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Comprehensive resource and environmental assessment of the feasibility of utilizing industrial waste

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Abstract
The study presents analysis of the properties and parameters of waste from high-temperature processing of mineral raw materials – blast-furnace and steelmaking slags, dump slags from copper smelting and ferrochrome production, and incinerator slag. We perform a detailed analysis of the material composition of the studied materials, identify key resource and environmentally significant indicators of the chemical composition and physical properties of the waste, and adopt these as indicators of the resource and environmental potential of the slags. The paper considers approaches to grouping raw materials of industrial origin into categories with similar resource value and environmental hazard. As an alternative for classifying waste from high-temperature processes, we propose a cluster-based approach that enables building a categorization system for industrial raw materials according to their properties and limiting the number of sampling features while maintaining sufficient coverage of the classified materials. After standardizing and checking the multicollinearity of the selected indicators of the slags' resource and environmental potential in the analysed dataset, the study finds that most indicators show low, absent, or random correlation. Using the Statistica software, we rank the studied materials via fuzzy clustering. Based on the resulting distribution, we define three cluster groups for treatment: resource-inert; resource-valuable with moderate environmental impact; and environmentally hazardous, requiring deep processing. The results show that granulated blast-furnace slags, lump blast-furnace slag, and ferrochrome production slag are suitable for manufacturing construction materials without preliminary dressing, provided the products meet environmental safety requirements. Steelmaking slags represent a resource-valuable material with moderate environmental impact and are suitable for producing metal concentrate. Copper-bearing slags and incinerator slags are environmentally hazardous and require deep processing with metal recovery, while tailings need stabilization and neutralization. The obtained results form the basis for further development of a methodology for comprehensive resource and environmental assessment of industrial mineral facilities, which is necessary for transitioning to closed-loop production cycles.

Keywords
waste from high-temperature processes; slags from SMW incineration; resource and environmental assessment; circular economy; correlation analysis; fuzzy clustering method; ranking of industrial facilities

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Introduction

For a long historical period until the mid-20th century, the global and Russian mining and metallurgical industry followed the linear principle "extraction of raw materials – dressing and smelting of finished products – waste disposal", which inevitably led to the accumulation of at least 100 billion tons of industrial waste in the Russian Federation [1] and caused anthropogenic environmental impact in the adjacent areas. An alternative concept capable of changing the current situation is the implementation of the closed-loop production cycle paradigm "cradle-to-cradle" [2, 3], in which production waste generated at all production process stages returns to the original process or serves as raw material for producing goods in other industrial sectors [1]. This reduces the consumption of primary

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natural resources, extends the lifecycle of already extracted resources in a manner similar to a circular natural system, maximizes the use of all products, and decreases the number of landfills and waste disposal sites [4, 5]. The goal of this concept is to achieve environmental equilibrium alongside the economic and social growth of the planet's population welfare [6, 7].

The high-temperature metallurgical processing is characterized by maximum resource intensity and, accordingly, generates the largest volume of waste, which requires special attention to waste management and minimizing environmental impact. At Russian metallurgical enterprises, the specific waste generation per 1 t of products amounts to 8-10 t, which is 1.5-3 times higher than in developed countries [8, 9]. Every 1 million t of smelted steel generates 800 thousand t of slags, 100 thousand t of dust, and 30 thousand t of sludges [4]. Their disposal disrupts the balance of natural geochemical cycles in the areas of their storage.

Metallurgical process waste in the form of slag dumps, i.e., industrial masses in the areas of industrial enterprises [10], currently represents active sources of environmental degradation that exert a complex and long-term impact on all elements of the biosphere [10-12]. The Ural metallurgical sector is the largest in Russia for the production of ferrous and non-ferrous metals. The main centres of ferrous metallurgy and heavy non-ferrous metals metallurgy in Magnitogorsk, Chelyabinsk, Nizhny Tagil, Novotroitsk, Yekaterinburg, Serov, and Zlatoust, feature a high concentration of stored production waste, with metallurgical slags being the most high-tonnage. According to various estimates, the slag dumps of the major Ural metallurgical enterprises accumulate from 350 to 550 million t of slags from blast-furnace, steelmaking, foundry, and ferroalloy production, which represent artificial mineral systems whose main features and properties stem from the technogenesis of their formation and which contain about 40-50 million t of ferrous, non-ferrous, and noble metals [1].

Slag from waste incinerator plants (WIP) is a relatively new type of waste for domestic production. Thermal treatment of waste is one of the most common methods for solid municipal waste (SMW) disposal abroad, as it reduces waste mass by 70 % and volume by up to 90 %, while also generating heat and electricity through the use of off-gases [13]. In the EU countries, about 96 million t of SMW are thermally treated annually, which accounts for 29 % of the total amount of generated waste; globally, approximately 2450 facilities for thermal treatment of SMW operate with a total capacity of 368 million t of waste per year [14]. The slag yield from SMW incineration is 15-25 % of the initial feedstock mass [12]. If this technology spreads in Russia and the target program indicators are achieved, it will lead to the formation of large-tonnage waste. Currently, SMW incineration residues are considered resources whose potential is not fully utilized; moreover, the physical and chemical properties of WIP slags are similar to those of metallurgical slags, and the accumulated experience in managing high-temperature metallurgical process waste can be fully applied when developing their treatment technologies [15].

As shown in [14], SMW incineration residues contain the main elements Si, Ca, Al, O in phases that belong to the three-component system SiO_2-CaO-Al_2O_3, which also forms the basis of most metallurgical slags. The mineral framework of WIP slags is similar to the mineral composition of blast-furnace slags and consists of calcium-bearing silicates, aluminosilicates, aluminates, quartz, calcite, anhydrite, with sulphates and chlorides in smaller amounts. However, in heavy-metal content the slags are close to copper-smelting slags.

Studies on the involvement of large-tonnage high-temperature process waste in reuse and lifecycle extension were carried out by V.A.Chanturiya, K.N.Trubetskoy, L.A.Vaysberg, I.V.Shadrunova, M.A.Pashkevich, E.G.Ozhogina, O.B.Kotova, T.N.Alexandrova, M.N.Sabanova, L.B.Khoroshavin and others. In domestic and international practice, metallurgical slags are typically processed to obtain secondary metal-containing products or construction materials, and less frequently serve as

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sources of iron-bearing or silicate components [16-18]. Many studies focus on the impact of ferrous metallurgy slag dumps on aquatic ecosystems [19, 20]. Considerably less attention goes to soil and plant contamination near metallurgical plants, as well as to the formation of soil-plant cover on the dumps themselves [21, 22]. Literary source [23] proposes a method for utilizing blast-furnace slag together with landfill leachate by means of lithification. However, the practical implementation of such studies remains sporadic, concentrates on resolving acute geoenvironmental situations, and as a rule lacks comprehensive resource and environmental analysis of closed-loop prospects. The experience of realized projects is insufficiently analysed both in terms of the resource value of products obtained from slags and from the standpoint of environmental hazard of these products, the slag processing technologies themselves, and the secondary waste newly generated. A framework for comprehensive resource and environmental assessment of prospects for re-involving industrial raw materials in recycling is not available.

Analysis of specific generation volumes and chemical composition of slags of various genesis [24, 25] shows that the largest-tonnage waste originates in ferrous metallurgy and the power industry, while the most toxic and difficult-to-utilize waste comes from non-ferrous metallurgy and waste incineration plants. Studies have repeatedly shown systematic and significant (by factors and orders of magnitude) exceedances of the maximum permissible concentrations (MPC) of heavy metals in environmental components within the zone of influence of dumps [26-28].

These data indicate the need to shift the priority in slag treatment toward comprehensive and deep processing rather than industrial landfilling, with proper monitoring of slag processing technologies and development of risk-control measures for public health when using products based on industrial raw materials. The study demonstrates that current methods for managing large-tonnage high-temperature process waste cannot effectively account for their resource potential (metal content and reuse feasibility) and environmental hazard (toxicity, MPC exceedances, impact on environmental components). Therefore, waste classification or grouping should employ two separate indicators – a resource indicator (assessment of reuse potential) and an environmental indicator (assessment of risks to nature and human health). Effective slag processing technologies should build on a complete resource and environmental assessment of industrial raw materials and ensure economically viable and environmentally safe integration of production waste into natural geospheric cycles. Only a comprehensive approach that accounts for both aspects can ensure deep waste processing instead of industrial disposal.

Assessment of slag resource potential is a comprehensive analysis aimed at forecasting the feasibility of processing slag into products in demand under current economic models of the metallurgical industry. The resource potential of slags is a function of the following variables: slag volume, qualitative characteristics, particle-size distribution, processing technologies, product demand, processing accessibility, and environmental impact. In this case, priority in the decision determining the feasibility of slag processing goes to qualitative characteristics, or material composition. This is the most technically and materially costly and informative stage of resource potential assessment for any industrial raw material, as it involves analysing a large volume of heterogeneous data whose relevance and reproducibility also undergo critical evaluation. The presence of silicate-series minerals, transitional mineral forms, and heterogeneous microscopic intergrowths of one mineral within others, combined with compositional changes of slags during storage, makes the assessment of their chemical and mineral compositions a multi-iteration process [29]. The starting point for resource assessment of slags is laboratory determination of the chemical (elemental) composition, carried out by X-ray fluorescence (XRF) or atomic emission analysis, which allow identification and quantification of a broad range of elements. These methods are the most common

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for bulk analysis of multicomponent industrial materials; in certain cases, atomic absorption spectrometry confirms the content of Pb and Cr.

Assessment of the environmental hazard of industrial raw material processing consists in determining the impact level of the production cycle on the environment through measurements of dust-gas emissions, discharges into water bodies, and toxicity analysis of secondary waste (dressing tailings). Modern slag processing technologies are not fully closed, and secondary tailings that also require disposal form as a result of processing. In most cases, slag processing tailings acquire additional toxicity due to the reduced particle size or increased water content of the newly formed waste [30, 31]. Therefore, assessment of the volume and quality of secondary waste is an important element for evaluating the environmental hazard of slag processing.

At the same time, the newly developed slag waste management methodology should operate on the basis of a system of resource and environmental indicators that allow coordinating slags by clusters of finished products and processing-related environmental hazard and integrating waste into product manufacturing chains under rapidly changing market conditions and emerging geoenvironmental challenges [32]. For this purpose, studies of the chemical and particle-size compositions and physical parameters were carried out for blast-furnace and steelmaking slags from PAO Magnitogorsk Iron and Steel Works (PAO MMK) and OAO South Ural Mining Company (OAO YuUGPK), dump slags from copper smelting at ZAO Karabashmed, ferrochrome production slag from PAO Klyuchevsky Ferroalloy Plant (PAO KZF), and slag from Moscow waste incineration plant N 3 “EFN-Ecotechprom MSZ 3” (WIP). Representative material samples were taken from slag dumps for the studies; their particle-size distribution was determined by sieve analysis, after which the slags were stage-crushed with removal of metallic inclusions and ground for elemental composition determination by the X-ray fluorescence method.

When setting the task, special attention went to the following components:

• those characterizing the potential for obtaining a meta-containing concentrate from the selected group of slags – mass fraction of metallic iron, mass fractions of FeO, Cu, Zn, Ni;

• those determining slag suitability for the cement industry and construction material production – mass fraction of hydraulically active phases, amorphous phase content, basicity modulus ($CaO + MgO/SiO_2 + Al_2O_3$), mass fraction of free CaO, content of material in the 5-70 and 0-5 mm fractions (these size classes are relevant for resource and environmental assessments, as they determine the feasibility of producing crushed stone and sand, as well as the potential dust load of slag), true and bulk densities;

• those underlying the main manifestations of environmental hazard for the selected group of slags – mass fractions of toxic metals (Pb, Cr), mass fractions of S and P as harmful impurities for many types of products, dust fraction content.

The selected indicators meet three criteria – relevance for resource potential assessment (metal recovery feasibility, suitability for the construction industry), relevance for environmental hazard assessment (toxicity, dust load, leachability), and feasibility of determination by standard analytical methods (XRF, sieve analysis, X-ray diffraction), which ensures reproducibility of results.

Methods

The outlined approach to slag waste management necessitates developing a comprehensive classification of industrial facilities not only by environmental hazard but also with regard to their resource value. Creating a practical tool that provides an organized set of the physicochemical properties of an industrial facility will maximize consideration of the resource-saving value of slag treatment and minimize environmental impact. Analysis of the results from studying slags of various genesis shows a wide range of contents of major chemical components and physical and production properties

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of the studied materials, which makes it impossible to conduct a resource and environmental assessment of slag processing and determine promising directions for their treatment without preliminary statistical processing.

Existing classifications of industrial mineral facilities [33] typically employ a traditional hierarchical approach that, despite its intuitive clarity and ease of implementation, does not allow analysing materials across several aspects at different levels, introducing new materials with properties different from those adopted, or forming a classification structure for new treatment directions. At the same time, attempts to apply artificial intelligence (AI) in the field of waste management and systematization of waste handling methods are underway to understand the effectiveness of various technologies based on AI [34].

The solution to the problem of ranking industrial mineral facilities is feasible through a cluster approach [35-37], which allows creating a flexible system of categories for industrial raw materials according to their characteristics and distributing materials among clusters by membership, without losing sufficient coverage of materials – which is especially relevant for raw materials suitable for multiple treatment directions.

For example, when selecting a treatment technology or reducing the negative environmental impact of copper-containing slags, they can be ranked by metallic iron, copper, and zinc content for processing to obtain secondary metal-containing products; by particle-size distribution and the presence of hydraulically active phases for producing construction, agricultural, and geotechnological products from the mineral part of slags; and by sulphur, lead, and other toxic element content, as these are harmful impurities for a wide range of products. The described characteristics and their combinations can be suitable for classifying other types of high-temperature process waste as well, while some apply exclusively to non-ferrous metallurgy slags. Cluster analysis methods allow dividing the studied set of industrial facilities into groups of compact subsets similar to each other by some parameter or group of parameters, called clusters.

When ranking industrial facilities into clusters, the most appropriate approach is to use fuzzy clustering methods [38], in which the same material can belong to several (or even all) clusters simultaneously, but with varying degrees of membership.

A cluster in an *n*-dimensional feature space is characterized by a centre (the geometric mean of the points) and a radius (the maximum distance of the points from the centre). A material belongs to a cluster if the distance from the material to the cluster centre is less than the radius. If this condition holds for two or more clusters, the material is disputed.

Data on the chemical composition and chemical and physical properties of slags serve as indicators determining the resource and environmental prospects of industrial facility processing. Moreover, the same indicators can account for the resource value of slags and at the same time act as unfavourable toxic components for the environment.

Slag processing to obtain metal concentrates is a key element of modern resource-saving technologies [39-41]; therefore, the mass fractions of metallic iron Fe_{met}, Cu, Ni, and Zn – whose concentrates have a consistently high market value (relative to other market participants) and are typically associated with noble and platinum-group metals, which increases the liquidity of industrial waste as a resource – were selected as indicators of slag resource potential. Iron oxides determine the feasibility of producing a corrective additive for the raw mix and ballast crushed stone. The basicity modulus and the degree of crystallinity indirectly determine the feasibility of using slag as a hydraulic additive to cement. The content of grains in the 5-70 mm fraction in slags determines the feasibility of producing crushed stone and fractionated aggregates.

In assessing the environmental hazard of slags, the presence of Fe_{met} and intermetallic compounds is considered an adverse factor, as it promotes oxidative leaching upon contact with water and atmospheric oxygen. In general, the environmental hazard associated with Pb-Cr-Zn-Cu-Ni-Mn is determined by their leachability and decreases in the order indicated [41]. A high degree of crystallinity and a low basicity

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modulus of the slag indicate the stability of its mineral phases. Slags with high crystallinity consist of stable minerals, and the risk of environmental contamination is minimal if such slags are stored properly. The presence of grains smaller than 5 mm in slags complicates the operations of storage, transportation, and processing.

Statistica software was used to perform cluster analysis, as this system is one of the most widely recognized statistical processing packages in global practice within the Windows environment. For the cluster analysis of the selected high-temperature process waste, the most well-known and frequently applied method was chosen – the fuzzy clustering algorithm, which is based on the method of undetermined Lagrange multipliers [42-44].

Basic fuzzy clustering algorithm for classifying industrial facilities by resource potential and environmental hazard:

1. Select parameters characterizing the treatment prospects of an industrial facility as a raw material source for obtaining secondary products, and parameters determining the potential environmental hazard during its storage and processing.

2. Normalize the selected variables and check for multicollinearity.

3. Choose the number of clusters based on a priori information about the studied materials and set the algorithm parameters: c – number of clusters; m – exponential weight; ε – accuracy at which computations are terminated. For the analysis, we set $c = 3$, $m = 2$, $\varepsilon = 0.05$.

4. Randomly generate the fuzzy partition matrix.

5. Calculate the cluster centres v_i.

6. Calculate the distances between materials from X and the cluster centres using the standard Euclidean norm $D_{ij} = \sqrt{\left\| x_j - c_i \right\|^2}$.

7. Recalculate the fuzzy partition matrix elements:

if $D_{ij} > 0$, $u_{ij} = 1 \Big/ \left[D_{ij}^2 \sum_{i=1}^{c} \frac{1}{D_{ij}^2} \right]^{\frac{1}{m-1}}$;

if $D_{ij} = 0$, $u_{ij} = \begin{cases} 1, i = j; \\ 0, i \neq j. \end{cases}$

8. Check the condition $\left\| U - U^* \right\|^2 < \varepsilon$, where U^* is the fuzzy partition matrix at the previous iteration of the algorithm. If "yes", terminate the computations; else return to step 3 of the algorithm.

The number of clusters was set to $c = 3$ based on a substantive analysis of common practices for managing high-temperature process waste, which distinguish three fundamentally different strategies: direct use without dressing (resource-inert waste), processing with extraction of useful components (resource-valuable waste), and disposal or placement after stabilization (environmentally hazardous waste).

Discussion

The chemical composition and physical properties of the studied materials are presented in Tables 1 and 2. The presented sample of seven slag types is limited by the current diversity of large-tonnage high-temperature process waste in the Ural industrial region. The resulting cluster structures are illustrative in nature and require confirmation on an expanded database (at least 20-30 types).

The quality of cluster analysis depends directly on the representativeness of the source data. Therefore, at the initial stage of the work, standardization of the source data and verification of multicollinearity of the selected resource and environmental indicators in the studied data set were carried out. To compare heterogeneous indicator parameters, their numerical values were reduced to a dimensionless form and a uniform range of variation by means of min-max data normalization (division by the sample mean).

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Table 1

Chemical composition of slags of various origins*

Slag type	Mass fraction, %									
	Fe_{met}	FeO	Cu	Zn	Ni	Pb	MnO	Cr	S	P
Granulated blast-furnace slag, OAO YuUGPK	0.3	0.7	Less than 0.002	Less than 0.002	0.001	Less than 0.002	0.90	Less than 0.002	1.140	0.045
Lump blast-furnace slag, PAO MMK	4.5	2.2	0.001	0.001	0.003	Less than 0.002	9.67	Less than 0.002	1.690	0.036
Steelmaking slag, PAO MMK	21.0	23.7	0	0	0.023	Less than 0.002	6.30	0.010	0.100	1.980
Electric steelmaking slag, PAO MMK	13.0	24.6	0.120	1.540	0.038	Less than 0.002	7.20	0.010	0.087	1.340
Copper-containing slag, ZAO Karabashmed	3.5	41.8	1.100	0.670	0.018	0.70	1.24	0.038	1.430	0.200
Ferrochrome production slag, PAO KZF	0.8	3.2	0.013	0.003	Less than 0.002	0.01	1.17	5.230	0.210	0.067
WIP	5.4	13.1	0.340	0.820	0.051	0.45	0.41	0.020	0.530	0.760

* The uncertainty of the analysis results for elements at a confidence level of 0.95 does not exceed the values specified in GOST 30510-97 "Slags of metallurgical production. Method of X-ray fluorescence analysis".

Table 2

Physical properties of slags of various origins

Slag type	Crystallinity	Basicity modulus	CaO_{free}, %	Density		Particle size distribution, %	
				true, g/cm^3	bulk, t/m^3	Less than 5 mm	5-70 mm
Granulated blast-furnace slag, OAO YuUGPK	8.2	1.1	0.3	2.8	1.2	84.3	15.7
Lump blast-furnace slag, PAO MMK	87.4	1.2	0.2	3.2	1.5	8.4	91.6
Steelmaking slag, PAO MMK	81.2	3.1	8.2	3.5	1.7	26.5	73.5
Electric steelmaking slag, PAO MMK	92.3	2.8	7.4	3.4	1.6	18.4	81.6
Copper-containing slag, ZAO Karabashmed	73.5	0.6	0.1	3.7	2.2	76.4	23.6
Ferrochrome production slag, PAO KZF	83.6	0.9	0.2	2.9	1.4	13.2	86.8
WIP	63.9	0.4	0.3	2.6	1.0	55.7	44.3

The absolute value of the correlation coefficient r indicates the strength of the relationship between variables; however, when evaluating relationships, one should also consider their significance, characterized by the coefficient p. The p-value shows the probability of obtaining the observed correlation by chance, i.e., in the absence of a real relationship between the variables. The smaller the p-value, the greater the significance of the correlation. At $p \leq 0.05$, the probability of observing a chance correlation is less than 5 %.

The correlation analysis results (Fig.1, 2) were examined to identify pairs of variables with correlation coefficients $r > 0.7$ at $p \leq 0.05$. The presented data show predominantly low, absent, or random correlation for both resource and environmental indicators. A statistically significant correlation was determined for the following indicators:

• resource indicators – between the basicity modulus and the mass fraction of metallic iron in slags ($r = 0.88$; $p = 0.009$); between the mass fractions of Cu and FeO ($r = 0.78$; $p = 0.039$); between the crystallinity and the content of grains in the 5-70 mm fraction ($r = 0.88$; $p = 0.009$); between the mass fractions of Ni and Zn ($r = 0.76$; $p = 0.047$);

• environmental indicators – between the mass fractions of Cu and Pb ($r = 0.94$; $p = 0.001$).

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Indicators	abc(r) ≥ 0 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1							
	Fe_{met}	FeO	Cu	Zn	Ni	Crystallinity, %	Basicity modulus	Content of 5-70 mm fraction grains, %
Fe_{met}	1.00	0.42	0.20	0.21	0.45	0.44	0.88	0.37
FeO	0.42	1.00	0.78	0.53	0.45	0.35	0.22	0.25
Cu	0.20	0.78	1.00	0.35	0.24	0.07	0.43	0.55
Zn	0.21	0.53	0.35	1.00	0.76	0.30	0.17	0.02
Ni	0.45	0.45	0.24	0.76	1.00	0.25	0.16	0.06
Crystallinity, %	0.44	0.35	0.07	0.30	0.25	1.00	0.33	0.78
Basicity modulus	0.88	0.22	0.43	0.17	0.16	0.33	1.00	0.46
Particle size distribution of 5-70 mm grains, %	0.37	0.25	0.55	0.02	0.06	0.78	0.46	1.00

Fig.1. Heat map of absolute correlations of resource indicators $n = 7$

Indicators	p ≤ 0.001 0.010 0.025 0.050 0.100 0.150 0.200 0.350 0.500 1							
	Fe_{met}	FeO	Cu	Zn	Ni	Crystallinity, %	Basicity modulus	Content of 5-70 mm fraction grains, %
Fe_{met}		0.344	0.667	0.646	0.309	0.319	0.009	0.413
FeO	0.344		0.039	0.220	0.310	0.444	0.640	0.594
Cu	0.667	0.039		0.436	0.603	0.888	0.332	0.203
Zn	0.646	0,220	0.436		0.047	0.507	0.711	0.961
Ni	0.309	0.310	0.603	0.047		0.593	0.732	0.900
Crystallinity, %	0.319	0.444	0.888	0.507	0.593		0.463	0.037
Basicity modulus	0.009	0.640	0.332	0.711	0.732	0.463		0.304
Particle size distribution of 5-70 mm grains, %	0.413	0.594	0.203	0.961	0.900	0.037	0.304	

Fig.2. Heat map of the significance of correlations of resource indicators $n = 7$

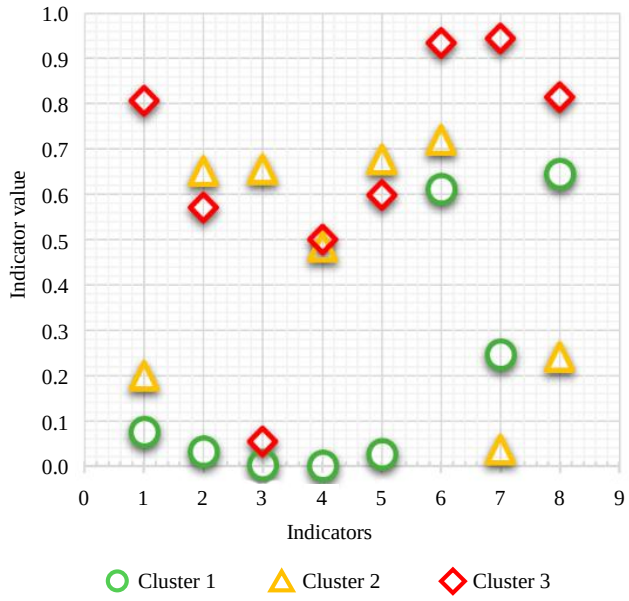
For cluster analysis, the absence of strong multicollinearity is more important than the precise estimation of each correlation. The vast majority of variable pairs (over 85 %) have $r < 0.7$, which allows using the Euclidean metric without distortions. Given the limited sample size, these interpretations should be regarded as preliminary. Final confirmation of the physical sense of the correlations requires expanding the database.

As a result of the cluster analysis, each industrial facility is represented as a point in an n-dimensional space, where n is the number of selected indicators; for slag resource potential assessment, $n = 8$, and for environmental hazard assessment, $n = 11$. Each industrial facility belongs to one cluster, characterized by the cluster centre (estimated average values of the selected indicators) (Fig.3, 4) and the distance between cluster centres.

The obtained data allow dividing the studied materials into clusters according to the selected resource and environmental indicators (Table 3). The resulting cluster structures are stable for $c = 2, 3, 4$ with respect to the distribution of blast-furnace and steelmaking slags; however, the three-cluster model provides the most meaningful interpretation and is supported by a silhouette index $S > 0.5$.

The observed mismatch of clusters (e.g., steelmaking slags belonging to cluster 3 based on resource indicators but to cluster 2 based on environmental indicators) cannot be revealed through a traditional literature review, which usually describes either the resource potential or the environmental hazard, but not their relationship for the same samples. This mismatch constitutes the main scientific result: it quantitatively demonstrates that a high resource value of a waste material does not guarantee its environmental safety, and vice versa. Therefore, a correct assessment of waste management prospects requires the simultaneous use of both groups of indicators.

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Cluster 1 – direct use. The materials are characterized by a minimal content of non-ferrous metals, relatively low crystallinity, and a medium particle-size distribution

Cluster 2 – require special processing. The main resource value is due to the presence of non-ferrous metals; the material is complex to process. The dressing tailings will require stabilization

Cluster 3 – require dressing. The materials are characterized by the presence of metallic iron and a low content of non-ferrous metals, with a stable crystalline structure. They represent a durable lump material

Fig.3. Mean values of resource indicators for various clusters: 1 – Fe_{met}; 2 – FeO; 3 – Cu; 4 – Zn; 5 – Ni; 6 – crystallinity, %; 7 – basicity modulus; 8 – content of 5-70 mm fraction grains, %



Cluster 1 – high hazard. The materials are characterized by a high probability of leaching and contamination of products with heavy metals. Strict production control and stabilization are required. This is the most toxic material

Cluster 2 – low hazard. It has a stable silicate structure and imposes a relatively low dust load. Production processes should be carried out with monitoring of the metallic iron content

Cluster 3 – medium hazard. The risk of contamination with heavy metals is lower than in Cluster 1. After processing and converting the metals into finished products, a repeat analysis will be required to verify compliance with the standards for slag-derived products

Fig.4. Mean values of environmental indicators for various clusters: 1 – Fe_{met}; 2 – S; 3 – Pb; 4 – Cr; 5 – Zn; 6 – Cu; 7 – Ni; 8 – MnO; 9 – crystallinity; 10 – basicity modulus; 11 – content of 0-5 mm fraction grains, %

Table 3

Ranking of research materials by cluster

Slag type	Cluster	
	Resource indicators	Environmental indicators
Granulated blast-furnace slag, PAO MMK	1	3
Lump blast-furnace slag, OAO YuUGPK	1	3
Steelmaking slag, PAO MMK, OAO YuUGPK	3	2
Electric steelmaking slag, PAO MMK	3	2
Copper-bearing slag, ZAO Karabashmed	2	1
Ferrochrome production slag, PAO KZF	1	3
WIP	2	1

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Analysis of the obtained "resource potential – environmental hazard" relationships for slags of various genesis allows the following conclusions regarding their treatment prospects:

• Granulated blast-furnace slags, lump blast-furnace slag, and ferrochrome production slag are characterized by a minimal content of non-ferrous metals, low crystallinity, and a medium particle-size distribution; therefore, they can be used without preliminary dressing or after sorting.

• Steelmaking and electric steelmaking slags were identified as a separate group of materials with the most stable, inert silicate structure and a low dust load due to a high degree of crystallinity and a low basicity modulus.

• Copper-containing and incinerator (WIP) slag are the most problematic raw materials for treatment and require special attention and control of production processes. Metal extraction will require deep processing, and the dressing tailings will require stabilization and detoxification.

Conclusion

The conducted studies confirmed that existing linear approaches to managing high-temperature process waste do not allow simultaneous consideration of both its resource value and environmental hazard. This work proposes and substantiates, for the first time, the introduction of two independent groups of indicators – resource indicators (mass fractions of Fe_{met}, Cu, Zn, Ni; basicity modulus; crystallinity; particle-size distribution) and environmental indicators (mass fractions of Pb, Cr, S, P; proportion of dust fractions; leachability of toxic elements). This separation, combined with the cluster approach, enables a transition from general principles of high-temperature waste management to its effective and safe treatment.

Applying the fuzzy clustering method to a dataset comprising seven slag types (blast-furnace, steelmaking, electric steelmaking, copper-containing, ferrochrome, and incinerator plant slags) demonstrated that ranking the materials by resource and environmental indicators yields non-coinciding cluster structures. This proves that a high resource value of waste does not guarantee its environmental safety, and vice versa. Consequently, a correct assessment of treatment prospects is impossible without simultaneously accounting for both groups of factors. Unlike existing qualitative classifications of industrial waste, this work introduces, for the first time, a quantitative two-criteria approach to their ranking based on independent sets of resource and environmental indicators. The proposed approach formalizes decision-making and can serve as a basis for digital waste management systems. It also reveals hidden environmental risks associated with conventional treatment methods – for example, in the production of abrasives from copper-containing slags.

Based on the obtained distribution, three treatment cluster groups were formulated:

• Resource-inert (Cluster 1 by resource indicators, Cluster 3 by environmental indicators) – granulated and lump blast-furnace slags, and ferrochrome production slag. They are suitable for direct use in the cement industry, in the production of crushed stone and silicate materials without deep dressing, while environmental risks are minimal (stable silicate matrix, low content of toxic elements).

• Resource-valuable with moderate environmental impact (Cluster 3 by resource indicators, Cluster 2 by environmental indicators) – steelmaking and electric steelmaking slags. The high content of metallic iron (13-21 %) and the inert crystalline structure allow efficient extraction of metal concentrate for recycling back into the process, while the processing tailings can be used in road construction and geotechnical barriers. Monitoring of dust emissions and leaching of residual heavy metals is required.

• Environmentally hazardous, requiring deep processing (Cluster 2 by resource indicators, Cluster 1 by environmental indicators) – copper-containing and incinerator slag. High concentrations of Cu, Zn, Pb, and Cr in combination with a low basicity modulus and a high proportion of dust fractions create a systematic exceedance of maximum permissible concentrations of heavy metals in environmental components. Treatment of such slags is possible only under the condition of integrated metallurgical processing with extraction of non-ferrous metals, followed by stabilization or detoxification of the tailings.

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Thus, the proposed cluster approach, with the introduction of separate resource and environmental indicators, not only enables the classification of accumulated industrial waste but also allows forecasting the most effective and safe directions for its management. The obtained results form the basis for further development of a methodology for the comprehensive resource and environmental assessment of industrial mineral facilities, which is essential for transitioning to closed-loop production cycles. The proposed approach should be regarded as a pilot methodological tool suitable for classifying industrial facilities under conditions of limited source data. Further research will focus on creating an open database of the physicochemical properties of slags, using machine learning methods.

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