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ANALYSIS OF GLOBAL AND NATIONAL PRACTICES OF IMPLEMENTING CIRCULAR ECONOMY PRINCIPLES IN UNDERGROUND COAL MINING

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АНАЛІЗ СВІТОВИХ І ВІТЧІЗНЯНИХ ПРАКТИК РЕАЛІЗАЦІЇ ПРИНЦИПІВ ЦИРКУЛЯРНОЇ ЕКОНОМІКИ ПРИ ПІДЗЕМНОМУ ВИДОБУВАННІ ВУГІЛЛЯ

Purpose. To identify current trends in the implementation of circular economy principles in underground coal mining through bibliometric and thematic analyzes of scientific publications, systematize global and Ukrainian practices of managing associated resource streams, and determine promising approaches to their integrated utilization in Ukrainian coal mines.

The methods. Bibliometric, network, thematic, and comparative analyzes were applied to scientific publications indexed in the Scopus database for 2000-2025. A dataset of 2,931 unique publications was compiled using six thematic search strategies. VOSviewer 1.6.20 was employed to analyze the co-occurrence of author keywords, visualize their relationships, and identify thematic clusters. A content analysis of scientific publications was conducted to systematize international technological practices and compare them with the experience of Ukrainian coal mines.

Findings. Eight thematic clusters were identified, and five main areas of circular resource utilization in coal mining were systematized: mining waste recycling, mined-out area backfilling, mine water utilization, coal mine methane recovery and utilization, and critical raw material extraction. An increase in publication activity was observed across the investigated areas, and the main trends in their technological development were identified. A comparison of international and Ukrainian practices demonstrated that mine water reuse and energy recovery from coal mine methane have already been implemented at individual mines in Western Donbas, whereas underground waste rock retention and critical element extraction require further development.

The originality. The thematic structure of research on circular resource utilization in coal mining was established through bibliometric and thematic analyses. Relationships among eight thematic clusters were identified, and five principal technological areas were systematized. Differences between global research trends and the practical implementation of the corresponding technologies in Ukraine were revealed.

Practical implementation. The findings can be used to identify promising approaches to the integrated utilization of associated resources in Ukrainian coal mines. For the conditions of Western Donbas, potential applications include underground waste rock retention, mine water reuse, energy recovery from coal mine methane, and the extraction of critical elements from coal and associated mining products.

Keywords: *underground coal mining, circular economy, bibliometric analysis, VOSviewer, waste rock, mined-out area backfilling, critical raw materials, Western Donbas.*

Introduction. Modern industry is evolving amid increasingly stringent requirements for the rational use of mineral resources, reduced environmental impacts, and a gradual transition from the traditional linear production model towards the principles of a circular economy. This transition is particularly relevant to underground coal mining, which generates substantial quantities of associated resources and waste streams in addition to coal, including waste rock, coal-bearing waste, mine water, methane, and coal preparation by-products. Under the conventional approach, most of these streams are primarily regarded as waste and sources of adverse environmental impacts. In contrast, circular economy principles promote their reuse and conversion into secondary material, energy, and mineral resources.

The increasing extraction of mineral resources is accompanied by growing volumes of mining waste, placing additional pressure on the environment and highlighting the need for its reuse. According to projections [1], global mining waste generation could increase from 227.3 billion tonnes in 2025 to 324.1 billion tonnes in 2034, representing a 42.6% increase (Fig. 1).

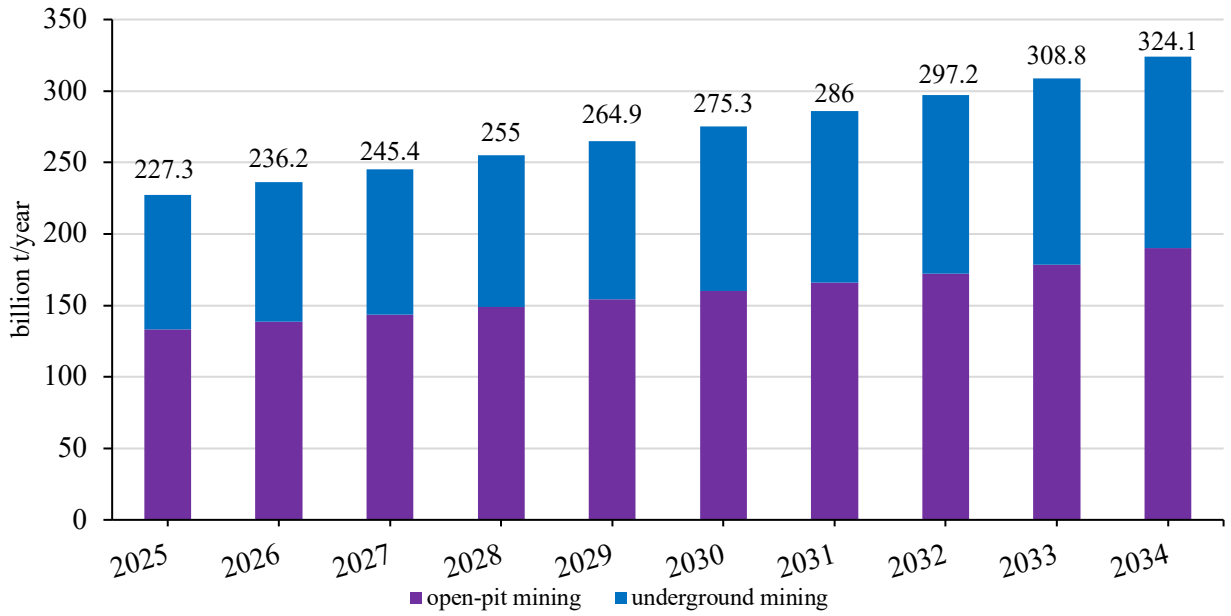


Fig. 1. Projected global mining waste generation by mining method, 2025–2034

Under these conditions, the implementation of circular economy principles aimed at reducing waste generation, reusing associated resources, and improving resource-use efficiency becomes particularly important. In underground coal mining, this requires the integrated utilization of resources.

Technologies aimed at achieving more comprehensive utilization of coal mine resources are gradually being developed and implemented worldwide. These include the processing and reuse of waste rock and coal-bearing waste, their application as backfill materials in mined-out areas, mine water treatment and reuse, coal mine methane capture and subsequent energy generation, and the recovery of valuable components from coal and waste generated during its extraction and processing. These developments are transforming the conventional concept of a coal mine, which can be regarded not merely as a

coal extraction facility but as an integrated production system in which associated products and waste streams are reused as material, energy, and mineral resources.

The relevance of this transition is further reinforced by changes in the structure of global demand for mineral resources. Alongside conventional waste management practices, increasing attention is being paid to the potential recovery of rare earth elements and other critical elements from coal, coal-bearing rocks, coal ash and slag, and other secondary sources.

The bibliometric analysis conducted in this study confirms the significance of this research area. At the same time, the results of thematic clustering indicate that the circular economy in coal mining has not yet emerged as a distinct research field but is developing at the intersection of several interconnected scientific and technological areas.

For Ukraine, this issue is of particular importance given the need to improve the efficiency of resource utilization in coal mines and reduce the volume of mining waste. A promising approach involves moving beyond the conventional view of waste rock, mine water, methane, and associated mineral components solely as by-products of coal extraction towards an integrated approach to their reuse, processing, and recovery. However, the practical implementation of such an approach requires identifying the most promising technological pathways, taking into account international experience and the specific operating conditions of Ukrainian coal mining enterprises.

The aim of this study is to identify current trends in the implementation of circular economy principles in underground coal mining through bibliometric and thematic analyzes of scientific publications, to systematically review international and Ukrainian practices for managing associated resource streams, and to identify promising approaches to their integrated utilization in Ukrainian coal mines.

Research methodology. To achieve the study aim, bibliometric, network, comparative, and content analyzes of scientific publications were conducted. The dataset was compiled from the Scopus database for the period 2000-2025. Searches were performed across titles, abstracts, and keywords (TITLE-ABS-KEY) using thematic search queries related to the circular utilization of resource streams generated by coal mining.

The search for scientific publications was conducted in two stages. In the first stage, a general dataset was compiled on the topic of *Circular Economy + Coal Mining* to examine the development of circular economy principles in coal mining. In the second stage, five key technological areas were investigated separately: mining waste management, mined-out area backfilling, mine water utilization, coal mine methane capture and utilization, and critical raw material recovery. The search queries also included terms related to waste reuse and recycling, the recovery and beneficiation of valuable components, and the reintegration of recovered resources into the production cycle.

The search and export of bibliographic data from the Scopus database were conducted on 24 August 2026. Publications from 2000 to 2025 were included in the analysis. Following six search stages (Table 1), a combined dataset of 2,967 scientific publications was compiled. After screening and removing 36 duplicate records based on DOIs, other bibliographic identifiers, and publication titles, the final dataset comprised 2,931 unique publications.

Table 1

Search strategy for the bibliometric study

No.	Research area	Number of publications	Search query
1	Circular economy	18	TITLE-ABS-KEY("circular economy" AND ("coal mining" OR "coal mine"))
2	Mining waste management	629	TITLE-ABS-KEY(("coal gangue" OR "coal mine waste") AND (recycling OR reuse OR utilization OR valorization))
3	Mined-out area backfilling	29	TITLE-ABS-KEY(("coal mine" OR "coal mining") AND (backfill OR backfilling) AND (waste OR gangue OR "fly ash"))
4	Mine water utilization	107	TITLE-ABS-KEY(("coal mine water" OR "coal mine drainage") AND (reuse OR treatment OR recovery OR utilization))
5	Coal mine methane utilization	322	TITLE-ABS-KEY(("coal mine methane" OR "ventilation air methane") AND (utilization OR recovery OR energy))
6	Critical raw material recovery	1862	TITLE-ABS-KEY((coal OR "coal fly ash" OR "coal gangue") AND ("rare earth elements" OR "critical elements" OR germanium OR gallium) AND (recovery OR extraction OR enrichment))

The thematic structure of the publications was analyzed using VOSviewer 1.6.20 based on the co-occurrence of author keywords. Prior to the analysis, synonymous terms, abbreviations, and spelling variants were consolidated using a thesaurus. A total of 6,949 keyword variants were identified. Applying a minimum occurrence threshold of 10,111 keywords were selected for further analysis. The resulting network comprised 1,076 links with a total link strength of 3,033, and the keywords were grouped into eight thematic clusters.

The identified bibliometric clusters were treated as thematic research groups formed on the basis of relationships between keywords rather than as predefined areas of the circular economy. Analysis of the cluster structure and publication content enabled the systematization of technological solutions according to the main areas of circular resource utilization in underground coal mining. Temporal changes in research topics were assessed using the average publication year of the keywords, while international and Ukrainian practices were compared in terms of the extent to which the respective technological solutions have been implemented in practice.

Research results. The bibliometric analysis revealed that research on circular economy principles in coal mining encompasses a wide range of thematic areas. The term *circular economy* itself appears in relatively few publications in the context of coal mining. However, individual aspects of circular resource utilization, including mining waste recycling, mine water and methane utilization, and the recovery of valuable elements, have already emerged as distinct fields of scientific research.

To characterize the structure of this research field, a co-occurrence analysis of author keywords was performed using VOSviewer. After consolidating synonymous terms and applying a minimum occurrence threshold of 10, a total of 111 keywords were included in the analysis. The resulting network comprised 1,076 links with a total link strength of 3,033, and eight thematic clusters were identified. The keyword co-occurrence network is presented in Fig. 2.

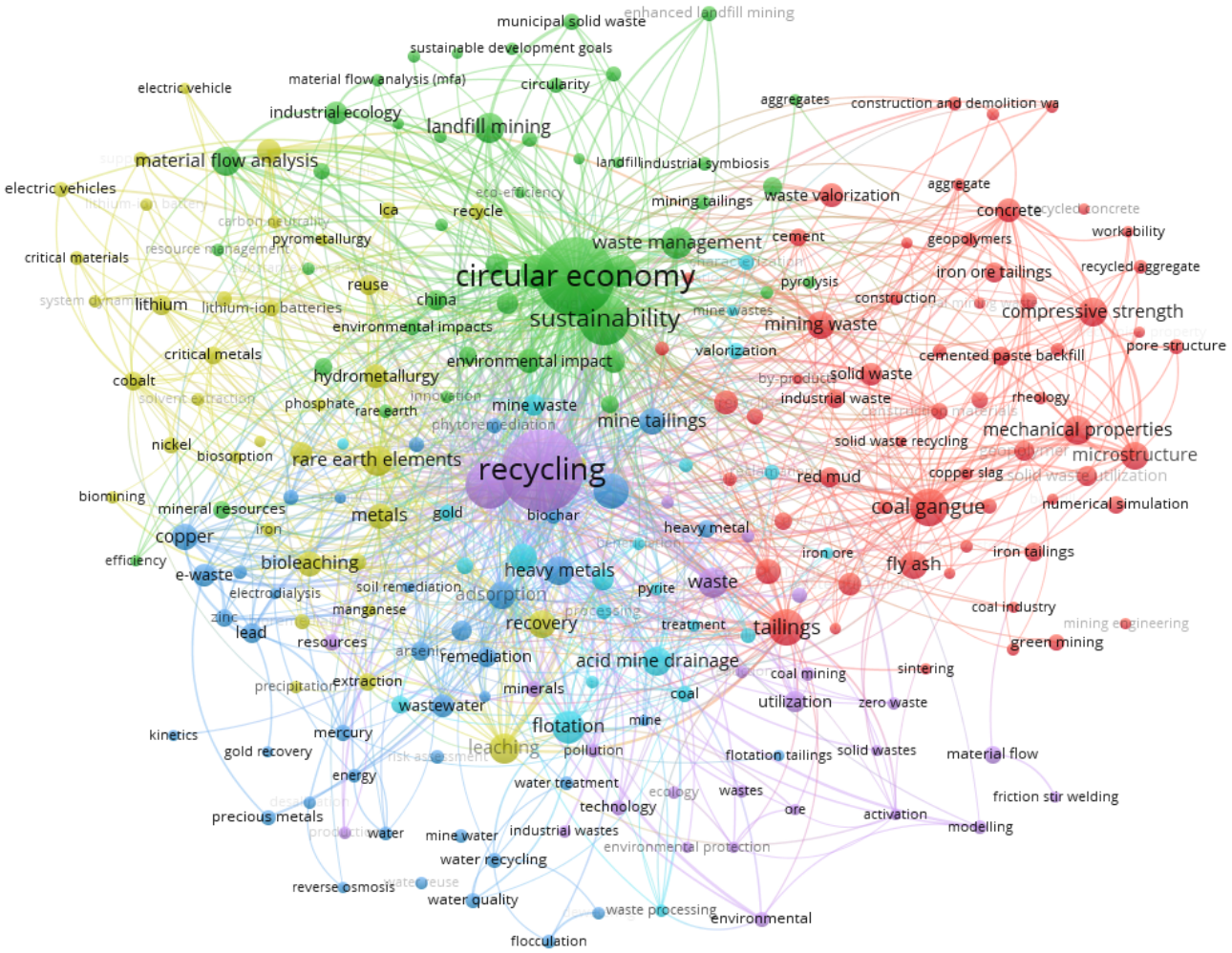


Fig. 2. Author keyword co-occurrence network in publications on circular resource utilization in coal mining

The network analysis revealed that *rare earth elements* was the most prominent term, with 546 occurrences, 89 links, and a total link strength of 817. Other prominent nodes included *coal* (281 occurrences), *coal gangue* (265), *trace elements* (142), *coal fly ash* (118), *fly ash* (101), *coal mine methane* (95), *geochemistry* (89), *leaching* (85), and *germanium* (83).

The findings indicate that the recovery of valuable elements from coal and associated mining and processing by-products is one of the major research areas. At the same time, the high frequency of terms such as *coal gangue*, *coal fly ash*, *fly ash*, *recycling*, and *recovery* reflects growing research activity in the processing of coal industry waste and its utilization as secondary raw materials.

Based on the clustering results, thematic groups were identified and characterized according to their principal keywords and the patterns of relationships between them (Table 2).

Table 2

Thematic characterization of clusters identified through VOSviewer analysis

Cluster	Main keywords	Thematic interpretation
1	coal, trace elements, geochemistry, models of occurrence, critical elements, lithium, minerals in coal	Coal geochemistry and critical elements
2	coal mine methane, coalbed methane, methane, mine water, coal mine drainage, acid mine drainage, resource utilization	Coal mine methane and mine water utilization
3	coal gangue, mechanical properties, compressive strength, geopolymer, concrete, coal mine waste	Recycling and utilization of coal mining waste
4	rare earth elements, coal fly ash, recovery, recycling, extraction, acid leaching, bioleaching, hydrometallurgy	Recovery of valuable elements from mining and processing waste
5	fly ash, coal ash, germanium, lignite, bottom ash, yttrium, critical raw materials	Coal ash and coal-bearing byproducts as secondary raw materials
6	circular economy, sustainability, waste management, resource recovery, critical minerals, life cycle assessment, energy transition	Circular economy and sustainable resource utilization
7	adsorption, lanthanides, separation, magnetic separation, solvent extraction	Technologies for the recovery and separation of valuable components
8	gallium, enrichment, distribution, occurrence, ICP-MS	Distribution, determination, and enrichment of associated elements

Cluster 1 encompasses studies on the geochemical composition of coal and its valuable element content. The main keywords are *coal, trace elements, geochemistry, models of occurrence, critical elements,* and *lithium*. In particular, the term *trace elements* has 142 occurrences and a total link strength of 223, indicating significant research interest in the concentrations, distribution, and modes of occurrence of valuable elements in coal.

Cluster 2 encompasses studies on coal mine methane and mine water. The most frequently occurring term is *coal mine methane* (95 occurrences), followed by *coalbed methane* (28), *gas* (27), *methane* (16), *acid mine drainage* (33), *coal mine drainage* (12), and *mine water* (15). These findings indicate significant research interest in coal mine methane and mine water as associated resources that can be beneficially utilized during coal mine operations.

Cluster 3 encompasses studies on the processing and reuse of mining coal waste. The central term is *coal gangue* (265 occurrences), which is associated with *mechanical properties, compressive strength, microstructure, geopolymer, concrete, solid waste utilization,* and *mining waste*. These findings indicate that research in this cluster on the utilization of waste rock as a secondary raw material, primarily for the production of construction materials.

Clusters 4, 5, 7, and *8* comprehensive studies on the identification, concentration, and recovery of valuable elements from coal and mining and processing waste. The associations between the term *rare elements* and keywords such as *recovery, extraction, leaching, bioleaching,* and *hydrometallurgy* indicate a shift from determining the concentrations and distribution of valuable elements towards developing technologies for their practical recovery.

Cluster 6 links the term *circular economy* (30 occurrences) with keywords such as *sustainability*, *waste management, resource recovery, life cycle assessment, critical minerals,* and *energy transition.* These findings indicate that the circular economy in coal mining encompasses several areas of sustainable resource utilization, including waste recycling, material reuse, the recovery of valuable components, and the utilization of energy resources.

Thus, the results of the cluster analysis demonstrate that the circular economy in coal mining encompasses various approaches to the utilization of material, mineral, and energy resources. Based on the identified thematic relationships, the subsequent analysis focuses on the main areas of circular resource utilization, their development in scientific research, and their practical implementation.

Mining waste management. According to Scopus data, 629 publications were identified in the *Mine Waste/Coal Gangue* research area between 2000 and 2025, approximately 77% of which were published during 2020–2025 (Fig. 3). This indicates a substantial increase in research interest in the recycling and reuse of coal mining waste.

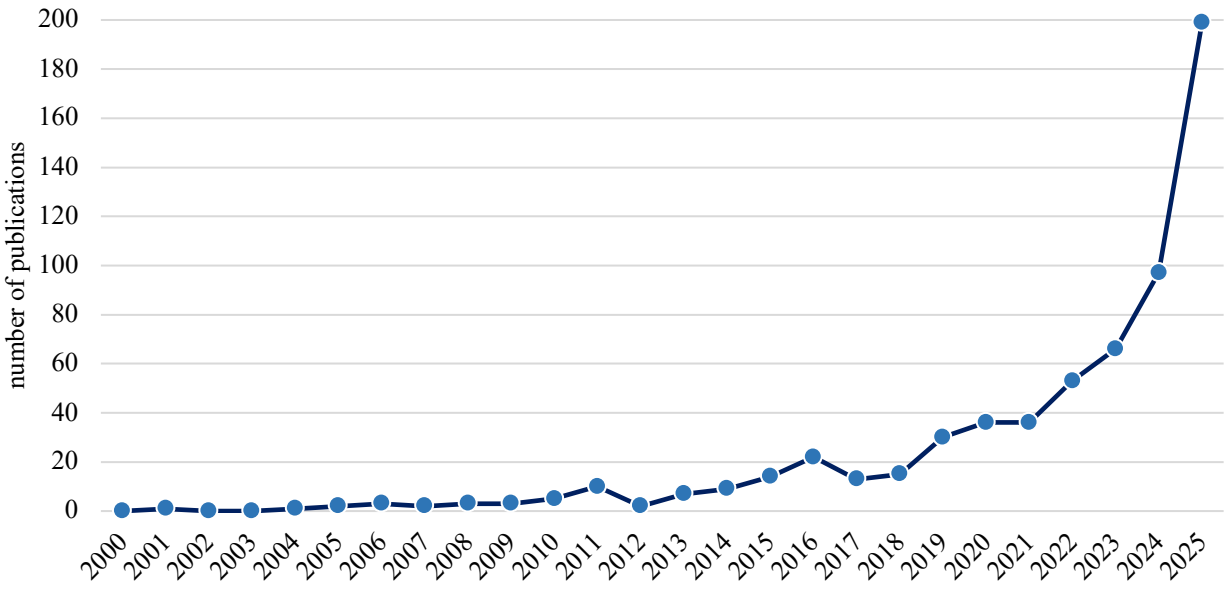


Fig. 3. Trends in the number of publications on mining waste management, 2000–2025

These findings are consistent with the thematic structure identified using VOSviewer. The term *coal gangue* has 265 occurrences and represents one of the largest nodes in the resulting network. The same cluster also includes *mechanical properties, compressive strength, microstructure, geopolymer, concrete, coal mining waste*, and *solid waste utilization*, indicating that current research is primarily focused on processing waste rock and utilizing it as a secondary raw material, primarily for the production of construction materials.

One of the fundamental studies in this field is [2], which examines the integrated utilization of coal mining waste in China. Using the Jincheng Anthracite Mining Group as a case study, the authors demonstrated the potential for establishing interconnected production cycles in which waste rock is used to manufacture materials, ash serves as a raw material for the construction industry, mine water is reused in industrial processes, and coal mine methane is utilized as an energy resource. This approach promotes the integrated utilization of coal mining by-products rather than their separate disposal or stockpiling.

The most highly cited publication in the compiled dataset is the review [3], which systematically examines the main approaches to the integrated utilization of coal gangue and the associated environmental risks. The authors demonstrate that coal gangue can be used as a secondary raw material for the production of construction materials, energy generation, agricultural applications, and other purposes.

A substantial body of research has focused on the utilization of coal gangue as a secondary raw material for cement and concrete production. Study [4] demonstrated that untreated coal gangue exhibits low reactivity owing to the stable crystalline structure of its constituent minerals. Therefore, mechanical, thermal, or combined activation methods are employed to enhance its suitability for use in construction materials.

A separate research area involves the preliminary recovery of residual coal from mining waste, followed by the utilization of the remaining waste rock. Study [5] proposed a two-stage process in which residual anthracite was first recovered from crushed coal gangue by flotation, after which the resulting tailings were used to produce fired bricks. Coal removal improved the mechanical properties of the bricks while reducing their water absorption and porosity.

Another approach involves the use of coal gangue and fly ash for backfilling mined-out areas [6]. Unlike surface disposal, this approach returns solid waste to the underground mine workings. This reduces the volume of surface waste dumps while allowing the backfill material to be used to control rock mass deformation and surface subsidence.

Mined-out area backfilling. A total of 29 specialized publications on the backfilling of mined-out areas in coal mines using secondary materials were identified in the Scopus database. Trends in the number of publications over the period 2000–2025 are presented in Fig. 4.

One of the early approaches involved the use of coal gangue to form a backfill mass, thereby reducing both surface waste disposal and coal losses in protective pillars [7]. Subsequent studies demonstrated the potential for partially replacing conventional backfill components with secondary raw materials. In particular, the use of fly ash as a

partial cement replacement was investigated for the Barapukuria underground coal mine (Dinajpur District, Bangladesh) [8], while technological solutions were developed for transporting coal gangue and achieving the required degree of backfilling in steeply inclined coal seams [9].

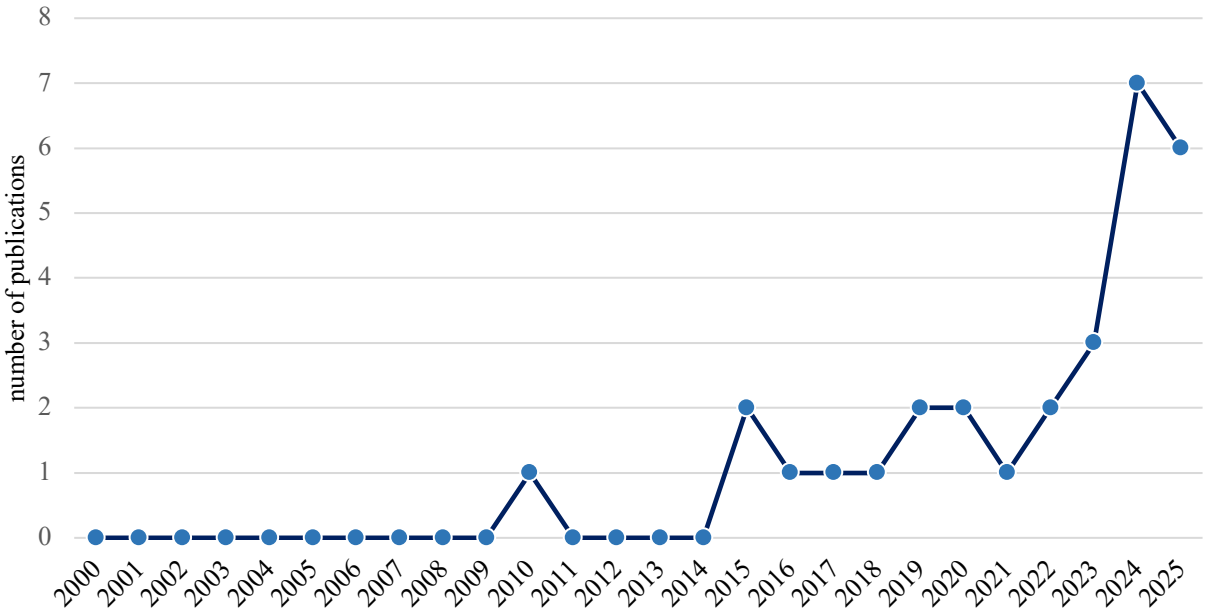


Fig. 4. Trends in the number of publications on mined-out area backfilling, 2000–2025

A significant advancement was the integration of underground separation of the coal-rock stream with backfilling. This approach involves separating the waste rock fraction directly underground and returning it to the mined-out area without transporting it to the surface [10]. Further developments include systems in which coal extraction and backfilling are carried out simultaneously, enabling the disposal of solid waste while controlling rock mass deformation.

Current research focuses on increasing the proportion of waste-derived components in backfill mixtures. Blending systems incorporating coal gangue and various industrial waste materials are being applied [11], while highly mineralized industrial water has even been proposed as an activator [12]. However, increasing the proportion of secondary raw materials requires assessment not only of the mechanical stability of the backfill but also of the long-term migration of potentially hazardous elements into groundwater [13].

A recent trend is the expansion of backfill functionality. In addition to waste utilization and rock mass control, the integration of backfilling with mineral CO_2 sequestration is being investigated [14]. Thus, this research area is evolving from conventional filling of mined-out areas towards multifunctional backfill systems that enable the return of waste-derived materials to the underground production cycle, control rock mass behavior, and potentially provide additional environmental benefits.

Mine water utilization. Mine water is a continuous by-product stream of underground coal mining and can be utilized in industrial processes, as well as serving as a

source of thermal energy and dissolved mineral components. The Scopus dataset compiled for the mine water research area comprised 107 publications, of which 57 (53.3%) were published during 2020–2025. In the VOSviewer network, the terms *acid mine drainage* (33 occurrences), *mine water* (15), *coal mine drainage* (12), and *resource utilization* (21) belong to the same thematic cluster, reflecting a shift in research from mine drainage treatment towards its utilization as a resource. Trends in the number of publications are presented in Fig. 5.

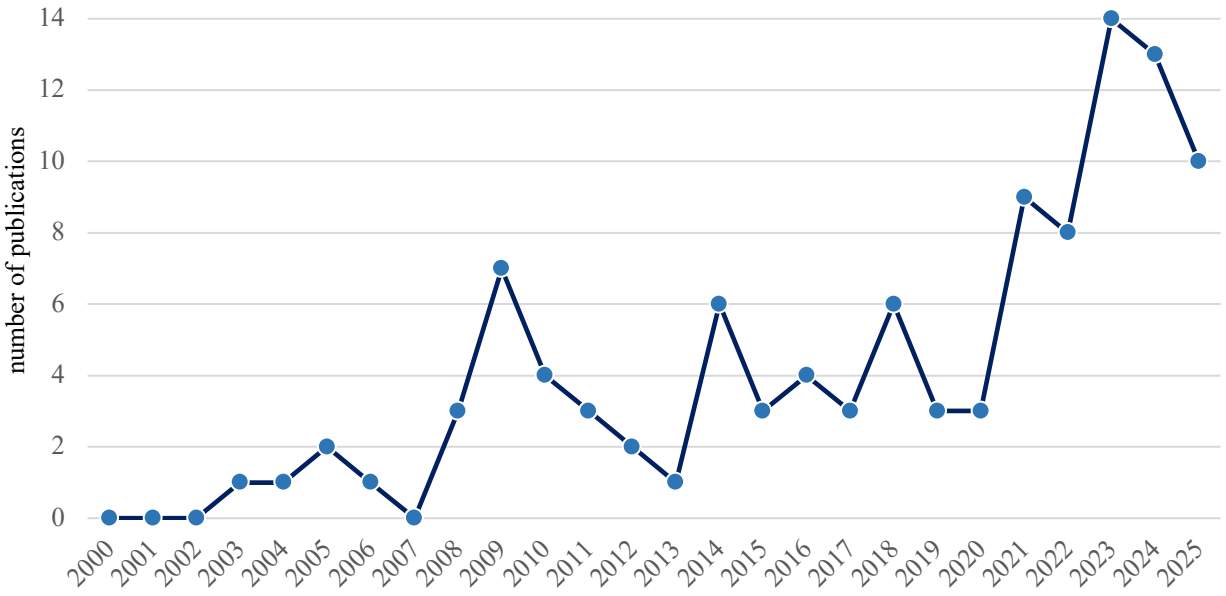


Fig. 5. Trends in the number of publications on mine water utilization, 2000–2025

Mine water treatment and reuse remain the primary focus of research. Experience from coal mines indicates that the required level of treatment depends on the intended end use of the water [15]. For more advanced treatment, membrane technologies are employed. The combined application of forward and reverse osmosis has enabled more than 80% of mine water to be recovered for reuse or discharged in compliance with regulatory requirements [16].

Another research direction involves the recovery of valuable components from mine water and the precipitates generated during its treatment. In particular, iron-rich precipitates can be used to recover iron oxide [17] and produce inorganic pigments [18], thereby serving as a secondary mineral resource.

Rare earth elements are of particular interest. In mine waters of the Appalachian Coal Basin (USA), their concentrations were found to be 1–4 orders of magnitude higher than those in natural waters, while treatment precipitates showed an additional enrichment of approximately 10^3 -10^4 times relative to the original mine water [17]. Experimental studies have also demonstrated the feasibility of recovering rare earth elements from acid mine drainage using ion-exchange resins [19].

Another promising area is the utilization of thermal energy from mine water. For coal mines in the United Kingdom, the available thermal capacity of pumped mine water has been estimated at approximately 47.5 MW, which could be harnessed for heat supply using heat pumps [20]. For a flooded coal mine in Shandong Province,

China, a mine water flow rate of 100 m^3/h corresponded to an estimated thermal capacity of 697.3 kW [21]. These findings demonstrate the potential of mine water as a source of thermal energy, particularly after mine closure.

An integrated approach to mine water utilization was investigated using Polish coal mines as case studies [22]. The proposed circular water value indicator accounts for the economic value not only of treated water but also of the products recovered during its treatment. For the investigative sites, its value ranged from €2.5 to €6/m^3. At the same time, mine water reuse requires careful monitoring of water composition, as changes in salinity, even after treatment, may adversely affect aquatic ecosystems [23].

Coal mine methane utilization. Coal mine methane simultaneously represents an occupational safety hazard, a potent greenhouse gas, and a potential energy resource; therefore, its recovery and utilization can provide safety, environmental, and energy benefits. In the compiled Scopus dataset, the term *coal mine methane* was identified in 322 publications, of which 149 (46.3%) were published during 2020–2025 (Fig. 6). In the VOSviewer network, *coal mine methane* has 95 occurrences, *coalbed methane* 28, *gas* 27, and *methane* 16. The average publication year for *coal mine methane* is 2017.47, compared with 2021.67 for *circular economy*, indicating that coal mine methane utilization technologies had begun to develop before the circular economy concept became widely adopted in coal mining research.

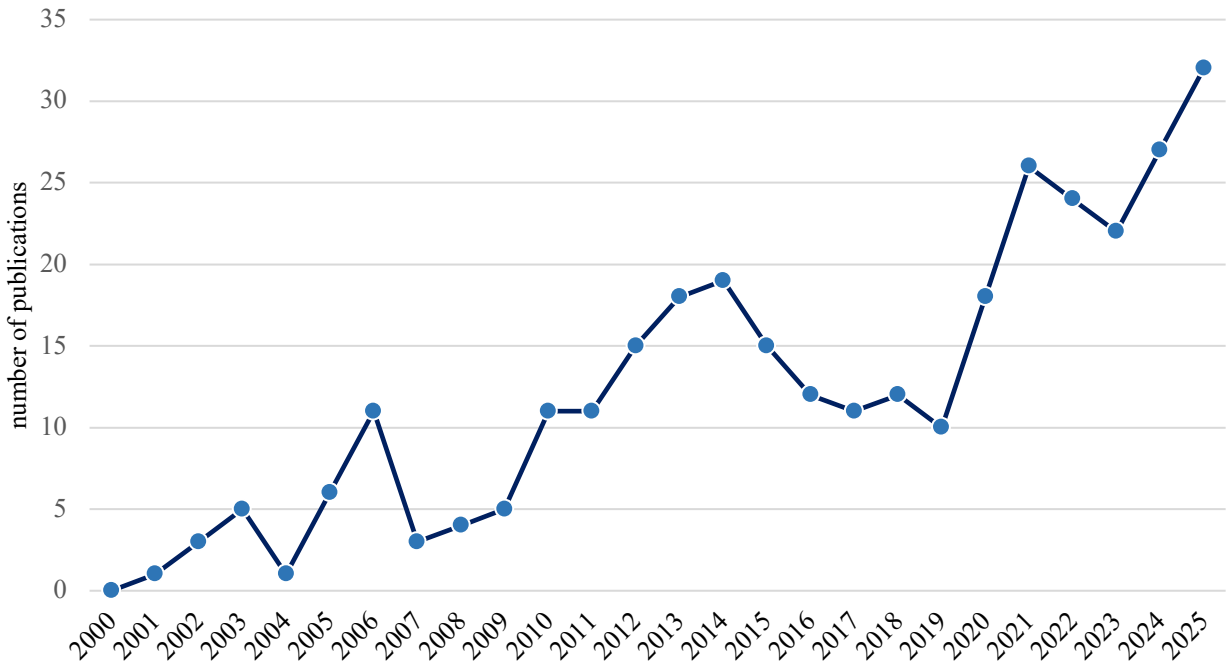


Fig. 6. Trends in the number of publications on coal mine methane utilization, 2000–2025

Utilization technologies are determined by the methane concentration and the stability of the methane–air mixture. Coal mines generate ventilation air containing approximately 0.1–1% CH_4, high-concentration gas from pre-mining drainage (60–95%), and methane from mined-out areas (30–95%) [24]. At sufficiently high concentrations, drained methane can be used for electricity and heat generation or, after appropriate treatment, as a gaseous fuel [25].

Vacuum pressure swing adsorption can be used to improve the quality of drained methane. This technology has been shown to increase the CH_4 concentration from 55.2% to 96–98%, with a methane recovery rate of 86–91% [26]. For low-concentration methane streams and ventilation air methane, catalytic and thermal oxidation technologies are being investigated [27, 28], as well as electrochemical conversion technologies. In particular, the utilization of low-concentration methane in a solid oxide fuel cell achieved an electrical efficiency of 38.2%, with stable system operation maintained for 400 h [29].

The efficiency of methane utilization as a resource largely depends on its recovery from the coal-bearing rock mass. Modern technologies include underground methane drainage, coal seam permeability enhancement, surface boreholes, and combined systems [30]. At the Luling coal mine, improvements in methane drainage were projected to enable the recovery of up to 70 million m^3 of CH_4 per year, of which approximately 58 million m^3 could be beneficially utilized [31].

Recent estimates provide a particularly clear indication of the scale of this effect. Study [32] analyzed coal mine methane (CMM) recovery and utilization in China in the context of achieving carbon neutrality. In 2020, Chinese coal mines generated approximately 22.86 Tg of CH_4, of which 7.26 Tg was recovered through methane drainage systems and 5.46 Tg was actually utilized. According to the authors, the cumulative utilization of CMM since 2005 has displaced approximately 53.21 million tonnes of standard coal equivalent, while simultaneously providing safety and climate benefits.

However, the availability of methane recovery technologies does not necessarily guarantee actual emission reductions. Using GOSAT satellite data, study [33] found that China's methane emissions continued to increase by approximately 1.1 ± 0.4 Tg CH_4 per year during 2010–2015, despite regulatory requirements for CMM drainage and utilization. A substantial share of this increase was attributed to coal mining. This indicates that the effectiveness of a circular model should be assessed not by the mere presence of methane drainage systems, but by the actual proportion of recovered methane that is beneficially utilized. Accordingly, the circularity of the methane stream should be measured not by the volume of methane drained alone, but by the ratio of beneficially utilized CH_4 to the total amount of methane generated during mining operations.

Recovery of critical raw materials. This research area is the largest among the thematic datasets compiled in this study. The Scopus dataset comprises 1,862 publications for the period 2000-2025, of which 1,105, or 59.3%, were published during 2020-2025 (Fig. 7). The highest publication activity was recorded in 2025, with 224 publications, followed by 220 in 2024, 194 in 2023, and 192 in 2022. This trend indicates a sharp increase in research interest in coal and associated mining and processing by-products as potential sources of critical and rare elements.

The results of the VOSviewer analysis confirm the dominance of this research area within the overall thematic structure. The largest node in the network is rare earth elements, with 546 occurrences, 89 links, and a total link strength of 817. Other highly represented terms include *germanium* (83 occurrences), *gallium* (61), *critical elements* (61), *lithium* (38), *critical metals* (30), and *critical minerals* (19). At the same time, the terms *recovery, leaching, extraction, separation*, and *resource recovery* form a distinct technological block, indicating a shift from geochemical characterization towards practical methods for recovering valuable components.

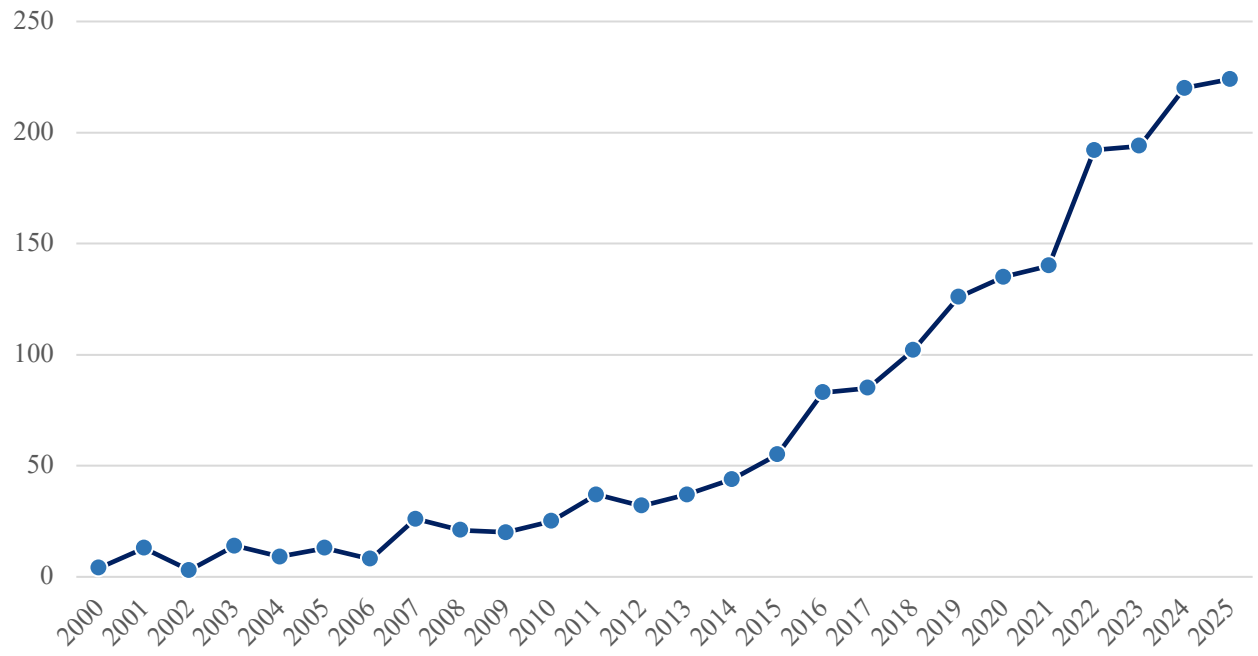


Fig. 7. Trends in the number of publications on critical raw material recovery, 2000–2025

Content analysis of the dataset indicates that current research follows three successful stages: identification of potential sources, determination of modes of occurrence and enrichment, and development of recovery technologies. This sequence provides the basis for transforming a geochemical anomaly into a viable secondary mineral resource.

Of fundamental importance to the first stage are studies [34-37], in which coal and coal-related products are considered potential sources of critical, rare, and rare earth elements. Study [34] summarized data on the occurrence of critical elements in coal and demonstrated the potential for their recovery when present at sufficiently high concentrations and in favorable modes of occurrence. Study [35] systematized data on the occurrence, modes of occurrence, and promising recovery methods of rare earth elements from coal and coal by-products. Subsequent studies [36, 37] further elucidated the enrichment patterns and modes of occurrence of valuable elements in coal.

One of the best-known examples of germanium enrichment is the Wulantuga deposit in Inner Mongolia. Study [38] investigated the petrological, mineralogical, and geochemical characteristics of Ge-enriched lignite from this deposit. The study confirmed that germanium can occur at concentrations of potential economic significance directly within a coal seam and may be associated with specific organic and mineral components. Such studies are essential for substantiating the transition from conventional bulk mining towards the selective formation of enriched rock mass streams.

Elevated concentrations of gallium and rare earth elements have also been identified in coal and associated rocks from the Guanbanwusu deposit in the Jungar Coalfield, China. Study [39] revealed anomalous enrichment of the coal in aluminum, gallium, and rare earth elements. Thus, under favorable geological conditions, coal deposits may represent sources not only of energy coal but also of critical elements.

Another important research area involves the use of coal ash and other coal combustion products as secondary mineral resources. Study [40] investigated the potential for recovering rare earth elements from coal fly ash, while study [41] examined the prospects for its integrated processing to produce geopolymers, silica-based materials, and other useful products. Thus, the resource potential of coal can be utilized not only during its extraction and combustion but also through the subsequent processing of the resulting waste materials.

Importantly, coal combustion can result in the relative concentration of non-combustible mineral components in the resulting ash. Study [42] investigated rare earth element concentrations in coal ash and demonstrated substantial variability depending on the characteristics of the feed coal and technological conditions. Similarly, study [43] examined six coal ash samples to assess their potential as sources of REEs. Thus, the energy utilization of coal does not necessarily represent the end of its resource cycle, as the resulting ash may constitute a secondary anthropogenic mineral resource.

Alongside studies of coal chemical composition, technologies for the recovery of rare earth elements are being actively developed. Study [44] investigated their recovery from coal and coal ash using acid leaching and demonstrated that preliminary thermal treatment increases the accessibility of valuable elements for subsequent extraction. Study [45] showed that roasting coal beneficiation middlings and coarse coal refuse enhances the efficiency of rare earth element recovery. A similar approach was applied in study [46], which investigated the acid leaching of rare earth elements directly from Illinois Basin coal (USA) following preliminary chemical and thermal treatment.

However, acid leaching represents only the initial stage in rare earth element recovery. Various technologies are subsequently applied for their concentration and separation. In particular, study [47] investigated the use of a TEHDGA-based sorbent for the recovery of rare earth elements from coal ash. Study [48] examined the potential application of nanofiltration and evaluated its technological and economic performance. An alternative approach was proposed in study [49], where biosorption was applied for the selective recovery of rare earth elements from coal utilization by-products.

Ukrainian practices and prospects for implementing circular economy principles in coal mining. In Ukraine, an integrated approach to implementing circular economy principles at the level of individual coal mining enterprises has not yet been established. The Western Donbas has significant potential for the development of such an approach, as mining operations in the region predominantly involve thin coal seams and generate substantial streams of associated resources and waste. According to previous studies, more than 80% of the region’s industrial coal reserves are concentrated in seams less than 0.8 m thick, whereas seams more than 1.0 m thick account for no more than 3% of the reserves [50].

One of the most significant challenges is the generation of waste rock. In 2025, the average geological thickness of the coal seams mined in the Western Donbas was 0.82 m, while the average operational ash content of the extracted rock mass reached approximately 44%. Cutting of the surrounding rock during mechanized extraction of thin coal seams additionally generated approximately 3.0-3.5 million tonnes of waste rock annually, excluding waste rock produced during mine development operations.

More than 130 million tonnes of waste rock have already accumulated on the surface in the Western Donbas, occupying approximately 190 ha of land. The ongoing monitoring of waste rock dumps operated by DTEK Pavlohradvuhillia PJSC confirms that surface disposal of waste rock remains an integral part of the current coal mining system [51].

A promising alternative is the selective mining of thin coal seams, with coal and waste rock streams separated directly at the longwall face and the rock fraction left in the mined-out area [52]. For the conditions of the Western Donbas, the feasibility of placing the rock cut from the surrounding strata underground without transporting it to the surface has been substantiated [53]. However, such technologies have not yet been widely implemented on an industrial scale. At the same time, the use of coal-bearing mine waste rock as a component of hardening mixtures for filling the space behind the support in mine workings has been tested at the Heroiv Kosmosu mine [54], confirming its potential for reuse as a technological material.

A higher level of practical implementation has been achieved in the utilization of water resources. At DTEK enterprises, a portion of mine water is reused for operational purposes, while coal preparation plants employ closed-loop water circulation systems [55]. In particular, at the Pavlohradska central coal preparation plant, the use of filter presses enables treated water to be returned to the technological cycle, thereby reducing freshwater consumption.

One of the most illustrative examples of the beneficial utilization of associated resources is coal mine methane recovery. At the Stepova mine, drained methane is used as fuel in a 1.6 MW cogeneration unit that generates electricity and heat. In the fourth quarter of 2020, 234 tonnes of methane were utilized, which, according to company data, resulted in a reduction in greenhouse gas emissions of approximately 5.9 thousand tonnes of CO_2 equivalent [56].

There is also potential to scale up such solutions at other mines. According to the Global Methane Initiative, the combined methane emissions from the Yuvileina, Zakhidno-Donbaska, and Stepova mines were estimated at approximately 128 million m^3/year, of which about 37 million m^3/year were captured by methane drainage systems [57]. Plans to construct new methane drainage facilities at the Heroiv Kosmosu mine indicate the further development of coal mine methane recovery systems, although they do not confirm its subsequent utilization for energy generation [58].

The least developed area at the industrial scale, yet one with significant potential, is the recovery of critical elements from coal and associated mining products. For the c_7^b coal seam at the Pavlohradska mine, the average germanium content was determined to be 17.62 g/t, which is 6.08 times higher than the global Clarke value for hard coal reported by the authors [59]. Studies of germanium and its geochemical associations have also been conducted for other coal seams in the Western Donbas [60].

At the same time, industrial-scale recovery of germanium, gallium, scandium, or rare earth elements from coal in the region has not yet been confirmed; therefore, this research area remains primarily at the stage of geochemical investigation and resource potential assessment. A promising approach involves identifying spatial patterns in the distribution of valuable components, followed by the selective formation of enriched

raw material streams. The relevance of such research is further reinforced by the inclusion of several of these elements in Ukraine's national lists of critical and strategic mineral raw materials [61, 62].

Thus, the research areas examined in Ukraine are characterized by different levels of practical implementation. Solutions already implemented include the reuse of mine water and the utilization of coal mine methane for energy generation. Promising areas include retaining waste rock underground, recovering critical elements and valuable components from mine water, and utilizing the thermal energy of mine water. These developments demonstrate significant potential for more comprehensive utilization of associated resources from Ukrainian coal mines.

Conclusions. Based on the analysis of 2,931 Scopus publications from 2000 to 2025, eight thematic clusters were identified, and five major areas of circular resource utilization in coal mining were distinguished: mining waste processing, mined-out area backfilling, mine water utilization, coal mine methane utilization, and critical raw material recovery.

The development of the research areas was found to be uneven. The largest number of publications focused on critical raw materials (1,862), whereas mining waste management accounted for the highest share of publications during 2020–2025 (77%). Cluster analysis showed that the circular economy integrates previously established technological areas focused on the reuse of associated resources generated by coal mining.

Analysis of international and Ukrainian experience revealed differences in the practical implementation of these technologies. In Ukraine, mine water reuse and the utilization of coal mine methane for energy generation have already been implemented at individual enterprises, whereas retaining waste rock underground and recovering critical elements require further development.

Thus, the study findings indicate the need to transition from individual waste utilization technologies towards the integrated utilization of associated resources generated by coal mining. For Ukrainian coal mines, particularly those in the Western Donbas, this approach offers opportunities to reduce waste generation and environmental impacts while obtaining additional material, energy, and mineral resources.

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АНОТАЦІЯ

Мета. Встановлення сучасних тенденцій розвитку принципів циркулярної економіки при підземному видобуванні вугілля на основі бібліометричного та тематичного аналізу наукових публікацій, систематизація світових і вітчизняних практик поводження з супутніми ресурсними потоками та визначення перспективних напрямів їх комплексного використання на вугільних шахтах України.

Методика. Застосовано бібліометричний, мережевий, тематичний і порівняльний аналіз наукових публікацій, індексованих у базі Scopus за 2000-2025 рр. Сформовано масив із 2931 унікальної публікації за шістьма тематичними пошуковими напрямами. За допомогою програмного забезпечення VOSviewer 1.6.20 проведено аналіз спільної появи авторських ключових слів, побудовано карту їх взаємозв'язків і виконано тематичну кластеризацію. На основі змістовного аналізу публікацій систематизовано світові технологічні практики та проведено їх порівняння з досвідом вугільних шахт України.

Результати. За результатами бібліометричного аналізу виділено вісім тематичних кластерів і систематизовано п'ять основних напрямів циркулярного використання ресурсів вуглевидобування: перероблення гірничих відходів, закладання виробленого простору, використання шахтних вод, утилізація метану та вилучення критично важливої мінеральної сировини. Встановлено зростання публікаційної активності за досліджуваними напрямами та визначено особливості їхнього технологічного розвитку. Порівняння світових і вітчизняних практик показало, що на шахтах Західного Донбасу вже застосовуються технології повторного використання шахтних вод та енергетичної

утилізації метану, тоді як залишення шахтної породи під землею й вилучення критично важливих елементів потребують подальшого розвитку.

Наукова новизна. На основі бібліометричного аналізу та тематичного аналізу встановлено структуру наукових досліджень циркулярного використання ресурсів вуглевидобування, визначено взаємозв'язки між вісьмома тематичними кластерами та систематизовано п'ять основних технологічних напрямів. Виявлено відмінності між світовими тенденціями досліджень і практичним застосуванням відповідних технологій в Україні.

Практична значимість. Результати дослідження можуть бути використані для визначення перспективних напрямів комплексного використання супутніх ресурсів вугільних шахт України. Для умов Західного Донбасу визначено можливості застосування технологій залишення шахтної породи під землею, повторного використання шахтних вод, енергетичної утилізації метану та вилучення критично важливих елементів із вугілля і продуктів його видобування.

Ключові слова: *підземне видобування вугілля, циркулярна економіка, бібліометричний аналіз, VOSviewer, шахтна порода, закладання виробленого простору, критично важлива мінеральна сировина, Західний Донбас.*

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