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Empirical model for bio-extraction of copper from low grade ore using response surface methodology

M. YAGHOBI MOGHADDAM[1], S. Z. SHAFAEI[1], M. NOAPARAST[1], F. DOULATI ARDEJANI[1], H. ABDOLLAHI[1], M. RANJBAR[2], M. SCHAFFIE[3], Z. MANAFI[4]

1. School of Mining, College of Engineering, University of Tehran, Tehran 1439957131, Iran;
2. Department of Mining Engineering, Shahid Bahonar University of Kerman, Kerman 76169133, Iran;
3. Department of Chemical Engineering, Shahid Bahonar University of Kerman, Kerman 76169133, Iran;
4. Hydrometallurgy Research Unit, R&D Center, Sarcheshmeh Copper Mine Complex, Kerman 15115416, Iran

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Abstract: The copper extraction in shaking bioreactors was modeled and optimized using response surface methodology (RSM). Influential parameters in the mesophilic bioleaching process of a low-grade copper ore including pH value, pulp density, and initial concentration of ferrous ions were comprehensively studied. The effect of leaching time on the response (copper extraction) at the 1st, 4th, 9th, 14th and 22nd days of treatment was modeled and examined. The central composite design methodology (CCD) was used as the design matrix to predict the optimal level of these parameters. Then, the model equation at the 22nd day was optimized using the quadratic programming (QP) to maximize the total copper extraction within the studied experimental range. Under the optimal condition (initial pH value of 2.0, pulp density of 1.59%, and initial concentration of ferrous ions of 0 g/L), the total copper extraction predicted by the model is 85.98% which is significantly close to that obtained from the experiment (84.57%). The results show that RSM could be useful to predict the maximum copper extraction from a low-grade ore and investigate the effects of variables on the final response. Besides, a couple of statistically significant interactions are derived between pH value and pulp density as well as pH value and initial ferrous ion concentration which are precisely interpreted. However, there is no statistically significant interaction between the initial ferrous ion concentration and the pulp density. Additionally, the response at optimal levels of pH value and pulp density is found to be independent on the level of initial ferrous concentration.

Key words: modeling; optimization; bacterial leaching; response surface methodology; copper extraction; copper ore

1 Introduction

Bioleaching process has been impressively developed during the recent decades [1−8]. Recently, the bioleaching of primary copper sulfide minerals and potential application of this process have been studied in Iran's copper industry as well as the application of mesophilic and thermophilic bacteria for increasing the extraction of copper [9−11]. Sarcheshmeh Copper Complex is one of the largest copper mines in the world, located in SE of Iran. About 20 million tons copper ore per year, containing 0.8% Cu, are mined and processed. Simultaneously, about 1 million tons of low-grade copper ore, a mixture of sulfide and oxide with grade of 0.3% Cu, which is not a suitable feed for pyrometallurgical process, should be treated using hydrometallurgical technique [2,3]. Thus, finding a new environmental friendly processing technology for the retained low grade copper ore is a major task [12]. So, alternative hydrometallurgical and pyrometallurgical technologies are currently available for copper extraction from the sulfide and oxide low-grade copper ore which operate at the commercial scales. Nonetheless, the pyrometallurgical processes consume a large quantity of energy and also cause environmental problems [12−15]. On the other hand, bacterial leaching consumes less energy and is an environmental friendly process [1−3,13−16]. Considerable physicochemical parameters, which have influence on the rate of the copper bio-extraction, have been identified such as pH value, temperature, ratio of ferric to ferrous ions, pulp density, fraction of inoculation, and initial ferrous iron concentration [2,3,10−12].

Corresponding author: M. YAGHOBI MOGHADDAM; Tel: +98-9133562652; Fax: +98-2188631202; E-mail: M.yaghobi@gmail.com; M_yaghobi@ut.ac.ir
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In statistical parlance, there could be an interaction between effective parameters in such a process. Examining the previous literatures on sulfide and oxide low-grade ores bioleaching provides no clues that whether such interaction between the important parameters exists or not. This is because in the previous studies, one- factor-at-a-time methodology has been used to optimize the physicochemical parameters [2,3,17−19]. This methodology is inefficient besides gives absolutely no information about the interactions between the parameters in a process. The only methodology which is able to provide an answer to this question is factorial design of experiments (DOE), which, through the use of statistical techniques such as response surface methodology (RSM), is capable of simultaneously considering several factors at different levels, and giving an appropriate model to describe the relationship between the various factors and the response [20]. RSM is a collection of statistical and mathematical methods for modeling and analyzing the engineering problems. In this technique, the principle goal is to optimize the response surface influenced by diverse process parameters. In addition, RSM determines the relationship between the controllable input parameters and the obtained response surfaces [21]. The design procedure for RSM is as follows [22]:

1) Designing a series of experiments for sufficient and reliable measurement of the desirable response;

2) Developing a mathematical model with a second order response surface and a maximum fitting;

3) Finding the most desirable set of experimental parameters which produce a maximum or minimum value of response;

4) Expressing the direct and interactive effects of the process parameters using two- and three-dimensional plots.

RSM has previously been applied in only a few cases of a bioleaching processes [23−27]. Besides, reliable information about first order interactions can only be obtained from the results of DOE. However, higher order interactions between the parameters are usually statistically insignificant and therefore the information about them is not quite useful [20]. Generally, changing one parameter and keeping other ones at a constant level has a huge disadvantage as it does not include the interaction effects among the variables and as a result, it does not show the complete effects of different parameters on the response [28,29]. To overcome this problem, modeling and optimizing studies are performed by using RSM. Besides, theories and essential aspects of RSM have been well explained in Refs. [20,30] associated with this subject. To determine several parameters and their interaction, RSM is often used because it decreases the number of experimental trials. As a result, it takes less effort and time than other applications. It is remarkable that, in recent years, RSM has been applied for modeling and optimizing the several mineral processing researches [26,27,31−35].

Literature review shows that despite there are many researches related to experimental works on bacterial leaching, few researches have also been conducted on the DOEs, and the bacterial extraction of copper from the oxide sulfide ore with an emphasis on the leaching period by using RSM and central composite design methodology (CCD) approaches have not been totally investigated. The aim of the present work is to identify and quantify the important physicochemical parameters, i.e., pH value, pulp density and initial ferrous ions concentration, as well as interactions between them in a sulfide and oxide low-grade copper ore bioleaching process by mixed mesophilic microorganisms, using appropriate methodology such as RSM. This study involved modeling and optimizing the process parameters affecting the total copper extraction as a response. In addition, CCD was used as the design matrix to identify the polynomial model for interpreting the interaction between the influential factors. After modeling and optimizing the parameters, the effect of leaching time on the variables (pH value, pulp density and initial concentration of ferrous ions) as well as on the response (copper extraction) at the 1st, 4th, 9th, 14th and 22nd days was comprehensively examined. Furthermore, the effect of changing variables on the response at the 1st, 4th, 9th, 14th and 22nd days of treatment was also investigated. The trend of copper extraction during the treatment time intervals was investigated.

2 Experimental

2.1 Low-grade copper ore

About 3500 kg low-grade copper ore was obtained from the Sarcheshmeh copper mine with 0.31% Cu content. The particle size distributions of the original ore and the ground sample [36] with three stages crushers and mill were obtained with d_{80} of ~30000 and ~85 μm. In addition, the grade of copper and iron with their distributions in different particle sizes of the original sample were achieved. The results of particle size and grade distributions are shown in Figs. 1(a) and (b), respectively. The representative sample including different size fractions were pulverized for the chemical and mineralogical assays. The chemical composition of this sample includes 0.31% Cu, 6.10% Fe and 1.72% S. The X-ray diffraction (XRD) analysis of the ore shows the presence of quartz and silicates as the main mineralogical components and chalcopyrite as the minor