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Original scientific paper

OPTIMIZING CADMIUM ION ADSORPTION: PREDICTIVE MODELING BASED ON LITERATURE DATA

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Abstract

The contamination of water with various heavy metal ions is a global problem and a challenge for research. Heavy metals in concentrations that exceed the permissible limits lead to considerable health problems. Accordingly, researchers are constantly working to find the most suitable technique for their removal. Among the conventional methods, adsorption stands out, in which various natural materials can be used to remove heavy metal ions, including cadmium ions. In this paper, a literature review is given on various natural materials that can be successfully used as biosorbents and optimization has been carried out to obtain optimal conditions for the removal of cadmium ions.

Keywords: *natural materials, wastewaters, Cd^{2+} ions, biosorption, response surface method*

1. INTRODUCTION

Water pollution with heavy metals is a serious environmental problem that threatens human health and aquatic ecosystems. Heavy metals such as lead, mercury, cadmium and arsenic are toxic and carcinogenic, and their presence in water can lead to serious health problems. They also tend to accumulate in organisms over time. Long-term exposure can cause a range of health problems, including damage to the kidneys, nervous system and reproductive organs, as well as an increased risk of cancer [1]. The main sources of water pollution from heavy metals include industrial processes, mining activity, agricultural runoff and inadequate waste disposal [2,3]. Numerous researchers are concentrating on finding a suitable method for removing cadmium ions from wastewater, as they are persistent and toxic. They end up in the water because compounds containing cadmium are inadequately disposed of in mines, paint factories, electroplating, plastics and cadmium-nickel batteries. There are several conventional methods for removing heavy metals from water, such as precipitation, ion exchange, reverse osmosis, adsorption, coagulation and flocculation [4,5]. However, adsorption stands out from the other methods as it has significant advantages, such as low cost, efficiency, ease of implementation and the possibility of using various agricultural materials (biomass) as adsorbents [5]. Agricultural materials are readily available, inexpensive and can be regenerated. The aim of this work is to summarize potential natural adsorbents for the removal of cadmium ions based on a literature review. The adsorption activities were also investigated using a Box-Behnken design to find the optimal parameters for successful removal of cadmium ions.

2. EXPERIMENTAL

In order to determine the optimal conditions for the removal of Cd^{2+} ions, experimental data from previously published studies were collected and analyzed. Numerous research groups have employed natural biosorbents to remove Cd^{2+} from wastewater, including black cumin seeds [5], banana, kiwi, and tangerine peels [6], watermelon rinds [7], chicken eggshells [8], *Rosa damascena* waste [9], and *Ziziphus lotus* fruit powder [10]. These biosorbents were tested under varying experimental conditions.

To optimize the biosorption process, the response surface methodology (RSM) was applied. A Box-Behnken experimental design was used to investigate the influence of three independent variables on cadmium removal efficiency: A - solution pH, B - initial concentration of cadmium ions (C_0), and C - biosorbent dosage. The ranges of investigated parameters were as follows: pH from 4 to 12, Cd^{2+} concentration from 10 to 200 mg/L, and biosorbent dosage from 0.03 to 20 g/L. The collected data were subjected to statistical analysis, including analysis of variance (ANOVA), to evaluate the adequacy and significance of the model used [11].

3. RESULTS AND DISCUSSION

The adsorption efficiency reported across different studies ranged from 33% to 91%, depending on the type of biosorbent and experimental conditions. It was found that the isotherms of Cd^{2+} removals on different adsorbents are best described by the Langmuir model [5,9,10], followed by the Freundlich [8] and Dubinin-Radushkevich models [7]. The kinetics of the process generally corresponds to a pseudo-second order model.

The results of the Analysis of variance are presented in Table 1 and show that the model is significant.

Table 1 - Analysis of variance for the removal of Cd^{2+}

Source	Sum of Squares	Degree of freedom	Mean Square	F-value	p-value	
Model	4211.95	9	467.99	2.553E+05	< 0.0001	significant
A-pH	1013.73	1	1013.73	5.529E+05	< 0.0001	
B-Co	101.94	1	101.94	55604.89	< 0.0001	
C-m	1482.28	1	1482.28	8.085E+05	< 0.0001	
AB	477.03	1	477.03	2.602E+05	< 0.0001	
AC	1105.92	1	1105.92	6.032E+05	< 0.0001	
BC	278.12	1	278.12	1.517E+05	< 0.0001	
A^2	793.05	1	793.05	4.326E+05	< 0.0001	
B^2	0.3229	1	0.3229	176.14	0.0009	
C^2	84.40	1	84.40	46037.63	< 0.0001	
Pure Error	0.0055	3	0.0018			
Cor Total	4211.95	12				

The model Fischer value (F-value) of 255269.55 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Probability values (p-value) are lower than 0.05 indicating the significance of investigated parameters on the efficiency of uptaking Cd^{2+} [12]. In accordance with the F-value in Table 1, the dosage of the biosorbent can be considered the most important factor for the removal of Cd^{2+}, followed by the interaction between the dosage of the biosorbent and the pH and the initial pH of the solution. Equation (1) represents a quadratic response model in which all linear, quadratic and elementary linear interactions are taken into account [12,13].

$$E = -740.00930 + 205.97983\,pH - 0.942410\,C_0 + 95.47519\,m + 0.292469\,pH \cdot C_0 - 13.65316\,pH \cdot m - 0.690388\,C_0 \cdot m - 13.18421\,pH^2 - 0.000148\,{C_0}^2 + 1.30600\,m^2 \quad (1)$$

The robustness of the model can be assessed using the experimentally determined (R^2) and the predicted ($R^2_{adjusted}$) coefficient of determination, both of which are 1.0000 [13]. The plot of actual versus predicted responses is shown in Figure 1a.

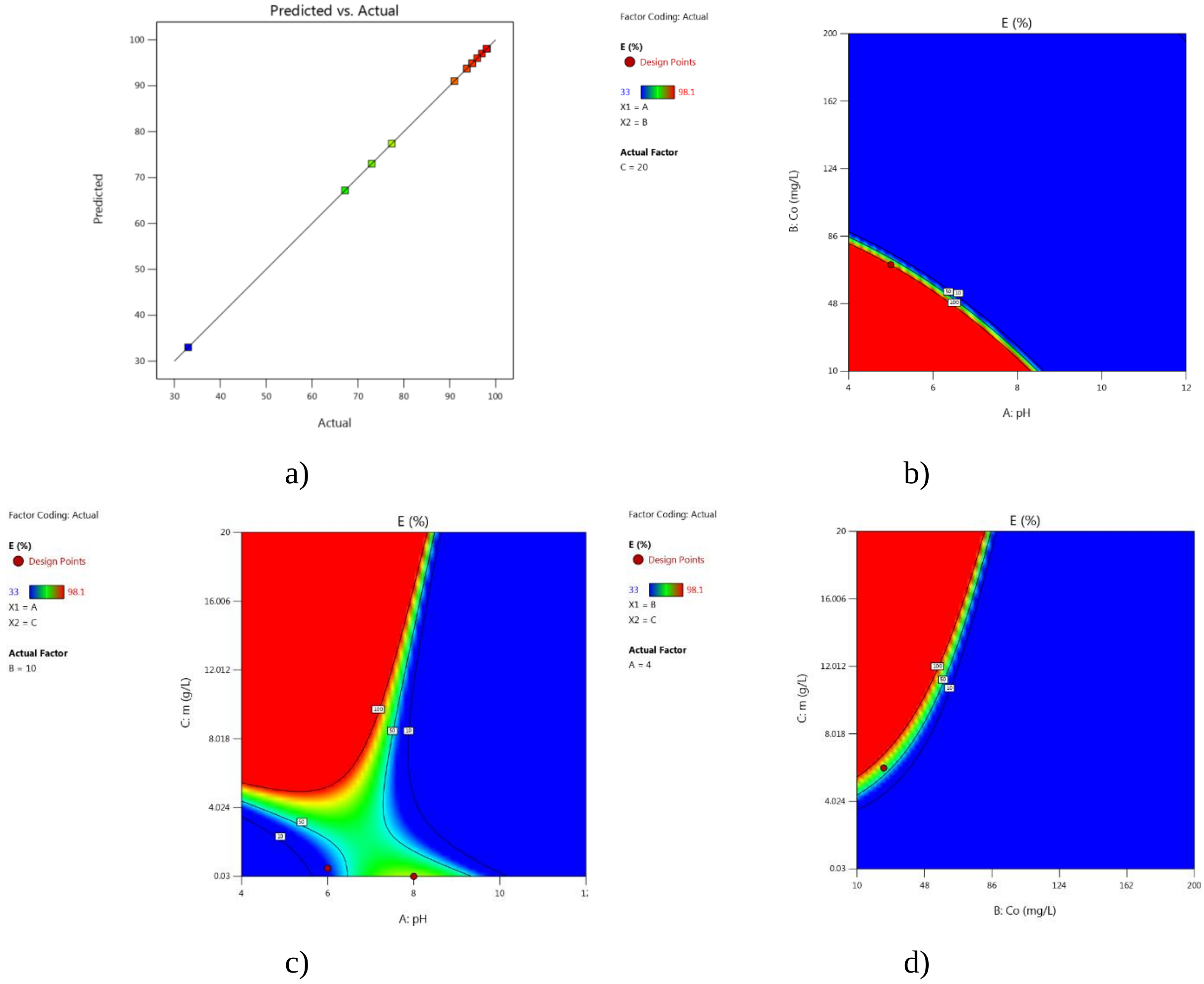

Figure 1. 2D surface response plots for the removal of Cd^{2+} (a) Actual vs predicted responsesand, the interaction between (b) pH and initial concentaration of Cd^{2+}, (c) pH and dosage of biosorbent, (d) initial concentaration of Cd^{2+} and dosage of biosorbent

Figure 1 (b, c and d) shows the 2D response surface plots of the interaction effects between the independent variables and the response. As shown in Figure 1b, the efficiency of Cd^{2+} removal is higher in an acidic environment than in a neutral or alkaline environment. Figure 1c illustrates the interaction between the pH value and the dosage of the biosorbent. Increasing the dose of biosorbent in an acidic environment also increases efficiency. A higher dose of biosorbent at a lower initial concentration of Cd^{2+} enables better removal of these heavy metal ions, as shown in Figure 1d. Based on the optimization carried out, it was found that the optimum values of the process parameters are as follows: pH 4, biosorbent dose 7.4 g/L and initial concentration of Cd^{2+} 30 mg/L. This is in good agreement with Assimeddine et al. [12], who stated that the adsorption process is more favourable at lower pH values than at higher pH values. In addition, a higher dose of biosorbent provides more binding sites that remove more Cd^{2+} ions.

4. CONCLUSIONS

Pollution of water bodies by heavy metals is a major environmental problem that endangers both human health and aquatic ecosystems. Heavy metals such as lead, mercury, cadmium and arsenic are toxic and carcinogenic, and their presence in water can lead to serious health problems. The removal of heavy metal ions from water is of great importance and the use of natural materials as biosorbents is increasingly being explored by researchers. The aim of this study is to determine the optimal conditions for the removal of Cd^{2+} from wastewater by analyzing available literature data and predictive models. The predictions suggest that optimal removal of Cd^{2+} occurs under more acidic conditions (pH 4), lower initial metal concentrations (30 mg/L) and higher biosorbent doses (7.4 g/L). However, these results need to be experimentally validated to ensure their reliability. Nevertheless, such predictions play a crucial role in the planning and optimization of experimental studies.

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