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Renewable-Resource Technologies in Mining and Metallurgical Enterprises Providing Environmental Safety

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Abstract: The article addresses the issue of mining and industrial waste stored in tailings and heaps in mining areas, and it explores the existing, as well as new, ways of reducing its harmful impact on the environment. On the basis of the Russian experience in mining industry in Ural, it presents a process which makes it possible to eliminate the amassed hazardous waste, retrieve the valuable material (metals) stored in it, and use the remaining waste as backfill in order to both: store it underground (and not on the surface) and prevent the disasters caused by the collapse of the abandoned shafts, thus prolonging the functioning of the mining areas. The process includes preliminary activation treatment of materials found in industrial waste in a disintegrator to protect the environment from toxic pollution. The promising results of the experiment have been discussed, taking into account the complexities of economic evaluation of the idea.

Keywords: geotechnology; georesources; deep mining; deep processing; deep recovery; comprehensive utilization; resource-producing technologies; man-made waste; waste disposal; environmental safety

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1. Introduction

The development of modern society is impossible without the growth of industrial production, the creation of new equipment, and the introduction of high-tech technologies. All this causes an increase in the consumption of mineral resources (including raw materials). An increase in the demand for extracted raw materials leads to intensification of the extraction of natural resources, which entails their depletion with a simultaneous increase in the human-made waste stored on the surface [1]. Due to the long absence of technical feasibility, economic expediency of the complete extraction of useful components, and environmentally friendly proposals for utilization or processing, it has been stored on the surface for centuries and accumulated in various storages, tailings, and dumps. Waste in storages is usually in a conditionally stable state. However, tailings have to be constantly monitored due to potential risks related to their internal stability, potential seismic events, and even terrorist attacks [2,3]. Long-term storage conditions (pressure, temperature, migration of water, and even surface insolation and drying cycles) can cause their physical and chemical activation. Various geochemical processes take place in the produced mass; new technogenic elements are formed, which are carried outside the storages, having a negative impact on the ecology, getting into the human environment [4,5], and causing direct [6,7] and indirect [8,9] risks to the safety of mining activities. These issues are especially important for countries trying to decrease the injury rates, thanks to the successful implementation of innovative labor safety technologies [10,11].

It must be underlined that the problem of mining waste in mining regions is global, and it is a subject of wide discussion on dual challenges of meeting demand for minerals and sustainable development [12]. Environmental and social policy must be introduced in both still-active mining regions [13] and “post-mining” regions, where mining traditions are maintained in spite of discontinued mining production [14,15].

Due to the fact that the lifetime of post-production accumulations is unlimited and the decomposition and transformation of man-made waste over time is infinite, the multiplicative damage resulting from its storage on the surface can subsequently multiply and exceed the value of the extracted useful components [16–18]. Until now, the main method of utilization of man-made waste has been its application to hardening mixtures. This technology was a subject of the Authors’ previous studies [19–21]. For the current study, Russian mineral deposits located in the Southern Urals can be an exemplary case, because the process of fast industrialization in the 20th century (in the USSR), combined with relatively low efficiency of technologies (compared to today’s technologies), produced a lot of industrial waste, still rich in minerals. Nowadays, environmental demands cause a need for “cleaner production” and, simultaneously, highlight the safety issues, social, and even political issues.

The accumulation of man-made waste goes hand in hand with the depletion of natural reserves, the limited and irreplaceable mineral resource base. In view of the decrease in the average useful component content of natural deposits and their comparability with anthropogenic formations in terms of volumes (Table 1) and the amount of useful components (Tables 2 and 3) in human-made accumulations, it is advisable to classify man-made formations as deposits [22].

Table 1. The approximate amount of man-made formations of the Southern Urals.

Tailing Dumps of the Processing Plant	Element Content					
	Copper	Zinc	Sulfur	Iron	Gold	Silver
	Thousand Tons				Tons	
Sibay	34.5	90.0	3650.0	5900.0	13.9	344.0
Uchalinsk	90.0	257.0	6300.0	8050.0	16.5	232.0
Buribay	25.0	11.6	1410.0	1280.0	6.60	56.8
Guy	120.0	92.0	10,600.0	5550.0	32.0	160.0
Total:	269.5	450.6	21,960.0	20,780.0	69.0	792.8

Table 2. Useful component content of man-made formations of the Southern Urals.

Tailing Dumps of the Processing Plant	Element Content					
	Copper	Zinc	Sulfur	Iron	Gold	Silver
	%				g/t	
Sibay	0.21	0.50	22.7	32.7	0.85	18.5
Uchalinsk	0.22	0.63	23.1	29.5	0.60	8.5
Buribay	0.45	0.21	25.6	23.1	1.20	10.3
Guy	0.30	0.23	26.6	13.9	0.70	4.0

Table 3. Chemical composition (in %) of metallurgical slags.

Metallurgical Plant	SiO_2	Al_2O_3	CaO	MgO	S	SO_3	MnO	Fe_2O_3	FeO	Other
Chusovoy	31.1	10.2	50.6	4.3	1.4	0.2	-	-	-	2.2
Orsko Khalilovsky	34.5	8.5	47.2	3.1	-	2.9	2.3	1.4	1.9	0.5
Chelyabinsk	39.6	9.3	41.0	6.9	0.1	0.5	0.4	-	-	2.2
Mednogorsk	37.0	12.1	35.4	8.9	1.6	1.8	0.6	-	-	2.6
Cherepovets	30.9	11.1	41.9	11.4	0.7	1.1	-	0.5	0.6	1.8
West Siberian	33.7	17.1	27.5	15.7	2.3	-	1.2	0.9	-	1.6
Nizhny Tagil	35.3	16.8	38.0	5.8	1.1	-	0.7	0.9	-	1.4
Novolipetsk	33.6	17.4	40.0	5.9	1.7	-	0.9	-	0.4	0.1
Nizhny Tagil *	30.9	19.0	29.9	9.7	0.5	-	0.4	0.7	-	9.9

* vanadium redistribution.

Man-made waste from mining, processing, and metallurgical industries contains useful components and constitutes man-made georesources [23–25]. With an increase in consumer demand for extracted raw materials, it is necessary to increase the requirements for the completeness and complexity of the use of the mineral resource base, and to develop a new scientific and methodological approach to the broad recovery of mineral resources and their preservation [26–28]. It is of special importance for regions (countries) with limited resources [29–31].

It should be noted that this problem is not limited to the area of a single enterprise or any state, but it has a global, planetary scale. In Russia, human-made accumulations are concentrated in traditional places of mining and processing of minerals (Figure 1). Consequently, the development of society, the growth of its well-being and the formation of a healthy generation is not possible without preserving the natural diversity of the Earth, saving the natural wealth of the depth, and strict control of the ecological state. Under these conditions, the most important vector of increasing the efficiency of mining and processing industries is to ensure environmental safety [32,33].

Figure 1. Metallurgical plants and tailing dumps of processing plants. 1: Cherepovets, 2: Novolipetsk, 3: Chusovoy, 4: Nizhny Tagil, 5: Chelyabinsk, 6: Uchalinsk, 7: Sibay, 8: Buribay, 9: Mednogorsk, 10: Guy, 11: Orsko Khalilovsky, 12: West Siberian.

2. From a Comprehensive Development Idea to Resource-Generating Technologies

Ensuring environmental safety has recently become a paradigm for the development of society. It is necessary to develop a system of measures that minimize the adverse effects of anthropogenic factors of environmental threats on the environment and humans themselves. At the same time, environmental safety, while maintaining traditional comprehensive measures that exclude the impact of mining and processing industries on the environment, should contribute to the introduction of resource-producing technologies that replenish and increase the mineral resource base along with the complexity of its development. The idea of introducing resource-producing technologies is not new. Academician A.E. Fersman put forward a comprehensive idea for the development of minerals in 1923. Later, due to the high importance of the mining industry in the USSR, this idea was developed in the vector of wide recovery of deposits [34]. In continuation of these works, a new classification of resources was proposed. In addition to natural resources, it also includes anthropogenic ones, formed in the course of mining and raw materials processing [35]. Further, during the studies [36], the presentation of the comprehensive utilization of mineral resources was deepened and new terms were introduced: resource-producing technologies, resource-producing functions of mining, and actually identified deposit resources. The subsequent development of ideas for the comprehensive utilization of mineral resources and resource-producing technologies of developing bowels under underground mining is described in [37] and it is associated with the fact that the mineral resources is perceived as a multi-purpose, constantly changing man-made supply. Further, the exploitation of mineral resources implies any form of their transformation during the extraction of minerals and the implementation of various activities related to the extraction as presented in the works [38,39]. Simultaneously with the comprehensive exploitation of georesources, the work focuses on maintaining the ecological balance of the environment. As follows from the analysis of previous studies, solving the problems of providing society with the necessary volume of mineral resources is based on balancing out the production and consumption of georesources, with the simultaneous preservation and enhancement of the natural diversity of the rock mass and the ecological potential of the environment.

In the modern scientific understanding, the comprehensive exploitation of mineral resources implies the integral presence of two inextricably linked conditions:

- organization of production that excludes (minimizes) waste generation and determines the use of intermediate products (man-made georesources) in a closed cycle of the utilization of natural and man-made georesources;
- exploitation of georesources through resource-producing technologies with a rational combination of traditional physical and technical as well as non-traditional physical and chemical technologies.

The main direction of comprehensive exploitation of georesources is the choice of technologies that exclude the transformational degeneration of territories, the degradation of the atmosphere and hydrosphere in the mining and metallurgical region. Consequently, a set of measures is needed to reduce the volume of generation and storage of solid and liquid industrial waste. The new expanded knowledge system provides an opportunity to create technologies for controlled industrial transformation of mineral resources in their complex exploitation and conservation. However, this system does not fully reflect the environmental safety of mining and metallurgical production. It is necessary to define a new concept of geotechnology—this is the establishment of patterns for the improvement of mining technical systems with the consequences of a controlled industrial transformation of mineral resources during their comprehensive utilization and taking into account environmental safety for nature and society. At the same time, it is necessary to take into account the impact of metallurgical production on the environment and integrate environmentally friendly metallurgical production into a combined system with mining and processing production.

Modern geotechnology is a combination of numerous sciences about the patterns of changes in mineral resources resulting from human impact and the methods of their exploitation and conservation [40]. The main goal of the sciences is to extend knowledge that makes it possible to manage the behavior of the rock mass, taking into account the comprehensive utilization and conservation with the use of environmentally friendly technologies.

The scientific representation of the world is not constant, nor is it absolute or static. A scientific picture (model) of the world is created by combining disparate scientific concepts and principles into a single whole, generalizing previously obtained knowledge and giving a general vector of ideas about the laws and properties of reality.

3. Comprehensive Utilization of Georesources through the Prism of Environmental Safety

In the light of the changed concept of geotechnology, the philosophy of comprehensive recovery of mineral resources is subject to a new perception, which assumes:

- preservation of the traditional concept of the depletion (non-renewability) of natural resources. It is required to introduce technologies for controlled transformation of mineral resources, taking into account the fact that they constitute places of accumulation of interconnected georesources of various types and purposes;
- recognition of the mineral resource base of an enterprise as replenished (inexhaustible). There is an increase in the mineral resource base due to the involvement of subeconomic and man-made georesources in the development and the use of previously unknown useful properties, along with the emergence, expansion, and implementation of the latest technologies;
- changing the approach to the development of geotechnology. It is supposed to abandon mono-technologies in the extraction and processing of georesources and the introduction of resource-producing technologies that promote comprehensive recovery;
- consideration of man-made formations in the study of technological processes with a clear understanding of interaction with natural geosystems and the overall impact of their comprehensive recovery on the ecosystem;
- maintaining the traditional use of rock mass for the extraction of minerals and utilization of man-made waste with the recreation and enhancement of their useful qualities, with a simultaneous transition to the preservation of the mineral resources diversity and reducing the likelihood of an environmental threat;

It is necessary to take into account that the development of science occurs in the process of the evolutionary advancement of society with a constant broadening of knowledge, the emergence of new ideas and concepts. Earlier concepts become special cases of new theories. The wide scope of research in modern geotechnology and metallurgy predetermines the inevitability of interdisciplinary research in a number of fundamental and applied scientific areas, where a special place should be given to environmental safety. Effective environmental safety is possible only if natural and man-made georesources are involved in the simultaneous industrial development. Effective industrial development of these mineral resources must be combined with traditional physical and applied technologies based on open and underground methods as well as non-traditional physical and chemical geotechnologies. Non-traditional physical and chemical technologies imply leaching (heap or underground) of useful components from substandard ores or from man-made waste of mining and metallurgical industries [41].

The introduction of resource-renewable technologies that can qualitatively improve economic efficiency and environmental safety involves:

- using the technological space of open pits and stopes for the implementation of the processes of physical and chemical geotechnology;
- using previously opened and underground stopes to reveal substandard reserves;
- using mineralized mining wastewater as an activator for the dissolution of valuable components [42];
- using man-made waste after deep processing for the production not associated with the mining sector [42];

- using man-made waste after deep processing in geotechnology with backfilling [43].

All these measures make it possible to reduce the conditional threshold of natural and man-made georesources involved in the development, to obtain an additional marketable product, and to dispose of man-made waste after deep processing [42–44]. In total, this will increase the financial efficiency of a mining [45–47] and processing enterprise [23,24,33,48–50] and ensure high environmental safety. Even after introducing all these measures, we will still be far from circular economy and closed-loop that still seem to be a wishful thinking in the case of mineral processing. However, circular economy and closed-loop form a right direction and should be promoted worldwide.

To improve environmental safety, as well as to increase the completeness and complexity of the development of geo-resources, it is necessary at the design stage of the mining and processing plant to form a single complex for the extraction, metallurgical processing, deep processing of ores and technogenic georesources. The disposal of man-made waste from mining and metallurgical industries after deep processing is an integral part of a single mining and metallurgical complex (Figure 2).

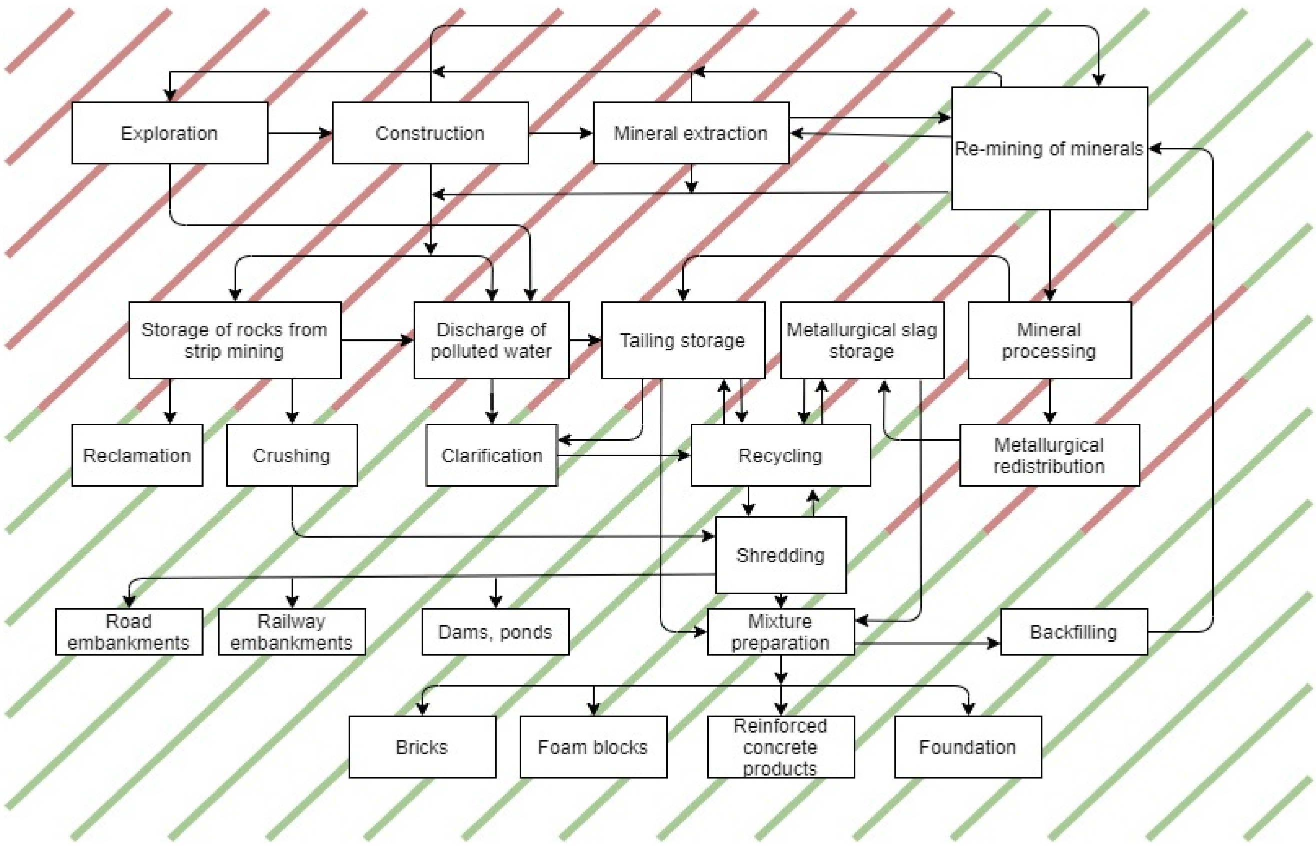

Figure 2. Organization scheme of the full cycle of mining and processing production. Zone of environmental safety Zone of environmental impact of an enterprise.

The organization of a full cycle of mining and processing production, simultaneously with the exploitation of the economic reserves of a deposit using traditional physical and technical technologies, makes it possible to include:

- subeconomic natural resources of depleted ores;
- ore of complex material composition, located both in deep rock masses and in dumps
- man-made georesources of processing and metallurgical industries using physical and chemical technologies.

Solid man-made waste can be in a static-equilibrium state for quite a long time and not have an aggressive effect on the environment. Liquid and suspended matter (pulp) are more mobile, and they are a source of an environmental threat from the moment they enter the environment. Consequently, it is necessary to pay special attention to industrial wastewater from mining and processing enterprises, from the point of view of their involvement in a cyclical environmentally safe renewable-resource technology. Mineralized wastewater is acidic or alkaline. Therefore, it is supposed to be used as a solvent, having previously been activated with modifying additives, when extracting valuable components of depleted ores or man-made waste by physical and chemical technologies. Subsequent processing of mineralized wastewater and productive solutions will allow, simultaneously with obtaining marketable products, for purifying them before discharge. The simultaneous exploitation of natural and man-made georesources by combined geotechnologies is mandatory when introducing renewable-resource technologies, and not a forced measure. The introduction of innovative renewable-resource technologies will increase the life of a mining and metallurgical enterprise due to the disposal of man-made waste by physical and chemical technologies.

4. Selected Results of Applying the Activation Process to Mineral Extraction

Figure 3 shows the location of the investigated anthropogenic materials. Studies on the additional extraction of a useful component from industrial waste (processing waste of the Gaysky mining plant—Tables 4–6, and metallurgical slags of the West Siberian metallurgical plant—Tables 7 and 8) were carried out with and without activation treatment. The investigated anthropogenic materials were irrigated with a solution of hydrochloric acid of varying concentration.

(**a**)

(**b**)

Figure 3. Location of the investigated anthropogenic materials: (**a**) metallurgical slags of the West Siberian metallurgical plant; (**b**) processing waste of the Gaysky mining and processing plant.

Table 4. Zinc extraction (%) without mechanical activation (A) and with mechanical activation (B).

Tests	Concentration of Hydrochloric Acid in the Solution, %													
	4.0		6.0		8.0		10.0		12.0		16.0		20.0	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	9.8	16.9	17.6	29.1	25.4	35.3	29.6	61.5	35.9	65.1	37.6	75.3	42.5	82.3
2	7.4	16.8	16.7	28.1	26.3	34.9	31.1	61.3	35.7	64.9	38.5	74.9	41.0	81.5
3	8.5	14.7	17.9	17.3	25.1	35.5	30.6	61.7	36.3	63.3	39.7	76.4	42.8	81.9
4	7.9	15.1	19.1	26.7	26.6	36.4	30.0	60.2	37.2	62.7	38.8	76.4	41.3	81.3
5	8.4	15.7	18.4	29.7	26.1	38.8	29.3	60.4	36.0	65.3	40.0	75.2	43.1	82.4
6	9.7	17.9	16.5	27.7	26.8	38.3	31.6	60.3	37.5	64.0	40.8	76.0	41.6	80.9
7	9.5	18.5	17.5	26.9	27.1	37.9	30.8	60.7	37.8	63.1	37.9	75.2	44.2	82.3
8	7.8	18.9	18.1	28.5	25.7	35.2	30.3	61.8	36.3	63.8	39.1	76.4	41.9	81.7
9	9.2	16.3	16.9	29.4	26.9	36.0	30.2	60.9	38.1	64.9	38.2	77.2	43.4	81.2
10	8.8	17.2	18.3	28.6	26.0	37.7	30.5	61.2	36.6	62.9	39.4	77.0	42.2	82.5

Table 5. Iron extraction (%) without mechanical activation (A) and with mechanical activation (B).

Tests	Concentration of Hydrochloric Acid in the Solution, %													
	4.0		6.0		8.0		10.0		12.0		16.0		20.0	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	12.3	26.1	17.6	43.0	23.1	53.6	26.9	62.4	29.8	71.2	33.0	75.6	35.9	79.5
2	13.5	24.9	18.8	44.5	24.6	54.6	28.1	63.6	31.4	72.4	33.9	77.1	35.5	81.0
3	12.6	27.1	19.8	43.3	23.4	52.4	27.2	62.7	30.8	71.5	33.0	75.9	37.3	79.8
4	13.8	26.4	19.1	42.1	24.6	53.9	28.4	63.9	28.9	72.7	34.2	74.7	36.5	81.3
5	12.9	25.2	17.9	44.3	23.7	52.7	29.2	61.5	31.1	71.8	34.8	76.9	35.0	80.1
6	12.0	26.7	19.4	43.6	22.8	54.2	26.0	63.7	29.2	73.0	32.1	76.2	36.8	78.9
7	14.1	25.5	18.2	42.4	25.6	53.0	27.5	63.0	31.7	70.6	33.3	75.0	35.9	81.1
8	14.2	27.0	19.7	43.9	24.0	54.5	26.3	61.8	29.1	72.8	32.4	76.5	35.3	80.4
9	13.2	25.8	18.5	42.7	24.9	53.3	27.8	63.3	29.5	72.1	33.6	75.3	35.6	79.2
10	14.4	27.3	20.0	44.2	24.3	54.8	26.6	62.1	30.5	70.9	32.7	76.8	36.2	80.7

Table 6. Copper extraction (%) without mechanical activation (A) and with mechanical activation (B).

Tests	Concentration of Hydrochloric Acid in the Solution, %													
	4.0		6.0		8.0		10.0		12.0		16.0		20.0	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	18.6	32.1	32.1	47.5	42.2	57.9	46.9	70.5	51.8	74.7	55.6	84.4	61.5	88.3
2	20.3	30.9	30.0	48.6	41.0	56.7	45.7	72.0	53.3	76.4	57.1	85.9	61.3	88.9
3	21.0	32.6	32.4	46.2	42.5	58.2	47.2	73.1	54.0	75.0	55.9	84.7	61.8	88.7
4	19.1	31.2	31.3	48.3	41.3	57.0	46.0	70.8	52.1	73.8	57.4	86.2	58.9	87.4
5	20.6	32.7	31.8	47.7	42.8	58.5	47.9	72.3	53.6	75.4	56.2	85.0	59.6	90.4
6	19.4	31.5	32.7	46.5	41.6	57.3	47.5	71.1	52.4	75.3	57.7	83.8	60.3	89.0
7	20.9	33.7	31.6	48.0	43.1	58.8	46.3	72.2	53.9	74.1	59.5	86.6	62.1	87.7
8	19.7	33.0	29.9	46.8	43.2	57.6	47.8	71.4	52.7	75.8	55.3	85.7	59.9	90.3
9	21.2	32.0	31.9	48.3	41.9	58.9	46.6	72.9	54.2	74.4	57.5	84.1	62.4	99.0
10	20.0	33.3	30.3	47.1	43.4	59.1	48.1	71.7	53.0	76.1	56.8	85.6	61.2	89.3

Table 7. Aluminum extraction (%) without mechanical activation (A) and with mechanical activation (B).

Tests	Concentration of Hydrochloric Acid in the Solution, %													
	4.0		6.0		8.0		10.0		12.0		16.0		20.0	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	11.3	25.8	16.6	33.1	22.1	43.8	26.9	52.3	28.8	61.7	31.9	65.5	35.8	69.2
2	12.5	25.2	17.8	34.5	23.5	44.1	27.1	53.6	30.4	62.4	33.9	67.2	35.6	70.8
3	11.6	26.9	18.8	33.9	22.7	42.6	26.2	52.9	31.8	61.0	33.0	65.8	37.4	69.7
4	12.8	26.7	18.1	32.3	23.5	43.9	28.4	53.7	29.5	63.1	33.9	64.8	36.4	71.4
5	11.9	24.9	17.9	34.7	22.8	42.9	28.2	51.4	30.2	61.9	35.1	66.7	35.1	70.3
6	11.0	26.7	18.4	33.6	22.8	44.2	25.0	73.8	28.5	62.8	31.9	66.7	36.7	68.7
7	13.1	24.8	17.2	32.4	24.7	43.1	27.5	53.0	30.9	60.8	33.3	65.1	35.8	71.4
8	13.2	26.0	18.7	33.9	24.1	44.5	26.9	51.4	30.1	62.1	30.9	66.4	35.4	70.1
9	12.2	26.3	17.5	32.7	24.7	43.2	26.8	53.9	30.5	62.7	32.7	65.4	35.7	69.4
10	13.4	28.1	19.1	34.2	23.3	44.8	26.4	53.1	30.4	61.3	33.9	66.7	36.1	70.5

Table 8. Magnesium extraction (%) without mechanical activation (A) and with mechanical activation (B).

Tests	Concentration of Hydrochloric Acid in the Solution, %													
	4.0		6.0		8.0		10.0		12.0		16.0		20.0	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	7.7	10.8	12.3	19.1	19.7	25.8	23.5	29.5	28.3	35.1	30.6	39.3	35.5	46.4
2	5.5	10.9	11.2	18.5	20.1	24.4	25.2	31.3	28.9	34.9	31.3	39.9	36.1	45.7
3	6.7	8.7	12.7	21.3	19.5	25.1	24.4	29.7	29.1	33.3	32.9	41.4	36.9	45.6
4	5.7	9.5	14.5	16.5	20.3	26.6	24.3	30.5	29.3	32.9	31.8	39.4	35.2	45.2
5	6.3	9.7	13.1	19.2	20.8	28.2	23.7	30.7	28.1	35.2	33.0	39.2	37.3	46.3
6	7.8	11.2	11.5	17.7	20.2	28.7	25.1	30.4	29.8	34.4	33.2	40.0	35.7	44.8
7	7.1	12.1	12.4	16.9	21.4	27.4	24.2	31.3	29.6	35.1	31.3	40.2	37.3	46.1
8	5.8	12.5	13.2	18.5	20.7	25.2	24.8	29.9	28.4	33.9	31.9	39.4	35.8	45.5
9	7.2	10.5	13.9	19.3	21.9	26.0	24.2	32.5	28.2	34.5	31.3	40.5	36.4	45.9
10	6.8	11.2	12.3	18.9	21.0	27.3	24.5	31.9	26.9	33.9	32.1	40.0	37.2	46.2

5. Discussion on Results of Implementing Activation Process Efficiency in the Light of Other Environmental Safety Issues

The results of the study have demonstrated a decrease in the final content of metals in industrial waste. The graphic forms of the results presented in Figures 4–8 based on the data from Tables 4–8 show an important increase in mineral extraction caused by activation.

It is important to notice that activation guarantees highest efficiency when combined with higher concentration of hydrochloric acid in the solution. Comparison of relative extraction increase for every analyzed metal and every concentration of hydrochloric acid is juxtaposed in Figure 9.

It may be noticed in Figure 9 that an increase in the efficiency of extraction seems to be relatively constant for every tested metal, regardless of the concentration of hydrochloric acid in the solution. The effectiveness of extraction increase is understood as the ratio between extraction rate with activation to extraction rate without activation. Data are taken from Figures 4–8. That increase may exceed 100% of the initial value (without activation). A limited number of tests focused on particular Russian plants does not entitle the researchers to give more general recommendations: however, the idea of activation seems to be very promising. As it is also costly, its application should always be preceded by relevant tests focused on local material. At the same time, it is necessary to take into account a number of restrictions on the use of physical and chemical technologies that were not taken into account earlier, which significantly reduces industrial and environmental safety.

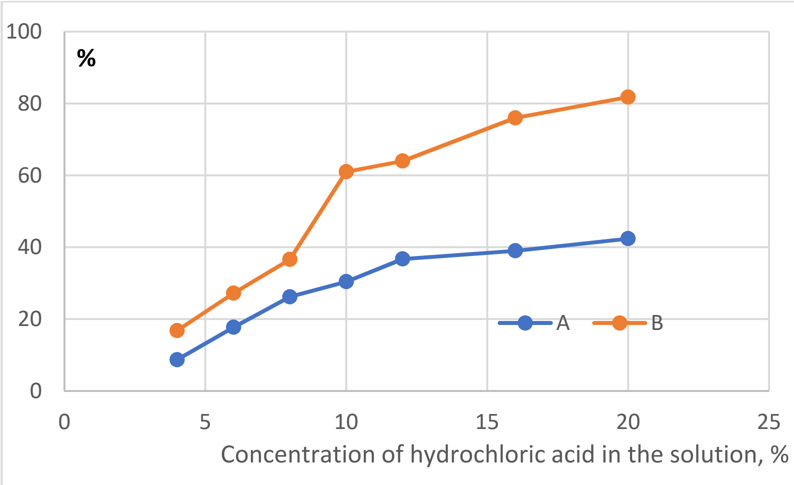

Figure 4. Average Zinc extraction (%) without mechanical activation (A) and with mechanical activation (B).

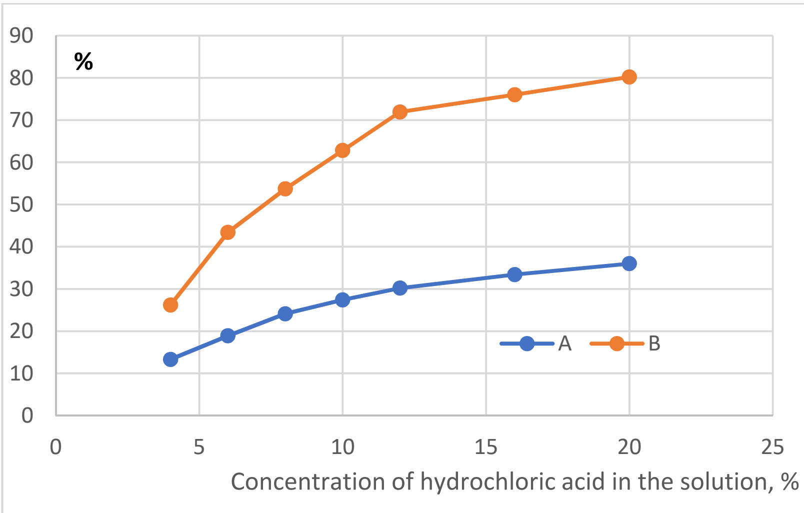

Figure 5. Average Iron extraction (%) without mechanical activation (A) and with mechanical activation (B).

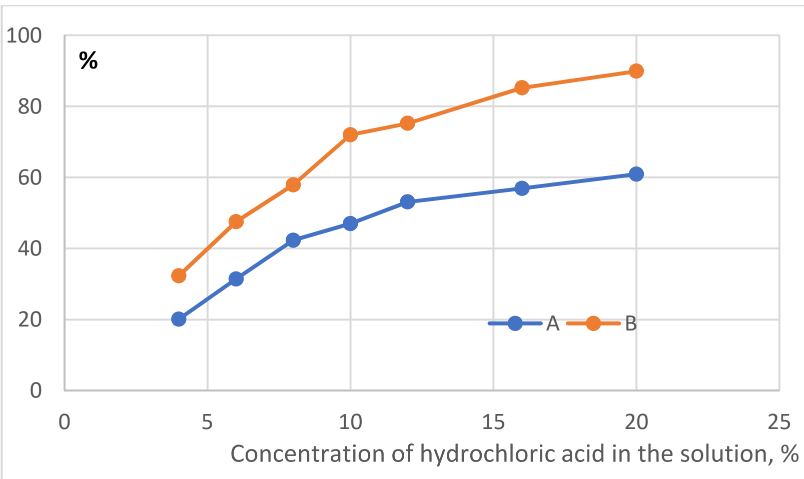

Figure 6. Average Copper extraction (%) without mechanical activation (A) and with mechanical activation (B).

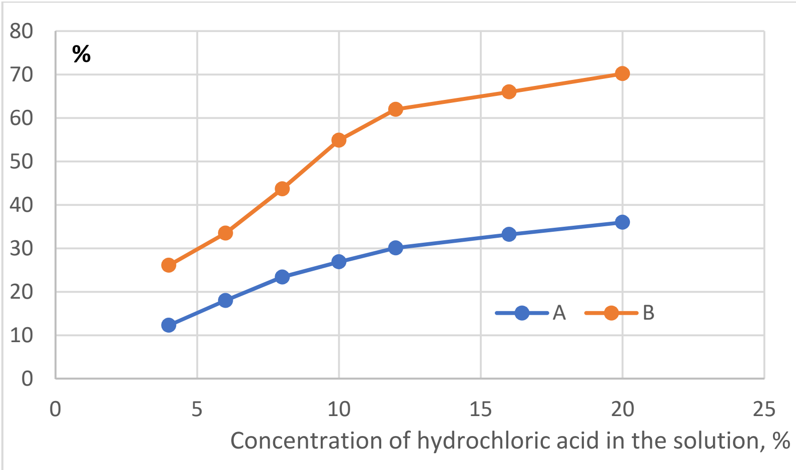

Figure 7. Average Aluminum extraction (%) without mechanical activation (A) and with mechanical activation (B).

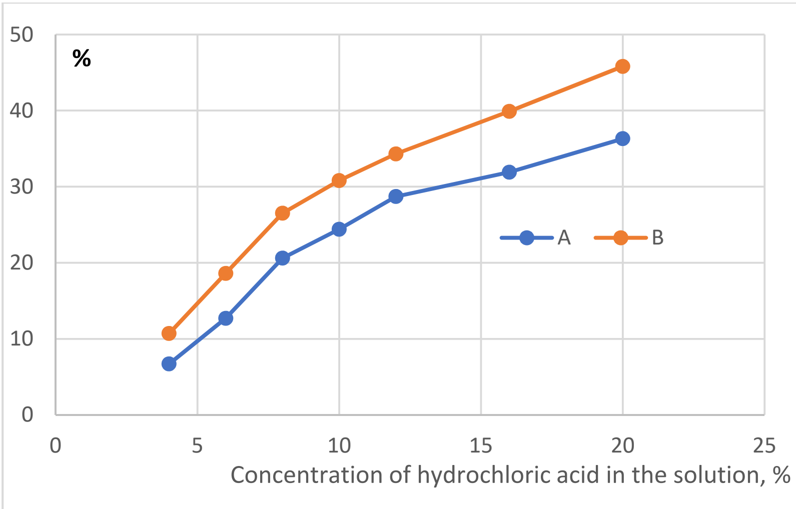

Figure 8. Average Magnesium extraction (%) without mechanical activation (A) and with mechanical activation (B).

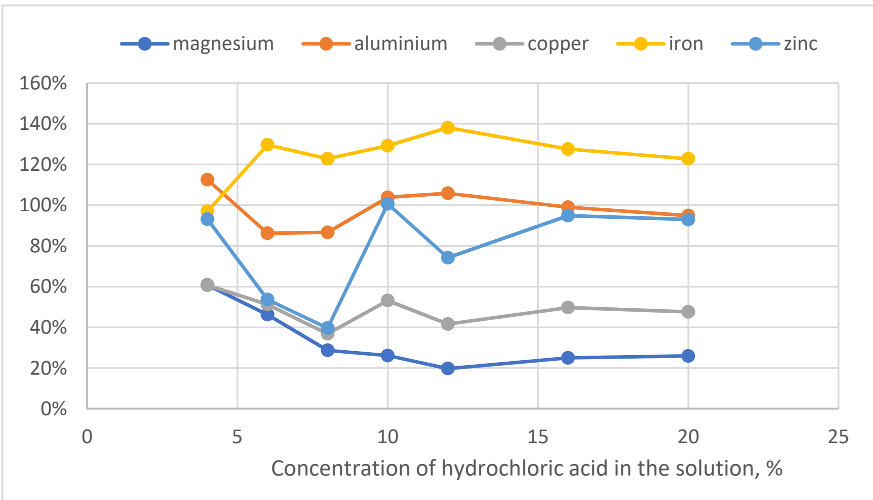

Figure 9. Effectiveness of extraction increase (%) for various minerals and concentrations of hydrochloric acid.

Due to the rather strong aggressiveness of solvents, the use of blocks for underground leaching and open pits for heap leaching has a number of significant disadvantages. As a result of mining operations, the near-contour zones of the quarries and the rock mass have a strong disturbance and increased fracturing around the production blocks. In addition, deposits are often mined in a combined way, which indicates the presence of a large number of voids in the under-pit area. A disturbed mass with a large number of voids has increased filtration. This makes it difficult to capture productive solutions and increases the likelihood of their entering the environment, which significantly augments the risk of disrupting the ecological balance.

As noted earlier, the basis for the resource-producing concept is the involvement in the simultaneous industrial development of natural and man-made georesources. Then, when mining a deposit by an underground method, heap leaching in a quarry becomes unsafe from the point of view of causing harm to those working in an underground mine. Experiments have shown that preliminary activation treatment of manufactured materials in disintegrators is necessary to accelerate the leaching process and the most complete extraction of the useful component. The mechanochemical technology of reprocessing and rational use of man-made waste from concentration and metallurgical industries is the most promising, from the point of view of achieving maximum environmental safety. It combines mechanical and chemical methods in an activation unit or disintegrator. The use of activation units in resource-producing technology excludes direct contact of aggressive solvents and productive solutions with the environment due to the fact that dissolution and collection take place directly in the disintegrator, which minimizes the disturbance of the ecological balance.

After extracting a useful component from manufactured materials (the waste of processing and metallurgical industries), man-made waste can be used as backfill material without restrictions on sanitary, environmental, and technological criteria.

The economic and ecological content of mechanochemical technology is as follows:

- increasing the mineral resource base of a mining and metallurgical enterprise;
- obtaining additional profit when extracting a useful component from man-made waste;
- reducing the volume of harmful components in the utilized man-made waste, which turn into a mobile state and affect ecosystems.

However, at present, mechanochemical technology does not provide a large volume of processing, and the use of disintegrators does not have wide industrial application. When introducing resource-producing technologies, it is necessary to preserve the basic principles:

- comprehensive utilization of resources (natural and anthropogenic);
- strategy for maintaining the mineral diversity of the Earth's deep rock mass;
- involvement of man-made waste in a closed production cycle and its utilization after deep processing.

At the same time, the preservation of the traditional fundamental principles of the exploitation of mineral resources is impossible without solving additional tasks that ensure maximum environmental safety:

- creation of financially affordable injection solutions, hermetic and stable in an aggressive environment;
- introduction of economically feasible technologies for sealing the disturbance and increased fracturing of the border zones of quarries and rock masses around the blocks to exclude the migration of leaching solvents and productive solutions into the environment;
- searching for compositions of solvents and modifying additives that ensure the selective transformation of metal ions into a productive solution to provide a given intensity and technical efficiency of leaching;
- providing the constructed artificial mass with properties such as increased resistance to aggressiveness and tightness while retaining its traditional purpose;

- expanding the application field of the mechanochemical technology of recycling and rational use of man-made waste;
- industrial implementation of activation units (disintegrators) in resource-producing technology.

Every single issue listed above could form a basis for another research program. This list is a set of directions for further research and development, rather than conclusions from the results presented in the current study. The complexity and fundamental importance of solving the listed tasks when introducing resource-producing technologies lies in the fact that the comprehensive utilization of georesources and the completeness of their use are not a function of the joint addition of separate technologies. The completeness of the utilization of geo-resources is a set of measures meant to create technological processes for an extended extraction cycle, ore processing, deep processing of man-made waste, and its disposal. The principle of environmental safety must become part of the deposit exploitation practice with the complex use of natural resources and the subsequent processing of anthropogenic materials. The obligatory implementation of this principle will make it possible to apply innovative technological solutions to the extraction, processing, and deep utilization of georesources. In every case, the required adaptation to the mining and geological conditions of the deposit and to the necessary consideration of the peculiarities of the material and mineral composition of ores and the chemical composition of industrial waste must be considered.

6. Conclusions

For a highly efficient implementation of renewable-resource technologies with the complexity of the development of georesources, it is necessary to take into account the variability of anthropogenic formations [51] and the requirements of environmental safety at the design stage of a mining and processing enterprise.

The industrial use of man-made georesources, the implementation of environmental safety requirements in the comprehensive recovery of natural georesources and involvement in recycling becomes possible only on the principles of a paradigmatic approach to research and implementation of innovative technological solutions. At the same time, a separately considered technological task cannot be isolated, but it is treated as a distinct element of a single technological scheme of a mining enterprise as a whole.

The environmental safety and efficiency of individual design solutions for the exploitation of natural and man-made deposits should be assessed anytime locally, from the point of view of the maximum environmental benefits of the entire technological scheme of a mining and metallurgical enterprise within the framework of a single renewable-resource technology.

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