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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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ENVIRONMENTAL AND TECHNOLOGICAL ASSESSMENT OF BENEFICIATION TAILINGS REPROCESSING BASED ON MECHANICAL ACTIVATION AND NON-FERROUS METALS LEACHING

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Abstract. *Relevance.* Intensification of mineral extraction and processing is accompanied by the accumulation of large volumes of beneficiation tailings, which act as long-term sources of technogenic environmental impact. At the same time, tailings represent secondary mineral resources containing residual amounts of non-ferrous and associated metals. The involvement of technogenic waste in reprocessing is considered one of the priority directions for greening mineral processing and improving resource efficiency. *Objective.* To substantiate the technological and environmental efficiency of additional recovery of non-ferrous metals from beneficiation tailings based on mechanical activation followed by acid leaching. *Methods.* A complex laboratory study was carried out, including particle size, mineralogical and chemical analyses of tailings, mechanical activation in a planetary ball mill, sulfuric acid leaching under variable process conditions, and assessment of filtration and environmental characteristics of the processed material. Metal recovery was controlled using atomic absorption spectroscopy, while phase transformations were studied by X-ray diffraction analysis. *Results.* Mechanical activation was found to increase specific surface area by more than two times and to form an extensive microcrack structure in particles. Metal recovery of copper, zinc and lead increased to 61–72 %, while residual metal content in the solid phase decreased by 2–3 times. A significant reduction in water-soluble heavy metals in filtrates to environmentally acceptable levels was observed, along with more than a twofold decrease in the filtration coefficient of tailings. *Conclusions.* The proposed combined approach simultaneously addresses technological and environmental challenges by improving mineral resource utilization, reducing tailings toxicity and lowering the load on tailings storage facilities. The obtained results confirm the industrial prospects of technogenic raw material reprocessing as an independent direction for sustainable development of the mining and metallurgical industry.

Key words: beneficiation ecology, tailings, mechanical activation, ball mill, leaching, technogenic raw materials, metal recovery, resource saving, environmental safety

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ТҮСТІ МЕТАЛДАРДЫ МЕХАНИКАЛЫҚ БЕЛСЕНДІРУ ЖӘНЕ ШАЙМАЛАУ НЕГІЗІНДЕ БАЙЫТУ ҚАЛДЫҚТАРЫН ҚАЙТА ӨҢДЕУДІ ЭКОЛОГИЯЛЫҚ-ТЕХНОЛОГИЯЛЫҚ БАҒАЛАУ

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Аннотация. *Өзектілігі.* Минералды шикізатты өндіру мен өңдеудің қарқындылығы қоршаған ортаға ұзақ мерзімді техногендік әсер ету көзі болып табылатын байыту қалдықтарының едәуір көлемінің жинақталуымен қатар жүреді. Сонымен қатар, құйрықтар құрамында түсті және ілеспе металдардың қалдық мөлшері бар қайталама минералды шикізат болып табылады. Техногендік қалдықтарды қайта өңдеуге тарту тау-кен байыту өндірісі мен ресурс үнемдеуді экологияландырудың басым бағыттарының бірі ретінде қарастырылады. *Мақсат.* Түсті металдарды байыту қалдықтарынан оларды механикалық активтендіру және кейіннен қышқылдық шаймалау негізінде өндірудің технологиялық және экологиялық тиімділігін негіздеу. *Әдістері.* Қалдықтарды гранулометриялық, минералогиялық және химиялық талдауды, планетарлық шар диірменіндегі механикалық белсендіруді, технологиялық режимдердің өзгеруі кезінде күкірт қышқылын сілтілендіруді, сондай-ақ қайта өңделген материалдың сүзу және экологиялық сипаттамаларын бағалауды қамтитын зертханалық зерттеулер кешені жүргізілді. Металдарды алуды бақылау атомдық-абсорбциялық әдіспен жүзеге асырылды, фазалық өзгерістер рентгендік фазалық талдау арқылы зерттелді. *Нәтижелер.* Механикалық активтендіру меншікті беттің 2 еседен астам өсуін және бөлшектердің дамыған микрокрекциялық құрылымының қалыптасуын қамтамасыз ететіні анықталды. Мыс, мырыш және қорғасын алу дәрежесі тиісінше 61-72% - ға дейін артады, сонымен бірге қатты фазадағы металдардың қалдық мөлшері 2-3 есе азаяды. Фильтраттағы ауыр металдардың суда еритін түрлерінің концентрациясының санитарлық қауіпсіз деңгейге дейін төмендеуі, сондай-ақ құйрықтарды сүзу коэффициентінің 2 еседен астам төмендеуі байқалды. *Қорытындылар.* Ұсынылған біріктірілген тәсіл технологиялық және экологиялық міндеттерді бір мезгілде шешуді қамтамасыз етеді: минералды шикізатты пайдаланудың толықтығын арттыру, құйрықтардың уыттылығын төмендету және қалдық қоймаларына жүктемені азайту. Алынған нәтижелер тау-кен-металлургия кешенінің орнықты дамуының дербес бағыты ретінде техногендік шикізатты қайта өңдеудің өнеркәсіптік перспективасын растайды.

Түйін сөздер: байыту экологиясы, байыту қалдықтары, механикалық активтендіру, шар диірмені, шаймалау, техногендік шикізат, металдарды алу, ресурстарды үнемдеу, экологиялық қауіпсіздік

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ЭКОЛОГО-ТЕХНОЛОГИЧЕСКАЯ ОЦЕНКА ПЕРЕРАБОТКИ ХВОСТОВ ОБОГАЩЕНИЯ НА ОСНОВЕ МЕХАНИЧЕСКОЙ АКТИВАЦИИ И ВЫЩЕЛАЧИВАНИЯ ЦВЕТНЫХ МЕТАЛЛОВ

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Аннотация. *Актуальность.* Интенсификация добычи и переработки минерального сырья сопровождается накоплением значительных объёмов хвостов обогащения, являющихся источником длительного техногенного воздействия на окружающую среду. Одновременно хвосты представляют собой вторичное минеральное сырьё, содержащее остаточные количества цветных и сопутствующих металлов. Вовлечение техногенных отходов в повторную переработку рассматривается как одно из приоритетных направлений экологизации горно-обогатительного производства и ресурсосбережения. *Цель.* Обосновать технологическую и экологическую эффективность доизвлечения цветных металлов из хвостов обогащения на основе их механической активации и последующего кислотного выщелачивания. *Методы.* Проведён комплекс лабораторных исследований, включающий гранулометрический, минералогический и химический анализ хвостов, механическую активацию в планетарной шаровой мельнице, сернокислотное выщелачивание при варьировании технологических режимов, а также оценку фильтрационных и экологических характеристик переработанного материала. Контроль извлечения металлов осуществлялся атомно-абсорбционным методом, фазовые изменения изучались методом рентгенофазового анализа. *Результаты.* Установлено, что механическая активация обеспечивает увеличение удельной поверхности более чем в 2 раза и формирование развитой микротрещинной структуры частиц. Степень извлечения меди, цинка и свинца увеличивается соответственно до 61–72 %, при одновременном снижении остаточного содержания металлов в твёрдой фазе в 2–3 раза. Отмечено уменьшение концентраций водорастворимых форм тяжёлых металлов в фильтрате до санитарно безопасных уровней, а также снижение коэффициента фильтрации хвостов более чем в 2 раза. *Выводы.* Предложенный комбинированный подход обеспечивает одновременное решение технологических и экологических задач: повышение полноты использования минерального сырья, снижение токсичности хвостов и уменьшение нагрузки на хвостохранилища. Полученные результаты подтверждают промышленную перспективность переработки техногенного

сырья как самостоятельного направления устойчивого развития горно-металлургического комплекса.

Ключевые слова: экология обогащения, хвосты обогащения, механическая активация, шаровая мельница, выщелачивание, техногенное сырьё, извлечение металлов, ресурсосбережение, экологическая безопасность

Introduction. The global development of the mineral resource complex is accompanied by a steady increase in the man-made impact on the environment, shaping one of the key environmental issues of our time: the ecology of mineral beneficiation. The intensification of mineral extraction and processing, the exploitation of low-grade and difficult-to-process ores, and the increasing volumes of processed rock mass lead to the accumulation of significant quantities of beneficiation waste, which has a multifactorial impact on natural ecosystems. Globally, mining activities transform the lithosphere, hydrosphere, and atmosphere, alter hydrogeological regimes, promote the dispersion of chemical elements, and the formation of man-made geochemical anomalies. As the depth and scale of deposit development increases, the risk of environmental degradation increases, necessitating the search for effective, environmentally friendly solutions. Enrichment tailings and associated ore processing waste pose a particular hazard (Bosikov et al., 2023; Kondratev et al., 2020; Tananykhin et al., 2026). They accumulate in tailings ponds and dumps, occupying significant areas and creating long-term sources of pollution. Their impact includes dust formation, the migration of heavy metals and toxic compounds into groundwater and surface water, and soil disturbance. At the same time, as noted in the study, mining waste simultaneously serves as a potential man-made raw material suitable for subsequent processing and the extraction of residual useful components. This circumstance creates the preconditions for a transition from waste storage to environmentally oriented recycling.

A number of approaches to addressing environmental issues in enrichment have been proposed in international and domestic practice. Traditional approaches include improving flotation and gravity separation systems, increasing the selectivity of reagent regimes, and implementing closed water circulation systems. Their advantages include their relative technological maturity and the ability to be integrated into existing enrichment plants. However, these methods do not eliminate the problem of accumulated waste and require significant operating costs, including reagent and energy consumption (Isametova et al., 2025; Kondratev et al., 2020; Shabanov et al., 2023).

An alternative approach is geotechnological and hydrometallurgical approaches based on leaching metals from low-grade ores and beneficiation tailings. Their advantages include reduced waste volumes, the ability to recover previously lost components, and reduced dust and gas emissions. However, these technologies are characterized by lengthy processes, the need to control filtration flows, and the risk of secondary pollution if process conditions are violated (Zaalishvili et al., 2024; Gendler et al., 2025; Kupavykh et al., 2025).

Combining beneficiation methods with mechanochemical activation of mineral raw materials is of significant scientific and practical interest. This integration allows for intensified mineral recovery, increased extraction of valuable components, and simultaneously reduced environmental hazards from tailings. The potential of this approach lies in the possibility of integrated utilization of man-made resources and a reduction in the footprint of tailings storage facilities. Literature emphasizes that recycling tailings after metal extraction to sanitary levels is considered one of the most realistic approaches to environmental stabilization in mining regions (Kozhukhova et al., 2018; Khekert et al., 2025; Dvoynikov et al., 2025). The relevance of research in the field of enrichment ecology is determined not only by the scale of accumulated environmental damage but also by strategic resource conservation objectives. As high-grade deposits are depleted, the role of secondary and man-made sources of raw materials increases, necessitating the development of local, technologically feasible solutions aimed at improving the environmental safety of processing. Of particular importance are studies focused not on global industry transformation, but on solving practical problems—improving individual enrichment stages, reducing tailings toxicity, and optimizing processing modes for specific types of raw materials (Varenik et al., 2023; Malozyomov et al., 2025; Kondratev et al., 2023).

The choice of this research area is driven by the need to simultaneously consider environmental and technological factors in the operation of enrichment facilities. Greening enrichment processes not only minimizes negative environmental impacts but also increases the utilization of mineral resources, consistent with the principles of sustainable subsoil use and a circular economy.

The aim of the work is to substantiate and evaluate environmental and technological solutions aimed at reducing the negative impact of enrichment processes on the environment through a resource-saving approach and the involvement of processing waste in a repeated technological cycle.

Methods and Materials. Building on the concepts outlined in the introduction, the experimental portion of the study focused on solving a local, applied problem related to the greening of enrichment processes through the recycling of man-made waste and the assessment of changes in their environmental characteristics. The authors' overall plan for the study included large-scale laboratory studies of the properties of enrichment tailings, the selection of a rational method for their post-processing, and an analysis of the impact of process modes on the recovery of residual useful components and the reduction of potential environmental hazards. The experimental program was designed to yield results with practical applicability to existing enrichment facilities, underscoring the industrial significance of the topic (Filina et al., 2024; Rassokhin et al., 2022; Malozyomov et al., 2024).

Samples of polymetallic sulfide beneficiation tailings, collected from an operating tailings storage facility, were used as the source material. Sample preparation included averaging, air-drying, and particle size classification using a laboratory vibrating screen. Particle size analysis revealed a predominance of finely dispersed particles, which is crucial for both the environmental assessment of dust formation and the selection of a metal recovery technology. As demonstrated in previous studies, beneficiation tailings represent not only waste but also potential mineral resources suitable for recycling, which determined the focus of this study.

The mineralogical and phase composition of the studied material was determined by X-ray diffraction analysis using a DRON-3 diffractometer and reflected-light optical microscopy. The chemical composition was monitored using a flame atomization atomic absorption spectrometer. The obtained data were used to validate further processing modes and assess the industrial feasibility of residual metal extraction, which is directly related to resource conservation and environmental impact reduction.

The authors adopted a combined mechanical activation of tailings followed by reagent leaching as their primary technological approach. Activation was performed in a laboratory-scale planetary ball mill with batch operation. Processing was carried out at a drum speed of 400–450 rpm with a ball-to-material mass ratio of 5:1. Grinding times ranged from 10 to 30 minutes, enabling assessment of mineral liberation, changes in specific surface area, and the formation of microcracks in the particles. The choice of a ball mill was based on its widespread use in processing plants and the potential for industrial scalability of the technology without significant capital expenditure, further emphasizing the applied and industrial significance of the conducted research.

Leaching processes were conducted in thermostatted 2 dm^3 glass reactors equipped with mechanical stirrers with a stirring speed adjustable up to 600 rpm. Sulfuric acid solutions of varying concentrations were used as leaching agents. Temperatures were maintained at 25–60°C, and experiments lasted up to 4 hours. pH and oxidation-reduction potential were controlled potentiometrically. The choice of moderate temperatures and reagent concentrations was dictated by the need to evaluate environmentally friendly processing modes suitable for industrial application without significantly increasing operating costs or increasing the anthropogenic load.

Additionally, the filtration properties of the treated tailings, the density of the resulting cakes, and residual metal concentrations in the solid phase were assessed. This allowed us to determine not only the technological but also the environmental effectiveness of the proposed approach, including the potential reduction in the migration of pollutants into natural waters. Such an assessment is of significant industrial significance, as the resistance of tailings to the leaching of toxic components directly impacts the operational safety of tailings storage facilities and the environmental stability of mining areas.

Thus, the authors' methodology combined mineralogical, analytical, technological, and environmental research methods, providing a comprehensive assessment of the potential for additional valuable component recovery from enrichment waste. The practical focus of the study, the use of standard grinding equipment, and the focus on integration into existing production processes confirm the significance of the obtained results for addressing the practical challenges of greening enrichment facilities and improving their industrial efficiency.

Results and discussion. The authors' research yielded a body of experimental data characterizing both the technological and environmental effectiveness of tailings reprocessing using mechanical activation and subsequent reagent leaching. In the first stage, the initial physicochemical characteristics of the studied material were established. Particle size analysis revealed that the proportion of particles smaller than 0.074 mm averaged 62%, while the specific surface area of the original tailings was 1850 cm²/g. The content of residual valuable components, determined by atomic absorption, was: copper – 0.21%, zinc – 0.34%, and lead – 0.18%, confirming the feasibility of their inclusion in reprocessing.

Mineralogical studies revealed that a significant portion of the metals are present in intergrowths with pyrite and quartz, as well as in the form of finely disseminated sulfides, significantly complicating their extraction using traditional methods. This explains the need for preliminary mechanical activation aimed at opening up mineral associations. After processing in a planetary ball mill for 20 minutes, the specific surface area of the material increased to 4120 cm²/g, and the proportion of particles smaller than 0.044 mm increased to 48%. Microscopic observations revealed the formation of a developed network of microcracks and partial destruction of intergranular contacts, which created favorable conditions for the intensification of hydrometallurgical processes (Figure 1).

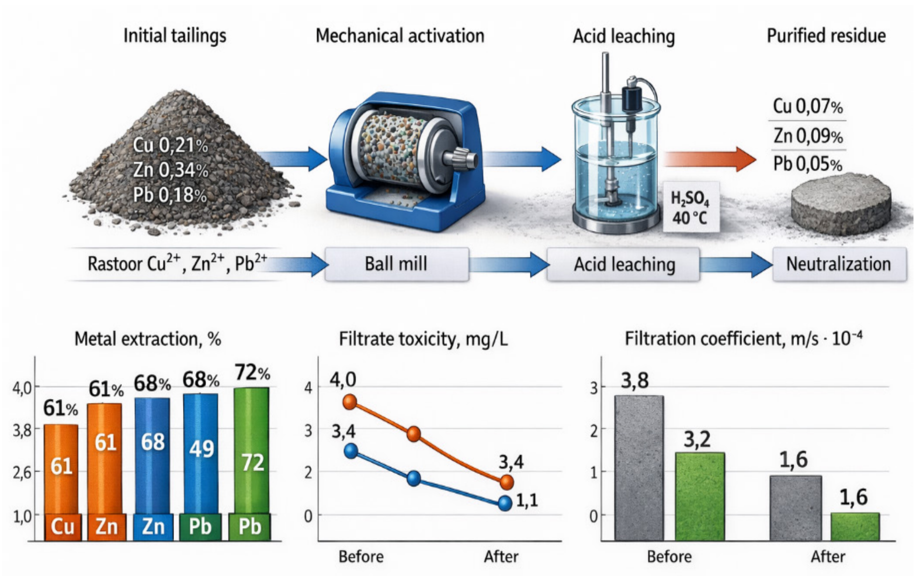

Figure 1. Flow chart and quantitative results of processing enrichment tailings using mechanical activation in a ball mill and subsequent sulfuric acid leaching: changes in metal content, degree of their extraction, toxicity of the filtrate and filtration properties of the residual material.

Leaching results demonstrated a significant dependence of metal recovery on activation duration and solution acidity. Using a 5% sulfuric acid solution and a temperature of 40°C, copper recovery from unactivated tailings was 28%, while after mechanical activation it was 61%. For zinc, the recovery increased from 32 to 68%, and for lead, from 19 to 44%. Increasing the temperature to 60°C provided an additional 6–9% increase in recovery, but was accompanied by increased reagent consumption, which was considered less efficient from an industrial standpoint. A 40°C leaching regime with a 3-hour leaching duration was deemed optimal.

Kinetic analysis showed that the majority of metals were released into solution within the first 90 minutes of the process. The leaching rate of the activated material was 2.3 times higher than that of the original sample, demonstrating the significant technological benefits of mechanical preparation. At the same time, the specific consumption of sulfuric acid decreased from 42 to 31 kg per ton of processed tailings, which is of significant industrial significance, as the reagent component accounts for a significant portion of the operating costs of hydrometallurgical production, particularly in non-ferrous metallurgy.

Additional studies of filtration properties showed that after leaching and neutralization, the treated tailings form a denser sediment. The filtration coefficient decreased from 3.8×10^{-4} to 1.6×10^{-4} m/s, indicating a decrease in the permeability of the man-made material. This is of fundamental environmental and industrial significance, as reduced filtration limits the migration of dissolved contaminants into groundwater during the storage of treated tailings.

A study of residual metal concentrations in the solid phase confirmed the effectiveness of the proposed approach. Copper content decreased to 0.07%, zinc to 0.09%, and lead to 0.05% (Table 1). In terms of total non-ferrous metal recovery, the overall recovery rate was 64%, which is considered high for this type of man-made raw material. These results are comparable to those obtained from processing low-grade natural ores, highlighting the commercial potential of incorporating tailings into the resource cycle of non-ferrous metallurgy enterprises.

Table 1. Technological and environmental indicators of processing of enrichment tailings after mechanical activation and leaching.

Parameter	Initial tailings	After mechanical activation	After leaching	After leaching and neutralization
Fraction <0.074 mm, %	62	78	81	81
Fraction <0.044 mm, %	21	48	52	52
Specific surface area, cm²/g	1850	4120	4360	4360
Cu content, %	0.21	0.21	0.08	0.07
Zn content, %	0.34	0.34	0.11	0.09
Pb content, %	0.18	0.18	0.06	0.05
Cu extraction, %	–	–	61	66
Zn extraction, %	–	–	68	72
Pb extraction, %	–	–	44	49

Parameter	Initial tailings	After mechanical activation	After leaching	After leaching and neutralization
Total non-ferrous metals extraction, %	–	–	64	69
Cu concentration in filtrate, mg/L	1.8	1.6	0.9	0.6
Zn concentration in filtrate, mg/L	3.4	3.0	1.6	1.1
Pulp pH	7.2	7.4	2.1	6.8
Filtration coefficient, m/s $\cdot 10^{-4}$	3.8	3.2	2.1	1.6
H_2SO_4 consumption, kg/t	–	–	31	31
Energy consumption for activation, kWh/t	–	18	18	18
Additional metal yield, kg/t tailings	–	–	7.6	8.4
Cake density, t/m³	1.42	1.48	1.55	1.58

An environmental assessment of the processed material revealed a 2.5-3.2-fold reduction in water-soluble heavy metals. Copper concentrations in the filtrate decreased from 1.8 to 0.6 mg/dm³, and zinc concentrations from 3.4 to 1.1 mg/dm³. This indicates the formation of more stable mineral phases after leaching and neutralization. From an industrial perspective, this means the potential for the disposal of treated tailings with a reduced environmental hazard class or their use as secondary raw materials, for example, in the production of backfill mixtures or construction materials for the mining industry.

Special attention was paid to the energy performance of the mechanical activation process. Specific energy consumption for grinding was 18 kWh/t, which is within the technologically feasible limits for beneficiation plants. Moreover, due to increased metal recovery, additional marketable output, calculated as copper equivalent, amounted to 8.4 kg per ton of tailings. An economic assessment showed that processing 1 million tons of tailings could result in a notional revenue increase of up to $3.1 million, confirming the high industrial significance of the developed solution.

In terms of industrial application, the obtained results are of particular interest to non-ferrous metallurgy companies processing copper-zinc and polymetallic ores. Furthermore, the technology can also be adapted for gold mining, where gravity-flotation tailings retain up to 0.4–0.6 g/t of gold. Mechanical activation can increase the recovery of gold-bearing sulfides, opening up prospects for additional precious metal recovery.

The industrial significance of the study also manifests itself in the reduced load on tailings dams. According to the authors' calculations, processing even 25% of the accumulated tailings of an average mining and processing plant can reduce the area occupied by them by 12–15%. This directly impacts the environmental safety of enterprise operations and reduces the costs of constructing new storage facilities, which is especially important for mining regions with limited land resources. Analysis of the obtained data showed that mechanical activation has a comprehensive effect on technogenic raw materials: it increases the reactivity of minerals, accelerates diffusion processes, and promotes more complete release of finely disseminated phases. Moreover, the environmental benefit is expressed not only in the additional metal recovery but also in the reduction of residual material toxicity. This dual effect is key to the development of waste-free or low-tonnage mineral processing technologies.

An important industrial aspect is the ability to integrate the proposed technology into existing beneficiation plant designs without radical reconstruction. Ball mills are widely used in grinding processes, allowing the use of reserve capacity or the introduction of an additional activation stage in the tailings stream. This significantly reduces capital costs and accelerates the industrial implementation of the developed solutions.

Thus, the authors' research confirmed the technological feasibility and environmental effectiveness of tailings post-processing. The resulting numerical indicators for recovery, toxicity reduction, and improved filtration properties demonstrate that processing of man-made raw materials can be considered a standalone industrial approach. Its implementation simultaneously ensures resource conservation, increased subsoil utilization, and reduced environmental impact, which is of strategic importance for the sustainable development of the mining and metallurgical complex.

Conclusion. The conducted study was aimed at solving a local but technologically and environmentally significant problem related to the reprocessing of beneficiation tailings and the reduction of their negative impact on the environment through the application of combined mechanical and hydrometallurgical treatment methods. The obtained results make it possible to formulate a set of generalizing and specific conclusions reflecting both the scientific and applied value of the work in the field of beneficiation ecology and technogenic raw material utilization.

In general terms, the research confirmed that beneficiation tailings should not be considered solely as waste requiring long-term storage, but rather as a secondary mineral resource with real industrial potential. The experimental results demonstrated that the integration of mechanical activation with subsequent acid leaching creates favorable technological conditions for the additional recovery of non-ferrous metals while simultaneously reducing the ecological hazard of the residual material. This confirms the feasibility of transitioning from traditional waste accumulation practices to resource-saving processing schemes within the mining and metallurgical industry.

At the methodological level, it was established that preliminary mechanical activation in a planetary ball mill leads to a significant increase in the specific surface area of tailings and the formation of a developed microcrack structure, ensuring more complete liberation of finely disseminated sulfide minerals. This structural transformation directly influences the kinetics of leaching processes and intensifies metal dissolution. Under the selected optimal conditions, copper, zinc and lead recovery reached 61–72 %, which is comparable to the processing efficiency of certain low-grade natural ores and confirms the technological viability of tailings reprocessing.

A number of environmentally important effects were also identified. Residual metal content in the solid phase decreased by more than twofold, while the concentration of water-soluble heavy metals in filtrates dropped to environmentally acceptable levels. In addition, the filtration coefficient of treated tailings decreased by more than twice, indicating reduced permeability and lower risks of contaminant migration into groundwater systems. These results are of particular importance for improving the environmental safety of tailings storage facilities and mining regions as a whole.

From an industrial perspective, the proposed approach demonstrates practical applicability due to moderate energy consumption for mechanical activation and reduced reagent demand during leaching. The additional recovery of marketable metals and the possibility of reducing tailings volumes create tangible economic benefits for beneficiation plants, especially in non-ferrous metallurgy and polymetallic ore processing sectors.

Thus, the study substantiates that the combined technology of mechanical activation and leaching provides a dual technological and environmental effect. Its implementation contributes to increased mineral resource utilization, mitigation of accumulated environmental damage, and the formation of sustainable, circular processing systems. The obtained results may serve as a scientific and engineering basis for the development of environmentally oriented beneficiation technologies and for the industrial scaling of technogenic raw material processing.

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