

# USING THE GOLD BULLION SLAG FROM INDONESIA AS LITHIUM RESOURCES WITH HCL LEACHING METHOD

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Primary resources are typically used in lithium extraction. However, it impacts the dependency on the availability of primary resources to fulfill the lithium demand. Therefore, the use of secondary resources can be an alternative to using lithium resources. Gold bullion slag is an example of a potential secondary resource used as a lithium source because it contains 0.009 % lithium. This research aims at increasing lithium recovery from the gold bullion slag by studying the effects of various variables to enhance lithium recovery. Lithium extraction was carried out via HCl leaching process with concentrations of 0.5, 1.0, 1.5, and 2.0 M at 25, 40, 55, and 70 °C for 15, 30, 60, and 120 minutes. Inductively coupled plasma-optical emission spectrometry (ICP-OES) was used to examine lithium level, whereas scanning electron microscope equipped with energy dispersive X-ray spectroscopy (SEM-EDX) was used to look over the morphology. The significance of the recovery value was analyzed statistically using analysis of variance (ANOVA). The optimum variables to reach 98 % as the highest lithium recovery percentage are 1 M HCl at 55 °C for 60 minutes. ANOVA results on the acid concentration significance of the recovery value show that the p-value (0.001) is smaller than the alpha value (0.005). While, ANOVA results on the temperature and time significance of the recovery value show that the p-value (0.894) is greater than the alpha value (0.005) and p-value (0.9986) is greater than the alpha value (0.005), respectively. Analysis showed that variation in HCl concentration affected the lithium recovery value; however, temperature and time of leaching had an insignificant effect on lithium recovery. These data show that slag can be used as alternative resources to produce the lithium

**Keywords:** lithium extraction, gold bullion slag, acid leaching, secondary resources, ANOVA

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## 1. Introduction

Lithium is one of the fundamental sources for a variety of technologies or electronics, and its request is estimated to grow on the global market in 2030 due to the increase in electric vehicles [1]. Deutsche Bank, United States Geological Society tells that the lithium supply and demand increase

from 2013 to 2022 and it predicted to increase continuously until 2025 [2]. Balancing the market's demand for lithium can be accomplished by determining the source of power lithium. Nowadays, lithium extraction is done using primary resources, such as brine water, spodumene, and lepidolite [3]. It was supported with the data from Deutsche Bank, United States Geological Society that since the new hard rock

assets bring market into balance in 2018 until 2020 [2]. Furthermore, the lithium market has been in surplus since 2021 and is predicted to remain so until 2025, while brine projects have begun to respond. It indicates that the high demand for lithium makes it dependent on the availability of primary resources, especially brine water. Lithium extraction from brine water and minerals requires 750 tons and 250 tons respectively to produce one ton of lithium [4]. Therefore, the use of secondary resources can be one of the most effective ways to using lithium resources. Lithium extraction process from secondary resources, especially spent lithium ion battery has been done by previous researcher. Those studies show that lithium extraction with spent LiB is promising because it can produce a high lithium recovery percentage and high lithium purity. Unfortunately, using spent LiB as lithium resources has some drawbacks, such as high acid consumption, the need for a high temperature heat treatment, pollution, and loss of lithium ions during the extraction process [5, 6]. As a result, there is still room for improvement in lithium extraction research from secondary resources.

Slag, especially gold bullion slag, is another secondary lithium resource that has the potential to be maximized. It caused by huge amounts of precious mineral are abandoned and left in the gold slag [7]. It can happen because there is an interconnected system of carrier metal cycles that consists of carrier metals, impurities, and minor metals [8]. Minor metals are the potential joint products if proper treatment is carried out. The interconnected system between carrier metals and by-product metals is illustrated as a wheel with four sections. Section I, the white area, contains carrier metals that are currently in use, Sections II and III contain elements that can be recycled to reduce environmental pollution and become more economically viable, and Section IV contains the most abandoned but still valuable element [8]. According to that wheel, Au is a potential joint product with Ag and Fe, while Cu is the carrier element. On the other hand, Cu and Fe are associated with Li. Therefore, there is a possibility that gold slag contains lithium. Gold demand has increased over the last decade as the jewelry market and medical applications have grown [9]. It causes the gold slag increases automatically. Gold bullion slag especially in Indonesia usually uses as geopolymer cements, roof tile concrete, circular light concrete and concrete block [10]. However, many people do not know yet that gold bullion slag contains lithium. As a result, the development of gold slag as a lithium resource to reduce reliance on the availability of primary resources at the same time as reducing the waste amount must be considered.

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## 2. Literature review and problem statement

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The paper [11] told the study about lithium extraction from spent LiB using nitration method then followed by roasting, water leaching and carbonation process. The nitration process was done to change the form of metallic components in spent LiB before a decomposition process. This method resulted in 93 % lithium extraction and 99.95 % purity of lithium carbonate. However, this method has some disadvantages, such as using a high temperature and a long process. The high temperatures were needed to do the nitra-

tion at 70 °C, roasting at 250 °C and carbonation at 95 °C. The water leaching for this study was carried out in four stages. So that, there are unanswered questions regarding its economic viability. This could be because the high temperature and long process are need high operation cost. The choice to control the relevant problems can be done with water leaching process in one stage. This is the approach used in [12].

The paper [12] reported the research about an efficient process to extract the lithium from spent LiB using acid roasting and water leaching methods. The pretreatment of raw material was done first to remove the impurities. The raw material was leached using N-methyl-pyrrolidone (NMP) at 80–100 °C for 1 hour. The pretreated raw material was mixed with  $\text{NH}_4\text{Cl}$  as an additive in the roasting process at 250–600 °C, followed by a one-stage water leaching process at 25–90 °C. This optimal result means that this method can extract more than 98 % of lithium. Unfortunately, this research has a drawback, such as the use of high temperatures in all methods. Therefore, there are unanswered questions regarding its economic viability. This could be because the high temperature needs the high energy and high cost. The choice to control the relevant problems is to use a simple method that does not use high temperatures in all methods in that research. It can reduce energy consumption because it does not use high temperatures. This is the approach used in [13].

The paper [13] described the research about changing the phase of lithium from spent LiB into the gas phase, which then condenses to dust. The raw material was pretreated first, then vaporized in a tube furnace with  $\text{CaCl}_2$  additives in a nitrogen atmosphere. The final product from that method was a dust that contained lithium. According to those methods, the lithium volatilization rate was 96.87 %. Unfortunately, this research also has some disadvantages, such as the vaporization method's use of very high temperatures up to 1450 °C and the possibility of Cl gas production. Therefore, there are unanswered questions regarding its economic viability and air pollution. This could be because the air pollution was caused by the possibility of Cl gas production through the vaporization method with  $\text{CaCl}_2$ . The choice to control the relevant problems is to avoid the use of chloride compounds while using vaporizing process. This is the approach used in [14].

The paper [14] shown the research about metal values recovery from spent LiB using acid leaching with HCl. Immersing the cathode in high temperature was done first, followed by acid leaching and the precipitation process. This method was successful in precipitating 95 % of the impurities while leaving 93 % of the lithium in the filtrate. Unfortunately, this research also has some disadvantages, such as the use of high temperature and loss of lithium ion during the extraction process. Because only 93 percent of the lithium remained in the filtrate, it was determined that approximately 7 % of the lithium percentage was lost during this process. There are unanswered questions regarding its pollution reduction and economic viability due to the high temperature. This could be because the immersing method separates the electrode material more effectively from the aluminum foil in the cathode. The choice to control the relevant problems can be done with selective precipitation to avoid the high temperature. This is the approach used in [15].

The paper [15] also did a research about metal values recovery from spent LiB using acid leaching with  $H_2SO_4$ . Removing four transition metals from spent LiB was done first, followed by lithium precipitation. The result of that research was an 81 % lithium recovery efficiency. There are unanswered questions regarding its pollution reduction and economic viability because the long process needs lots of solvent to do selective precipitation. This could be because the impurities need to be removed before doing the lithium extraction process. The choice to control the relevant problems can be achieved by choosing the right solution that can remove transition metals all at once. This is the approach used in [16].

The paper [16] used a solvent extraction method with Versatic 10 to do lithium extraction from spent LiB. The methods that used on this research were solvent extraction to remove the transition metals as impurities and carbonation process to extract the lithium. This research can extract the lithium as lithium carbonate with a purity of 99.61 %. There are unanswered questions regarding its pollution reduction and economic viability due to the high temperature and efficiency due to the loss of lithium ions during the extraction process. This could be because approximately 8 % of the lithium percentage was lost during the separation of lithium from transition metal. The choice to control the relevant problems can be achieved by using another solvent that can increase the lithium extraction rate. This is the approach used in [17].

The paper [17] said that 99 % of lithium can be extracted from spent LiB using calcination and leaching method. The calcination method was done at 500 °C for 5 hours and the leaching method was done at 70 °C for 1 hour. Unfortunately, this research still uses high temperatures, up to 500 °C, to do the lithium extraction. Therefore, there are unanswered questions regarding its high temperature. All of this permits to declare that it is relevant to conduct a research on using slag as lithium resources to reduce pollution, save energy, and create a more efficient process.

### 3. The aim and objectives of the study

The aim of research is to employ the secondary resources, especially gold slag, to perform lithium extraction using HCl leaching with variations of HCl concentration, temperature, and leaching time.

The following objectives were met in order to reach this aim:

- to know the gold slag potential as lithium raw material;
- to find out the effect of HCl concentration on the lithium extraction process;
- to find out the temperature effect on the lithium extraction process;
- to find out the effect of leaching time on the lithium extraction process and then determine the optimum variables in this research;
- to find out the acid leaching process effect on the composition and morphology of gold bullion slag.

### 4. Materials and methods

The principal process during this research is the leaching of gold bullion slag with HCl as leaching agent to extract lithium. The procedure begins with drying the sample, comminution and screening. The grain size of the raw material was 250 mesh. The raw material was tested by ICP-OES to evaluate the lithium level in the sample before the extraction process. Then the leaching process was done using HCl (37 %, w/w). The residue was dried in the oven then analyzed with SEM. The leaching process has three variables; HCl concentration, temperature, and reaction time. The variables that used in this research can be seen on Table 1.

Table 1 shows that the variables that will be used in this research are acid concentration, temperature, and time. Acid concentration that will be used in this research are 0.5; 1; 1.5 and 2 M while the temperature variables are 25, 40, 55 and 70 °C. This leaching process will be done for 15, 30, 60, and 120 minutes.

Table 1

Research Variables

$C$ (M)	$T$ (°C)	$t$ (min)
1	2	3
0.5 M	25	15
		30
		60
		120
		15
	40	30
		60
		120
		15
	55	30
		60
		120
		15
	70	30
		60
		120
15		

Continuation of Table 1

1	2	3
1 M	25	15
		30
		60
		120
	40	15
		30
		60
		120
	55	15
		30
		60
		120
	70	15
		30
		60
		120
1.5 M	25	15
		30
		60
		120
	40	15
		30
		60
		120
	55	15
		30
		60
		120
	70	15
		30
		60
		120
2 M	25	15
		30
		60
		120
	40	15
		30
		60
		120
	55	15
		30
		60
		120
	70	15
		30
		60
		120

### 5. Lithium extraction process from gold bullion slag research results

#### 5.1. Characterization of Gold Slag as lithium raw material

Gold bullion slag is a sample that has been carried out the process of pre-treatment with drying, comminution, screening, and leaching with H<sub>2</sub>O, then the residue of leaching is dried and comminution. Table 2 shows the results of the ICP-OES test on the initial concentration of gold bullion slag. According to Table 2, the gold bullion slag used as raw material in this research contains 0.009 % lithium in the 3.093 sample masses.

Table 2

Characterization of gold bullion slag by ICP-OES

Concentration Read	Sample masses (g)	Sample Concentration (%)	Sample Concentration (ppm)
0.309	3.093	0.009	99.924

If compared with lithium concentration in lithium ore, especially lithium ore in Indonesia, lithium concentration in this slag has a higher level. The lithium concentration in this raw material is 0.009 %, and the lithium level in the mica schist that used in [18] is 0.006 %. It indicates that gold bullion slag has the potency to be the lithium raw material. Microstructure of gold bullion slag that washed with aquadest for 90 minutes at 150 °C was analyzed using SEM can be seen in Fig. 1.

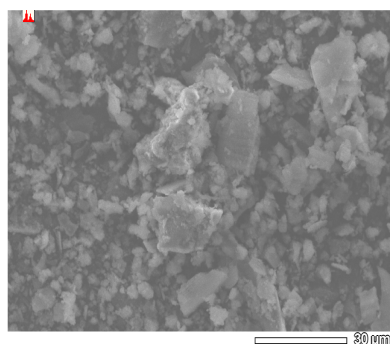


Fig. 1. Morphology of gold bullion slag by scanning electron microscope analysis

Based on Fig. 1, gold bullion slag has an irregular shape and dominated with the small particle. In addition, the particle was also distributed equally and was not agglomerated. Lithium as a light element has very low emission and cannot be detected using EDX [14]. Energy dispersive x-ray spectroscopy analysis was done to determine the initial element distribution in gold bullion slag. The results of the energy dispersive x-ray spectroscopy analysis of gold bullion slag can be seen on Table 3.

The element distribution of the gold bullion slag sample in Table 3 shows that the gold bullion slag contains O, Na, Al, Ca, Fe, Mg, Cr, Cu, Si, and Zn. Among all elements, Si (21.87 %) and O (43.58 %) dominate the morphological structure of the sample while the minor elements in gold bullion slag are Zn (3 %), Cr (0,92 %) and Mg (1.5 %). This result shows that gold bullion slag has a similar composition

with mica schist in Indonesia such as Al, Fe, Si, Ca, Na and Mg [19].

Table 3

Energy dispersive x-ray spectroscopy analysis of gold bullion slag

ZAF Method Standardless Quantitative Analysis					
Fitting Coefficient: 0.4239					
Element	(keV)	Mass %	Error %	K	Atom %
O K	0.525	43.58	0.52	45.583	60.74
Na K	1.041	7.73	0.49	5.8382	7.50
Mg K	1.253	1.50	0.37	0.8968	1.38
Al K	1.486	5.05	0.32	3.7565	4.18
Si K	1.73	21.87	0.31	19.226	17.36
Ca K	3.69	7.21	0.38	9.7629	4.01
Cr K	5.411	0.92	0.67	1.0789	0.4
Fe K	6.398	4.39	0.84	5.1811	1.75
Cu K	8.04	4.74	1.73	5.3118	1.66
Zn K	8.630	3.00	2.23	3.3659	1.02
Total		100.00		Total	100.00

#### 5.2. The effect of HCl concentration on the Lithium extraction process

The leaching process with HCl aims to extract the precious metal from the slag. The leaching process was done with variations in concentration, temperature, and time. Then the sample was filtered to separate the residue and filtrate. The filtrate was characterized by ICP-OES to determine the composition of the filtrate so the recovery value can be obtained. The effect of HCl concentration on the lithium recovery percentage is shown in Fig. 2. All graphics shows that the lithium recovery percentage from the HCl leaching process tends to increase at a concentration of 0.5 M to 1 M from the lowest 62 % to the highest 98 %. When the acid concentration was rose from 1 to 1.5 M, the result was that the lithium recovery percentage decreased significantly and continued to decrease until 2 M. The percentage of lithium recovered falls until it reaches 27 %.

The significance of HCl concentration effect on the recovery value by using a statistical analysis approach, namely ANOVA (Analysis of variance). The ANOVA analysis of HCl concentration variable can be seen in Table 4.

Table 4

Analysis of variance (ANOVA) table on HCl concentration variable

Source	Sum of Squares	Degrees of freedom	Mean Sum of Squares	F	p
Between	2.52	3	0.84	198.524	0.001
Within	0.254	60	0.004		

The confidence level in the testing of concentration variables of HCl at 95 % has an alpha value of 0.05 [15]. The ANOVA results in Table 4 shows that the F-value of this variable was 198.524 while p-value was 0.001. Alpha value will be compared with p-value to determine the significance of HCl concentration effect on the recovery value.

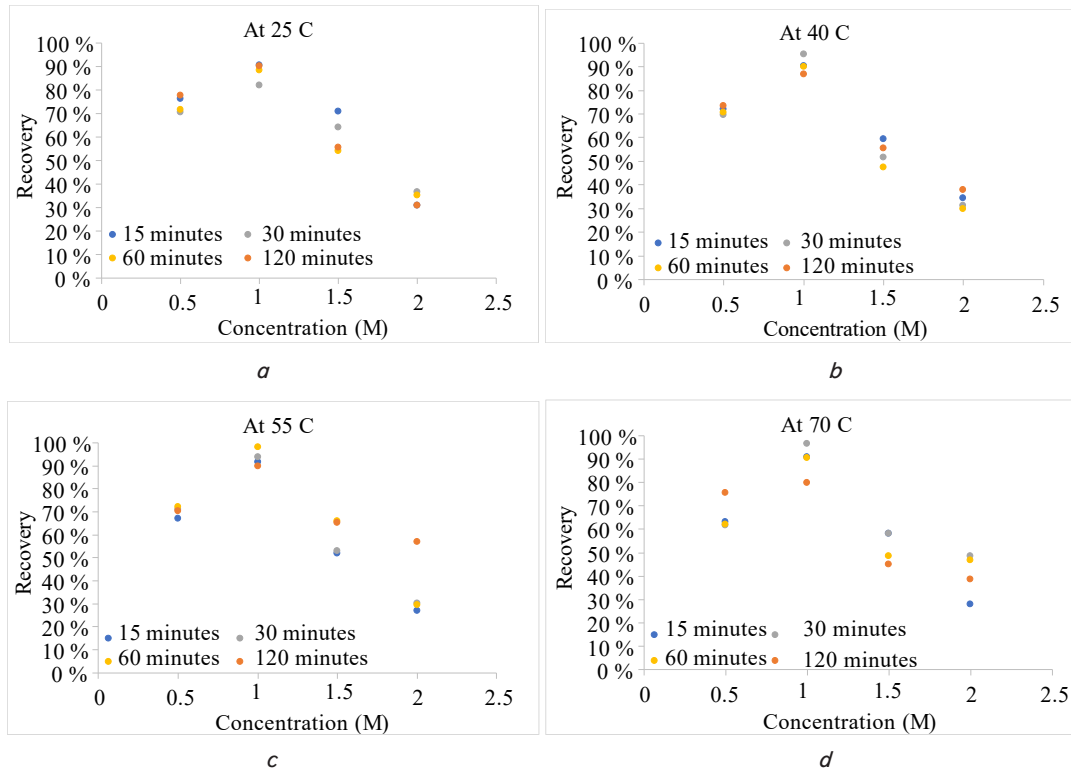


Fig. 2. Recovery value of HCl leaching at: *a* – 25 °C; *b* – 40 °C; *c* – 55 °C; *d* – 70 °C

**5.3. The effect of temperature on the Lithium extraction process**

The effect of temperature and concentration on time variations to lithium recovery percentage can be seen in Fig. 3. Based on Fig. 3, the highest lithium recovery percentage is around 98 % while the lowest lithium recovery

percentage is around 27 %. The highest lithium recovery percentage achieved at 55 °C for 60 minutes and 1 M HCl. While the lowest lithium recovery percentage achieved at 55 °C for 15 minutes and 2 M HCl. All the graphics show that the gain in lithium recovery percentage did not change drastically.

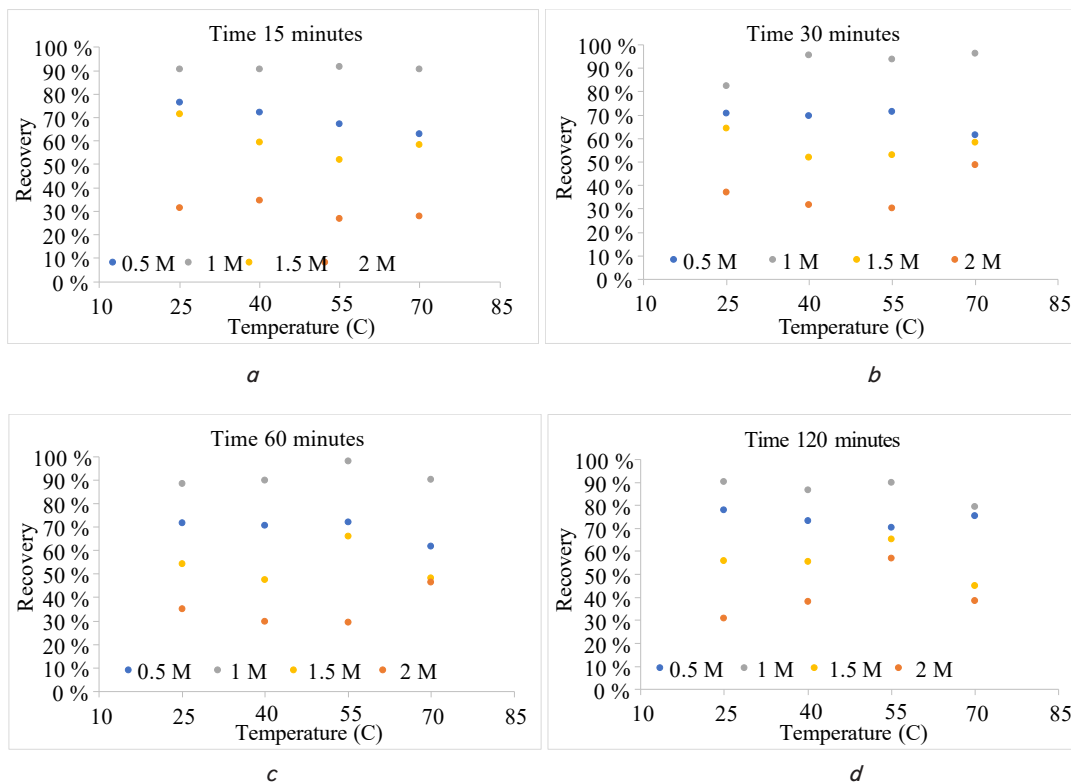


Fig. 3. Recovery value of HCl leaching for: *a* – 15 minutes; *b* – 30 minutes; *c* – 60 minutes; *d* – 120 minutes

The effect of leaching temperature on the recovery value can be seen with the ANOVA statistical analysis approach (analysis of variance). The ANOVA analysis about the influence of leaching temperature on the recovery value can be seen on Table 5.

Table 5

Analysis of variance (ANOVA) table on temperature variable

Source	Sum of Squares	Degrees of freedom	Mean Sum of Squares	F	p
Between	0.021	3	0.007	0.203	0.894
Within	0.841	24	0.035		

The confidence level in the test variable temperature of 95 % has an alpha value of 0.05 [15]. Table 5 shows that F-value on temperature variable is 0.203 while the p-value is 0.894. Alpha value will also be compared with the p-value to specify the influence of leaching temperature on the recovery value.

5.4. The effect of leaching time on the lithium extraction process

Fig. 4 shows the effect of time and temperature on concentration variations to lithium recovery percentage. The lithium recovery percentage has a tendency to decrease

slightly after 60 minutes. It indicates that the long leaching time will make other elements dissolve first, obstructing the solubility of lithium in HCl. During the leaching process with time variations, the highest recovery value is 98 %, while the lowest recovery value is 31 %.

To see the effect of differences in the time of leaching of the value of recovery, do approach to the analysis of ANOVA (analysis of variance). The confidence level in the leaching time variable test of 95 %, which has 0.05 of alpha value [20]. ANOVA analysis to specify the influence of differences in leaching time on recovery value can be seen on Table 6.

Table 6

Analysis of variance (ANOVA) table on temperature variable

Source	Sum of Squares	Degrees of freedom	Mean Sum of Squares	F	p
Between	0.003	3	0.001	0.022	0.996
Within	2.771	60	0.046		

Table 6 shows that F-value on temperature variable is 0.022 while the p-value is 0.996. P-values had to be compared to alpha values in order to specify the influence of leaching time on recovery value.

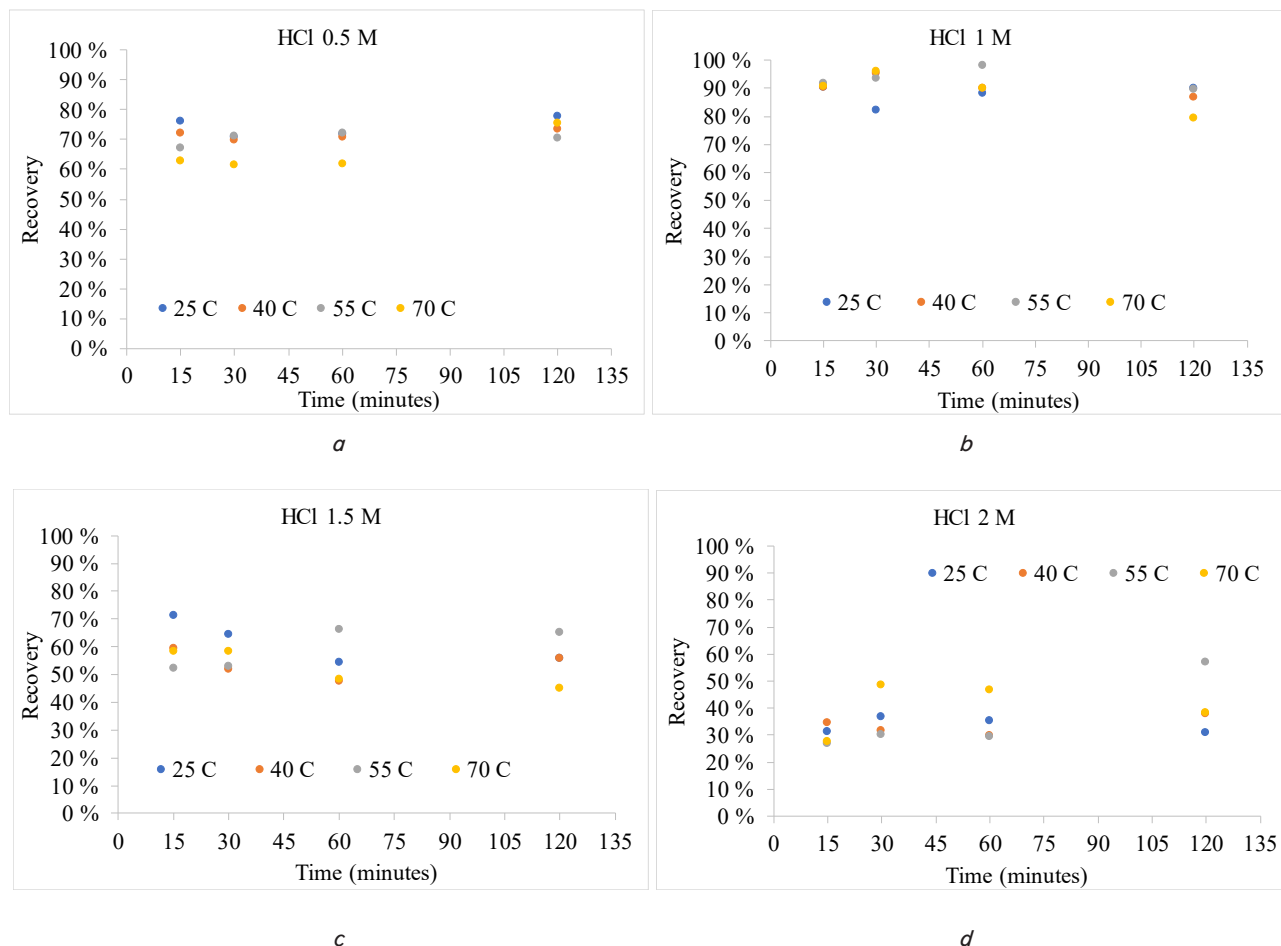


Fig. 4. Recovery value of HCl leaching on: a – 0.5 M; b – 1 M; c – 1.5 M; d – 2 M

**5.5. The effect of the acid leaching process on the morphology and composition of gold bullion slag**

Fig. 5 shows SEM analysis that performed a leaching residue with 1 M HCl at 55 °C for 60 minutes. The morphology of leaching residue according to Fig. 5 is irregular shape and dominated with larger particles. In addition, the particle was not distributed equally, and there are smaller particles on the large particle. Research [21] showed that the leaching process to increase the lithium level break the granules become much smaller. The changes of particles size of the sample showed an increase in the level of adsorption on cation monovalent whose impact on the composition of cations that can exchange.

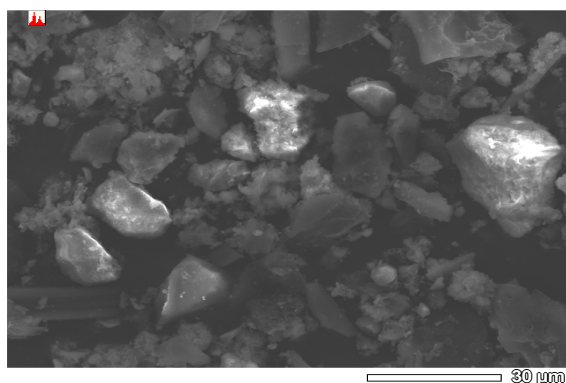


Fig. 5. Morphology of final gold bullion slag sample by scanning electron microscope analysis

Energy dispersive x-ray spectroscopy analysis of leaching residue was needed because the effect of acid leaching can be seen by knowing the composition of the leaching residue. The energy dispersive X-ray spectroscopy analysis of leaching residue can be seen on Table 7.

Table 7

Energy dispersive X-ray spectroscopy analysis of leaching residue

ZAF Method Standardless Quantitative Analysis					
Fitting Coefficient: 0.4194					
Element	(keV)	Mass %	Error %	K	Atom %
O K	0.525	31.6	0.42	23.166	62.61
Si K	1.739	16.57	0.15	20.112	18.7
Cl K	2.621	1.11	0.21	1.124	0.99
Cu K	8.04	2.95	0.95	3.999	1.47
Zn K	8.630	3.11	1.21	4.249	1.51
Zr L	2.042	40.4	0.51	42.902	14.04
Ag L*	2.983	0.01	0.54	0.006	0
Au M*	2.121	4.27	0.67	4.439	0.69
Total		100.00		Total	100.00

Table 7 shows that the residue was dominated with Zr (40.40 %), O (31.60 %) and Si (16.57 %). While the minor elements are Ag (0.01 %), Cl (1.11 %), Cu (2.95 %) and Zn (3.11 %). There are differences in element concentration between Table 7 and Table 3. There were elements Na, Mg, Al, Ca, and Fe in gold bullion slag as raw materials in Table 3, but those elements disappeared in Table 7. It indicates that those elements may have solubilized in HCl during

the leaching process. While elements Cu, Zn and Si still appear with the same concentration in Table 7. It indicates that those elements do not react with HCl. The element Cl in the leaching residue indicates that the gold bullion slag reacted with HCl, and there is a possibility that some elements in the gold bullion slag bond with the Cl ion to make a chloride compound.

**6. Discussion of the research results of Lithium extraction process from gold bullion slag**

HCl concentration was variated on this research and the results can be seen in Fig. 2. According to Fig. 2 that the lithium recovery percentage will increase along with the increasing HCl concentration due to the proton concentration and the speed of diffusion of ions in it. In the study [22], the most probable reaction between the HCl ionization reaction and the leaching reaction is an endothermic reaction, where the protons used for lithium leaching come from the ionization of HCl. When HCl is consumed in an interphase customary liquid, the gradient concentration of H<sup>+</sup> between the solid-liquid interface and the solution gradually increases, which can speed up diffusion [22]. Both of these things can increase the recovery to reach its maximum value. According to [22], when it has reached the maximum value for the added concentration of HCl, the diffusion speed is not going to change, so Li<sup>+</sup> has been adequately replaced. The reduction of lithium recovery percentage that occurred was also mentioned in [23], in which the equilibrium reaction between HCl and lithium has been reached at 1 M, leading to a contrast reaction if the concentration is increased so that the lithium recovery percentage will decrease. An ANOVA analysis was needed to be done to determine the effect of HCl concentration on the recovery value. According to Table 4, p-value is smaller than the alpha value (0.005). If the p-value is smaller than the alpha value, the conclusion from Table 4 is that the HCl concentration variable is significant to the recovery value. Thus, the difference in the concentration of HCl has a different effect on the recovery value.

Temperature variations were done after the HCl concentration variations. The results of temperature variations to lithium recovery percentage can be seen in Fig. 3. According to Fig. 3, there is no correlation between the influence of temperature and lithium recovery percentage because there is not the same tendency among all graphics. However, the higher temperature tends to make the lithium recovery percentage decrease. It also happened on study [23] that the rate of chemical reactions and the rate of ion transfer is affected by temperature. If the K and Na gain had reached its maximum, it would have disrupted the Li exchangeable rate in the sample and decreased the recovery value that had passed an optimum temperature [24]. It is shown in Fig. 3 that the recovery value tends to decrease until 28 % at 70 °C. The ANOVA results in Table 5 show that the p-value (0.894) is greater than the alpha value (0.005), which indicates that the temperature variable is not significant to the recovery value. It shows that low temperature can use with attention to other variables that have significant effects because higher temperature will impact to the loss lithium. It can happen because the high pressure (100 kPa) at 70 °C will give a higher specific volume of saturated liquid and saturated vapor [19]. In consequence, a lot of elements, including lithium, could vaporize.



Time variations were also done on this research because the previous research showed that lithium extraction was influenced by leaching time [11, 25]. The results of the leaching time effect on recovery value can be seen in Fig. 4. Based on Fig. 4, the lithium recovery value did not change significantly after the leaching time was done for 60 minutes. In addition, some graphics showed that the lithium recovery percentage decreased along with the increasing leaching time. This decrease occurred because of the competitive adsorption capacity of Li, K, and Na [26]. It was also mentioned in [21] that this decrease could be due to competition for the absorption of Na and K ions which tend to increase solubility along with the length of leaching time. However, Fig. 4 shows that leaching time from 60 minutes to 120 minutes tend to slightly increase. It happens because the larger capacity adsorption solution leaches more as the leaching duration increases [27]. Table 6 of the ANOVA results shows that the p-value (0.996) is greater than the alpha value (0.005), which indicates that the leaching time variable is not significant to the recovery value. It demonstrates that the shortest time can be used while paying attention to other variables with a significant effect. The shortest time could be the better way to do the lithium extraction using the leaching method because a paper [25] reported that the efficiency of lithium extraction with acid leaching increased as the leaching time increased, but the efficiency did not change significantly after 35 minutes. In addition, the paper [28] also reported that the lithium leaching efficiency continued to increase after 30 minutes, but it looked constant while the leaching time was increased until 60 minutes. Based on Fig. 2–4, the optimum variables to reach 98 % as the highest lithium recovery percentage are 1 M HCl at 55 °C for 60 minutes.

The limitation of this study is that the raw material contains a small amount of lithium. It makes the process of producing lithium carbonate as a battery raw material from gold slag more time-consuming. The long process has the possibility of causing a loss of lithium during the extraction process. It automatically makes the lithium extraction percentage go down. In addition, the increasing percentage of lithium extraction in this research was influenced by acid concentration. The high concentration of acid makes it possible to produce environmentally unfriendly waste. Therefore, we have to know the safe limit of the acid concentration used in order to not produce waste that is not environmentally friendly if we want to use this method.

The disadvantages of this research include the lack of a pre-treatment process that could increase the lithium concentration and the lack of a solid-liquid ratio. As a result, the pre-treatment process and variations in the solid-liquid ratio can be studied further in future research. Combining the acid leaching process with evaporation and precipitation methods can be used to develop this study. These methods may have an effect on the percentage of lithium recovered, and high purity lithium can be obtained. The difficulties that may arise along the way include increasing the lithium concentration prior to performing the precipitation method. It can happen because the minimum lithium concentration to be precipitated is around 20 g/L [29].

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## 7. Conclusion

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1. Gold slag has the potential to be a lithium raw material because it contains 0.009 % lithium, which is higher than the lithium content of mica schist in Indonesia. In addition, the lithium was successfully extracted from gold slag using the HCl leaching process.

2. The variable of acid concentration gives the significant effect to increase the lithium recovery percentage. It can be seen through ANOVA analysis that HCl concentration has a value of p (0.001) less than alpha (0.005).

3. The leaching temperature variable did not have a significant effect to the lithium recovery percentage. It can be seen through ANOVA analysis that leaching of gold bullion slag samples at 25, 40, 55, and 70 °C has a p-value (0.894) higher than alpha (0.005).

4. Leaching time variable also did not have a significant effect on increasing the lithium recovery percentage. It can be seen through ANOVA analysis that leaching of gold bullion slag samples for 15, 30, 60, and 120 minutes has a p-value (0.996) more than alpha (0.005). Therefore, the most effective parameter is 1 M HCl as the concentration of HCl with the high recovery value, which amounted to 98 %, at 55 °C for 60 minutes.

5. The morphology and composition of gold-bullion slag were impacted by acid leaching in the lithium extraction process.

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## Conflict of interest

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The authors declare that we have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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## Data availability

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Manuscript has no associated data.

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