

EFFECT OF TEMPERATURE AND CHARGE PREPARATION CONDITIONS ON THE CONVERSION DEGREE OF MOLYBDENUM MIDDLING DURING SODA ROASTING BASED ON CO₂ RELEASE

Bolotpay Baimbetov ¹, Tansholpan Tussupbekova ^{1,2*}, Guldana Makasheva ²

¹Satbayev University, Almaty, Kazakhstan

²LLP KazHydroMed, Karaganda, Kazakhstan

*Corresponding author: Tansholpan Tussupbekova, e-mail: tansholpan_87.09@mail.ru

Keywords:

molybdenum middling,
molybdenite, soda
roasting, sodium
carbonate, carbon
dioxide, conversion
degree, vibration,
charge preparation.

ABSTRACT

This study investigates the conversion degree of molybdenum middling during soda roasting based on the amount of CO₂ released. The initial molybdenum middling obtained from the Shatyrkul-Zhaysan cluster was characterized by chemical analysis, X-ray diffraction, mineralogical analysis, and SEM-EDS. The material contained 22.23% Mo, 7.52% Cu, 16.54% Fe, and 28.6% S, with molybdenite and chalcopyrite as the main mineral phases. SEM-EDS analysis confirmed the presence of Mo-, S-, Cu-, and Fe-bearing phases, as well as gangue and oxidized components. Soda roasting was carried out using a charge composed of molybdenum middling and sodium carbonate at a mass ratio of 1:1. The conversion degree was calculated from the integral volume of CO₂ released during roasting. The results showed that simple mechanical mixing of the charge provided a conversion degree of 16.9–39.7%, indicating limited interaction between solid reactants. When vibration was applied during roasting at 650 °C, the conversion degree increased to 49.33%. The highest conversion degree, 54.89%, was achieved when vibration during roasting was combined with preliminary moistening of the charge by adding 10% water. Chemical analysis of the roasted products showed that the lowest sodium content, 17.766%, corresponded to the maximum CO₂-based conversion degree, indicating more active participation of sodium carbonate in soda roasting reactions. The obtained results show that the efficiency of soda roasting depends not only on temperature but also on contact conditions between sodium carbonate and sulfide mineral particles.

INTRODUCTION

Molybdenum is one of the strategically important metals widely used in ferrous and non-ferrous metallurgy, the chemical industry, the production of special steels, heat-resistant alloys, catalysts, and other functional materials (Lasheen et al. 2015). Most molybdenum is used in the metallurgical industry as an alloying element that improves the strength, corrosion resistance, heat resistance, and operational reliability of steels and alloys.

The main industrial mineral of molybdenum is molybdenite, MoS₂. In natural and technogenic molybdenum-bearing products, it is often associated with copper and iron sulfides, which complicates the production of a marketable molybdenum concentrate and the subsequent processing of raw materials (Castro et al. 2016, Yuki Semoto et al. 2021). Therefore, the processing of low-grade molybdenum middling formed during the beneficiation of complex copper-molybdenum ores is particularly relevant (Tripathy and Rakhasia, 2006).



The Republic of Kazakhstan has a significant molybdenum resource base. Complex copper-molybdenum deposits are known in the country, including Aktogay, Aidarly, Bozshakol, Kounrad, Shatyrkul, Zhaysan, and other deposits (Galevskii et al., 2020). However, most of these ores are characterized by a complex material composition, fine dissemination of molybdenite, and the presence of associated sulfide minerals. As a result, part of the molybdenum may pass into non-commercial middling or be lost with beneficiation tailings (Karimova L et al. 2024). A previously published review on the processing of molybdenum ores and concentrates noted that the development of effective methods for involving low-grade and non-commercial molybdenum raw materials in processing is an urgent task for expanding the raw material base and increasing molybdenum recovery (Lasheen et al., 2015).

Traditional processing of molybdenite concentrates is based on oxidative roasting, with the conversion of MoS_2 into oxide forms followed by hydrometallurgical processing of the calcine (Lasheen et al. 2015, Fan et al. 2019, Ping et al. 2019). However, this approach is most effective for commercial concentrates with a high molybdenum content. When processing low-grade middling and materials of complex composition, additional difficulties arise due to the increased content of copper and iron sulfides, the possible formation of poorly soluble phases, material sintering, and the release of sulfur-containing gases (Sun et al., 2022).

One promising direction for processing sulfide molybdenum raw materials is soda roasting using sodium carbonate (Yubiao Li et al. 2019, P.V. Aleksandrov et al. 2017, Tussupbekova T. et al. 2025, Karimova et al., 2026). The essence of the process is that molybdenite, in the presence of Na_2CO_3 and atmospheric oxygen, is converted into sodium molybdate Na_2MoO_4 , while sulfur from sulfide minerals can be bound as sodium sulfate Na_2SO_4 . This approach makes it possible to convert molybdenum from a poorly soluble sulfide form into a water-soluble molybdate form and, at the same time, reduce the probability of sulfur dioxide release into the gas phase.

Alternative methods for molybdenite decomposition in alkaline oxidative media are also being studied worldwide. Thus, Aracena et al. 2015 studied the dissolution of molybdenite concentrate in the NaClO – NaOH – H_2O system and showed that, in an alkaline medium, molybdenite can pass into solution with the formation of molybdate ions, while the final reaction products are sodium molybdate and sodium sulfate. Under optimal conditions, MoS_2 dissolution reached about 99%, whereas the dissolution of copper and iron was insignificant. Thermal treatment with sodium chloride and mechanical activation followed by leaching have also been investigated as alternative approaches (Aleksandrov et al., 2017; Li et al., 2019; Wang et al., 2025). This confirms that the conversion of molybdenite into molybdate forms is one of the key directions in modern processing of molybdenum-bearing raw materials.

Of particular interest is the molybdenum middling obtained from the copper-molybdenum ore of the Shatyrkul-Zhaysan cluster. According to previous studies, this middling contains 22.23% Mo, 7.52% Cu, 16.54% Fe, and 28.6% S, indicating its complex sulfide composition (Karimova L et al. 2024, Tussupbekova T. et al. 2025). The main minerals are molybdenite, chalcopyrite, pyrite, magnetite, hematite, and iron hydroxides. A significant part of the molybdenite occurs in a liberated form; however, some grains form intergrowths with chalcopyrite and other minerals, which may affect the completeness of reactions during roasting.

Previous studies established that, during soda roasting of molybdenum middling, increasing the temperature from 500 to 650 °C promotes an increase in molybdenum recovery during subsequent water leaching from 92.08 to 97.73% (Tussupbekova T. et al. 2025). The influence of roasting conditions on phase transformations in low-grade molybdenum intermediates was also considered by Karimova et al. (2026). However, for a deeper understanding of the process, it is important to consider not only the final extraction of molybdenum into solution but also the degree of molybdenite conversion directly during

roasting. This approach makes it possible to establish the relationship between temperature, the phase composition of the calcine, and the completeness of MoS_2 conversion into molybdate compounds.

Thus, the quantitative assessment of molybdenite conversion during soda roasting of molybdenum middling is of scientific interest. In the present work, the amount of CO_2 released was used as the main criterion for process completeness, since its formation is directly related to the consumption of sodium carbonate in soda sintering reactions. This approach makes it possible to evaluate the progress of the process directly during roasting, rather than only by the results of subsequent leaching.

Despite numerous studies on the oxidative and soda roasting of molybdenite concentrates, the conversion behavior of low-grade molybdenum middling with a complex sulfide composition remains insufficiently studied. Most previous works have mainly focused on the final molybdenum recovery during leaching or on the phase composition of roasted products. However, less attention has been paid to the direct assessment of the roasting process based on CO_2 evolution, which reflects the consumption of sodium carbonate and the progress of soda roasting reactions during thermal treatment.

In addition, the influence of charge preparation and dynamic conditions during roasting has not been sufficiently considered. For complex molybdenum middling containing molybdenite, chalcopyrite, iron sulfides, and gangue minerals, the contact between sodium carbonate and sulfide particles plays a critical role. Insufficient contact can limit the conversion of MoS_2 into sodium molybdate even at elevated temperatures. Therefore, the use of vibration during roasting and preliminary moistening of the charge may be considered as promising approaches to intensify the interaction between solid reagents.

The scientific novelty of this study lies in the evaluation of the conversion degree of molybdenum middling during soda roasting based on the integral amount of CO_2 released. In contrast to previous studies that mainly evaluated the efficiency of roasting by subsequent molybdenum leaching, this work uses CO_2 evolution as an additional quantitative criterion for assessing the progress of soda roasting reactions. The study also determines the influence of temperature, vibration applied during roasting, and preliminary charge moistening on the completeness of molybdenum middling conversion.

The aim of this work is to evaluate the conversion degree of molybdenum middling during soda roasting based on the amount of CO_2 released and to determine the effect of temperature and charge preparation conditions on the completeness of soda roasting reactions.

MATERIALS AND METHODS

Molybdenum middling obtained during the processing of copper-molybdenum ore from the Shatyrkul-Zhaysan cluster was used as the research object. The middling was produced by a flotation scheme that included bulk flotation of copper-molybdenum ore followed by selective separation of the bulk concentrate. During the selective separation of the copper-molybdenum concentrate, sodium sulfide was used to depress copper sulfides, and thermal treatment of the pulp was applied to improve separation efficiency.

The chemical composition of the initial molybdenum middling was determined using a set of analytical methods. The content of the main components was determined by chemical analysis, the content of precious metals by fire assay, and the elemental composition by inductively coupled plasma mass spectrometry. The phase composition of the initial material and roasted products was determined by X-ray diffraction using a Bruker D2 Phaser diffractometer. Mineralogical examination of ore minerals was carried out in reflected light on polished sections using an OLYMPUS BX53 microscope equipped with a SIMAGIS XS-3CU video camera and Mineral C7 software by SIAMS.

According to chemical analysis, the initial middling contained, wt.%: Mo — 22.23; Cu — 7.52; Fe — 16.54; S — 28.6; SiO₂ — 11.42; Al₂O₃ — 2.13; CaO — 1.15; MgO — 1.24. The silver content was 167.0 g/t, gold 10.60 g/t, and rhenium 62.3 g/t.

According to X-ray diffraction analysis, the phase composition of the initial molybdenum middling was mainly represented by molybdenite and chalcopyrite. The content of molybdenite was 71.2%, and that of chalcopyrite was 28.8% (Figure 1).

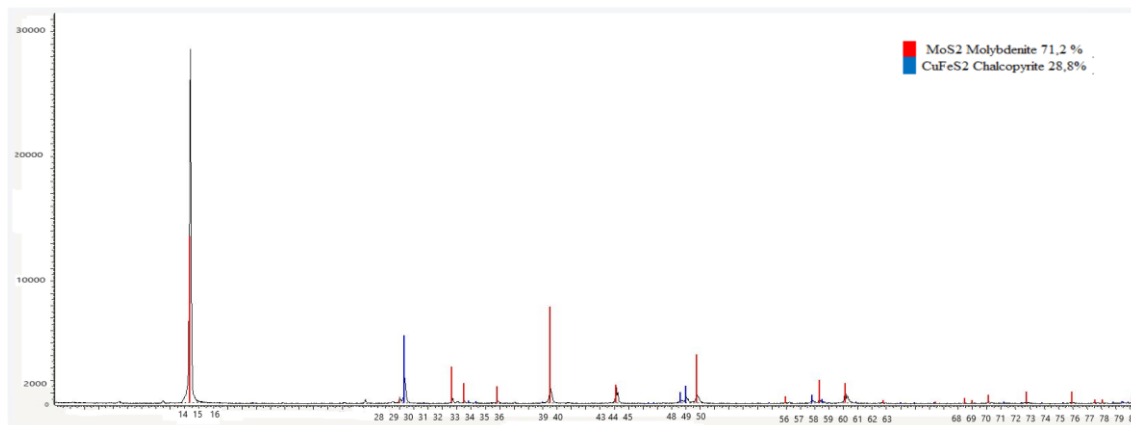


Figure 1. X-ray diffraction pattern and phase composition of the initial molybdenum middling

Mineralogical analysis showed that molybdenite was the main molybdenum-bearing mineral (Figure 2). The ore mineralization of the middling was represented by molybdenite, chalcopyrite, pyrite, magnetite, hematite, iron hydroxides, and gangue minerals. According to mineralogical examination, a significant part of molybdenite occurred in a liberated form; however, about 20% of the grains were intergrown with other ore minerals, mainly chalcopyrite. The length of molybdenite grains ranged from 0.003 to 0.5 mm.

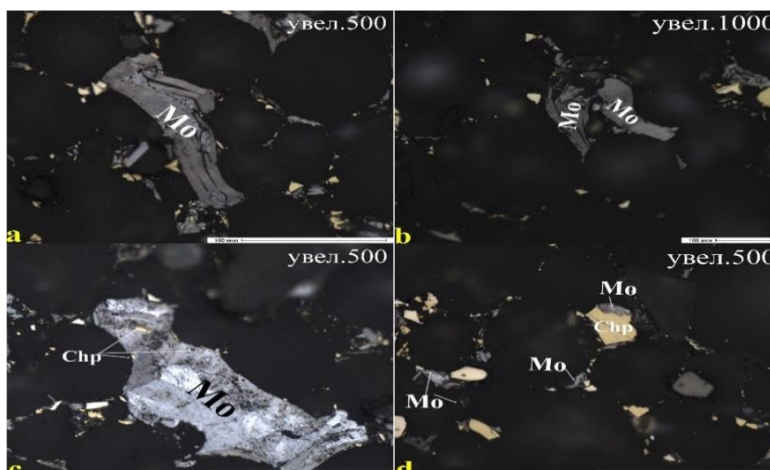


Figure 2. Characteristics of molybdenite forms, magnification 500/100

The surface morphology and local elemental composition of the initial molybdenum middling were additionally studied by scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS). The analysis was performed at an accelerating voltage of 10 kV. The obtained SEM images were used to characterize the morphology of mineral particles, while EDS analysis was used to determine the local elemental composition of selected areas.

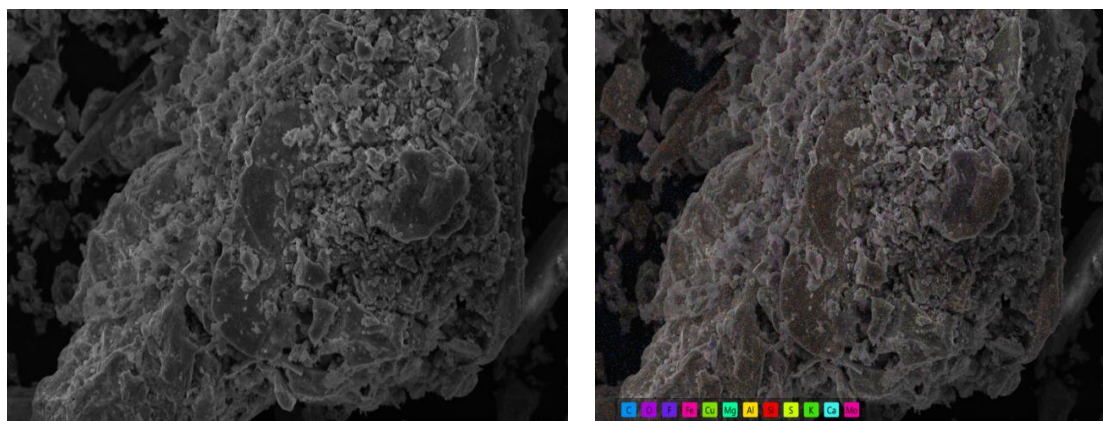


Figure 3. SEM microphotograph (a) and corresponding EDS elemental mapping (b) of the initial molybdenum middling

Table 1. SEM-EDS elemental composition of the initial molybdenum middling

Element	At. %	Wt. %
C	15.7	6.5
O	40.9	22.6
F	2.2	1.5
Mg	0.8	0.7
Al	2.2	2.0
Si	5.3	5.2
S	14.5	16.1
K	0.6	0.8
Ca	1.0	1.3
Fe	5.6	10.8
Cu	4.2	9.3
Mo	7.0	23.2

According to the SEM-EDS data, the analyzed area of the initial molybdenum middling contained Mo, S, Cu, Fe, O, Si, Al, Ca, and other minor elements. The presence of Mo and S confirms the occurrence of molybdenum-bearing sulfide phases, mainly molybdenite. The detection of Cu and Fe indicates the presence of associated copper- and iron-bearing minerals, including chalcopyrite and iron-containing phases. The presence of Si, Al, Ca, and O is related to gangue minerals and oxidized components of the material.

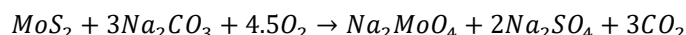
It should be noted that SEM-EDS analysis characterizes the local elemental composition of the selected area and therefore was used as an additional method to confirm the complex composition of the initial molybdenum middling. The SEM images show that the material consists of irregularly shaped particles with heterogeneous surface morphology. Such a structure may limit uniform contact between molybdenite and sodium carbonate during simple mechanical mixing. Therefore, the SEM-EDS results additionally support the assumption that the efficiency of soda roasting depends not only on temperature but also on the quality of contact between sodium carbonate and sulfide mineral particles.

To convert molybdenite into molybdate compounds, soda roasting of the molybdenum middling was carried out. Sodium carbonate, Na_2CO_3 , was used as the reagent. Before roasting, the initial molybdenum middling was thoroughly mixed with sodium carbonate to obtain a homogeneous charge. The mass ratio of sulfide material to sodium carbonate was 1:1. The mass of the charge for one experiment was 2 g.

Roasting was carried out in a SNOL 15/1200 muffle furnace in an oxidizing air atmosphere. The temperature in the furnace working zone was controlled using a DEPK 145-0919.1000.1 thermocouple. The experiments were carried out at temperatures of 550, 650, and 750 °C. The holding time at the specified temperature was 120 min.

To quantitatively assess the completeness of soda roasting, the conversion degree was calculated based on the volume of carbon dioxide released. This indicator was selected because CO₂ is formed during the interaction of sodium carbonate with molybdenite and associated components of the charge, and its amount reflects the progress of soda sintering reactions.

The main reaction between molybdenite and sodium carbonate in an oxidizing atmosphere can be represented as follows:



According to this equation, during the complete conversion of molybdenite into sodium molybdate, CO₂ release is stoichiometrically related to sodium carbonate consumption. Therefore, the actual volume of CO₂ released was used as a criterion for the conversion degree of the charge during roasting.

The conversion degree was calculated using the following equation:

$$E = \frac{V_{\text{actual. CO}_2}}{V_{\text{theoret. CO}_2}} \times 100\%$$

where E is the conversion degree, %; $V_{\text{actual CO}_2}$ is the actual integral volume of CO₂ released during roasting, cm³; and $V_{\text{theoretical CO}_2}$ is the theoretical volume of CO₂ calculated from reaction stoichiometry for complete process completion, cm³.

The actual volume of CO₂ was determined as the total amount of gas released over the entire roasting period at a given temperature. The theoretical volume of CO₂ was calculated based on the amount of sodium carbonate participating in soda sintering reactions.

RESULTS AND DISCUSSION

The actual volume of CO₂ was determined from the area under the curve of CO₂ concentration versus time. The calculation was performed using the trapezoidal method, taking into account an air flow rate of 7.5 L/h. The theoretical volume of CO₂ for the studied charge was 155.74 mL.

The results obtained during laboratory experiments and calculations are presented in Table 2.

Table 2. Generalized results for calculating the conversion degree during soda roasting of molybdenum middling

Experiment	Experimental conditions	Max. CO ₂ , %	Time to maximum, min	$V_{\text{act. CO}_2}$, mL	$V_{\text{theor. CO}_2}$, mL	Conversion degree, %
1	550 °C, simple charge mixing	0.46	25	26.3	155.74	16.9
2	650 °C, simple charge mixing	1.25	16–32	61.8	155.74	39.6
3	750 °C, simple charge mixing	2.57	10	61.9	155.74	39.7
4	650 °C, vibration 30 V, without water	1.38	18	76.83	155.74	49.33
5	650 °C, vibration 30 V, with 10% water added	1.42	22	85.49	155.74	54.89

According to Table 2, during simple mixing of molybdenum middling with sodium

carbonate, the conversion degree ranged from 16.9 to 39.7%. Even with a pronounced CO₂ maximum in experiment 3, the total actual volume of gas released was only 61.9 mL, corresponding to a conversion degree of 39.7%. This indicates that simple mechanical mixing does not provide sufficient contact between sodium carbonate particles and sulfide minerals.

When vibration at 30 V was applied at 650 °C, the conversion degree increased to 49.33%. The actual CO₂ volume was 76.83 mL, which is higher than in the experiments with simple mixing. This indicates a positive effect of vibration on the progress of soda roasting reactions.

The highest result was obtained in experiment 5, where vibration at 30 V was used and 10% water was added to the charge. In this case, the actual CO₂ volume increased to 85.49 mL, and the conversion degree reached 54.89%.

To further evaluate changes in the solid phase after soda roasting, the chemical composition of the initial molybdenum middling and roasted products was analyzed. The results are presented in Table 3.

Table 3. Chemical composition of the initial molybdenum middling and roasted products after soda roasting

Product/ experiment	Conditions	Cu, %	Fe, %	S, %	Na, %	Mo, %
Experiment 1	550 °C, simple charge mixing	2.688	4.258	9.186	24.228	12.577
Experiment 2	650 °C, simple charge mixing	3.762	5.970	15.927	19.569	12.384
Experiment 3	750 °C, simple charge mixing	4.200	6.601	15.692	20.317	13.658
Experiment 4	650 °C, vibration 30 V, without water	3.746	5.904	15.938	18.269	12.473
Experiment 5	650 °C, vibration 30 V + 10% water	3.768	5.966	16.578	17.766	11.616

The chemical composition of the roasted products was additionally analyzed to evaluate changes in the solid phase after soda roasting. Since the charge consisted of molybdenum middling and sodium carbonate at a mass ratio of 1:1, the content of ore components in the initial charge was approximately two times lower than in the original concentrate. Therefore, the composition of the roasted products should be interpreted considering dilution by sodium carbonate and the formation of sodium-containing reaction products.

The Mo content in the roasted products ranged from 11.616 to 13.658%, which is close to the calculated Mo content in the initial charge. This indicates that the solid products obtained after roasting were generally comparable in terms of molybdenum content. At the same time, the sodium content was the most informative parameter. In experiment 1 at 550 °C, the Na content was 24.228%, which is consistent with the low CO₂-based conversion degree of 16.9% and indicates a significant amount of sodium-containing compounds remaining in the solid product.

With increasing temperature to 650 °C, the Na content decreased to 19.569%, while the conversion degree increased to 39.6%. Under vibration conditions, the Na content decreased further to 18.269%, and the conversion degree increased to 49.33%. The lowest Na content, 17.766%, was obtained in experiment 5 with vibration and 10% water addition, where the maximum conversion degree of 54.89% was achieved. This confirms that vibration and charge moistening promote more active participation of sodium carbonate in soda roasting reactions.

The sulfur content in the roasted products of experiments 2–5 ranged from 15.692 to 16.578%, which indicates that sulfur was not completely removed into the gas phase. A significant part of sulfur likely remained in the solid product in the form of sulfate compounds. This is consistent with the mechanism of soda roasting, where sulfur from sulfide minerals can be bound as sodium sulfate.

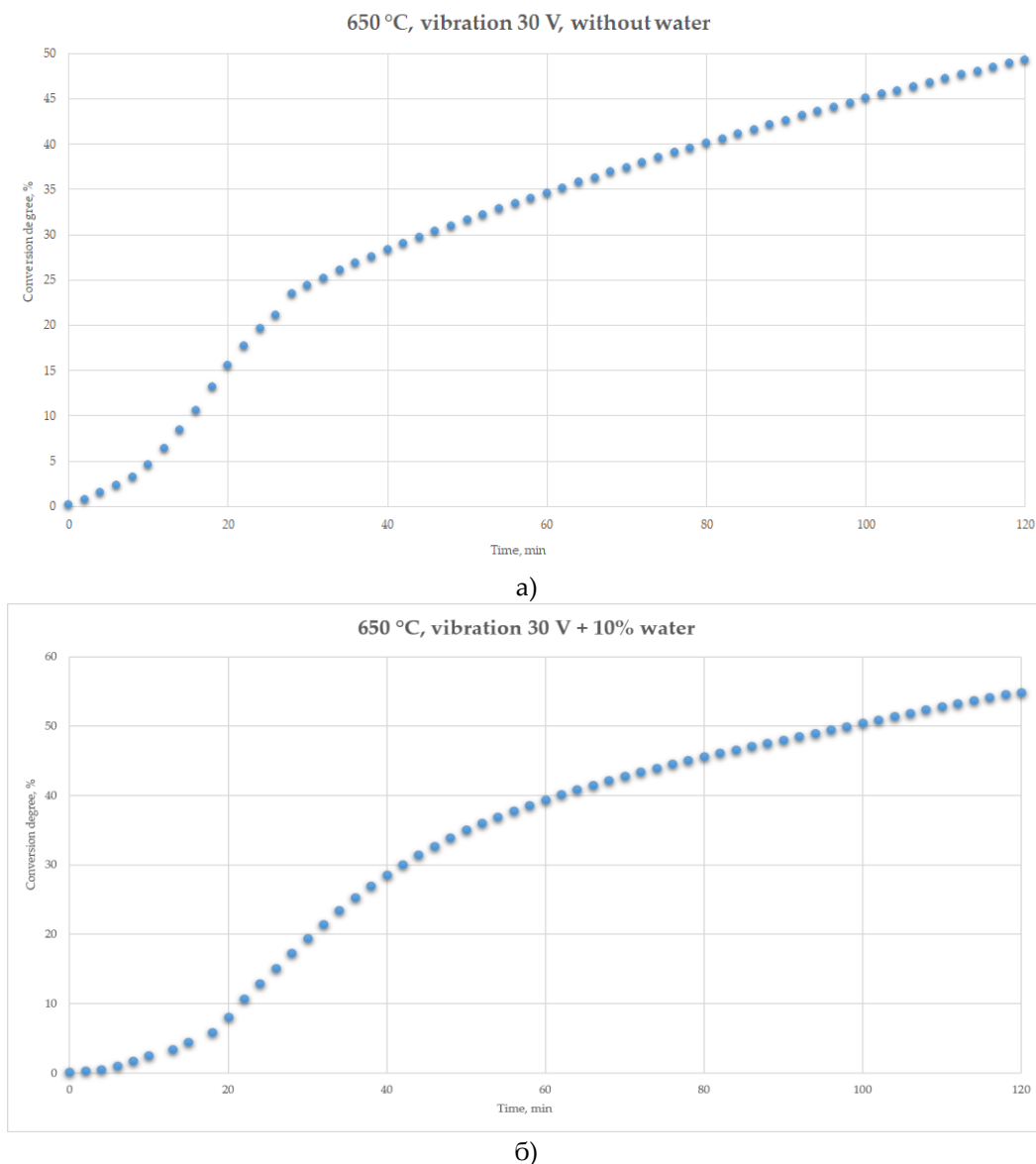


Figure 4. Comparison of the conversion degree of molybdenum middling under different soda roasting conditions:
a) 650 °C, vibration 30 V; b) 650 °C, vibration 30 V + 10% water

Comparison of the simple mixing experiments with experiment 4 shows that vibration significantly increases the conversion degree. Under simple mixing conditions, the maximum conversion degree was about 39.6–39.7%, whereas under vibration at 30 V it increased to 49.33%. The absolute increase relative to experiment 3 was 9.63 percentage points. Thus, vibration made it possible to increase the conversion degree by approximately 9.6 percentage points.

This effect can be explained by the fact that vibration promotes a more uniform distribution of sodium carbonate particles within the charge, reduces local compaction of the layer, and improves gas permeability. As a result, oxygen from the air more easily enters the reaction zone, and Na_2CO_3 particles more frequently come into contact with the surface of molybdenite and associated sulfide minerals.

An additional increase in the conversion degree was observed in experiment 5, where the charge was preliminarily moistened by adding 10% water and roasting was carried out under

vibration at 30 V. Compared with experiment 4, the conversion degree increased from 49.33 to 54.89%. The absolute increase was 5.56 percentage points, and the relative increase in conversion degree was 11.3%.

The positive effect of moistening can be explained by improved contact between the particles of molybdenum middling and sodium carbonate. When a small amount of water is added, sodium carbonate is more evenly distributed over the surface of mineral particles. After heating and removal of moisture, sodium carbonate remains more uniformly distributed in the charge, increasing the contact area between the reactants and promoting more complete soda sintering reactions.

Thus, the conducted experiments confirm that simple mechanical mixing is insufficient for soda roasting of molybdenum middling. To increase the conversion degree, preliminary charge preparation is required to ensure close contact between molybdenite, sodium carbonate, and atmospheric oxygen.

CONCLUSIONS

Soda roasting experiments were carried out using a charge consisting of molybdenum middling and Na_2CO_3 at a mass ratio of 1:1. The conversion degree was evaluated based on the volume of CO_2 released during roasting.

It was established that, under simple mixing conditions, the conversion degree was 16.9–39.7%, indicating that the process mainly proceeded on the surface of mineral particles. When vibration at 30 V was applied, the conversion degree increased to 49.33%. The highest value, 54.89%, was obtained under vibration at 30 V with the addition of 10% water.

The chemical analysis of the roasted products additionally confirmed the effect of charge preparation conditions on the process, when vibration was applied during roasting and the charge was preliminarily moistened, the sodium content in the roasted product decreased to 17.766%, which is consistent with the maximum CO_2 -based conversion degree. This indicates more active participation of sodium carbonate in soda roasting reactions when the contact between the solid reactants is improved.

Thus, vibration and charge moistening improve the contact between molybdenum middling and sodium carbonate, promote more complete soda roasting reactions, and increase the conversion degree of the studied molybdenum material.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

FUNDING: This research received no external funding.

INSTITUTIONAL REVIEW BOARD STATEMENT: Not applicable.

INFORMED CONSENT STATEMENT: Not applicable.

DATA AVAILABILITY STATEMENT: The data supporting the findings of this technical study are available from the corresponding author upon reasonable request.

ACKNOWLEDGEMENTS: The authors express their gratitude to the staff of Satbayev University and LLP KazHydroMed for technical and methodological support during the experimental work.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES: During the preparation of this manuscript, the authors used artificial intelligence tools for language editing and improvement of the text structure. The authors reviewed and edited all AI-assisted content and took full responsibility for the accuracy and integrity of the final manuscript.

REFERENCES

- T.A. Lasheen, M.E. El-Ahmady & others. (2015). Molybdenum Metallurgy Review: Hydrometallurgical Routes to Recovery of Molybdenum from Ores and Mineral Raw

- Materials. Mineral Processing and Extractive Metallurgy Review. May, 36(3):145-173. [10.1080/08827508.2013.868347](https://doi.org/10.1080/08827508.2013.868347)
- G.V. Galevskii, O.A. Polyakh, V.V. Rudneva, A.E. Anikin. (2020). Analysis of the current state of molybdenum mineral and raw material base, mining and processing of molybdenum-containing ores. Ferrous Metallurgy. Bulletin of Scientific , Technical and Economic Information, 76(7), 665–675. DOI: [10.32339/0135-5910-2020-7-665-675](https://doi.org/10.32339/0135-5910-2020-7-665-675).
- S. Castro, A. Lopez-Valdivieso, J.S. Laskowski. (2016). Review of the flotation of molybdenite. Part I: Surface properties and floatability. International Journal of Mineral Processing. Volume 148, 10 March 2016, Pages 48-58. <https://doi.org/10.1016/j.minpro.2016.01.003>
- Yuki Semoto, Gde Pandhe Wisnu Suyantara & others. (2021). Effect of Sodium Metabisulfite on Selective Flotation of Chalcopyrite and Molybdenite. Minerals 2021, 11(12), 1377; <https://doi.org/10.3390/min11121377>
- Karimova L., Kairalapov Y., Tussupbekova T., Oleinikova T., Makasheva G. (2024). Hydrometallurgical processing of molybdenum middling from Shatyrkul-Zhaysan cluster ore. Journal of Mining and Metallurgy Section B Metallurgy. 60(1):71-83. [10.2298/JMMB230725006K](https://doi.org/10.2298/JMMB230725006K)
- Fan Xiao-hui, Deng Qiong, Gan Min, Chen Xu-ling. (2019). Roasting oxidation behaviors of ReS₂ and MoS₂ in powdery rhenium-bearing, low-grade molybdenum concentrate. Transactions of Nonferrous Metals Society of China. 2019. Vol. 29. Issue 4. P. 840–848. [10.1016/S1003-6326\(19\)64994-0](https://doi.org/10.1016/S1003-6326(19)64994-0)
- Ping Wang, Yajing Pan, Xiao Sun, Yongqiang Zhang. (2019). Leaching molybdenum from a low-grade roasted molybdenite concentrate. SN Applied Sciences. April 2019. 1(4):311. [10.1007/s42452-019-0326-6](https://doi.org/10.1007/s42452-019-0326-6)
- Yubiao Li, Zhiming Li & others. (2019). A fundamental study of leaching kinetics and mechanisms of molybdenite assisted by mechanical activation. Minerals Engineering. 131 (2019): 376-384. [10.1016/j.mineng.2018.11.026](https://doi.org/10.1016/j.mineng.2018.11.026)
- P.V. Aleksandrov, A.S. Medvedev, V.A. Imideev, and D.O. Moskovskikh. (2017). Chemistry and Mechanism of Interaction Between Molybdenite Concentrate and Sodium Chloride When Heated in the Presence of Oxygen. The Minerals, Metals & Materials Society and ASM International. DOI: [10.1007/s11663-016-0889-1](https://doi.org/10.1007/s11663-016-0889-1)
- Tussupbekova T., Baimbetov B & others. (2025). Research on The Firing of a Low-Quality Molybdenum Product with Sodium Carbonate. University Proceedings. 1(98). [10.52209/1609-1825_2025_1_25](https://doi.org/10.52209/1609-1825_2025_1_25)
- Aracena, A., Rubilar, R., Jerez, O., & Carvajal, D. (2015). Dissolution of MoS₂ concentrate using NaClO from 283 to 373 K. Canadian Metallurgical Quarterly. <https://doi.org/10.1179/1879139515Y.0000000028>
- Hu SUN, Guang-hui LI & others. (2022). Features and mechanisms of self-sintering of molybdenite during oxidative roasting. Transactions of Nonferrous Metals Society of China. 32(1):307-318. DOI: [10.1016/S1003-6326\(22\)65796-0](https://doi.org/10.1016/S1003-6326(22)65796-0).
- Prabhat K. Tripathy, R. H. Rakhasia. (2013). Chemical processing of a low grade molybdenite concentrate to recover molybdenum. Mineral Processing and Extractive Metallurgy IMM Transactions section C. July. 115(1):8-14. DOI: [10.1179/174328506X91329](https://doi.org/10.1179/174328506X91329).
- Yongliang Wang, Xiumin Jia, Hui Liu. (2025). Effect of Mechanical Activation on Acid Leaching of Molybdenum from Low-Grade Refractory Ore. Mining Metallurgy & Exploration. May. 42. 1877-1888 DOI: [10.1007/s42461-025-01269-2](https://doi.org/10.1007/s42461-025-01269-2)
- Lyutsiya Karimova, Tansholpan Tussupbekova & others. (2026). Optimizing Oxidative Roasting of Low-Grade Molybdenum Intermediates on Phase-Controlled Process Parameters. HighTech and Innovation Journal. 7(1), 163-177. <https://doi.org/10.28991/HIJ-2026-07-01-011>

Information about authors



Bolotpay Baimbetov – Candidate of technical sciences, Professor, Mining and Metallurgical Institute named after O.A. Baikonurov, Department of Metallurgy and Mineral Processing, Almaty, Kazakhstan.

E-mail: b.baimbetov@satbayev.university

ORCID: <https://orcid.org/0000-0003-4442-5038>



Tansholpan Tussupbekova – Doctoral student of the Department of Metallurgy and Mineral Processing at Satbayev University, Almaty, Kazakhstan

E-mail: tansholpan_87.09@mail.ru

ORCID: <https://orcid.org/0000-0003-2940-8715>



Guldana Makasheva – Doctoral student of the Department of Metallurgy and Mineral Processing at Satbayev University, Almaty, Kazakhstan.

E-mail: mguldanka@mail.ru

ORCID: <https://orcid.org/0000-0003-2875-9433>
