



Bio-Hydrometallurgical Extraction of Nickel from Low-Grade Laterite Nickel Ore

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ABSTRACT: The laterite deposit in the Bavanat area of Fars province is promising for nickel metal extraction. The ore is an oxide type and in this research, microbial leaching experiments were done using common bacteria (*Thiobacillus*) for nickel sulfide ores. Characterization of the sample showed that the nickel grade was about 1.14%, which was dispersed in the matrix of iron ores. In the microbial leaching process, primary experiments were carried out with a 9K culture medium that did not have favorable results. New experiments were carried out with the addition of required materials such as sulfur to culture media. Primary experiments with this culture media showed that after 20 days, 21% of the nickel in the ore sample was extracted. The effective parameters on microbial leaching include microbial leaching time, sulfur content added to the culture media, and mineral content that were optimized by this method. Optimal values for the above parameters were 10 days, 10%, and 10 g, respectively. The maximum amount of nickel extraction in optimum conditions reached 65%. After this step, iron impurities were removed from the solution of microbial leaching using a combination of precipitation (with sodium hydroxide) and solvent extraction method. Finally, the solution was subjected to solvent extraction which used a selective nickel organic solvent (Cyanex 301 is a highly selective solvent for a nickel) and a pure nickel solution with 112 ppm was obtained.

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1- Introduction

Nickel is an important and strategic metal and has many applications in industry. More than 60% of world nickel production is used to increase the strength and resistance of stainless steel (against corrosion). Nickel has wide applications in the building industry, water supply and distribution systems, food industry, energy supply, chemical industry, transportation industry, electronics, etc (Due to its high-temperature resistance and strength versus failure) [1, 2]. Nickel ores are found in two forms, sulfide and oxide (laterite). Although, the sulfide type has a higher grade. Studies show that more than 70% of nickel worldwide is deposited in laterite ores [2, 3]. In the northeast region of Shiraz province in Iran, southeast of the city of Ghaderabad, and south of the city of Korei, a range of nickel laterite with an area of about 200 km² has been identified that have good potential for nickel extraction [4].

Nickel recovery from sulfide ores is carried out using the pyrometallurgical method and from laterites by both pyrometallurgical (Caron process) and hydrometallurgical (such as High-Pressure Acid Leaching (HPAL), Atmospheric Acid Leaching (AL) and some recently developed method as Atmospheric Chloride Leaching Process (ACLP)) methods [5]. Laterite pre-concentration is generally difficult to process, and most of the physical methods are not commercial [6]. High consumption of energy and environmental pollution in

the Caron process, the high cost of titanium autoclaves in a high-pressure acid leaching and high consumption of acid, dissolution of undesirable elements, and less nickel recovery in atmospheric acid leaching method have limited the use of the above-mentioned methods in the world. If a suitable way to use of bioleaching technique for laterite ores can be found, many of the problems with the other methods will be eliminated, which is considered an advantage of the bioleaching method [5, 7, 8].

Microbial leaching (bioleaching) has been developed and applied for the recovery of sulfide minerals of some metals such as copper, zinc, cobalt, nickel, cadmium, antimony, zinc, lead, gallium, indium, and manganese using chemolithoautotrophic bacteria [9]. Many studies have been conducted to extract metals such as copper and zinc from oxide resources however some researchers have argued for the use of this method at an industrial scale [7, 10-12]. The recovery of nickel from laterite has been performed by various researchers. K.A.K. Alibhai *et al.* have proposed different mechanisms, such as redox, complexification, and chelating for the dissolution of mineral compounds (limonite - laterite ore) by microorganisms [13]. Sukla *et al.* in a study showed that about 90% of nickel and 34% of cobalt in laterite can be extracted using oxalic acid, citric acid, and malic acid produced by microorganisms. In this experiment, isolated and purified microorganisms were used, which were harvested from the same

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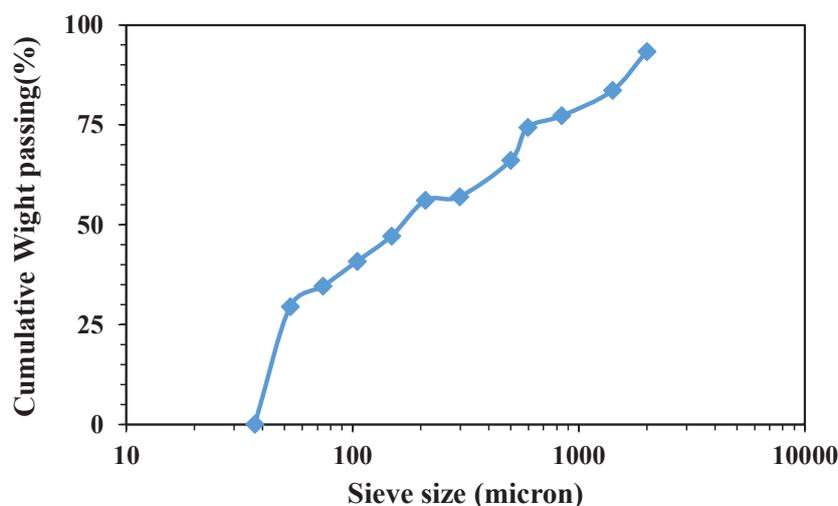


Fig. 1. Particle size analysis of the sample.

area[14]. In another study by Mohapatra *et al.*, the ability of the *Aspergillus Niger* fungus was investigated in the extraction of nickel from laterite. In this research, the parameters of the amount of raw material, pulp density, temperature, and reaction time have been investigated and optimized and the model related to the interaction of these parameters has been drawn together. Lee studied bioleaching of nickel laterite using *Aspergillus* fungus. During the process, reactions occurred and compounds were produced that were capable to dissolve heavy metals. The results of the experiment showed that the fungus can extract metals such as aluminum, cobalt, chromium, iron, copper, manganese, nickel, and zinc [15]. Ilyas *et al.* Performed microbial leaching of metals such as nickel, using thermophilic acidophilic bacteria. Microorganisms have been used in the sulfobacillus groups. The results of their experiments showed that the obtained recovery efficiency of nickel, copper, aluminum, and zinc metals was 81, 89, 79, and 83%, respectively [16]. Cobalt and Nickel laterite bioleaching was surveyed in 2013 by Biswas *et al.* with *Aspergillus Niger*. The temperature and fermentation were considered process parameters in this experiment. Acids used for extraction include citric acid and oxalic acid [17]. In 2014, Raštegari *et al.* recovered nickel and chromium using acidophilic species. Effect parameters such as ferric iron concentration, initial pH, and density are investigated. The highest amount of chromium and nickel recovery was 55.6 and 58.2%, respectively [18].

A study shows that recoveries of Ni and Co to 58.4 and 60.6 %, respectively, after 3 h at 90°C using supernatant metabolites of the halophilic bacterium [19].

The chemical-physical process of Ni extraction from low-grade nickel laterite ore by oxalic acid shows that the Ni

grade and recovery reached from 3.2 and 84 %, respectively. The initial grade of Ni is 0/08 % [20].

The low grade of nickel in laterite, lack of independent nickel-bearing minerals, mineralogical complexity, high energy requirements, and environmental pollution are the main problems with laterite processing with conventional methods. It seems that the use of the bioleaching method concerning environmental benefits and low operating costs is the appropriate option to overcome the shortcomings of other methods. In this research, the ability of nickel extraction from laterite resources, using conventional bacteria have been investigated.

The novelty of this paper is that so far this type of bacterium (*thiobacillus ferrooxidans*) has been used for sulfide ores and for the first time it has been used to extract nickel from oxide ores. Also, subsequent methods such as adding acid to the process are new and until the present study, this process has not been observed in such research.

2- Material and Methods

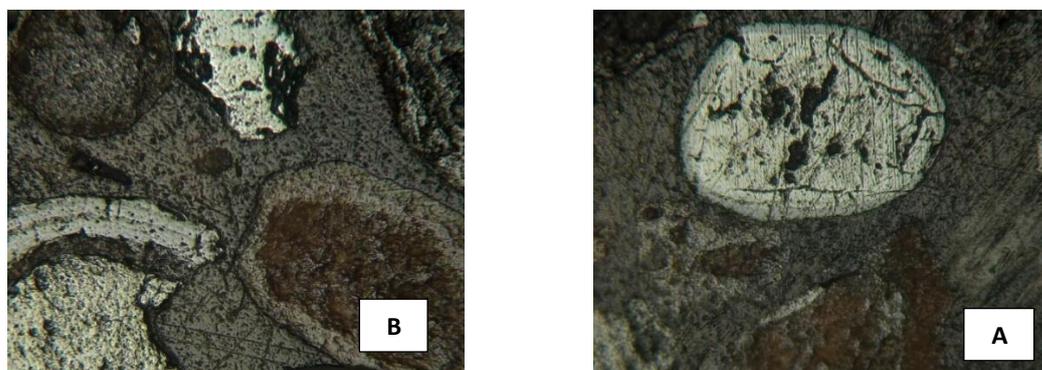
2- 1- Sample preparation and characterization

In this research, about 100 kg of the mineral sample (nickel laterite) has been systematically prepared from the Chah Ghayb Bavanat mine. After drying, the sample was crushed by a jaw crusher, gyratory, and grinding by a ball mill, respectively. The sample final size for bioleaching experiments was under 250 microns. Because the Degree of liberation studies for different sizes of Laterite ores have shown that nickel particles smaller than 250 microns are released and their surface is carried out available for contact with the leaching agent.

Fig. 1 shows the results of the sample particle size analyses.

Table 1. Ore sample chemical analysis by XRF method.

Name	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	Cr ₂ O ₃	NiO	S	LOI	other
Amount	28.9	2.86	2.84	4.9	43.9	4.24	1.46	0	10.08	0.82

**Fig. 2. (A) an image of the oolitic hematite in a polished section, and (B) an Image of hematite and magnetite minerals in a polished section.**

Sample recognition includes mineralogy studies, chemical analysis, dimensional analysis, etc. using equipment such as optical microscopy, electron microscope (SEM), X-ray apparatus (XRF or XRD), dimensional analysis devices such as sieve, atomic absorption device or ICP method, etc. is done. The purpose of these studies is to study mineral and ores and their distribution, texture, mineralization, and their relationship with each other, and to study the shape and dimensions of different minerals to determine the degree of liberation and predict their behavior against grinding and softening.

In Table 1, the chemical analysis of the representative sample is shown. Based on the results, the nickel and iron content of the sample is 1.41 and 29%, respectively.

The sample was studied by XRD apparatus and the determined minerals are quartz (SiO₂), hematite (Fe₂O₃), dolomite (CaMg(CO₃)₂) and magnetite (Fe₃O₄). The results show that the mineralogical composition of the sample is not complex sample. In addition to quartz, the presence of iron minerals is evident in the sample. As expected, like most nickel-based laterite sources in the world, none of the common nickel minerals are present in the sample, and nickel is present as a substitute for other minerals.

In this section, a polished section was prepared and studied using a polarized optical microscope. As shown in Figs. 2 to 4, the major minerals observed in these studies confirm the results of the XRD analysis. Most hematite minerals are formed in oolitic shapes, which are visible in the pictures. The margin of Iron-bearing minerals is martite.

2- 2- Bactria and culture media preparation

The used bacteria (*Acidotubasilius ferrooxidans*) are prepared from the microorganism bank of the Iranian Research Organization for Science and Technology (IROST). For experiments, 9K medium was used its composition is shown in Table 2. For sterilization of solutions 1 and 3, the autoclave was used at 121 °C for 15 minutes and sterilized with Syringe Filter 2. Finally, all three solutions are mixed and poured into the plates (Fig. 5).

Table 2. The amount of material in 1-liter culture media composition.

Name	Amount
Solution 1	
K ₂ HPO ₄	0.5g
MgSO ₄ . 7H ₂ O	0.5g
Ca(NO ₃) ₂	0.01g
Distilled water	500ml
Solution 2	
FeSO ₄ .7H ₂ O	44.22g
H ₂ SO ₄	1ml
Distilled water	250ml
Solution 3	
Agar	15g
Distilled water	250ml

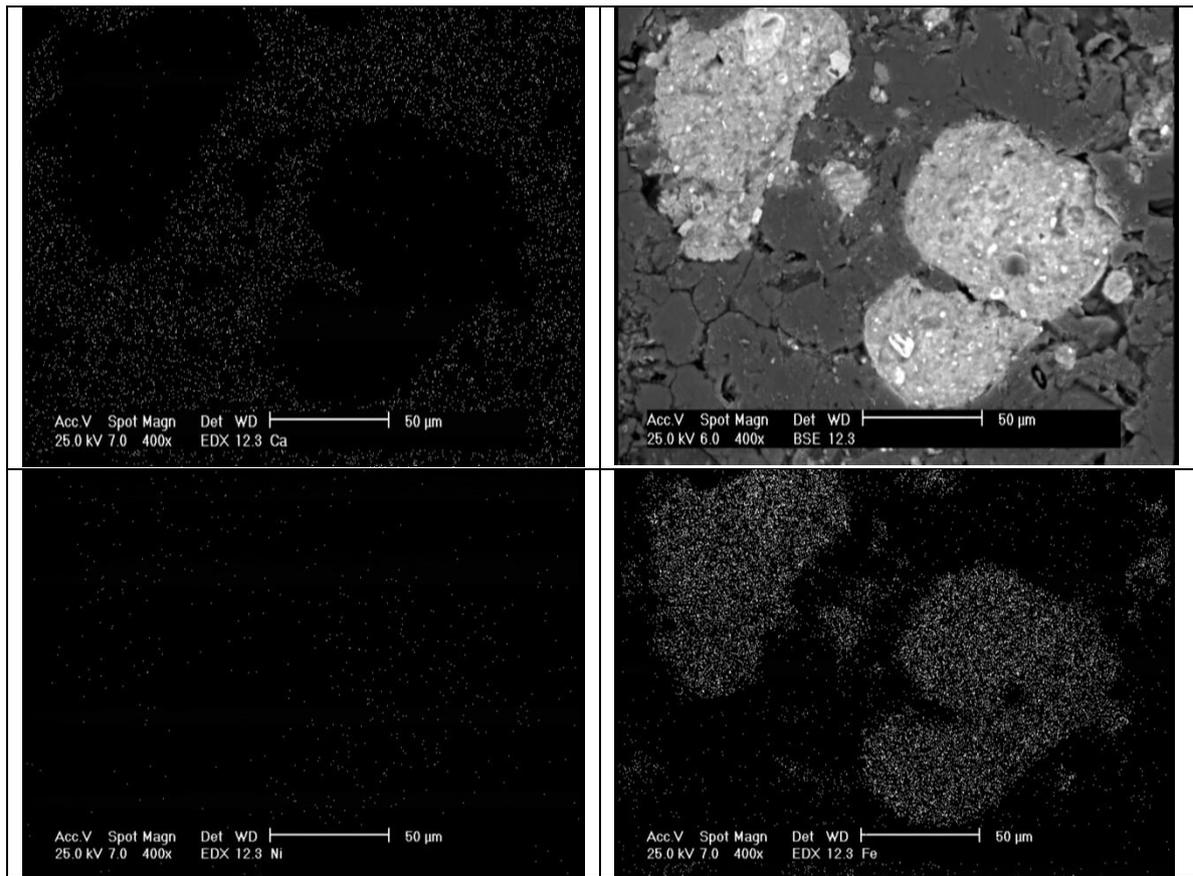


Fig. 3. Iron mineral under the electron microscope - no calcium presence and clear nickel presence in the matrix iron.

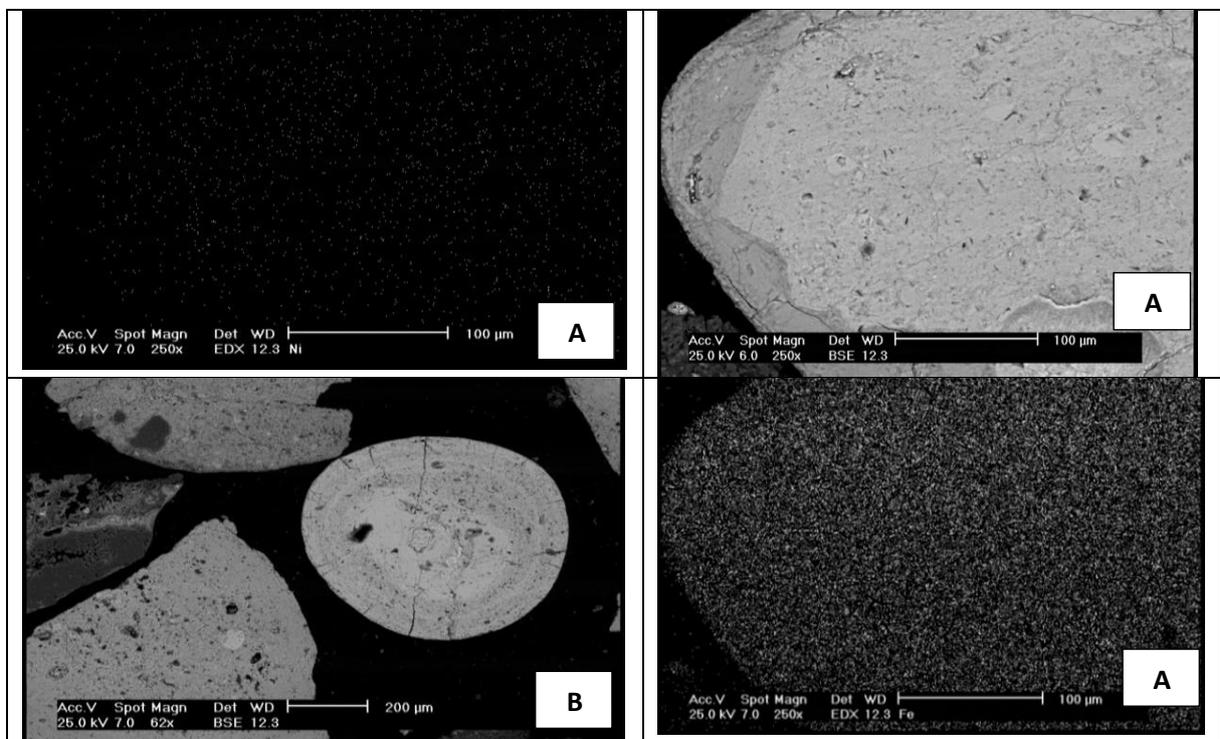


Fig. 4. (A) Iron under the electron microscope - the absence of calcium and the presence of nickel in the iron minerals text is seen; (B) An oolitic hematite image under an electron microscope.



Fig. 5. Cultured plate containing thiobacillus ferrooxidans.

3- Test Method

All microbiological tests must be carried out in sterile environments. It is necessary to sterilize all tools, containers, work tables, culture media, and all parts that are in some way associated with microorganisms. In this research, an autoclave was used to sterilize dishes and culture media.

The chemical structure of some materials, such as vitamins, and antibiotics, are altered by heat, so the filtration method was used to sterilize the solutions. In this method, the solution or liquid is transported through a very small pores filter. Because the bacteria are larger than the filtrate pores, they remain on the surface of the filter and separate from the sterilized liquid.

In the bacterial culture process, the number of inoculum bacteria should always be clear and specific to the environment. By McFarland's standard method, the number of bacteria is counted before inoculation. McFarland's No. 1 (300 million bacteria/ml) and 10% inoculation ratio were used in all cultures, in this study. After cultivation, the Erlenmeyer was placed at 30 ° C and 100 rpm in a shaker incubator.

The centrifuges system was used to separate the bacteria from the liquid culture medium, culture them in a new container, and also to filter the solutions before analyzing the nickel content.

All experiments were carried out in 500 ml Erlenmeyer (containing 100 ml sterile culture media). One day after the cultivation of bacteria and its proliferation in Erlenmeyer, the sterile mineral is added to the Erlenmeyer. Erlenmeyers were again placed back in the incubator and sampled at regular time intervals to determine the amount of Ni, pH, and bacte-

rial count.

In the previous step, solvent extraction was used to remove the iron remaining in the solution by using sodium hydroxide treatment.

4- Results and Discussion

4- 1- Microbial leaching of Nickel-bearing laterite sample without sulfur addition

In initial experiments, the bacterium was cultured in a 9K medium. This culture medium contains all the nutrients required by the bacteria in standard amounts. One day after the cultivation of the bacteria, the Nickel-bearing laterite sample was added to the Erlenmeyer and placed inside the shaker of the incubator. The conditions and results of the experiments are shown in Tables 3 and 4. To determine the percentage of dissolved minerals in water and also in non-bacterial media during the experiment, two control containers containing water and a non-bacterial culture medium were considered in all experiments. By increasing the amount of the added mineral to the environment, the extraction percentage decreases, which can be due to the increase in solids and also the reduction of the number of bacteria due to non-compliance with the metals in the sample.

Table 4 shows that pH has changed after bacterial growth. Also, by comparing the non-bacterial Erlenmeyer 1 control and the Erlenmeyer 1, 2, and 3, it is observed that the changes in pH are not noticeable. As predicted, and given the poor results, it is clear that the use of this bacteria is not possible without the addition of the required materials. Table 5 shows the number of bacteria in the environment.

Table 3. The percentage of nickel extracted by bacteria in 100 ml Nutrient Brass culture medium at 30 °C.

	Added ore sample (g)	Nickel extraction (%)		
		5 days	10 days	20 days
Erlenmeyer 1	5	10	10	11
Erlenmeyer 2	10	9	9	10
Erlenmeyer 3	15	5	5	6
Culture media without bacteria	1	3	3	4
Sterilized distilled water	1	-	-	1

Table 4. pH value of the medium in bioleaching experiments with 9K medium without adding bacteria to the environment.

	pH						
	Before bacteria inoculation	After bacteria inoculation					
		Before adding ore sample	After adding ore sample				
			Added ore sample (g)	Start day	5 day	10 day	20 day
Erlenmeyer 1		5	4	4	4	4	
Erlenmeyer 2	2	1	10	4	4	4	4
Erlenmeyer 3		15	5	5	5	5	
Culture media without bacteria		2	10	4	4	4	4
Sterilized distilled water	7.5	7.5	10	7	7	6	6

Table 5. Number of bacteria in the medium in microbiological cultures with 9K medium without adding bacteria to the environment.

	Bacteria count per milliliter				
	1 day after bacteria inoculation	After adding ore sample			
		Added ore sample (g)	5 days	10 days	20 days
Erlenmeyer 1		5	3.5×10^6	2×10^5	2×10^5
Erlenmeyer 2	10^9	10	3.5×10^6	1.5×10^5	2×10^5
Erlenmeyer 3		15	3.5×10^6	2×10^5	1.5×10^5
Culture media without bacteria		10			
Sterilized distilled water		10			

Table 6. Microbial leaching and control Erlenmeyers conditions with 9K medium without adding bacteria to the environment.

	bacteria inoculation	Adding ore sample
Erlenmeyer 1	yes	yes
Culture media without adding ore sample (Erlenmeyer 2)	yes	no
Culture media without bacteria inoculation (Erlenmeyer 3)	no	yes

Table 7. The amount of nickel extracted in microbial leaching experiments with 9K medium by adding bacteria to the environment.

	Nickel extraction (%)		
	5 days	10 days	20 days
Erlenmeyer 1	20	21	21
Culture media without adding ore sample (Erlenmeyer 2)		0	
Culture media without bacteria inoculation (Erlenmeyer 3)	3	3	4

Table 8. pH value of the medium in microbial leaching experiments with 9K medium by adding bacteria to the environment.

	pH						
	Before bacteria inoculation	After bacteria inoculation					
		Before adding ore sample	After adding ore sample				
			Start day	5 days	10 days	15 days	20 day
Erlenmeyer 1		1	2	3	3	3	4
Culture media without adding ore sample (Erlenmeyer 2)	2	1	1	0	0	0	0
Culture media without bacteria inoculation (Erlenmeyer 3)		2			4		

4- 2- Microbial leaching of Nickel-bearing laterite sample by adding the required materials to the medium

In previous experiments, it was observed that due to the lack of sufficient sulfur in the medium to convert to sulfuric acid by bacteria, the leaching process is stopped. As a result, new experiments were performed by adding sulfur to the medium. 3 Erlenmeyer containing the medium is prepared by adding 5% sulfur to the environment. Erlenmeyer 1 and 2

were cultured in bacteria, but no minerals were added to Erlenmeyer 2 and no bacteria were cultured in Erlenmeyer 3 but the mineral was added. Erlenmeyer 2 was used as a control to determine how the bacterial growth process in parallel medium with Erlenmeyer 1 and Erlenmeyer 3 as a control was used to determine the amount of organic matter dissolution in a bacterial culture medium. All the results are shown in Tables 6 to 8.

Table 9. Number of environmental bacteria in to determine microbial leaching susceptibility experiments to 9K medium by adding bacteria to the environment.

	Bacteria count per milliliter				
	1 day after bacteria inoculation	After adding ore sample			
		5 days	10 days	15 days	20 days
Erlenmeyer 1	10 ⁹	3×10 ⁷	2×10 ⁷	2×10 ⁷	1.5×10 ⁶
Culture media without adding ore sample (Erlenmeyer 2)		2×10 ⁸	2×10 ⁸	2.5×10 ⁷	2×10 ⁶
Culture media without bacteria inoculation (Erlenmeyer 3)					

Table 10. The percentage of nickel extracted in microbial leaching experiments with 9K medium by adding bacteria to the environment.

	Nickel extraction (%)						
	2 days	5 days	8 days	10 days	14 days	18 days	21 days
Erlenmeyer 1	15	20	21	21	22	22	22
Erlenmeyer 2	12	20	21	22	22	22	22

As shown in Table 7, the percentage of nickel extraction in Erlenmeyer 1 is much higher than that of Erlenmeyer 3 (no bacteria), which indicates bacterial function. The change in the amount of nickel extraction in the Erlenmeyer 3 is less than to time that is due to the initial pH of the environment and without bacteria, acid production is not continued and the pH is rising rapidly.

There is no mineral in Erlenmeyer 2 and only as a control is used to measure the pH and count the number of bacteria and compare it with the other two Erlenmeyers [21, 22].

At 5-day intervals, pH is measured in all three Erlenmeyers and its values are shown in Table 8. Obviously, the initial pH of each of the three Erlenmeyers is equal before the bacterial culture. One day after bacterial cultures in Erlenmeyer 1 and 2, their pH was measured again, with a significant reduction in pH indicating acid production by bacteria in the culture medium. Because no bacterium has been cultured in Erlenmeyer 3, there is no change in the pH of the environment before the addition of nickel –a laterite mineral. Immediately after the addition of minerals to the Erlenmeyers 1 and 3, their pH was again measured. During the experiment and at regular intervals, the pH value was reduced and then increased in Erlenmeyer 1, probably due to the completion of the nutrient source of the bacterium (sulfur). Counting live bacteria also confirms this. In Erlenmeyer 3, the pH increased and remained constant until the end of the experiment, which due to the absence of bacteria practically did not produce

acid, which reduced the pH.

4- 3- Determination of the optimal time of Nickel-bearing laterite microbial leaching

The Nickel-bearing laterite microbial leaching operations were performed in 2 Erlenmeyers with similar conditions for 20 days to determine the optimum time. A sampling at specified intervals from Erlenmeyer and the percentage of extracted nickel was determined. The optimal time for microbial leaching is 10 days from the moment the mineral is added to the Erlenmeyer containing the bacterium (Table 8). This is because according to the results presented in Table 10, after 10 days there is no increase in nickel extraction.

4- 4- Determination of the optimal amount of sulfur in the culture medium

Due to the fact that sulfuric acid results from the oxidation of sulfur by a bacterium, it can be attributed to the amount of acid produced by the bacterium to the amount of available sulfur [23]. To determine the optimal amount of sulfur, four experiments were carried out with a culture medium containing different sulfur contents. 4 Erlenmeyer containing culture medium is prepared by combining the ingredients listed in Table 2. The bacterium was cultured in all of the Erlenmeyers and after adding minerals with sulfur levels of 3, 6, 10, and 15%, a microbial leaching operation was carried out for 10 days. The results are shown in Tables 10 to 12.

Table 11. The amount of added sulfur to the environment and the percentage of nickel extraction.

	Elemental sulfur (%)	Nickel extraction after 10 days (%)
Erlenmeyer 1	3	10
Erlenmeyer 2	6	21
Erlenmeyer 3	10	43
Erlenmeyer 4	15	41

Table 12. pH value of the medium in microbial leaching experiments with 9K medium by adding bacteria to the environment.

	Elemental sulfur (%)	pH				
		Before bacteria inoculation	After bacteria inoculation			
			Before adding ore sample	After adding ore sample		
				Start day	5 days	10 days
Erlenmeyer 1	3		1.5	2	5	5
Erlenmeyer 2	6	2	1	2	3	4
Erlenmeyer 3	10		1	1	2	2
Erlenmeyer 4	15		1	1	2	2

Table 13. Determination of the optimal ratio of solid to liquid in microbial leaching experiments in 100 ml 9K culture medium.

	Added ore sample (g)	Nickel extraction (%)
Erlenmeyer 1	5	65
Erlenmeyer 2	10	43
Erlenmeyer 3	15	33

According to the tables, it is observed the best result is obtained from a medium containing 10% sulfur. The increasing trend of nickel extraction percentage from Erlenmeyer 1 to 3 indicates the bacteria's ability to oxidize more sulfur. In Erlenmeyer 4, which has 15% sulfur in its culture medium, the bacteria may not be able to consume it because of the high sulfur content. It should be noted that the number of bacteria cultured in all of the Erlenmeyers is equal and McFarland Standard No. 1, resulting in an optimal amount of 10% for sulfur with this number of bacteria.

4- 5- Determination of the optimum ratio of mineral to the culture medium (solid-to-liquid ratio)

Three experiments with different solid-to-liquid ratios have been designed to determine the optimum state of nickel

extraction percentage. The results are shown in Table 13. The volume of the culture medium in each of the three Erlenmeyers is 100 ml.

It can be seen that the best result is obtained in Erlenmeyer 1. However, in Erlenmeyers 2 and 3, due to the increase in the solid-to-liquid ratio and the decrease in the amount of effective acid relative to the mineral, the extraction percentage has decreased.

4- 6- Removal of impurities

During the microbial leaching process, other elements also enter the solution with nickel. Some of them, such as Fe and Mg, cause problems in the later stages of the process. The analysis of the final solution obtained from the previous step is given in Table 14.

Table 14. Chemical analysis of samples from microbial leaching.

Element	Mg	Fe	Ni
Amount (ppm)	569	2300	200

Table 15. Conditions for iron precipitation experiments with three factors: sodium hydroxide, ammonia, and lime.

Solution volume (ml)	Initial pH	Temperature (Celsius degree)	Final pH
100	1	65	10, 5, and 3

**Fig. 6. Turbidity of the solution due to the formation of iron sediment.**

4- 6- 1- Iron precipitation

The iron and nickel Pourbaix diagram in the aqueous environment indicates that iron separation is possible using the precipitation method. By adjusting the pH of a solution in a certain range, Fe^{+3} and many other impurities can precipitate. To remove iron from the solution of the previous stage, several precipitation experiments were carried out using sodium hydroxide at different pH. First, a 15 molar solution of NaOH was prepared and added to the leach solution by burette and gradually. Table 15 shows the conditions of precipitation experiments. During the addition of alkali substances to the solution, its color changed and clouded (Fig. 6). After settling the sediments, the solutions were sampled and sent to the ICP laboratory for analysis.

In Table 16, the results of the analysis of the sample solution after iron precipitation by alkali at the final pH of 10 are given.

As expected from the iron and nickel Pourbaix diagram

in the aqueous environment, the results of Table 16 also show that, although iron was removed from the solution, all of the nickel was deposited. At this pH, almost all of the elements in the solution are precipitated. Therefore, in the next experiment, the lower value for the final pH is considered and its amount is reached 5. As in the previous step, at this stage, the addition of alkali materials began to change and the color of the sample became cloudy.

In the current test, the pH reached the final 5, but as shown in Table 16, a large amount of nickel has been precipitated. Therefore, in the next experiment, the final pH reached 3. In Table 17, the results of the analysis of the sample solution after iron fermentation in the final pH are given.

The results of the above table are relatively favorable for iron removal and unwanted nickel deposits. By applying optimal conditions, finally, the iron grade in the solution reached 92 ppm. Table 17 provides an analysis of the final solution obtained from this step.

Table 16. Sample analysis results at final pH 10, 5, and 3.

Element	Final pH	nickel	Iron
	10	100	100
Precipitation amount (%)	5	60	100
	3	10	96

Table 17. Sample chemical analysis after iron deposition.

Element	Ni	Fe	Mg
Amount (ppm)	180	92	488

Table 18. Results of the analysis of samples from the solvent extraction step.

Element \ Sample Name	Reference solution (ppm)	After one step of solvent extraction (ppm)
Mg	488	480
Ni	180	100
Fe	92	12

4- 6- 2- Removal of iron by solvent extraction method

In the previous step, by using sodium hydroxide treatment, iron was removed from the solution of approximately 96% of the solution, and its grade ranged from 2300 ppm to 92 ppm. However, the amount of iron in the solution is still high. The solvent extraction method was used to remove the iron remaining in the solution. The solvent extraction experiment was performed on the solution of the previous stage in the following conditions:

Temperature = 25 Celsius degree

$$\text{Aqueous / Organic ratio} = \frac{1}{1}$$

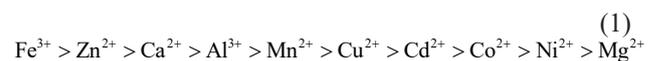
$$\frac{\text{DEHPA}}{\text{Keyoseae}} = 5\%$$

Mixing time duration = 1 hour

pH = 3

The result of the analysis of the solution obtained from the SX test (blue phase) is shown in Table 18.

According to the absorption diagram of the elements on DEHPA in the sulfate environment (Fig. 8), it was expected that the first element to be absorbed would be Fe and the remainder would be based on the prioritization noted in Eq. (1) [23].



The results of Table 18 indicate that the amount of iron eventually decreased to 12 ppm. This amount of iron remains high for the rest of the process and should be reduced. Also, the amount of nickel reduction is significant. As a result, the SX experiment was performed with the same conditions as the first one, only with a few drops of sulfuric acid, pH of the initial solution to 1.5, so that according to Fig. 7, conditions could be provided to absorb iron without absorbing nickel.

The experiment was carried out in two steps:

Table 18. Results of the analysis of samples from the solvent extraction step.

Sample name Elemen	Reference solution	After one step of solvent extraction	After two-step solvent extraction
Mg	488	485	480
Ni	180	173	170
Fe	92	16	4

Table 19. Results of the analysis of samples from the solvent extraction step.

Sample name Elemen	Reference solution	After one step of solvent extraction	After two-step solvent extraction
Mg	488	485	480
Ni	180	173	170
Fe	92	16	4

The first stage was mixed with an organic solvent after the pH of the solution was 1.5.

Temperature = 25 Celsius degree

Aqueous / Organic ratio = $\frac{1}{1}$

$\frac{\text{DEHPA}}{\text{Keyoseae}} = 5\%$

Mixing time duration = 1 hour

pH = 1.5

Then the organic phase and the water were separated.

The second stage, the water phase from the previous step, is now in contact with the new organic solvent according to the above conditions. The water and organic phase are separated and the blue sample is sent to the laboratory to determine the elements.

In Table 19, the results of the analysis of the sample obtained from the solvent extraction step are presented.

At this stage, the amount of iron in the sample is sufficiently reduced and the amount of nickel wasted is adequately low.

4- 7- Nickel solvent extraction

Due to the presence of other impurities such as magnesium in the solution leaching, it is possible to obtain a pure solution of this element by selective extraction of nickel by organic solvents.

Cyanex 301 is one of the most selective solvents for nickel, which can concentrate nickel without simultaneously extracting any of the impurities. The solvent extraction experiment is carried out on the solution obtained from the previous step under the following conditions:

Temperature = 25 Celsius degree

Aqueous / Organic ratio = $\frac{1}{1}$

$\frac{\text{Cyanex 301}}{\text{Keyoseae}} = 5\%$

Mixing time duration = 1 hour

pH = 1.5

The results of the analysis of the solution obtained from the SX test (aqueous phase) are given in Table 20. Concentrated

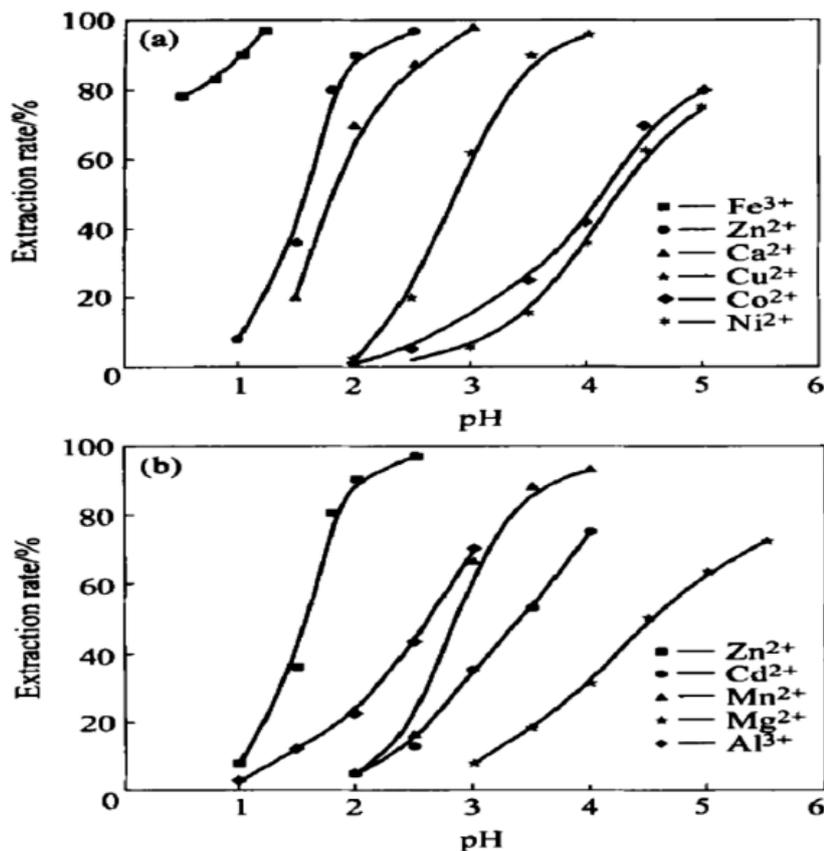


Fig. 7. Adsorption isotherms by DEHPA for different metals.

sulfuric acid has been used to strip organic solvents under the following conditions:

Temperature = 25 Celsius degree

Aqueous / Organic ratio = $\frac{1}{1}$

Acid concentration = 150 (g/l)

Mixing time duration = 0.5 hour

The result of the analysis of the aqueous solution obtained from the stripping experiment is shown in Table 21.

As shown in Table 21, finally, a solution with a nickel grade of 112 ppm is obtained.

5- Conclusion

The studied ore sample has been prepared from nickel laterite of the Chah Gheyb mine in the Bavanat region of Fars and sample identification and characterization experiments have been performed. At this stage, it was found that about

1.14% is nickel in samples of iron minerals are dispersed matrix iron ores.

In microbial leaching operation, experiments were initially carried out with a 9K culture medium. As expected, it did not have favorable results, so new materials were added to the bacteria. Early experiments with this culture showed that after 20 days, 21% of the nickel contained in the mineral sample was extracted. In the same way, the parameters affecting microbial leaching were optimized by the same method. The duration of microbial leaching, the percentage of added sulfur to the composition of the culture medium, and the amount of mineral were determined to achieve optimal conditions, which are equal to 10 days, 10%, and 10 g, respectively. The highest amount of nickel extraction in the above conditions was 65%. After this step, impurities such as iron should be removed from the solution environment by solvent extraction method. This was accomplished by combining the precipitation (with sodium hydroxide) and solvent extraction method. Finally, the solution, which was removed from iron, was subjected to solvent extraction using a selective nickel organic solvent. A pure nickel solution was produced at 112 ppm.

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