resources

Article

Modern Technologies Providing a Full Cycle of Geo-Resources Development

Cheynesh B. Kongar-Syuryun [1,*], Alexander V. Aleksakhin [2], Evgeniya N. Eliseeva [2], Anna V. Zhaglovskaya [3], Roman V. Klyuev [4] and Denis A. Petrusevich [5]

[1] Mining Department, Saint-Petersburg Mining University, 21st Line, 2, 199106 St Petersburg, Russia
[2] Economics Department, National University of Science and Technology «MISiS», Leninsky Avenue, 4, 119991 Moscow, Russia
[3] Department of Industrial Management, College of Economics and Industrial Management Named after V.A. Romenets, National University of Science and Technology «MISiS», Leninsky Avenue, 4, 119991 Moscow, Russia
[4] Department of Technique and Technology of Mining and Oil and Gas Production, Moscow Polytechnic University, 38, B. Semenovskaya St., 107023 Moscow, Russia
[5] Higher Mathematics Chair, Institute of Artificial Intelligence, MIREA—Russian Technological University (RTU MIREA), Vernadsky Avenue, 78, 119454 Moscow, Russia
* Correspondence: kongarsiuriun@gmail.com

Abstract: Resource-dependent countries and economies are found to be particularly sensitive to global shocks. A unifying parallel is drawn between resource-dependent countries and regions with depleted mineral resources. The objective factors of losses of accessed reserves are analyzed. A unifying parallel is drawn between sub-standard ores and industrial waste. The paper proposes shifting geotechnology development from simple mineral extraction towards technologies that provide a full cycle of geo-resources development. A radical way of ensuring a full cycle of geo-resources development is the involvement of sub-standard ores and industrial waste in a closed processing cycle. The utilization of industrial waste without a valuable component extracting or reducing a harmful component to a background value is palliative. A comparative description of various technologies that allow extracting valuable components from sub-standard ores and industrial waste is made. The paper proposes a variant of chemical–physical technology that makes it possible to extract a valuable component from industrial waste to a minimum value. The activation of industrial waste with a disintegrator before a chemical extraction significantly increases the yield of a valuable component from 2.6 to 218.5%. A differentiated approach is needed regarding the choice of leaching solution, its percentage, as well as the leaching method and the need for activation processing of valuable components and industrial ones. The combined highly efficient physical–chemical and physical–technical technologies will ensure the maximum extraction of the valuable component from 52.6 to 98.8% in the full cycle of natural and industrial geo-resources development.

Keywords: geotechnology; geo-resources; leaching; industrial waste; utilization

check for updates

Citation: Kongar-Syuryun, C.B.; Aleksakhin, A.V.; Eliseeva, E.N.; Zhaglovskaya, A.V.; Klyuev, R.V.; Petrusevich, D.A. Modern Technologies Providing a Full Cycle of Geo-Resources Development. *Resources* **2023**, *12*, 50. https://doi.org/10.3390/resources12040050

Academic Editor: Xianlai Zeng

Received: 18 February 2023
Revised: 31 March 2023
Accepted: 7 April 2023
Published: 11 April 2023

1. Introduction

The global economy is currently experiencing dramatic fluctuations due to various financial and political shocks. Crises in individual market segments or countries can lead to global fluctuations and upheavals around the world [1]. Global shocks in international markets increase the risks to individual economic sectors or enterprises [2] and can lead to business losses, cause side effects, provoke the spread of economic and financial shocks to other enterprises, and lead to their bankruptcy [3]. Mining and processing enterprises are part of the global economic system and are also subject to cataclysms during global shocks. The states that depend on the import and export of raw materials are among those most acutely experiencing periods of financial crises, which is associated with a rise in their price [4]. The rise in the cost of resources is associated not only with economic and political shocks but also with disasters or war damage at mining enterprises [5,6] that reduce the volume of minerals extracted. There have been known disasters in which part or all of a deposit's reserves have been lost for good [7]. Thus, sustainable resource development in the context of global shocks is a priority. Currently, the availability of technologies and equipment does not allow us to fully involve a deposit's reserves in an efficiently justified development [8,9]. There is a situation at mining enterprises where the development of already accessed reserves is unprofitable due to objective factors [10,11]:

- Reserves are located outside the open pit side;
- Pinching-out ore body is distributed along the perimeter;
- Low-grade, sub-standard, and thin bed seams;
- Local areas of deposit remote from the main ore body;
- Reserves are located in difficult mining and geological conditions or under protected objects.

At the same time, a large amount of industrial waste is formed in the process of mineral extraction and subsequent processing [12–14]. The volume of industrial formations on the Earth's surface is increasing exponentially due to the lack of economically justified and environmentally friendly technologies for the deep processing of raw materials that ensure the extraction of valuable components to a zero level [15,16]. As a result of the long-term presence of waste on the Earth's surface, it undergoes a constant geochemical transformation:

- Changes in the mineral–chemical composition [17];
- Formation of new compounds [18];
- Depletion of valuable components due to the removal of elements outside the mass [19];
- Environmental pollution [20,21].

The emergence of an ecological catastrophe is possible not only as a result of natural processes occurring in industrial mass, but also as a result of terrorist acts [22] as well as war damage.

Due to the unlimited life of industrial mass, the processes ongoing in them and affecting the ecosystem can occur for a long time before the following conditions occur [16,23]:

- The components have completely dissolved and taken out of the mass;
- The components have passed into insoluble forms, which reduces their mobility;
- The components have formed new safe chemical compounds.

Despite the fact that industrial wastes are the most powerful source of environmental impact and have a serious impact on the health of workers and residents of the region [24], they are a valuable raw material for industry [25–27]. The huge industrial masses contain significant amounts of ferrous, non-ferrous, noble, and rare-earth metals (Supplementary Materials: Tables S1 and S2). Such masses can be classified as industrial deposits and industrial raw materials [28–30]. However, industrial formations are not involved in a complete and closed cycle of comprehensive exploitation [31,32].

Consequently, at mining and processing enterprises in conjunction with metallurgical plants, the objective conditions have been formed for testing or piloting the industrial implementation of innovative technologies in the full cycle of development of natural and industrial resources [31,33,34]. The full cycle of deposit development implies the abandonment of mono-technologies in the extraction and processing of natural and industrial resources and the introduction of highly efficient physical–chemical and physical–technical technologies that ensure the maximum extraction of valuable components [15]. The combination of traditional technologies for the extraction and processing of natural resources and innovative extraction methods will make it possible to minimize the valuable component in the waste and reduce the harmful components to the sanitary requirements level [35]. After that, the waste disposal in the mined-out space formed as a result of open-pit and underground mining will ensure maximum environmental safety and economic feasibility [36–38].

Intensification of the economic advancement of an enterprise and ensuring its financial stability in the international market is possible only with the provision of complete and comprehensive development of natural and industrial geo-resources [39]. In earlier studies, it has been suggested that it is possible to increase the extracted useful component volume by 15–25% due to the involvement of industrial waste in mining [15,31,35].

The lack of engineering solutions for the comprehensive exploitation of geo-resources with a completed technological cycle leads to huge losses of valuable components and the formation of large industrial waste volumes. When designing mining and metallurgical enterprises, it is necessary to consider them in the context of a single object in the full cycle of closed production with the use of innovative technologies for the deep processing of geo-resources. In this regard, the creation of technological principles for the deep processing of geo-resources and the development of technologies for the rational use of mature and current industrial resources seems to be a very urgent task. To solve this problem, it is necessary to establish the possibility and degree of extraction of a valuable component from industrial waste by leaching, identify the effect of fineness of grinding on the yield of a valuable component, and determine the effect of the change in the pH factor on the recoverability of metals.

2. Tasks and Methods

Currently, processing is lagging behind extraction in technological aspects and technical capabilities [40]. Therefore, the following stages can be distinguished for solving this problem:

- Assessment of the economic-organizational activities of a mining and processing enterprises in the context of a single object;
- Development of conversion principles based on the application of innovative technologies for the comprehensive exploitation of natural and industrial geo-resources;
- Search for an algorithm to assess the risk of using innovative technologies;
- Substantiation of the investment attractiveness of deep processing of geo-resources;
- Comparative analysis of economic efficiency.

Modern financial and economic theory predetermines the main provisions of the economic efficiency of innovative technologies:

- Complex consideration of negative and positive properties of raw materials that characterize the level of business, namely the ability to increase dividends, increase the value of an enterprise, and increase reliability, liquidity, and profitability;
- Implementation by creating an economic and mathematical algorithm describing the relationship between development rates, production volumes, payback time interval, financial costs, total recoverable value, risks of introducing innovative technologies, etc.

Previous studies [15,40–42] have demonstrated positive results in the extraction of valuable components from sub-standard ores or industrial wastes using the chemical leaching method (Figure 1).

Research has demonstrated the advantage of agitation leaching over heap leaching. Selective dissolution (agitation leaching) of industrial waste in special solutions with intensive mixing and continuous oxygen injection into the resulting mass is characterized by a higher rate and better qualitative-quantitative indicators of the valuable component extraction.

An increase in the proportion of fine fractions increases the total contact area of the sprayed material with the solutions [43]. Thus, it is reasonable to assume that industrial waste must be ground before leaching. Mechanical-activation processing in a disintegrator is the most effective preparation method [15,34,43]. During activation processing in the disintegrator, the grinding material is subjected to multiple mechanical exposures of the finger-rods rotating in opposite directions (Figure 2). The particles moving in the disintegrator basket from the center to the periphery collide with each other and additionally experience a sequential mechanical exposure of the fingers. This high-energy exposure leads to a weakening of the structural bonds of the material, its rapid destruction, and grinding. The weakened grain structure contributes to the deeper penetration of the solution.

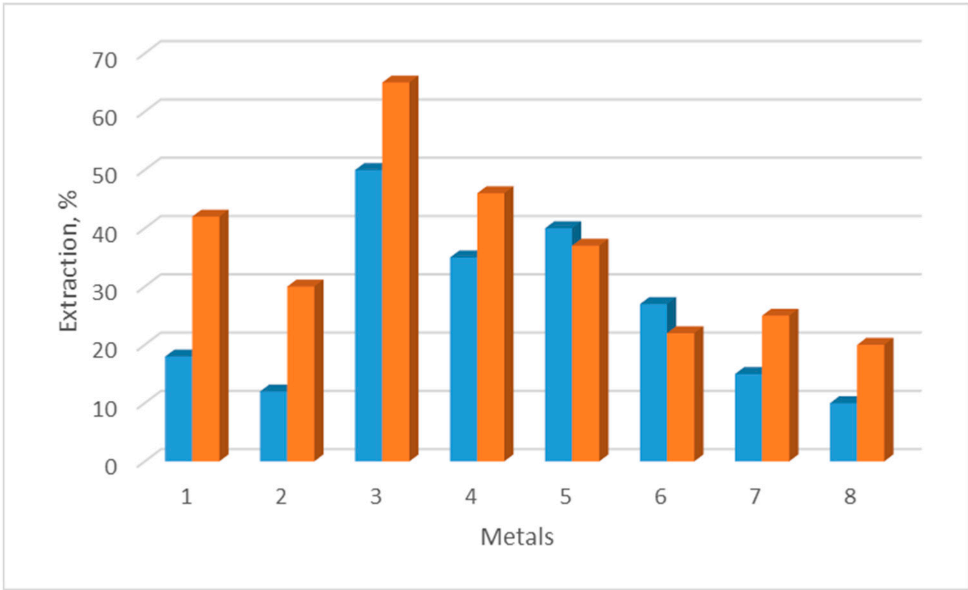

Figure 1. Extraction of a valuable component depending on the activation method: (1) Lead from sub-standard ore, (2) Lead from metallurgical slag, (3) Zinc from sub-standard ore, (4) Zinc from metallurgical slag, (5) Copper from sub-standard ore, (6) Copper from tailings, (7) Iron from sub-standard ores, (8) Iron from tailings. Blue column is hydrochloric acid irrigation; orange column is anolyte irrigation.

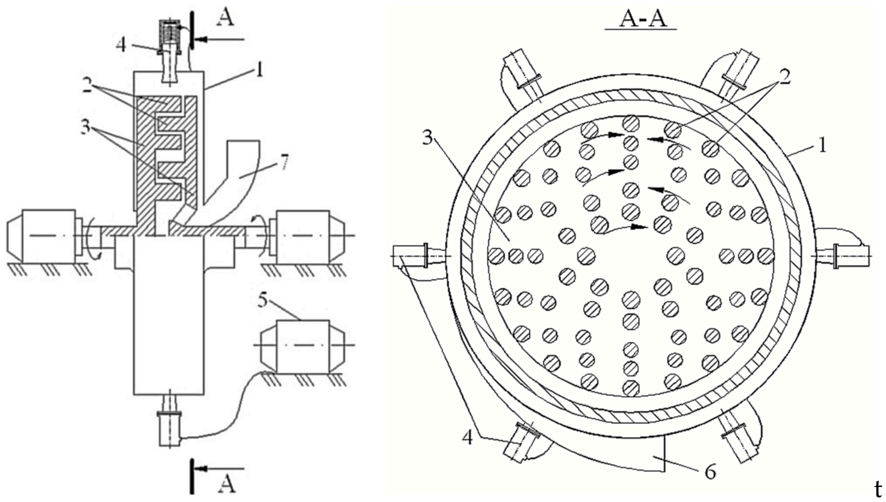

Figure 2. Activation installation (disintegrator): (1) Cap; (2) Fingers; (3) Discs; (4) Nozzles; (5) Pump; (6) Drain; (7) Feed funnel.

The studies were carried out using industrial waste from the Buribay Mining and Processing Plant (concentration tailings) and the Cherepovetsk Metallurgical Plant (slags of the metallurgical processing).

Previous studies have shown that similar values of the carbonates and hydroxides solubility prevent the selective precipitation of bivalent ions of copper, iron, zinc, and other metals from solutions of these salts [44]. However, the solubility of sulfides and sulfites of the same metals differs significantly [45]. Consequently, the selective extraction of valuable components from industrial waste containing sulfites or sulfides is very promising. The theoretical and practical prerequisites for approval of the theory [45] were the values of industrial solubility of oxides, carbonates, and sulfides of metals [46], which are the main valuable components of the investigated industrial waste.

When a sulfide-containing agent ($NaHS$ or H_2S) is introduced into a sulfuric acid solution, hydrosulphuric acid is formed, which subsequently dissociates:

$$H_2S \underset{\leftarrow}{\overset{\rightarrow}{}} H^+ + HS^-,$$
$$HS^- \underset{\leftarrow}{\overset{\rightarrow}{}} H^+ + S^{2-} \tag{1}$$

Hydrosulfuric acid is weak in both extents of decomposition:

$$K_1 = \frac{[H^+]\cdot[HS^-]}{[H_2S]} = 6.0 \times 10^{-8}$$
$$K_2 = \frac{[H^+]\cdot[S^{2-}]}{[HS^-]} = 1.0 \times 10^{-14}$$
$$K_{gen.} = K_1 \cdot K_2 = 6.0 \times 10^{-22}$$

It follows that the concentration of the sulfide ion involved in the metal deposition depends on the solution alkalinity—the pH factor (the concentration of hydrogen ions (pH) in the solution). Consequently, the completeness of the extraction of metals (zinc, copper, iron, etc.) from industrial waste depends not only on the concentration of the sulfide-containing agent introduced but also on the alkalinity (pH factor) of the solution. Calculations have been made according to this theory and are presented for clarity in Figure 3.

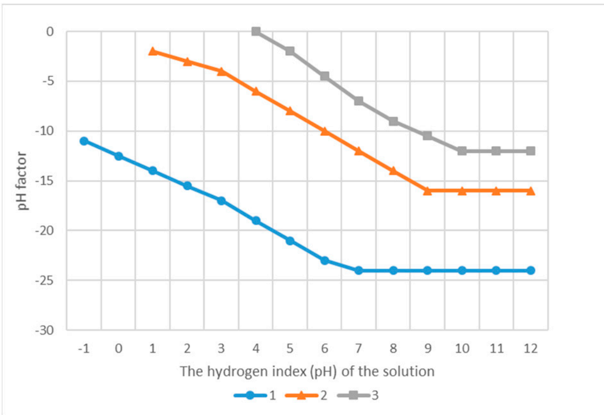

Figure 3. Dependence of the concentration of dissolved hydrogen sulfide on the pH of the solution at a residual concentration of copper (1), zinc (2), iron (3) equal to 0.01 g·dm$^{-3.}$

The graphs in Figure 3 represent that the copper sulfides deposition occurs at a negative pH factor, the intensity of the zinc sulfides deposition begins when the solution acidity is higher than 1.0 (pH $\geq$ 1.5), and the ferrous sulfides deposition begins at acidity above 4.0 (pH $\geq$ 4.0). Consequently, it is possible to produce selective sequential extraction of the valuable component (copper => zinc => iron) by adjusting the solution acidity, and achieve its maximum extraction from industrial waste by differential concentration of the agent.

A sulfide-containing agent (contains sulfur up to 18%)—sodium hydrosulfide ($NaHS$)—is a waste of chemical production that was used as a working solution in the extraction of copper, iron, and zinc from the concentration tailings of the Buribay Mining and Processing Plant—Equations (2)–(4):

$$ZnSO_4 + NaHS = ZnS + NaHSO_4, \tag{2}$$

$$CuSO_4 + NaHS = CuS + NaHSO_4, \tag{3}$$

$$Fe_2(SO_4)_3 + NaHS = 2FeSO_4 + NaHSO_4 + S, \tag{4}$$

$$H_2SO_4 + NaHS = NaHSO_4 + H_2S, \quad (5)$$

$$2NaHSO_4 \rightleftarrows Na_2SO_4 + H_2SO_4. \quad (6)$$

A negative factor in the extraction of valuable components (metals) from industrial waste (in this case, concentration tailings) with sulfur-containing solutions (reagents) is the insignificant release of hydrogen sulfide (H_2S) into the gas phase—Equation (5). The volume of released hydrogen sulfide is directly proportional to the solution acidity (pH factor), the conditions of its supply, and the mixing intensity—Equation (6). The introduction of sodium hydrosulfide ($NaHS$) into the bottom part significantly reduces the release of hydrogen sulfide (H_2S).

Several different cycles of research were carried out. This allows us to present a general view of the deep processing of industrial waste and the extraction of valuable components. The extraction of metals (copper, zinc, iron) was carried out from the concentration tailings of the Buribay Mining and Processing Plant by irrigation with sodium hydrosulfide of differential concentration. The solution acidity (pH factor) was changed by introducing caustic soda (NaOH) into it. Research on the extraction of noble metals (silver, gold) from the concentration tailings of the Buribay Mining and Processing Plant and metals (aluminum, magnesium) from the metallurgical slags of the Cherepovetsk Metallurgical Plant was carried out according to standard methods. In the study of gold and silver leaching, the concentration tailings were irrigated with a working solution of sodium cyanide of differential concentration. The study of aluminum and magnesium extraction from metallurgical slags was carried out by irrigation with hydrochloric acid of differential concentration.

3. Results and Discussions

3.1. Analysis of Results

In the study, several leaching methods were used: 1—heap leaching; 2—heap leaching after activation processing of industrial waste; 3—agitation leaching; 4—agitation leaching after activation processing of industrial waste. Each cycle was repeated 10 times to confirm the veracity of the results. This number of repetitions excludes randomness and is considered sufficient. The average values of the experimental data are shown in Tables 1–3 and are presented in Figures S1–S3.

Table 1. Extraction of copper, zinc, iron (%) from concentration tailings.

	Concentration of Sodium Hydrosulfide in the Work Solution, %															
	8.0				**12.0**				**16.0**				**20.0**			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Zn	25.4	31.3	77.6	83.3	29.6	34.5	84.9	89.1	33.6	39.3	90.5	94.3	39.1	42.2	95.4	98.8
Fe	24.6	33.8	44.1	51.9	50.1	61.4	70.5	82.7	81.3	84.5	89.2	93.8	94.9	96.0	97.2	98.5
Cu	42.8	55.1	58.5	77.8	47.9	62.3	64.6	85.4	52.2	69.0	71.6	96.4	53.9	70.1	73.3	97.5

Table 2. Extraction of aluminum and magnesium (%) from metallurgical slags.

	Concentration of Hydrochloric Acid in the Work Solution, %															
	8.0				**12.0**				**16.0**				**20.0**			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Al	22.7	38.6	32.1	53.4	31.8	53.0	45.5	63.9	33.0	59.8	51.5	72.7	37.4	69.7	59.2	77.8
Mg	20.8	28.2	22.4	34.2	28.1	35.2	30.9	42.7	33.0	39.2	35.4	46.5	37.3	46.3	41.5	52.6

Table 3. Extraction of silver and gold (%) from concentration tailings.

	Concentration of Sodium Cyanide in the Work Solution, g/L															
	8.0				12.0				16.0				20.0			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Au	35.8	41.2	45.5	48.3	51.4	56.3	55.7	59.5	60.2	65.1	64.6	70.7	68.7	73.7	74.1	79.3
Ag	59.8	62.3	64.7	66.9	63.4	64.9	67.7	70.1	80.3	83.6	85.2	88.8	77.3	78.1	79.8	81.0

An analysis of the conducted experiments reveals that the activation processing of industrial waste has a significant effect only at the initial stage (during copper leaching) during the separated extraction of metals from concentration tailings by leaching with sodium hydrosulfide solution. Further mechanical processing is not so effective. As can be seen in the zinc leaching diagram, the difference between agitation leaching and the same method of activated material leaching is 1–3%. This phenomenon is explained by the fact that, initially, before the extraction of copper and irrigation of the waste with a low-alkalinity solution, an activation processing was carried out. Consequently, the need for re-processing has disappeared. At the third stage of leaching, when irrigation with high-acidic solutions and extraction of iron, the effect of activation processing is insignificant and the use of grinding in the disintegrator is impractical. The difference in the yield of the valuable component when a solution with a concentration of 20% is irrigated with sodium hydrosulfide is 2–4%. This can be explained by the fact that copper and zinc were previously extracted from industrial waste by sequential separation. Thus, industrial wastes have preliminary preparation, which accelerated or enhanced the processes of simple heap leaching.

The results obtained in the study correlate with studies [12,15,31,33,34]. However, previous studies did not reveal the conceptual features of the involvement of industrial waste in recycling [12,14]. Particular cases of extracting valuable components from industrial raw materials, such as gold [33] or separately zinc [34], were considered. A comparative analysis of heap leaching and agitation leaching was not carried out on the example of raw materials represented by a single industrial formation. Comparative analysis of heap leaching and agitation leaching on the example of raw materials represented by a single industrial formation, conducted by this study, allows us to identify the most effective way to involve industrial waste in recycling. In addition, in previous studies, no attention was paid to the possibility of successive precipitation of a valuable component by adjusting the acidity (pH factor) of the aggregate (solution).

The extraction of a valuable component from metallurgical slags using various leaching methods and activation processing demonstrates a positive dynamic (Table 2).

It should be noted that experiments on heap leaching of metallurgical slags demonstrated an insignificant yield of the valuable component. However, there is a stable decrease in the content of metals in metallurgical slags after leaching with an increasing concentration of hydrochloric acid in the work solution. At the same time, the use of mechanical activation processing of metallurgical slags before heap leaching gives a significant increase in the yield of the valuable component: up to 40% for magnesium and up to 80% for aluminum. The use of agitation leaching in the case of metallurgical slags is not a priority since the increase in the yield of the valuable component was less and amounted to no more than 10% for magnesium and up to 45% for aluminum. This can be explained by the fact that strong stone-like or glass-like masses are formed as a result of metallurgical treatment and subsequent solidification of liquid slags after they are released from the blast furnace. They have a sufficiently strong structure that makes it difficult for the work solutions to penetrate deeply. After the activation processing of slags in the disintegrator, they are crushed and the structure is weakened, which improves the quality of wetting.

Studies on the extraction of gold from quartz oxidized ore by heap leaching with cyanide solutions demonstrated satisfactory results [47]. It was decided to test this method on the concentration wastes of the Buribay Mining and Processing Plant when extracting gold and silver from them. The intensification and quality of leaching were changed by introducing a preliminary activation processing of waste into the technological scheme and using selective (agitation) leaching (Table 3).

The analysis of the experimental data reveals that when extracting gold and silver from concentration wastes, the activation processing and agitation leaching have insignificant effects on the quality of the valuable component extraction. When silver leaching, an increase in the concentration of sodium cyanide in the work solution is characterized by an increase in the quality of extraction. Analogical experiments on gold leaching demonstrated that the rates of the valuable component extraction increase up to a sodium cyanide concentration of 16 g/L in the working solution, after which there is a slight drop. It can be concluded that the optimal concentration of sodium cyanide in the working solution during silver leaching is 16 g/L.

3.2. Full Cycle of Geo-Resources Development as a Way to Maximize the Extraction of a Valuable Component: Purposes and Objectives of Full Cycle of Geo-Resources Development

As can be seen from the conducted experiments, the maximum extraction of the valuable component can be achieved using an integrated approach. It is possible to extract the target components to the background content by a combined application of a mechanochemical activation of industrial waste with leaching (heap or agitation). A feature of combined leaching is the preliminary mechanical processing (activation) of industrial waste in a disintegrator. The activation leads to a decrease in the grain size, making it possible to weaken the crystal structure and increase the irrigated surface area of the particles.

As follows from the conducted research, an increased yield of a valuable component is observed in the case of agitation leaching in comparison with heap leaching. Such a significant difference is noticeable when extracting zinc. This phenomenon is explained by the fact that during heap leaching, a certain effect of surface passivation is observed; that is, the waste grains are in a static position. Under such circumstances, complete irrigation of all grain does not occur. While agitation leaching creates new (fresh) mineral surfaces, in this case, there is 100% contact of the grain surface with the solution.

Optimization of technological processes must ensure the full cycle of geo-resources development. Optimization should be based on deep analysis of the material composition of industrial waste and on careful selection of recommended innovative technologies that ensure the completeness and safety of the valuable component extraction. The introduction of innovative technologies that provide a full cycle of geo-resources development will allow us:

- To obtain an economic effect from the realization of valuable components extracted from industrial waste;
- To increase the mineral resource base of the enterprise by replacing primary mineral resources through the introduction of industrial waste into the development;
- To increase the life of the enterprise by involving poor, sub-standard ores and industrial waste in processing;
- To reduce the cost of storing industrial waste;
- To make effective use of the territories freed up;
- To prevent the dangerous impact of natural leaching from industrial mass on the environment.

Thus, the fields most important to ensuring the full cycle of geo-resources development are:

- The involvement of poor, sub-standard ores and industrial waste in the processing;
- Creation and implementation of fundamentally new technologies for raw materials extraction from industrial mass, based on traditional physical–technical methods in conjunction with physical–chemical methods;
- Development of a comprehensive waste-free (low-waste) cycle of a closed system of the main (extraction) and auxiliary (processing and metallurgical redistribution) industries.

The full cycle of geo-resources development should be understood as the introduction of technologies at mining and processing enterprises that allow extracting useful components from mined raw materials to a zero level. Based on this, when designing a mining and processing enterprise, it is necessary to consider the presence of valuable components in industrial waste at any stage of extraction and processing. In this regard, it is necessary to create a continuous chain for processing the mined raw materials and extracting valuable components from them to the zero level, where the involvement of industrial waste in recycling is one of the stages.

3.3. Economic Efficiency Assessment of Implementation of Full Cycle of Geo-Resources Development

When deciding on the feasibility of involving industrial waste in additional processing for a particular mining and processing enterprise condition, effective assessment methods should be used to obtain the greatest economic effect [48]. There are many methods for calculating the environmental effect and minimizing the impact on the environment [49–51]. It should be noted that the proposed methods for assessing the methods of industrial geo-resources involvement are based on the multiplicative effect. All proposed methods consider the net economic additional profit and the effect of reducing (or completely eliminating) the impact of industrial formations on the environment. The paper [49] substantiates the cumulative multiplicative effect of the non-waste (low-waste) technology implementation. The calculation is made considering the reduction in the likely consequences of environmental disasters and the reduction in the degree of industrial damage to the ecosystem degradation as a result of mining and metallurgical production. However, as follows from the analysis, all the methods are complicated in the calculations; there are a lot of different coefficients and assumptions, which does not allow the effect to be calculated with even approximate accuracy [52].

The proposed method of recycling industrial geo-resources allows us not only to prevent the negative impact on the environment, but also creates the possibility of obtaining additional profits. In this context, the prevention of negative impact is paramount. In this regard, we take the economic effect of minimizing the impact of waste on the environment as unconditional [53]. Consequently, it is necessary to understand the presence of additional profit from the sale of the resulting products produced during additional processing of industrial geo-resources. At the same time, the overall zero profitability of the proposed technology allows us to assert that the overall multiplicative effect is significant due to the presence of an unconditional environmental effect [54].

It is necessary to consider that the proposed technologies implementation is associated with significant and constantly increasing investment and operating costs. Therefore, the calculation of economic efficiency from the proposed innovative technologies comes down to a simple difference between the value of the products obtained after recycling industrial geo-resources, and the investment costs associated with the introduction and implementation of the proposed technology. In a previous study [33], a simplified assessment of industrial deposit reserves is given by the example of mining and processing tailings in the Southern Urals. Considering the received results of valuable components extraction from industrial waste, the summary Table 4 presents information on possible volumes of the received valuable component at the introduction of the offered technology where «reserves» of each component are taken from research [33]. Ideal conditions for the calculation were taken: production extraction of a valuable component from industrial waste did not change relative to the results obtained by the laboratory method.

After the reprocessing of industrial geo-resources, the remaining product can be considered as alternative components for the production of:

- Backfill;
- Construction material;
- Pavement;
- Embankments for dams, roads, railways, and so on.

Table 4. Summary information of reserves in industrial masses and volume of possible extraction.

Tailing Dumps of the Processing Plant	Copper		Zinc		Iron		Gold		Silver	
	1	2	1	2	1	2	1	2	1	2
	Thousand Tons						Tons			
Sibay	34.5	33.637	90.0	88.92	5900.0	5811.5	13.9	11.0	344.0	305.5
Uchaly	90.0	87.75	257.0	253.9	8050.0	7929.2	16.5	13.1	232.0	206.0
Buribai	25.0	24.375	11.6	11.46	1280.0	1260.8	6.60	5.24	56.8	50.5
Guy	120.0	117.0	92.0	90.9	5550.0	5466.8	32.0	25.4	160.0	142.1

1—Reserves [33]; 2—Extraction.

Our model does not include profit from the use of residual products after recycling when evaluating economic efficiency. The project implementation plan provides for the creation of a processing plant with a capacity of 200 thousand tons of industrial waste from the processing plant per year for two calendar years (Table 5).

Table 5. Project implementation plan.

Work Stages	Quarter								Expenses, Million Rubles
	1	2	3	4	5	6	7	8	
Geological and technological mapping of tailings. Contouring, study of raw materials. Development of technical assignment and feasibility study of investments.	X	X							20
Adaptation of technology, development of a production project.		X	X	X					45
Experimental design works, development of technical project and working design documentation.			X	X	X				45
Production of non-standard technological equipment.				X	X	X			200
Complete by standard equipment.						X	X		180
Performing construction and installation work.							X	X	70
Pre-commissioning, commissioning.								X	50
Total:									**610**

The presented costs are indicative. They were obtained by expert assessments through a survey of specialists and are subject to clarification at the design stage. On the day of writing the article, the ruble-dollar exchange rate was 69.13, therefore, the cost of the project to implement the proposed technology is 8,823,954.87 U.S. dollars. Annual revenues of the enterprises were calculated on the basis of annual productivity, valuable component percentage in industrial waste, recoverability of this component established by laboratory method, and metal prices on international exchanges on the day of writing the article. The cost per ton of metals contained in the studied industrial formations on the London Metal Exchange is the following: copper—9324.48 USD $; zinc—3598.25 USD $; iron—129.07 USD $; and per troy ounce of raw materials: silver—23.79 USD $ (0.765 USD $ per one gram); gold—1927.6 USD $ (61.98 USD $ per one gram).

Table 6 presents the production indicators calculated on the basis of metal value on international exchanges and the waste volume on tailing dump determined in [33].

Table 6. Production indicators of the tailings processing enterprise.

Tailing Dumps of the Processing Plant	Waste Volumes [47]	Productivity	Annual Revenue	Payback	Term of the Work
	Million Tons	Thousand Tons	Million USD	Month	Year
Sibay	28.5	200	15.610	7	142.5
Uchaly	40.8	200	15.994	6.5	204
Buribai	5.5	200	15.523	7	27.5
Guy	40	200	10.591	10	200

Analysis of the obtained indicators shows that the subsequent processing of industrial waste, namely tailings, is effective. The payback period for different tailing dumps is 6.5 to 10 months. As can be seen from Table 6, it is possible to vary the productivity and achieve the most effective indicators of the processing plant. No discounting of cash flows has been performed in the estimates presented above due to the proximity of cost estimates, the unreliability of ten-year forecasts of metal prices, the difficulty of predicting geopolitical events, and as a consequence, the unpredictability of financial and economic cycles and the difficulty of determining the discount multiplier in a financial crisis. VAT refunds and income from the use of the product remaining after processing as backfill components, in civil engineering, and so on, were also not considered. The benefit value related to environmental damage was also not assessed due to insufficient data.

4. Conclusions

The results of a multifactorial experiment have shown that activation processing of industrial waste in disintegrators before leaching has a differentiated effect on the extraction of a valuable component. The degree of mechanical activation influence depends on the work solution used during leaching and industrial waste being recycled.

The extraction of target components, concentrated in industrial waste, to the background value can be achieved by applying a combined recycling approach. The combination implies the preliminary mechanical activation of industrial waste and the subsequent leaching process. Reducing the valuable component in industrial waste to background values and harmful components to a safe level will ensure maximum environmental safety and economic feasibility of disposal.

The introduction of combined highly efficient physical–chemical and physical–technical technologies will ensure the maximum extraction of the valuable component in the full cycle of the development of natural and industrial geo-resources. The full cycle of geo-resources development will make it possible to produce additional products; increase the competitiveness of the enterprise in financial globalization; minimize the industrial load of mining and metallurgical enterprises on the environment; and improve the geo-ecological situation of mining regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources12040050/s1, Figure S1: Dependence of the metals extraction from the concentration tailings on the concentration of sodium hydrosulfide in the work solution and on the activation method; Figure S2: Dependence of metal extraction from metallurgical slags on the concentration of hydrochloric acid in the work solution and on the activation method; Figure S3: Dependence of the metal extraction from concentration tailings on the concentration of sodium cyanide in the work solution and on the activation method; Table S1: Content of valuable components in tailing dumps of the Southern Urals; Table S2: Chemical composition (in %) of metallurgical slags.

Author Contributions: Conceptualization, A.V.A.; methodology, E.N.E.; formal analysis, C.B.K.-S. and E.N.E.; investigation, R.V.K. and D.A.P.; resources, A.V.Z. and D.A.P.; data curation, C.B.K.-S.; writing—original draft preparation, A.V.A.; writing—review and editing, C.B.K.-S. and E.N.E.; visualization, A.V.Z. and R.V.K.; supervision and project administration, C.B.K.-S. and A.V.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data obtained by the authors themselves as a result of the study are contained in this article. The data borrowed and analyzed in this study can be found at: Refs. [33,34].

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Alamsyah, A.; Ramadhani, D.P.; Kristanti, F.T.; Khairunnisa, K. Transaction Network Structural Shift under Crisis: Macro and Micro Perspectives. *Economies* **2022**, *10*, 56. [CrossRef]
2. Stroykov, G.A.; Babyr, N.V.; Ilin, I.V.; Marchenko, R.S. System of comprehensive assessment of project risks in energy industry. *Int. J. Eng. Trans. A Basics* **2021**, *34*, 1778–1784. [CrossRef]
3. Reinhart, C.M.; Kenneth, S.R. The Aftermath of Financial Crises. *Am. Econ. Rev. Am. Econ. Assoc.* **2009**, *99*, 466–472. [CrossRef]
4. Resniova, E.; Ponomarenko, T. Sustainable Development of the Energy Sector in a Country Deficient in Mineral Resources: The Case of the Republic of Moldova. *Sustainability* **2021**, *13*, 3261. [CrossRef]
5. Bacova, D.; Khairutdinov, A.M.; Gago, F. Cosmic Geodesy Contribution to Geodynamics Monitoring. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *906*, 012074. [CrossRef]
6. Litvinenko, V. Advancement of geomechanics and geodynamics at the mineral ore mining and underground space development. *Geomech. Geodyn. Rock Masses* **2018**, *1*, 3–16.
7. Blokhin, D.I.; Ivanov, P.N.; Dudchenko, O.L. Experimental study of thermomechanical effects in water-saturatedlimestones during their deformation. *J. Min. Inst.* **2021**, *247*, 3–11. [CrossRef]
8. Ponomarenko, T.; Nevskaya, M.; Jonek-Kowalska, I. Mineral Resource Depletion Assessment: Alternatives. Problems. Results. *Sustainability* **2021**, *13*, 862. [CrossRef]
9. Kazakov, B.P.; Levin, L.Y.; Shalimov, A.V.; Zaitsev, A.V. Development of energy-saving technologies providing comfortable microclimate conditions for mining. *J. Min. Inst.* **2017**, *223*, 116–124. [CrossRef]
10. Du, X.; Zhou, K.; Cui, Y.; Wang, J.; Zhou, S. Mapping Mineral Prospectivity Using a Hybrid Genetic Algorithm–Support Vector Machine (GA–SVM) Model. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 766. [CrossRef]
11. Wu, C.; Zhang, Y.; Zhang, J.; Chen, Y.; Duan, C.; Qi, J.; Cheng, Z.; Pan, Z. Comprehensive Evaluation of the Eco-Geological Environment in the Concentrated Mining Area of Mineral Resources. *Sustainability* **2022**, *14*, 6808. [CrossRef]
12. Service, R.F. Industrial waste can turn planet-warming carbon dioxide into stone. *Science* **2020**, *369*, 1156–1159. [CrossRef] [PubMed]
13. Khayrutdinov, A.; Paleev, I.; Artemov, S. Replacement of traditional components of the backfill mixture with man-made waste. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *942*, 012005. [CrossRef]
14. Carmo, F.F.; Lanchotti, A.O.; Kamino, L.H.Y. Mining Waste Challenges: Environmental Risks of Gigatons of Mud, Dust and Sediment in Megadiverse Regions in Brazil. *Sustainability* **2020**, *12*, 8466. [CrossRef]
15. Khayrutdinov, M.M.; Kaung, P.A.; Chzho, Z.Y.; Tyulyaeva, Y.S. Ensuring Environmental Safety in the Implementation of the Resource-renewable Technologies. *Bezop. Tr. Promyshlennosti* **2022**, *2022*, 57–62. [CrossRef]
16. Łupieżowiec, M.; Rybak, J.; Różański, Z.; Dobrzycki, P.; Jędrzejczyk, W. Design and Construction of Foundations for Industrial Facilities in the Areas of Former Post-Mining Waste Dumps. *Energies* **2022**, *15*, 5766. [CrossRef]
17. Tost, M.; Ammerer, G.; Kot-Niewiadomska, A.; Gugerell, K. Mining and Europe's World Heritage Cultural Landscapes. *Resources* **2021**, *10*, 18. [CrossRef]
18. Lyashenko, V.I.; Golik, V.I.; Klyuev, R.V. Evaluation of the efficiency and environmental impact (on subsoil and groundwater) of underground block leaching (UBL) of metals from ores. *Min. Sci. Technol.* **2022**, *7*, 5–17. [CrossRef]
19. Pashkevich, M.A.; Parshina, M.V. Assessment of the risk of acidic water formation in the areas affected by mining and metallurgical enterprises. *J. Min. Inst.* **2002**, *152*, 82–84.
20. Tcvetkov, P.; Cherepovitsyn, A.; Fedoseev, S. Public perception of carbon capture and storage: A state-of-the-art overview. *Heliyon* **2019**, *5*, e02845. [CrossRef]
21. Sekhohola-Dlamini, L.M.; Keshinro, O.M.; Masudi, W.L.; Cowan, A.K. Elaboration of a Phytoremediation Strategy for Successful and Sustainable Rehabilitation of Disturbed and Degraded Land. *Minerals* **2022**, *12*, 111. [CrossRef]
22. Bac-Bronowicz, J.; Kowalczyk, P.; Bartlewska-Urban, M. Risk Reduction of a Terrorist Attack on a Critical Infrastructure Facility of LGOM Based on the Example of the Żelazny Most Tailings Storage Facility (OUOW Żelazny Most). *Stud. Geotech. Mech.* **2020**, *42*, 376–387. [CrossRef]
23. Blinova, E.; Ponomarenko, T.; Knysh, V. Analyzing the Concept of Corporate Sustainability in the Context of Sustainable Business Development in the Mining Sector with Elements of Circular Economy. *Sustainability* **2022**, *14*, 8163. [CrossRef]
24. Gendler, S.G.; Prokhorova, E.A. Assessment of the cumulative impact of occupational injuries and diseases on the state of labor protection in the coal industry. *Min. Inf. Anal. Bull.* **2022**, *10*, 105–106. [CrossRef]
25. Li, X.; Chertow, M.; Guo, S.; Johnson, E.; Jiang, D. Estimating non-hazardous industrial waste generation by sector, location, and year in the United States: A methodological framework and case example of spent foundry sand. *Waste Manag.* **2020**, *118*, 563–572. [CrossRef] [PubMed]

26. Han, G.; Zhang, J.; Sun, H.; Shen, D.; Wu, Z.; An, X.; Meye, S.M.; Huang, Y. Application of Iron Ore Tailings and Phosphogypsum to Create Artificial Rockfills Used in Rock-Filled Concrete. *Buildings* **2022**, *12*, 555. [CrossRef]
27. Chen, F.; Liu, J.; Zhang, X.; Wang, J.; Jiao, H.; Yu, J. Review on the Art of Roof Contacting in Cemented Waste Backfill Technology in a Metal Mine. *Minerals* **2022**, *12*, 721. [CrossRef]
28. Tcvetkov, P. Engagement of resource-based economies in the fight against rising carbon emissions. *Energy Rep.* **2022**, *8*, 874–883. [CrossRef]
29. De Carvalho, F.A.; Nobre, J.N.P.; Cambraia, R.P.; Silva, A.C.; Fabris, J.D.; dos Reis, A.B.; Prat, B.V. Quartz Mining Waste for Concrete Production: Environment and Public Health. *Sustainability* **2022**, *14*, 389. [CrossRef]
30. Oblitsov, A.Y.; Rogalev, V.A. Prospective ways of diamondiferous rock enrichment wastes utilization at M.V.Lomonosov diamond deposit. *J. Min. Inst.* **2012**, *195*, 163–167.
31. Šajn, R.; Ristović, I.; Čeplak, B. Mining and Metallurgical Waste as Potential Secondary Sources of Metals—A Case Study for the West Balkan Region. *Minerals* **2022**, *12*, 547. [CrossRef]
32. Zglinicki, K.; Małek, R.; Szamałek, K.; Wołkowicz, S. Mining Waste as a Potential Additional Source of HREE and U for the European Green Deal: A Case Study of Bangka Island (Indonesia). *Minerals* **2022**, *12*, 44. [CrossRef]
33. Shaforostova, E.N.; Kosareva-Volod'ko, O.V.; Belyankina, O.V.; Solovykh, D.Y.; Sazankova, E.S.; Sizova, E.I.; Adigamov, D.A. A Tailing Dump as Industrial Deposit; Study of the Mineralogical Composition of Tailing Dump of the Southern Urals and the Possibility of Tailings Re-Development. *Resources* **2023**, *12*, 28. [CrossRef]
34. Gorbatova, E.A.; Kharchenko, S.A.; Ozhogina, E.G.; Yakushina, O.A. Mineralogy of blast furnace gslas. *Vestn. IG Komi SC UB RAS* **2017**, *4*, 24–28. [CrossRef]
35. Golik, V.I.; Klyuev, R.V.; Martyushev, N.V.; Brigida, V.; Efremenkov, E.A.; Sorokova, S.N.; Mengxu, Q. Tailings Utilization and Zinc Extraction Based on Mechanochemical Activation. *Materials* **2023**, *16*, 726. [CrossRef] [PubMed]
36. Ignjatovic, L.; Krstic, V.; Radonjanin, V.; Jovanovic, V.; Malešev, M.; Ignjatovic, D.; Đurdevac, V. Application of Cement Paste in Mining Works, Environmental Protection, and the Sustainable Development Goals in the Mining Industry. *Sustainability* **2022**, *14*, 7902. [CrossRef]
37. Chakrawarthi, V.; Raj Jesuarulraj, L.; Avudaiappan, S.; Rajendren, D.; Amran, M.; Guindos, P.; Roy, K.; Fediuk, R.; Vatin, N.I. Effect of Design Parameters on the Flexural Strength of Reinforced Concrete Sandwich Beams. *Crystals* **2022**, *12*, 1021. [CrossRef]
38. Khairutdinov, A.; Ubysz, A.; Adigamov, A. The concept of geotechnology with a backfill is the path of integrated development of the subsoil. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *684*, 012007. [CrossRef]
39. Khayrutdinov, M.M.; Golik, V.I.; Aleksakhin, A.V.; Trushina, E.V.; Lazareva, N.V.; Aleksakhina, Y.V. Proposal of an Algorithm for Choice of a Development System for Operational and Environmental Safety in Mining. *Resources* **2022**, *11*, 88. [CrossRef]
40. Tayebi-Khorami, M.; Edraki, M.; Corder, G.; Golev, A. Re-Thinking Mining Waste through an Integrative Approach Led by Circular Economy Aspirations. *Minerals* **2019**, *9*, 286. [CrossRef]
41. Han, Z.; Golev, A.; Edraki, M. A Review of Tungsten Resources and Potential Extraction from Mine Waste. *Minerals* **2021**, *11*, 701. [CrossRef]
42. Kanwal, Q.; Li, J.; Zeng, X. Mapping Recyclability of Industrial Waste for Anthropogenic Circularity: A Circular Economy Approach. *Acs. Sustain. Chem. Eng.* **2021**, *9*, 11927–11936. [CrossRef]
43. Ermolovich, E.A.; Ermolovich, O.V. Effects of mechanical activation on the structural changes and microstructural characteristics of the components of ferruginous quartzite beneficiation tailings. *Int. J. Min. Sci. Technol.* **2016**, *26*, 1043–1049. [CrossRef]
44. Öhlander, B.; Chatwin, T.; Alakangas, L. Management of Sulfide-Bearing Waste, a Challenge for the Mining Industry. *Minerals* **2012**, *2*, 1–10. [CrossRef]
45. Kozin, V.Z.; Koltunov, L.V.; Morozov, Y.P. Improving the technology of neutralization of mine waters of the Levikhinsky mine. *Mining J.* **1997**, *11*, 211–214.
46. Perelman, V.I. *Chemist's Quick Reference Book*; Chemistry: Moscow, Russia, 1955; 560p.
47. Rubtsov, Y.I. Influence of input parameters of sodium cyanide on the extraction of gold from quartzite ores. *Min. Inf. Anal. Bull.* **2012**, *1*, 315–319.
48. Eliseeva, E. Environmental management as an important element of the concept of sustainable development of the organization. *Int. Multidiscip. Sci. GeoConference Surv. Geol. Min. Ecol. Manag. SGEM* **2019**, *19*, 299–306.
49. Rybak, Y.; Khayrutdinov, M.; Kongar-Syuryun, C.; Tyulyayeva, Y. Resource-saving technologies for development of mineral deposits. *Sustain. Dev. Mt. Territ.* **2021**, *13*, 406–415. [CrossRef]
50. Ismailov, T.T.; Logachyov, A.V.; Luzin, B.S.; Golik, V.I. Substantiation of gold extraction efficiency from enrichment tails. *Min. Inf. Anal. Bull.* **2009**, *11*, 153–159.
51. Tam, V.W.Y.; Tam, C.M. Evaluations of existing waste recycling methods: A Hong Kong study. *Build. Environ.* **2006**, *41*, 1649–1660. [CrossRef]
52. Sobierajewicz, P.; Adamczyk, J.; Dylewski, R. Ecological and Economic Assessment of the Reuse of Steel Halls in Terms of LCA. *Appl. Sci.* **2023**, *13*, 1597. [CrossRef]

53. Sorokin, A.B.; Zheleznyak, L.M.; Suprunenko, D.V.; Kholmogorov, V.V. Designing modules of system dynamics in decision support systems. *Russ. Technol. J.* **2022**, *10*, 18–26. [CrossRef]
54. Mandych, I.A.; Bykova, A.V.; Gaiman, O.B. Features of assessing the investment attractiveness of high-tech projects. *Russ. Technol. J.* **2022**, *10*, 75–86. [CrossRef]