theta)^n, \tag{15}$$

where $\theta = \Gamma/\Gamma_\infty$ denotes the surface coverage by the reaction products, Γ and Γ_∞ the surface concentrations at time t and after completion of the reaction, respectively, k the rate constant, and n is the order of the reaction.

When $n = 1$,

$$-\ln(1 - \theta) = k_1 t. \tag{16}$$

When $n = 2$,

$$\frac{\theta}{1 - \theta} = k_2 t. \tag{17}$$

Sobkowsk and Czerwiński [39] concluded that the first-order is only for low surface concentrations of a solid, confirmed by using plots of $-\ln(1 - \theta)$ versus time as Eq. (16), and the second-order is for higher concentrations of a solid, confirmed by using plots of $\theta/(1 - \theta)$ versus time as Eq. (17). In addition, Trasatti and Formaro reported that the plot of $-\ln(1 - \theta)$ versus time is not linear for very long times, when the coverage reaches a stationary value for the adsorption of glycolaldehyde onto a platinum electrode [40]. In the case of the sorption of basic dyes from aqueous solution onto sphagnum moss peat, Ho and McKay [22] found that $\log(q_e - q_t)$ versus time was only applicable in the early stage of the reaction. In the case of adsorption of gases onto a solid surface, Sobkowsk and Czerwiński reported that the first-order rate equation could only be used for a low surface concentration of gases adsorbed onto a solid surface, and the second-order rate evaluation could be applied to higher concentrations [39].

Several adsorption results were examined using the Ritchie equation [33]. In the early years, the Elovich equation was applied to describe gas and vapour adsorption systems, such as the adsorption of carbon monoxide during the oxidation of polyvinylidene chloride [41], the chemisorption of hydrogen onto graphon [42], the measuring of the kinetics of the chemisorption of H_2 onto a $MoS_2 + Al_2O_3$ catalyst [43], and the adsorption of water vapour by Vycor fibre [44]. These systems did not fit the Elovich equation very well. Ritchie [33] examined these results using Eq. (13) when $n = 2$. Eq. (13) becomes

$$\frac{q_\infty}{(q_\infty - q)} = \alpha t + 1. \tag{18}$$

The value for q_∞ is obtained from the intercept at $(1/t) = 0$ on a plot of $(1/q)$ against $(1/t)$. Ritchie found a good linear relationship between t and $q_\infty/(q_\infty - q)$ for the results of Austin et al. [41], Bansal et al. [42], Deitz and Turner [44], and Samuel and Yeddanapalli [43]. In recent years, the Ritchie equation has also been applied to solution/solid adsorption systems, for example, the adsorption of cadmium ions onto bone char [37], and the adsorption of Cd(II) onto acid-treated jackfruit peel [45].

2.5. Second-order rate expressions

In 1984 [13], Blanchard et al. presented the overall exchange reaction of NH_4^+ ions fixed in zeolite by divalent metallic ions in the solution which can be written:

$$Z_{(2NH_4^+)} + M^{2+} \rightarrow Z_{(M^{2+})} + 2NH_4^+, \tag{19}$$
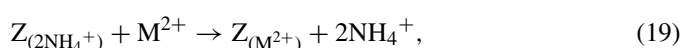
where $Z_{(2NH_4^+)}$ and $Z_{(M^{2+})}$ are the amounts of NH_4^+ ion fixed in the zeolite (meq/g), and M^{2+} and NH_4^+ are the concentrations (meq/dm^3).

The authors assumed that the metallic concentration varies very slightly during the first hours, and the kinetic order is two with respect to the number $(n_0 - n)$ of available sites for the exchange; thus, the differential equation can be written as

$$-\frac{dn}{dt} = K[n_0 - n]^2 \tag{20}$$

and integration gives

$$\frac{1}{(n_0 - n)} - \alpha = Kt, \tag{21}$$

where n is the amount of M^{2+} fixed or the amount of NH_4^+ released at each instant, n_0 the exchange capacity, and K is the rate constant.

Considering the boundary condition $n = 0$ for $t = 0$, it follows that $\alpha = 1/n_0$. By plotting $1/(n_0 - n)$ as a function of time, a straight line must be obtained, the slope of which gives the rate constant, K, and the intercept gives the exchange capacity. In recent years, the Blanchard second-order expression has been used to describe the kinetics of exchange processes between sodium ions from zeolite A and cadmium, copper, and nickel ions from solutions [46].

An expression of second-order rate based on solid capacity has also been presented for the kinetics of adsorption of divalent metal ions onto peat [9–12]. Peat contains polar functional groups such as aldehydes, ketones, acids, and phenolics. These groups can be involved in chemical bonding and are responsible for the cation exchange capacity of the peat. Thus, the peat–copper reaction may be represented in two ways [47]:

$$2P^- + Cu^{2+} \leftrightarrow CuP_2 \tag{22}$$

and

$$2HP + Cu^{2+} \leftrightarrow CuP_2 + 2H^+, \tag{23}$$
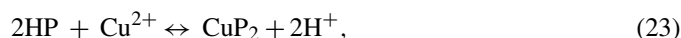
where P^- and HP are polar sites on the peat surface.

In an attempt to present the equation representing adsorption of divalent metals onto sphagnum moss peat during agitation, the assumption was made that the process may be second-order and that chemisorption occurs involving valency forces through sharing or the exchange of electrons between the peat and divalent metal ions as covalent forces. The rate of the second-order reaction may be dependent on the amount of divalent metal ions on the surface of the peat, and the amount of divalent metal ions adsorbed at equilibrium [9,12]. The rate expression for the adsorption described by Eqs. (24) and (25) is

$$\frac{d(P)_t}{dt} = k[(P)_0 - (P)_t]^2 \tag{24}$$

or

$$\frac{d(HP)_t}{dt} = k[(HP)_0 - (HP)_t]^2, \tag{25}$$

where $(P)_t$ and $(HP)_t$ are the number of active sites occupied on the peat at time, t, and $(P)_0$ and $(HP)_0$ are the number of equilibrium sites available on the peat.

The driving force, $(q_e - q_t)$, is proportional to the available fraction of active sites. The kinetic rate equations can be rewritten as follows:

$$\frac{dq_t}{dt} = k(q_e - q_t)^2, \tag{26}$$

where k is the rate constant of adsorption (g/mg min), q_e the amount of divalent metal ions adsorbed at equilibrium (mg/g), and q_t is the amount of divalent metal ions on the surface of the adsorbent at any time, t (mg/g).

Separating the variables in Eq. (26) gives

$$\frac{dq_t}{(q_e - q_t)^2} = k \, dt \tag{27}$$

and integrating this for the boundary conditions $t = 0$ to $t = t$ and $q_t = 0$ to $q_t = q_t$, gives

$$q_t = \frac{q_e^2 kt}{1 + q_e kt} \tag{28}$$

which is the integrated rate law for a second-order reaction. Eq. (28) can be rearranged to obtain

$$q_t = \frac{t}{\frac{1}{kq_e^2} + \frac{t}{q_e}} \tag{29}$$

which has a linear form of

$$\frac{t}{q_t} = \frac{1}{kq_e^2} + \frac{1}{q_e}t \tag{30}$$

and

$$h = kq_e^2, \tag{31}$$

where h is the initial adsorption rate (mg/g min) as q_t/t approaches 0, and Eq. (29) can be rearranged to obtain

$$q_t = \frac{t}{\frac{1}{h} + \frac{t}{q_e}} \tag{32}$$

and

$$\frac{t}{q_t} = \frac{1}{h} + \frac{1}{q_e}t. \tag{33}$$

The rate of a reaction is defined as the change in concentration of a reactant or product per unit time. Concentrations of products do not appear in the rate law because the reaction rate is studied under conditions where the reverse reactions do not contribute to the overall rate. The reaction order and rate constant must be determined by experiments. In order to distinguish the kinetics equation based on the concentration of a solution from the adsorption capacity of solids, this second-order rate equation has been called a pseudo-second-order one [9]. The pseudo-second-order model constants can be determined experimentally by plotting t/q_t against t. Although there are many factors which influence the adsorption capacity, including the initial adsorbate concentration [12,48–51], the reaction temperature [10,12,50], the solution pH value [52,53], the adsorbent particle size [48] and dose [12,48,51], and the nature of the solute [12,54], a kinetic model is concerned only with the effect of observable parameters on the overall rate. The pseudo-second-order expression has been successfully applied to the adsorption of metal ions, dyes, herbicides, oils, and organic substances from aqueous solutions (Table 1).

Recently, a theoretical analysis of the pseudo-second-order model was reported [139]. The advantage of the Azizian derivation is that when the initial concentration of solute is low, then the adsorption process obeys the pseudo-second-order model. Conversely pseudo-first-order models can be applied to higher initial concentrations. The rate constant of the pseudo-second-order model is a complex function of the initial concentration of the solute.

Table 2 shows a comparison of second-order rate equations of Sobkowsk and Czerwiński [39], Ritchie [33], Blanchard et al. [13], and Ho [9]. In earlier years, Sobkowsk and Czerwiński used the second-order rate equation based on the adsorption capacity of a solid for higher concentrations of solids with the rate of reaction of carbon dioxide adsorption onto a platinum electrode [39]. Ritchie presented a second-order empirical equation to test the adsorption of gases onto solids [33]. Blanchard et al. reported a similar rate equation for the exchange reaction of NH_4^+ ions fixed in zeolite by divalent metallic ions in solution [13]. Ho described adsorption which included chemisorption and gave a different idea of the second-order equation called a pseudo-second-order rate expression [9].

In many cases, the equilibrium adsorption capacity is unknown, and chemisorption tends to become immeasurably slow and the amount adsorbed is still significantly smaller than the equilibrium amount [140]. On the other hand, achieving equilibrium takes a long time in some adsorption systems [141–143]. However, the pseudo-second-order equation has the following advantages: it does not have the problem of assigning an effective adsorption capacity, i.e., the adsorption capacity, the rate constant of pseudo-second-order, and the initial adsorption rate all can be determined from the equation without knowing any parameter beforehand.

Table 1
Pseudo-second-order kinetic model of various related systems from the literature

Adsorbent	Adsorbate	References
2-Mercaptobenzimidazole clay	Hg(II)	[55]
Activated carbon	2,4-Dichlorophenoxy-acetic acid	[56]
Activated carbon	Cd(II)	[57]
Activated carbon	Cd(II)	[58]
Activated carbon	Cd(II), Ni(II)	[59]
Activated carbon	Congo red	[60]
Activated carbon	Direct blue 2B, Direct green B	[61]
Activated carbon	Hg(II)	[62]
Activated carbon	Hg(II)	[63]
Activated carbon	Methylene blue	[64]
Activated carbon	Paraquat dichloride	[65]
Activated carbon	Co(II)	[66]
Activated carbon	Pb(II)	[67]
Activated carbon	Pb(II)	[68]
Activated carbon	Pb(II), Hg(II), Cd(II), Co(II)	[69]
Activated clay	Basic red 18, Acid blue 9	[70]
Aeromonas caviae	Cr(VI)	[71]
Alginate	Ni(II)	[72]
Anaerobic granular sludges	Ni(II), Co(II)	[73]
Aspergillus niger	Acid blue 29	[74]
Aspergillus niger	Basic blue 9	[75]
Aspergillus niger	Congo red	[76]
Aspergillus niger	Pb(II), Cd(II), Cu(II), Ni(II)	[77]
Azadirachta indica (Neem) leaf	Congo red	[78]
Azadirachta indica (Neem) leaf	Pb(II)	[79]
Baker's yeast	Cd(II)	[80]
Banana stalk *Musa paradisiacal*	Hg(II)	[81]
Beech leaves	Cd(II)	[11]
Bentonite	Acid red 57, Acid blue 294	[82]
Bi$_2$O$_3$	Cr(VI)	[11]
Blast furnace slag, dust, sludge, carbon slurry	Chlorophenols	[83]
Bottom ash	Cu(II), Pb(II)	[11]
Calabrian pine bark	Zn(II), Pb(II)	[84]
Calcined alunite	Phosphorus	[85]
Calcined Mg–Al–CO$_3$ hydrotalcite	Cr(VI)	[86]
Cassava waste biomass	Cu(II), Cd(II)	[87]
Chitin	Cd(II)	[88]
Chitin, chitosan, *Rhizopus arrhizus*	Cr(VI), Cu(II)	[38]
Chitosan	Cu(II)	[89]
Chitosan	Ni(II)	[90]
Clinoptilolite	Pb(II)	[91]
Coconut coir pith	2,4-Dichlorophenol	[92]
Coconut coir pith	Cr(VI)	[93]
Coir	Cu(II), Pb(II)	[94]
Cypress leaves	Pb(II)	[11]
Date pits	Methylene blue	[95]
Date pits	Phenol	[96]
Diatomaceous clay	Methylene blue	[97]
Dolomite	Phosphate	[98]
Fly ash	Congo red	[99]
Fly ash	Omega chrome red ME, *o*-cresol, *p*-nitrophenol	[100]
Fly ash	Victoria blue, OCL, PNP, OCRME	[11]

Table 1 (*Continued*)

Adsorbent	Adsorbate	References
Grafted silica	Pb(II), Cu(II)	[101]
Grape stalks	Cr(VI)	[102]
Iron oxide-coated sand	As(V), As(III)	[103]
Jordanian low-grade phosphate	Pb(II)	[104]
Juniper fiber	Cd(II)	[105]
Juniper fiber	Phosphorus	[106]
Mesoporous silicate	Phosphate	[107]
Mg–Al–CO$_3$ hydrotalcite	Cr(VI)	[108]
Microcystis	Ni(II), Cr(VI)	[109]
Microporous titanosilicate ETS-10	Pb(II)	[110]
Mixed clay/carbon	Acid blue 9	[111]
Mucor rouxii	Pb(II), Cd(II), Ni(II), Zn(II)	[112]
Myriophyllum spicatum	Pb(II), Zn(II), Cd(II)	[113]
Na-bentonite	Oil	[114]
Oil shale	4-Nitrophenol	[115]
Peat	Basic blue 69, Acid blue 25	[11]
Peat	Basic green 4, Basic violet 4, Basic blue 24	[116]
Peat	Cu(II)	[117]
Peat	Cu(II)	[11]
Peat	Cu(II)	[118]
Peat-resin particle	Basic magenta, Basic brilliant green	[119]
Perlite	Cd(II)	[120]
Perlite	Methylene blue	[121]
Pith	Basic red 22, Acid red 114	[122]
Reed leaves	Cd(II)	[11]
Rhizopus oligosporus	Cu(II)	[123]
Rhodotorula aurantiaca	Pb(II)	[124]
Sago	Cu(II), Pb(II)	[125]
Sawdust	Cd(II), Pb(II)	[126]
Sawdust	Phenol	[127]
Schizomeris leibleinii	Pb(II)	[128]
Sepiolite	Pb(II)	[129]
Spent grain	Pb(II), Cd(II)	[130]
Sphagnum moss peat	Chrysoidine, Astrazon blue, Astrazone blue	[22]
Sphagnum moss peat	Cu(II), Ni(II)	[131]
Sphagnum moss peat	Cu(II), Ni(II), Pb(II)	[12]
Sugar beet pulp	Pb(II)	[132]
Sugar beet pulp	Pb(II), Cu(II), Zn(II), Cd(II), Ni(II)	[133]
Surfactant-modified clinoptilolite	Phosphate	[134]
TNSAC	Phosphate	[11]
Tree fern	Basic red 13	[135]
Tree fern	Cd(II)	[136]
Tree fern	Cu(II)	[49]
Tree fern	Pb(II)	[50]
Vermiculite	Cd(II)	[137]
Waste tyres, sawdust	Cr(VI)	[138]
Wollastonite	Ni(II)	[11]
Wood	Basic blue 69, Acid blue 25	[21]

Table 2
Comparison of second-order models

Author	Year	Linear form	Plot
Sobkowsk and Czerwiński	1974	$\frac{\theta}{1-\theta} = k_2 t$	$\frac{\theta}{1-\theta}$ vs. t
Ritchie	1977	$\frac{q_\infty}{q_\infty - q} = \alpha t + 1$	$\frac{q_\infty}{q_\infty - q}$ vs. t
Blanchard et al.	1984	$\frac{1}{n_0 - n} - \alpha = Kt$	$\frac{1}{n_0 - n}$ vs. t
Ho	1995	$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t$	$\frac{t}{q_t}$ vs. t

3. Conclusion

Adsorption rate equations have considered the adsorption capacities of solids since Lagergren's first-order equation was presented. Several rate equations were reported with the same idea in the following years. In earlier years, Elovich's equation and Ritchie's equation were applied to the adsorption of gases onto solid faces. Later, application of these equations to the adsorption of pollutants from aqueous solutions were investigated. A second-order rate equation was used to describe chemisorption for the adsorption of gases used to describe ion exchange reactions. The pseudo-second-order rate expression was used to describe chemisorption involving valency forces through the sharing or exchange of electrons between the adsorbent and adsorbate as covalent forces, and ion exchange. In recent years, the pseudo-second-order rate expression has been widely applied to the adsorption of pollutants from aqueous solutions. The advantage of using this model is that there is no need to know the equilibrium capacity from the experiments, as it can be calculated from the model. In addition, the initial adsorption rate can also be obtained from the model.

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