Mobile technology for coal recovery and land restoration in accordance with circular economy approach

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Abstract. This article presents a mobile technology designed for the reclamation of land degraded by mining activities through the advanced processing of coal tailings. The system enables the efficient recovery of remaining coal while minimizing environmental impact. The mobile processing plant eliminates the need for permanent installations and can be relocated as needed. The process begins with the extraction of deposited material from sedimentation tanks, settling ponds, or mine water reservoirs. Depending on site conditions, this is done using suction dredgers for waterlogged areas or excavator-loaders for dry sites. The extracted material is then mixed with water and transported via pipeline to the processing plant. Inside the plant, the material undergoes preliminary separation, removing large particles (>100 mm) and organic debris. It is then homogenized in agitation tanks and processed in hydrocyclones, where the combustible fraction is separated from the mineral fraction. The recovered coal, with a calorific value of 16–24 MJ/kg, can be further enriched for use in combined heat and power plants. The mineral fraction can be repurposed for construction or land reclamation, making this technology a sustainable solution aligned with circular economy principles. Laboratory and industrial-scale tests confirm its effectiveness in waste reduction and energy recovery.

1 Introduction

The European Union's dependence on fossil fuels for electricity generation has significantly declined since 2000, when 52% of the EU's electricity supply was derived from coal, gas, and other fossil sources. By 2023, this share had dropped to 33%, reflecting a major shift toward renewable energy. The most notable reductions occurred after 2009, driven by the rapid expansion of wind and solar power, which have progressively replaced fossil-based energy sources [1]. Compared to 2022, coal production fell by 22% to 274 million tons, while consumption declined by 23% to 351 million tons. The 100-million-ton reduction in coal consumption over the course of a year marks one of the most significant annual declines ever observed in the EU.

Among member states, Germany (37%) and Poland (27%) remained the largest coal consumers, collectively accounting for nearly two-thirds of the EU's total coal use. In terms of production, the EU generated just 50 million tons of coal, an 82% decrease from the 277

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million tons produced in 1990. Currently, Poland and the Czech Republic are the only EU countries still producing coal, with Poland being the only nation that still relies heavily on coal for electricity generation [2].

With large-scale coal mining still in operation, mining waste management remains a pressing environmental challenge in Poland. Among the various types of mining waste, fine-grained tailings, including coal slurries and post-flotation muds, contain the highest residual carbon content [3,4]. Their high organic content makes them difficult to process and dispose of efficiently. As a result, the development of technologies for energy recovery and waste valorization is essential for both environmental protection and sustainable resource utilization [5].

Coal slurry beneficiation has long been explored as a method for recovering residual combustible material. Historically, coal slurries were either blended with raw coal for direct combustion in fluidized-bed boilers or stored in settling ponds. However, the tightening of environmental regulations has largely banned these practices, necessitating the development of new recovery technologies.

In 2009, a major research initiative in Poland—"Identification of Coal Slurry Deposits in Poland's Fuel Balance and Technological Development Strategy for Their Utilization" (No. N R09 0006 06/2009)—sought to assess the potential for integrating coal slurry resources into the national fuel supply. This project identified 62 coal slurry impoundments, containing an estimated 16.5 million Mg (Megagram = 1metric ton) of deposited coal slurry (Sobko et al., 2011). These findings underscore the significant untapped energy potential of fine coal waste and the urgent need for effective beneficiation solutions.

New developments in mobile coal recovery installations, advanced hydrocyclone separation, and waste-to-energy conversion provide promising avenues for the efficient utilization of coal waste. These approaches align with the circular economy principles, offering a pathway to reduce environmental impact while recovering valuable energy resources.

2 Initial tests

The primary challenge associated with coal tailings in coal slurry impoundments is their high content of fine particles smaller than 0.1 mm. This fine fraction also contains the highest ash content, making its removal crucial for efficient beneficiation.

To develop an optimal recovery technology, three coal slurry samples were selected from different impoundments located in southern Poland within the Upper Silesian Coal Basin. Samples were acquired from the depth of 2-3 meters of the impoundment and were named K1, J and S. Preliminary tests were conducted using a pilot-scale installation with a processing capacity of 500 kg/h. These initial experiments helped optimize process efficiency, refine the hydrocyclone separation system, and assess the behaviour of fine coal particles under varying feed conditions. The system uses conventional conical hydrocyclones. The first (classifying) cyclone performs an initial separation of particles by size. The underflow, containing coarser solids, is then directed to the second – concentrating cyclone – which further enriches the combustible fraction. The second cyclone is not used for dewatering purposes but rather for density-based upgrading of the material.

The grain size distribution of the tested samples is presented in Table 1, while the proximate analysis, including sulfur content determination, is summarized in Table 2.

Table 1. Grain size analysis of coal slurries used for initial tests in the 500 kg/h capacity installation.

Grain size, mm	Yield, wt%		
	K1	J	S
> 2,0 mm	1.21	0.14	0.41
2,0 - 1,0 mm	2.24	1.03	0.84
1,0 - 0,5 mm	13.58	3.44	1.02
0,5 - 0,4 mm	7.25	5.14	2.58
0,4 - 0,3 mm	8.24	4.11	5.87
0,3 - 0,2 mm	11.24	10.44	9.81
0,2 - 0,1 mm	14.25	8.25	19.73
< 0,1 mm	41.99	67.45	59.74

Table 2. Coal slurry proximate analysis with sulfur content and LHV determination.

Parameter	K1	J	S
W (moisture), % (m/m)	34.14	41.24	38.74
A (ash), % (m/m)	54.17	67.25	57.11
V (volatiles), % (m/m)	14.25	11.12	12.21
S (total sulphur), % (m/m)	0.88	1.22	0.57
LHV (Lower Heating Value), MJ kg-1	7.14	4.74	6.11

Parameters that were verified during the tests were solid to water ratio (S/W ratio) and feed pressure in the hydrocyclones. Upon completion of each test proximate analysis of concentrate and reject (mineral fraction) and grain size analysis were carried out in order to select optimal beneficiation conditions. Results of tests for the three samples are presented in Table 3.

Table 3. Results of initial tests on the 500 kg/h capacity installation.

		Concentrate				**Reject (mineral fraction)**				
	S/W	W, % (m/m)	A, % (m/m)	S, % (m/m)	Yield, %	W, % (m/m)	A, % (m/m)	S, % (m/m)	Yield, %	-0.1 mm, %
	1:2	24.14	18.47	0.61	32.41	38.41	54.25	0.31	67.59	12.14
	1:3	25.41	16.57	0.62	30.47	39.81	51.25	0.29	69.53	11.01
	1:4	24.22	15.74	0.64	28.47	40.21	44.25	0.22	71.53	10.32
	1:5	25.11	14.21	0.62	25.41	38.54	45.29	0.29	74.59	10.22
	Classifying cyclone inlet pressure. bar									
K1	0.6	24.14	11.41	0.61	17.11	38.41	55.29	0.29	82.89	5.11
	0.8	24.87	15.24	0.57	24.21	37.41	56.21	0.34	75.79	9.54
	1.0	24.65	18.74	0.63	28.41	38.54	55.21	0.33	71.59	10.25
	1.2	25.03	24.25	0.64	33.25	35.54	55.17	0.31	66.75	14.25
	Concentration cyclone inlet pressure, bar									
	1.0	24.71	12.54	0.64	18.74	36.22	54.17	0.34	81.26	4.22
	1.2	24.25	14.25	0.62	21.25	37.55	53.28	0.32	78.75	6.51
	1.4	25.06	15.66	0.63	23.05	38.54	51.25	0.35	76.95	11.25
	1.6	24.22	18.25	0.64	27.55	34.58	52.28	0.31	72.45	15.22
	S/W ratio									
	1:2	24.11	32.14	1.08	17.14	35.87	51.87	0.24	82.86	11.25
	1:3	24.51	28.41	1.06	14.25	38.47	52.25	0.21	85.75	10.24
	1:4	23.87	25.41	1.07	11.25	38.41	53.25	0.25	88.75	9.84
	1:5	24.25	22.25	0.99	8.14	38.45	54.25	0.26	91.86	8.57
	Classifying cyclone inlet pressure, bar									
	0.6 bar	24.21	16.28	1.05	5.74	38.45	52.25	0.21	94.26	12.24
J	0.8 bar	24.25	19.25	1.08	10.54	38.24	51.25	0.23	89.46	13.25
	1.0 bar	23.28	23.58	1.11	12.03	38.21	52.26	0.22	87.97	14.03
	1.2 bar	24.57	29.51	1.05	15.22	35.47	53.25	0.23	84.78	14.82
	Concentration cyclone inlet pressure, bar									
	1.0	24.51	21.47	1.11	8.41	38.74	54.14	0.21	91.59	15.41
	1.2	23.58	25.69	1.08	11.41	36.37	52.26	0.24	88.59	14.52
	1.4	24.33	27.25	1.09	13.25	37.85	54.21	0.24	86.75	13.24
	1.6	23.55	29.58	1.05	16.87	37.25	53.25	0.23	83.13	12.21
	S/W ratio									
S	1:2	24.21	27.71	0.58	22.14	37.59	54.25	0.17	77.86	12.41
	1:3	24.17	24.32	0.59	18.47	38.54	52.31	0.18	81.53	13.87
	1:4	25.14	22.14	0.57	15.21	38.74	53.25	0.17	84.79	15.21

		Concentrate				**Reject (mineral fraction)**				
	S/W	W, % (m/m)	A, % (m/m)	S, % (m/m)	Yield, %	W, % (m/m)	A, % (m/m)	S, % (m/m)	Yield, %	-0.1 mm, %
K1	1:2	24.14	18.47	0.61	32.41	38.41	54.25	0.31	67.59	12.14
	1:3	25.41	16.57	0.62	30.47	39.81	51.25	0.29	69.53	11.01
	1:4	24.22	15.74	0.64	28.47	40.21	44.25	0.22	71.53	10.32
	1:5	25.11	14.21	0.62	25.41	38.54	45.29	0.29	74.59	10.22
	Classifying cyclone inlet pressure. bar									
	0.6	24.14	11.41	0.61	17.11	38.41	55.29	0.29	82.89	5.11
	0.8	24.87	15.24	0.57	24.21	37.41	56.21	0.34	75.79	9.54
	1.0	24.65	18.74	0.63	28.41	38.54	55.21	0.33	71.59	10.25
	1.2	25.03	24.25	0.64	33.25	35.54	55.17	0.31	66.75	14.25
	Concentration cyclone inlet pressure, bar									
	1.0	24.71	12.54	0.64	18.74	36.22	54.17	0.34	81.26	4.22
	1.2	24.25	14.25	0.62	21.25	37.55	53.28	0.32	78.75	6.51
	1.4	25.06	15.66	0.63	23.05	38.54	51.25	0.35	76.95	11.25
	1.6	24.22	18.25	0.64	27.55	34.58	52.28	0.31	72.45	15.22
	1:5	24.25	18.61	0.58	12.25	36.21	54.21	0.16	87.75	16.28
	Classifying cyclone inlet pressure, bar									
	0.6	24.71	15.24	0.6	10.41	38.41	52.25	0.18	89.59	8.74
	0.8	25.13	17.25	0.61	13.05	37.48	53.27	0.17	86.95	9.24
	1.0	25.17	21.25	0.58	15.47	39.51	52.79	0.19	84.53	10.28
	1.2	24.51	24.87	0.59	18.24	40.25	51.28	0.15	81.76	13.25
	Concentration cyclone inlet pressure, bar									
	1.0	24.71	18.52	0.58	12.41	40.12	50.41	0.18	87.59	10.14
	1.2	24.22	23.37	0.59	16.23	38.74	54.14	0.19	83.77	12.03
	1.4	24.51	25.35	0.61	19.18	39.12	54.11	0.15	80.82	13.54
	1.6	25.15	28.94	0.61	24.25	38.22	55.26	0.18	75.75	14.87

The conducted tests revealed that a higher S/W ratio (1:5) resulted in a lower concentrate yield across all samples (K1, J, S), indicating a dilution effect that reduced the recovery of the combustible fraction. However, the ash content in the concentrate was lower under these conditions.

Increasing the classifying cyclone inlet pressure from 0.6 to 1.2 bar generally improved concentrate yield, yet it also led to a higher ash content in the concentrate. In contrast, a moderate inlet pressure (1.2–1.4 bar) in the concentration cyclone provided the best balance between ash reduction and concentrate recovery.

Among the tested samples, Sample J exhibited the highest ash content in the concentrate under all conditions, making it the most challenging to beneficiate. In contrast, Sample K1 demonstrated the most consistent beneficiation performance, maintaining an optimal balance between yield and ash removal.

Regardless of the processing conditions, it is important to note that the content of fine particles (-0.1 mm) significantly decreased in comparison to the feed material (see Table 1), indicating effective separation of ultra-fine material during the beneficiation process.

3 Mobile installation for coal recovery

Based on the initial laboratory tests, the COBANT company has been developing a mobile installation for coal recovery since 2018. This innovative solution aims to extract combustible material from coal slurry deposits and old impoundments, producing solid fuel while separating a mineral fraction that can be repurposed for construction applications. Additionally, this process contributes to the reclamation of post-industrial areas, making them suitable for forestation, commercial development, or other uses. A general idea of the mobile installation is provided in Figure 1.

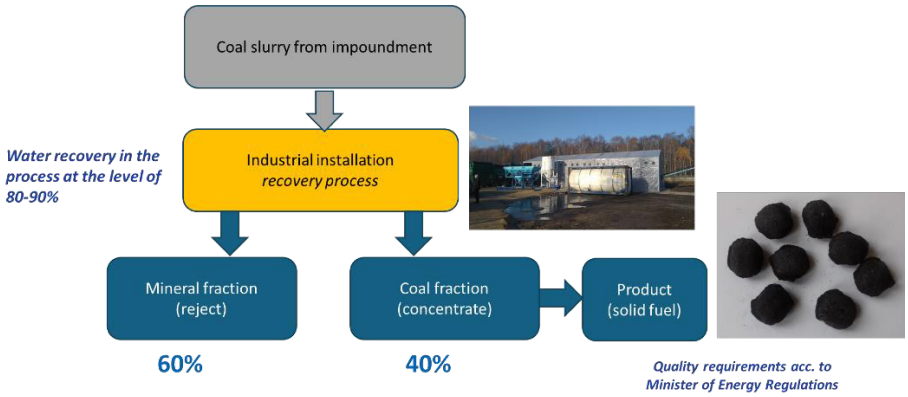

Fig. 1. General idea of the mobile installation.

The coal recovery process in the installation operates using gravity separation methods (see Figure 1), specifically employing classifying and concentration hydrocyclones. Before entering the system, the coal slurry is homogenized in mixing tanks to achieve the desired solid concentration and then pumped into the processing circuit.

The dewatering process is performed using dewatering screens, resulting in the separation of two distinct products:

- Coal concentrate (combustible fraction)
- Mineral fraction (inert byproduct)

The entire process is fully automated and monitored at every stage to ensure efficiency and consistency. To maintain product quality, a mobile laboratory conducts real-time quality control analyses, including technical coal analysis (ash content, moisture content, and Lower Heating Value - LHV). Additionally, particle size analysis and ultimate analysis are performed several times per week in the company's stationary laboratory to ensure process stability and product standardization.

The final product from the installation undergoes further processing to produce coal briquettes, which can be commercially sold (see Figure 2).

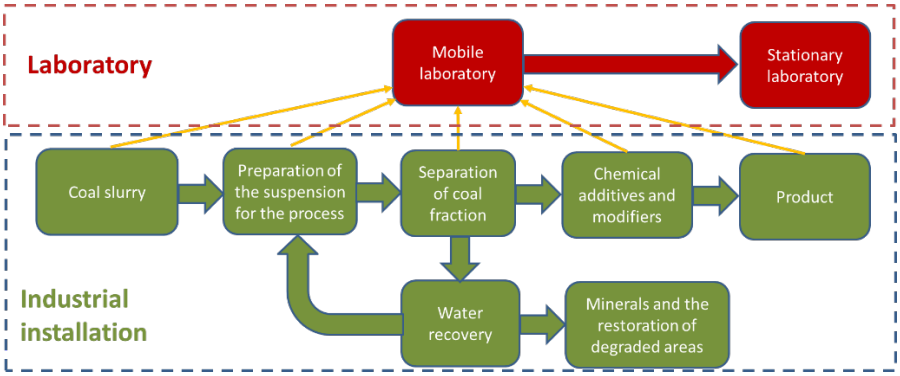

Fig. 2. General idea of the mobile installation.

The mobile coal recovery installation was deployed at one of the coal slurry impoundments in the Upper Silesian Coal Basin (Figure 3) to evaluate its operational performance and assess the quality of the recovered material. As part of this study, an analysis was conducted on both the feed material entering the installation and the final product obtained after processing.

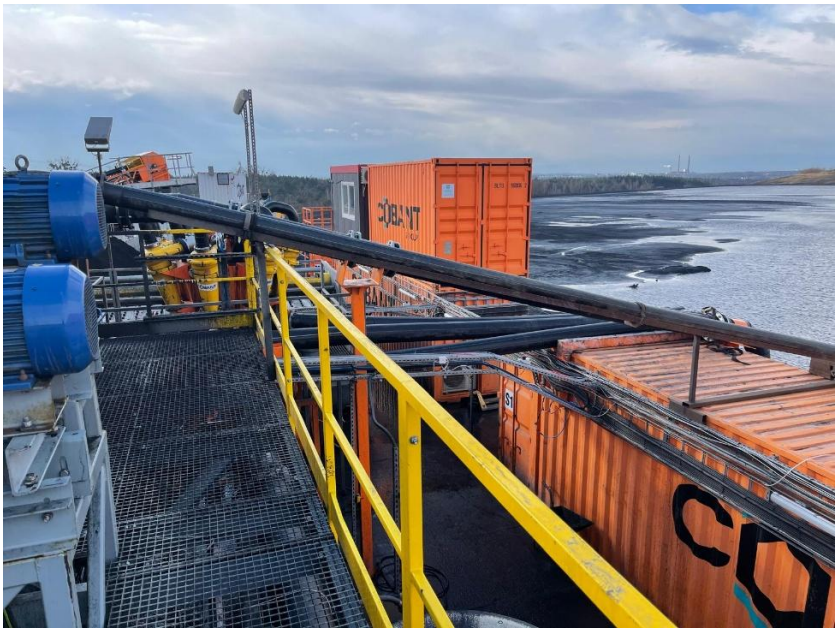

Fig. 3. View of the installation located near one of the coal impoundments in the Upper Silesia Coal Basin.

To ensure a representative evaluation, coal waste samples were collected following applicable standards, with a total sample weight of approximately 50 kg.

- Sample A was taken from wells W2 and W3, located 30 meters from the embankment of the slurry pond.
- Sample B was collected between W2 and W3, at a distance of 50 meters from the embankment.

After collection, the samples were secured and transported to the laboratory, where they were averaged to form an analytical sample, following ISO procedures. The samples were then subjected to chemical analysis in accordance with the applicable standards of the Polish Committee for Standardization, including:

a) Ash content determination
b) Volatile matter analysis
c) Total moisture content measurement
d) Transient moisture content measurement
e) Heat of combustion determination (Lower Heating Value - LHV) with calorific value calculation (Higher Heating Value - HHV)
f) Total sulfur content analysis
g) Combustible sulfur determination
h) Laser particle size distribution analysis

These tests provided critical insights into the composition and quality of the raw coal slurry, ensuring an accurate assessment of the efficiency of the beneficiation process.

Table 4 presents the results of the proximate and ultimate analysis for the collected samples A and B. Additionally, a particle size analysis was performed, revealing that the slurry material contains, as in the case of initial tests, a high proportion of fine particles smaller than 0.10 mm (see Table 5).

Table 4. Results of technical and ultimate analysis of coal slurries sampled from the impoundment (as received).

	Parameter	**A**	**B**
Proximate analysis	Wt, % (m/m)	35,97	37,33
	W_{ex}, % (m/m)	31,58	33,31
	A, % (m/m)	28,36	29,51
	V, % (m/m)	12,45	11,43
	LHV, MJ kg^{-1}	13,51	11,25
Ultimate analysis	S_t, % (m/m)	0,55	0,64
	S_C, % (m/m)	0,47	0,55

Table 5. Particle size analysis of sample A and B

Grain size, mm	**Yield, γ,% (V / V)**	
	Sample A	**Sample B**
> 2,00	0,00	0,00
2,00 – 1,50	2,23	0,00
1,50 – 1,00	3,76	0,03
1,00 – 0,90	3,44	1,02
0,90 – 0,80	1,24	0,14
0,80 – 0,70	2,11	1,11
0,70 – 0,60	1,21	0,87
0,60 – 0,50	3,21	0,54
0,50 – 0,40	6,44	1,11
0,40 – 0,30	8,47	2,45
0,30 – 0,20	11,33	14,53
0,20 – 0,10	14,88	16,18
< 0,10	41,68	62,07

The results indicate that both samples exhibit a relatively low calorific value, measuring 11.25 MJ/kg and 13.51 MJ/kg, respectively, which renders them unsuitable for direct combustion or gasification. To enhance their usability, the raw material was processed through the mobile installation to separate the combustible fraction from the mineral content. The mass balance of the process for both samples is presented in Table 6.

The mass balance analysis of the processed material indicates that the yield of the combustible fraction was higher in Sample A (44.46%) compared to Sample B (32.19%), as shown in Table 6. The lower yield in Sample B may be attributed to its higher content of fine particles (-0.10 mm), which are more challenging to separate using hydrocyclones.

Table 6. Mass balance of products from the installation

Fraction	**Yield, % (m/m)**	**Yield, % (m/m)**
	Sample A	**Sample B**
Combustible fraction	44,46	32,19
Mineral fraction	55,54	67,81

Following separation, proximate and ultimate analysis was conducted on the recovered combustible fraction, with results summarized in Table 7. The data reveals a significant improvement in the calorific value, increasing to 19.44 MJ/kg for Sample A and 16.87 MJ/kg for Sample B. Additionally, ash content decreased to 12.98% and 14.06%, respectively, highlighting the effectiveness of the beneficiation process in improving fuel quality.

Table 7. Proximate and ultimate analysis of the combustible fraction (as received)

	Parameter	**A**	**B**
Technical analysis	W_t, % (m/m)	20,06	20,11
	W_{ex}, % (m/m)	13,78	14,03
	A, % (m/m)	12,98	14,06
	V, % (m/m)	26,93	25,44
	LHV, MJ kg^{-1}	19,44	16,87
Ultimate analysis	S_t, % (m/m)	0,51	0,57
	S_C, % (m/m)	0,44	0,49

Despite the improved calorific value, the fine and unconsolidated nature of the recovered combustible fraction makes it unsuitable for direct use in power plants or domestic heating due to handling and transport limitations. To address this, a chemical binder developed by the company was added to enhance mechanical strength, reduce moisture content, minimize ash formation, and lower sulfur oxide emissions during combustion. The resulting coal briquettes were then analyzed for their properties, as presented in Table 8.

Table 8. Proximate and ultimate analysis of coal briquettes (as received)

	Parameter	**A**	**B**
Proximate analysis	W_t, % (m/m)	14,99	15,06
	W_{ex}, % (m/m)	8,78	9,68
	A, % (m/m)	10,38	11,25
	V, % (m/m)	32,36	30,53
	LHV, MJ kg^{-1}	24,11	22,78
Ultimate analysis	S_t, % (m/m)	0,41	0,46
	S_C, % (m/m)	0,35	0,40

4 Conclusions

The results of this study highlight several key advantages and outcomes of the COBANT mobile coal recovery installation:

- **Efficient recovery and beneficiation:** The mobile system successfully separated a substantial combustible fraction from coal tailings (recovering roughly 30–45% of the slurry by mass). This beneficiation significantly upgraded the fuel quality – increasing the material's calorific value from a low ~11–13 MJ/kg (in raw slurries) to about 17–19 MJ/kg after processing – while reducing ash content in the recovered coal to around 13%, a dramatic improvement over the unprocessed waste.
- **Conversion to high-quality fuel:** The fine coal concentrate obtained from the tailings can be further transformed into solid briquettes suitable for commercial use. With the addition of a binder to improve handling and combustion properties, the briquetted fuel achieved calorific values on the order of 22–24 MJ/kg, comparable to run-of-mine coal, and exhibited low ash (≈10–11%). This makes the recovered coal fully usable in combined heat and power plants or for municipal/residential heating, effectively closing the resource loop from waste to energy.
- **Reduced environmental impact:** Implementing the processing installation directly at the waste site minimizes the environmental footprint of recovery operations. The mobility of the unit eliminates the need to haul raw slurry to distant facilities, thereby cutting transportation requirements and associated CO_2 emissions. Moreover, the improved fuel quality (higher energy content and lower ash/sulfur) means that when the recovered coal is combusted, it will generate fewer pollutants per unit of energy – contributing to lower overall emissions (e.g. less particulate matter and sulfur oxides) compared to burning unbeneficiated coal waste. In sum, the technology not only recovers energy but does so with a smaller carbon and pollution footprint.
- **Land reclamation and waste reduction:** A key benefit of this approach is the restoration of land previously occupied by coal slurry ponds and tailings impoundments. By extracting and repurposing the coal and mineral fractions from these residues, the process eliminates the remaining waste in the impoundment and allows for the rehabilitation of the site. The removal of harmful tailings mitigates risks to soil and water (such as acid drainage or groundwater contamination) and enables the degraded land to be reclaimed for environmental or community use. This contributes directly to landscape restoration and reduces the long-term liability associated with mine waste dumps.
- **Sustainable resource management and circular economy:** The mobile recovery system exemplifies circular economy principles in the mining sector. It converts mining waste into valuable products, ensuring that almost all components of the extracted material are reused or returned to productive use. The recovered coal re-enters the energy supply chain, while the inert mineral fraction **has the potential** to be repurposed as construction aggregate or for land rehabilitation and backfilling, pending further suitability assessments . This holistic utilization of resources means minimal residual waste is left behind. By maximizing resource recovery from what was once a waste stream, the technology supports sustainable resource management and aligns with modern waste valorization and resource-efficiency strategies.

Overall, the study demonstrates that deploying a mobile coal recovery installation is a viable and sustainable solution for both energy recovery and environmental remediation in coal mining regions. The approach effectively addresses a pressing waste management challenge by reclaiming energy from fine coal tailings while restoring lands degraded by past mining activities. In doing so, it transforms an environmental liability into a useful asset, illustrating how principles of sustainability and circular economy can be put into practice. These findings have important implications for sustainable resource management, as they show that it is possible to recover valuable resources from industrial waste and simultaneously achieve land reclamation. By integrating waste reduction, energy production, and land restoration, the described technology offers a comprehensive tool for mining companies and policymakers seeking to reduce the environmental impact of mining and move toward more circular, resource-efficient practices. The success of this mobile beneficiation system in laboratory and field tests underlines its practical viability, suggesting that broader implementation could help advance both energy and environmental goals in the coal sector and beyond.

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