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Coal Dust and Methane as a Hazard in Coal Preparation Plants

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Abstract: This article presents the results of analysis of the hazards posed by coal mine dust and methane in the coal preparation plants of hard coal mines in Poland. It was shown how the number of workplaces in plants at risk of coal dust explosion and the highest permissible dust concentration changed in the period from 2003 to 2022 when compared with coal production. The methodology of assessing mine dust hazards was based on hazard ratios related to one million tons of hard coal enriched in preparation plants. As a result of the analysis, it was found that the explosion hazard index with zone 20 showed an increasing trend in the analyzed period, while the explosion hazard indices with zones 21 and 22 analyzed together and the maximum permissible dust concentration showed decreasing trends following a decrease in hard coal production. In the case of methane, no zone 0 explosion hazards were found, and there were only a few instances of zone 1 explosion hazards. However, it was determined that the explosion hazard index for zone 2 showed an increasing trend during the analyzed period, which is directly proportional to the coal produced and is a result of increasing depth of mining.

Keywords: coal dust; coal preparation plant; explosion hazard; coal production

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1. Introduction

Coal dust and methane represent two of the most critical hazards in coal preparation plants, significantly impacting both worker safety and operational efficiency. Coal dust, a by-product of mechanical processes such as coal extraction, transportation, and beneficiation, poses severe risks due to its potential to cause catastrophic explosions under specific conditions [1,2]. Similarly, mine dust frequently encountered in these environments presents hazards ranging from injuries and fatalities to long-term occupational illnesses [3].

The generation of mine dust in coal preparation plants occurs during the mechanical extraction and transport of coal, as well as during the processing of coal and waste rock. Key factors influencing dust generation include:

- geological characteristics of the coal seam and the properties of the coal mined (location, mineral composition, hardness, degree of coalification, etc.),
- mining method, run-of-mine haulage method to the coal preparation plant (type of machinery and equipment for mining and loading, modes and means of transport),
- technology adopted for the preparation of coal in the preparation plant (beneficiation methods, type of machinery and equipment),
- Physical properties of the dust, such as particle size and dispersibility.

Suspended coal dust is transported by air currents, with some particles depositing on structures and machinery. Resuspension of this deposited dust can elevate atmospheric concentrations, posing persistent hazards to workers [4,5].

Coal dust recognized as a hazardous factor in a coal preparation plant originates from a coal seam and has a volatile content of more than 10% (particle size <1 mm). All currently mined hard coal seams in Poland contain more than 10% volatile matter in dry ash-free conditions. Such dust mixed with air in quantities of 50 to 1000 g/m^3 constitutes a mixture that, under the right conditions and as a result of initiation, can lead to an explosion.

Explosive dust atmospheres are divided into three zones based on the International standard IEC 60079-10-2 [6], which in the case of coal dust are classified as follows:

- zone 20—a place in which an explosive dust atmosphere, in the form of a cloud of dust in air, is present continuously, or for long periods or frequently,
- zone 21—a place in which an explosive dust atmosphere, in the form of a cloud of dust in air, is likely to occur in normal operation occasionally,
- zone 22—area in which an explosive dust atmosphere, in the form of a cloud of combustible dust in air, is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

Prolonged exposure to coal dust at high concentrations poses significant health risks to workers. This is addressed in the Regulation of the Minister of Labour and Social Policy [7,8], which establishes the Maximum Allowable Concentration (MAC) for workplace dust exposure. The MAC represents the concentration level that, over an 8-h workday and a typical workweek, should not cause adverse health effects during a worker's lifetime or affect the health of future generations. This regulation underscores the importance of maintaining strict control over workplace dust concentrations to safeguard worker health.

The regulation specifies permissible dust concentrations based on the silica content in the dust. The Maximum Allowable Concentration (MAC) values cited in Table 1 are derived from [7], rather than [8], as the comparison focuses on results prior to 2018.

Table 1. Maximum allowable dust concentrations at workplaces, mg/m^3 [7].

Dust Fraction	**Silica Content in Dust, %**			
	<2	**2 to 10**	**10 to 50**	**>50**
Inhalable (<100 μm)	10	4	2	2
Respirable (<7 μm)	-	2	1	0.3

Adverse effects of coal dust mine on human health have been widely investigated [9–12] contributing to obstructive lung disease, pulmonary fibrosis, and lung cancer, in addition to the Coal Workers' Pneumoconiosis (CWP) and silicosis that receive greater attention. Therefore, fighting coal dust not only contributes to the safety in terms of explosion hazard but also contributes to the overall health of workers.

The second important hazard in coal preparation plant is methane. Methane is emitted during all dry processing operations, yet crushing and grinding common in coking coal processing plants (and to a lesser extent in thermal coal processing plants) significantly contributes to its release. Conveyor belts, especially at transfer points, also release methane from the material they transport. Other places where methane accumulates in coal processing plants are all sorts of bunkers for raw coal, concentrate, and occasionally coal tailings.

The increasing depth of coal mining, which has reached an average of 780 m in Poland and can exceed 1000 m in some cases, has led to a rise in methane emissions in processing plants. The average annual increase in mining depth for Poland is 7–8 m, and the relative methane content has grown from approximately 10 m^{3}CH$_4$/Mg in 2003 [13] to around 15 m^{3}CH$_4$/Mg in 2022 [14].

To assess the risk of Explosive Atmospheres, areas are categorized into three zones: zone 0 (where Explosive Atmospheres are continuous or frequent), zone 1 (where they may occur during normal operations), and zone 2 (where they are unlikely but may persist for short periods if they do occur).

The aim of this study is to analyze and compare the total coal production with coal dust explosion indicators and methane hazard at workplaces in coal preparation plants.

Data were collected from all of the polish coal preparation plants from 2003 to 2022. New indexes were derived based on the yearly production and occurrence of hazard zones, which allow an assessment of the trends in relation to the total coal production.

2. Coal Dust Control in Hard Coal Preparation Plants

Coal dust hazard and methane in hard coal preparation plants is controlled using administrative and legal regulations as well as technical methods. Administrative-legal regulations include the application of directives, laws, orders, recommendations, and regulations and organizational measures. A number of recommendations and orders are of a local nature, related to the conditions prevailing at a particular site. Technical methods aim at eliminating or at least minimizing the amount of dust and methane in the atmosphere surrounding workplaces to non-explosive levels and not exceeding the Maximum Allowable Concentrations (MAC). Technical methods involve dust collection or water spraying on areas where dust is generated and extensive ventilation in case of methane. The following are selected examples that illustrate solutions in this area applied in mechanical processing plants. One such solution is the MB-M-25A circulating dust collector. The results of dust collection tests carried out at a coal preparation plant using this dust collector are described in [15,16]. It was shown that the operation of the dust collector results in a significant decrease in the amount of dust precipitating on the surfaces around the coal preparation equipment. The largest decreases in the precipitation of the coal dust, more than twofold, were recorded in the vicinity of the screens.

As a result of the work carried out at ITG KOMAG, interesting design solutions have been developed that allow them to be used in many places in mining plants where a dust explosion hazard arises [17]. These devices are of four different types. The most popular one, which has been applied in several coal processing plants, is the UO type dust collector [18]. In this device, air mixed with coal dust is sucked in and introduced into the device through a vortex nozzle with a fan. Inside the dust collector, the coal dust introduced into it with the air is mixed with water. The high kinetic energy of the water droplets imparted by the vortex nozzle makes the dust removal highly efficient. Dust removal efficiency is estimated at 99% of the dust of the inhalable dust fraction and 97% of the respirable dust fraction [19].

Another interesting solution that has found application in coal processing plants is the PASAT-type sprinkler system [18]. This system has been installed in one mine above the transfer from the crushers to the belt conveyors, and in another mine above the transfer of the belt conveyor system. The PASAT system can be equipped with several sprinkler batteries, creating a curtain of water mist that dampens and loads the rising dust that falls onto the conveyor. The system uses compressed air, which reduces the use of water needed to reduce the dust concentration. The PASAT system is supplied with water directly from the mine's fire main. The sprinkler unit is equipped with filters, reduction and shut-off valves, and a UV25 type sterilizer. The system is activated by sensors detecting the movement of the conveyor belt. A view of the sprinkler system is shown in Figure 1. PASAT-type sprinkler systems demonstrate reliable operation and high dust reduction efficiency.

In the case of methane, technical methods of hazard mitigation involve placing measurement sensors in critical locations (wells, bunkers) that operate within the mine's automated methane monitoring system. The accumulation of methane at a concentration exceeding 1% in these locations triggers the shutdown of the electrical power supply in the hazardous area.

One measure to prevent the formation of an explosive atmosphere is to ventilate areas where such an atmosphere may occur. For instance, in some coal processing plants, the start-up of technological processes, including transportation, is preceded by the activation of ventilation fans.

A commonly used technical measure to eliminate potential ignition sources from explosion-hazardous areas is the use of electrically powered safety devices in these areas. These devices comply with ATEX Directives.

Figure 1. View of the PASAT sprinkler system.

3. Indexes for Coal Dust and Methane Hazards Estimation in Hard Coal Preparation Plants

The analysis of the coal dust hazard in hard coal mines covers the period from 2003 to 2022, which is marked by extremely dynamic organizational changes in the Polish hard coal mining industry. In 2003, there were 41 mines in operation [20], and each operated a preparation plant with a different range of coal beneficiation range. In 2022, there were 20 mines operating 30 mine sites, i.e., practically former mines [21]. There was also a significant decrease in coal production [22] as shown in Table 2 and in Figure 2.

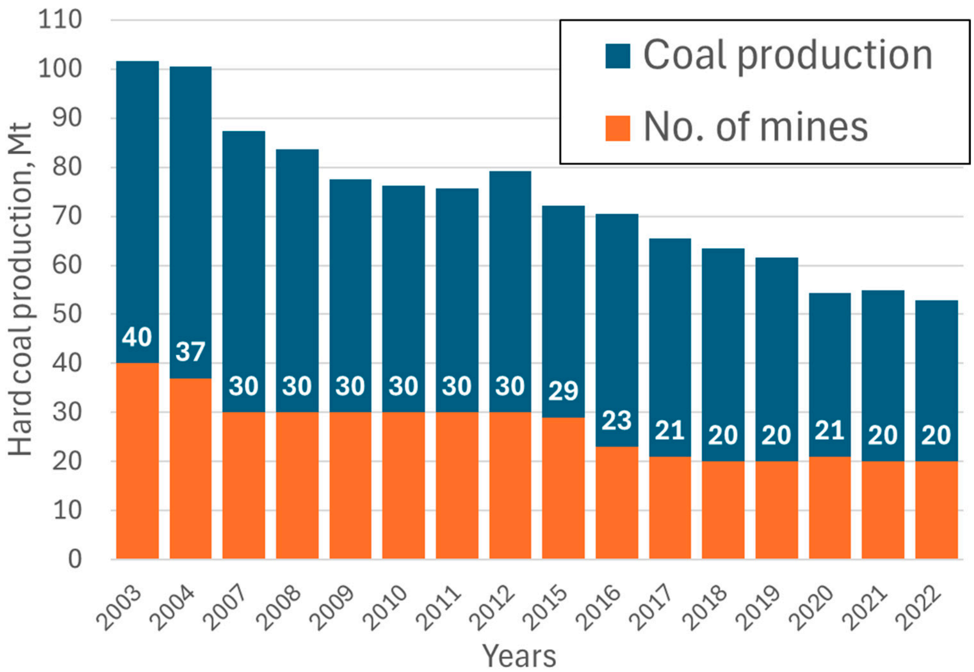

Figure 2. Hard coal production and number of mines in Poland 2003–2022 [22].

Information on hazards at workplaces in the coal preparation plants of Polish mines was obtained from annual reports on the state of natural and technical hazards in hard coal mining periodically issued by the Central Mining Institute [13,14,23–34]. Information on the number of workplaces in coal preparation plants operating in explosive dust atmospheres and the number of workplaces where permissible dust concentrations were exceeded in the years 2003 to 2022 are presented in Table 2.

Table 2. Hard coal production in Poland [35] versus number of workplaces in zone 20 and zones 21 + 22, zone 2 methane hazard and number of workplaces with exceeded maximum permissible dust concentrations (MACs) [13,14,23–34,36] in the years 2003 to 2022.

Year	Coal Production, Million Mg	No. of Workplaces in Zone 20	No. of Workplaces in Zone 21 + 22	No. of Workplaces in MAC	No. of Workplaces in Zone 2 Methane Explosive Atmosphere
2003	101.7	30	504	395	240
2004	100.5	30	587	303	325
2007	87.4	44	508	472	225
2008	83.7	10	458	541	274
2009	77.5	10	414	588	225
2010	76.2	12	400	516	232
2011	75.7	12	393	478	351
2012	79.2	15	410	516	279
2015	72.2	24	364	415	280
2016	70.4	21	309	458	251
2017	65.5	19	309	380	352
2018	63.4	17	308	315	217
2019	61.6	17	196	265	219
2020	54.4	19	190	203	237
2021	55.0	31	253	185	259
2022	52.8	19	157	177	282

No data available for years 2005, 2006, 2013, and 2014.

In order to observe trends related to changes of the abovementioned hazards in time and in relation to production, it was decided to develop indexes that could allow an estimation of hazards based on the available historical data.

Indexes were elaborated for workplaces with explosive dust atmospheres zone 20 (high risk zones) and lower risk zones as the sum of zones 21 and 22. The example mathematical expression for the index IEZ_{20} is the following:

$$IEZ_{20} = \left(\frac{N_{20}}{N_{20} + N_{21+22}} \cdot \frac{1}{P} \right) \cdot 100 \quad (1)$$

where IEZ_{20} is the explosion hazard index for workplaces at high explosion risk. This index measures the proportion of workplaces in explosive dust atmosphere zone 20 (high explosion risk) (N_{20}) relative to the total number of workplaces in explosive dust atmosphere zones 20, 21, and 22 (cumulative explosion risk), normalized by annual coal production (P). By multiplying by 100, the index expresses this proportion as a percentage, providing a standardized indicator to assess and compare the relative risk of zone 20 workplaces across different years or production scales. This metric highlights the specific contribution of high-risk areas to overall safety concerns in coal preparation plant operations. Similarly, index IEZ_{21+22} indicates workplaces where the number of explosion hazard risk is low and is derived in similar way as IEZ_{20}. In Figure 3 the total number of workplaces in explosive dust atmosphere zones (sum of zones 20, 21, and 22) was plotted against yearly coal production.

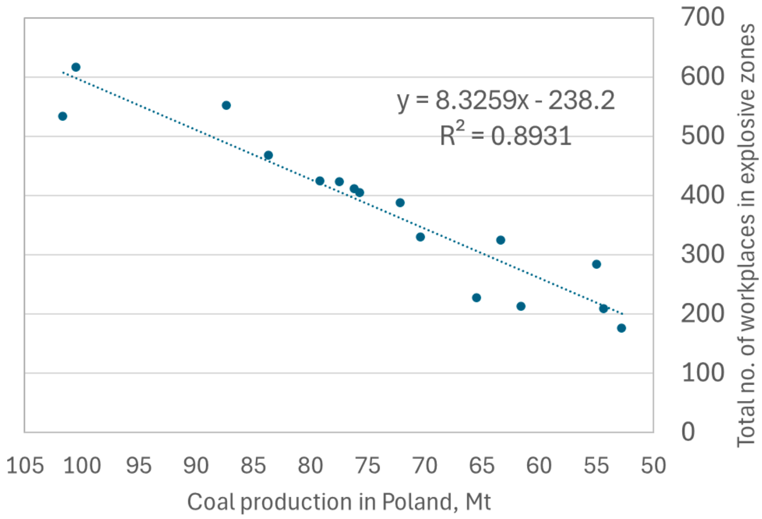

Figure 3. Total number of workplaces in explosive dust atmosphere zones 20, 21, and 22 plotted against total coal production in Poland in 2003–2022 [13,14,23–34,36].

The plot in Figure 3 demonstrates a strong correlation between the decline in coal production, driven by mine closures, and the reduction in workplaces located in explosion hazard zones within coal preparation plants. The Pearson correlation coefficient for this dataset is 0.945, indicating a very strong relationship. Despite the overall downward trend in the total number of workplaces in explosion hazard zones, the proportion of workplaces in zone 20 (high risk) has been increasing, even as coal production continues to decline (Figure 4).

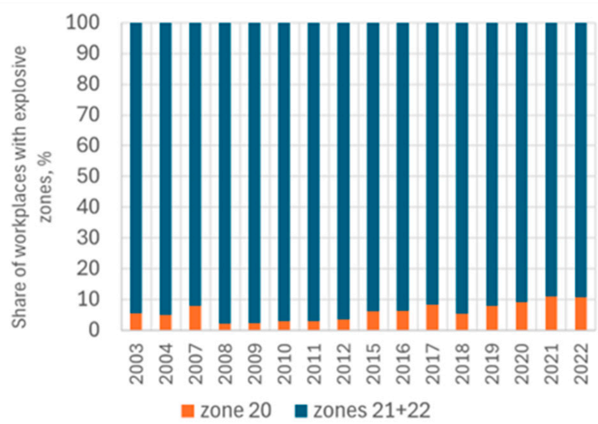

Figure 4. Share of workplaces in explosive zone 20 (high risk) and zones 21 + 22 (lower risk) in Poland in 2003–2022.

The dynamics of the change in calculated indexes IEL_{20} and IEL_{21+22} can be observed in Figure 5 where an upward trend is visible for both indexes. Despite the fact that the coal production is decreasing, the relative number of workplaces with dust Explosive Atmospheres is increasing. In fact, this trend is particularly visible in case of the number workplaces in zone 20 (high risk) since the Pearson coefficient shows a negative value of -0.592, indicating that the number is increasing despite the coal production shrinking. On the other hand, Pearson coefficient for zones 21 + 22 has a value of 0.591, indicating decrease of low risk zones with decreasing production trend.

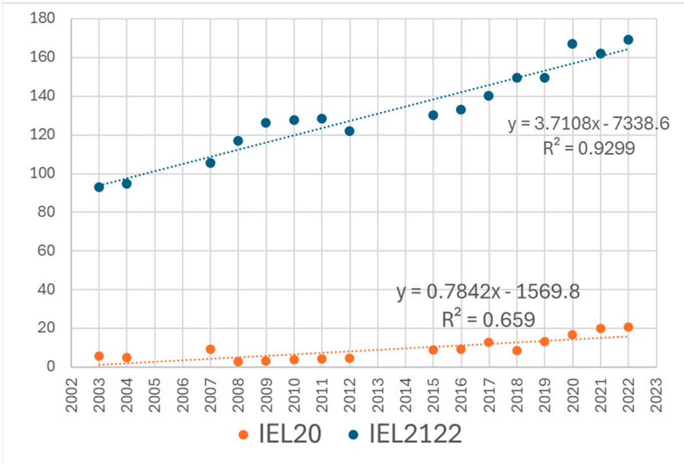

Figure 5. Calculated indexes IEL_{20} (high risk) and IEL_{21+22} (low risk), indicating dust Explosive Atmospheres at workplaces in hard coal preparation plants in Poland in relation to total coal production from 2003 to 2022.

To evaluate trends in the Maximum Allowable Concentration (MAC) for dust exposure in coal preparation plant workplaces, the MAC values were analyzed in relation to annual coal production. The proposed IMAC index is calculated by dividing the reported number of workplaces exceeding dust MAC by the respective coal production for each year. The calculated IMAC index for 2003–2022 is presented in Figure 6. In this case, no clear trend is observed, which is further reflected in the Pearson correlation coefficient of 0.145, indicating a weak relationship between production and reported number of workplaces in dust MAC.

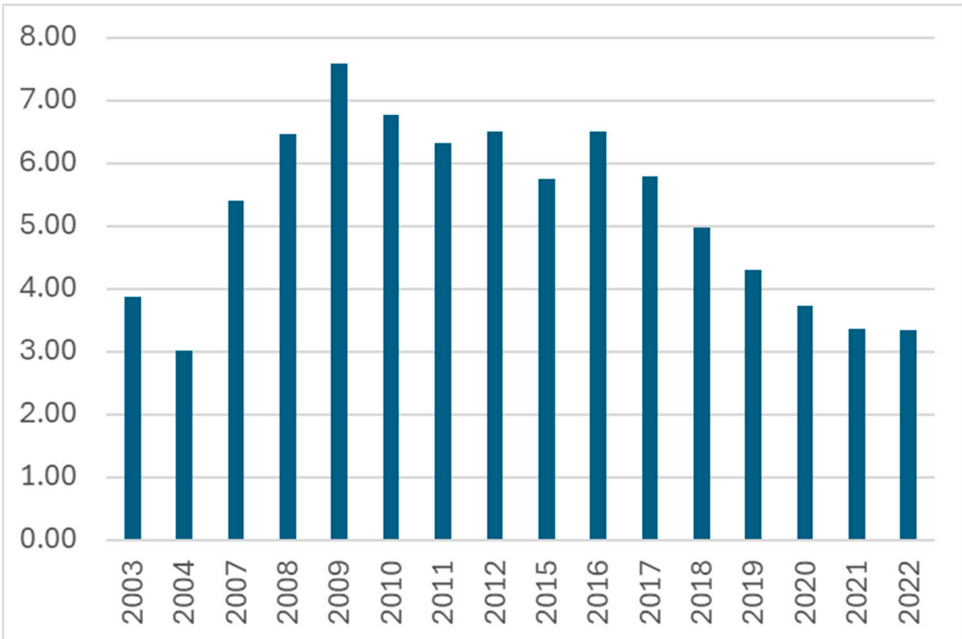

Figure 6. Changes in calculated IMAC index for 2003–2022.

To assess the risk of methane Explosive Atmospheres in the workplace in coal preparations plants, the number of workplaces in zone 2 was compared at first with annual production resulting in the IMC index. Analysis of the data shows that, during the analyzed period, no zone 0 methane explosion hazard was found at workplaces in the processing plant. Zone 1 occurred at 24 workplaces in 2007, at two workplaces in 2009, 2011, and 2012, and at one workplace in 2015, 2016, 2017, 2021, and 2022. Therefore, occurrences of zones

0 and 1 were neglected from the analysis. In the case of zone 2, there is a clear increasing trend showing index growth despite the decrease in coal production. This comparison does not provide any logical explanation as methane content in coal depends on the coal origin, mining depth rather than production rates. Therefore, it was decided to compare the number of workplaces in methane explosive atmosphere with data on the annual average methane content in coal provided in the reports of State Mining Authorities starting from 2000 to 2022 [21]. Results of the comparison are shown in Figure 7.

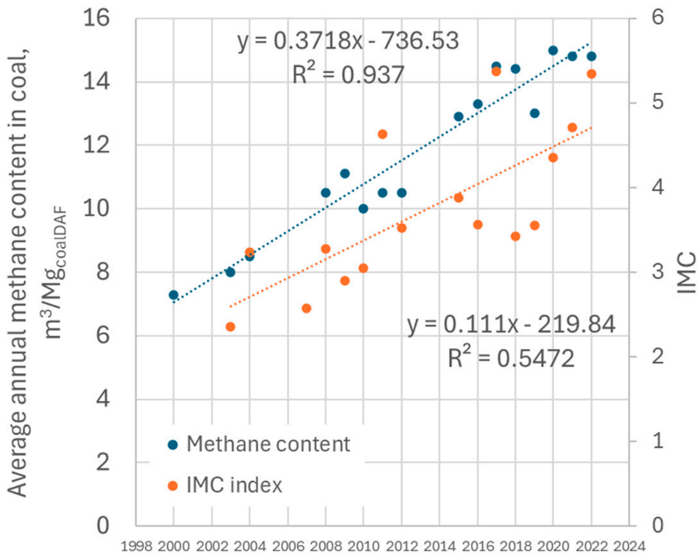

Figure 7. Changes in calculated IMC index and average annual methane content in coal from 2000 to 2022.

There is a clear correlation between increasing methane content in coal and the IMC index for coal preparation plant which is reflected in Pearson coefficient of 0.71 for the analyzed set of data.

4. Discussion

The analysis of coal dust and methane explosion hazards in coal preparation plants highlights significant trends and evolving risks over the two decades from 2003 to 2022. The period was characterized by substantial organizational changes within the Polish hard coal mining sector, including a sharp decline in the number of operational mines and coal production volumes. Despite these reductions, certain hazard indicators show concerning upward trends, reflecting complex relationships between workplace safety and operational adjustments.

The total number of workplaces in explosive dust atmosphere zones (zones 20, 21, and 22) exhibited a strong correlation with coal production, as evidenced by a Pearson coefficient of 0.945. This finding aligns with the general expectation that fewer mines and lower production volumes would reduce workplace hazards. However, the share of workplaces in high-risk zone 20 increased relative to the total number of workplaces in explosive zones, even as overall production declined. The calculated index IEZ_{20} demonstrated a negative correlation with production ($r = -0.592$), suggesting that high-risk areas may persist despite overall safety improvements. This is a surprising result that may indicate an obsolete infrastructure and inefficient safety measures.

The findings of this study align with the work of Dong et al. 2023 [37], who employed the Systems-Theoretic Accident Model and Process (STAMP) combined with the Rank-order Centroid (ROC) method to identify critical risk factors in non-coal mine explosion accidents. Dong et al.'s emphasis on systemic risks—such as inadequate licensing, confusion in safety management systems, and failures in supervision—might reflect some of the hassle in Polish coal preparation plants. Their approach offers a valuable framework for improving risk identification by integrating broader systemic considerations into hazard assessment methodologies. Niu et al. 2023 [38] highlight the critical role of human factors in explosion hazards. Their study shows that unsafe acts—such as habitual violations driven by mental state and other factors—are significant contributors to coal mine gas explosions. This aligns with our findings that, despite declining production, the proportion of workplaces in high-risk zones continues to grow. These insights underscore the need to address behavioral and organizational factors alongside physical hazards. Integrating frameworks like the Human Factor Analysis and Classification System (HFACS-GE) and Bayesian Networks (BNs) could help identify and mitigate unsafe acts, enhancing safety compliance in coal preparation plants.

On the other hand, technological advancements such as positive–negative pressure dust removal systems [39] can play a pivotal role in dust control. Their study showed that a positive- and negative-pressure composite dust removal system reduced average dust concentration in coal preparation plants by over 78%.

The IMAC index, representing workplaces exceeding the Maximum Allowable Concentration (MAC) for dust, did not show a clear trend over the analyzed period. The weak Pearson correlation coefficient of 0.145 suggests no consistent relationship between coal production and dust-related hazards. This may reflect variability in workplace conditions, safety measures, or monitoring practices, rather than a direct influence of production volumes. Fluctuations in IMAC index may be also attributed to changes in coal geology where access to coal with a higher silica content may be encountered. This is in line with a broader studies [9,40] in US mines, which show large variations in silica content depending on the strata and distance from longwall operation.

The IMC index, which evaluates workplaces exposed to methane in zone 2 Explosive Atmospheres, revealed an increasing trend despite declining coal production. This anomaly underscores the influence of factors such as methane content in coal seams that increases with mining depth, and geological conditions rather than production levels alone. A stronger correlation (r = 0.71) was observed between the IMC index and annual average methane content in coal, highlighting the need for targeted mitigation strategies that address these underlying factors.

The observed trends underscore the complexity of managing safety hazards in coal preparation plants. While declining production and mine closures have contributed to a reduction in overall risk, persistent or increasing risks in high-priority areas, such as zone 20 and methane hazards, warrant closer attention. These findings highlight the importance of robust safety protocols, continuous monitoring, and adaptive hazard management strategies to address dynamic risks effectively.

5. Conclusions and Further Recommendations

The comprehensive analysis of workplace hazards in Polish coal preparation plants between 2003 and 2022 highlights critical insights into the evolution of safety risks:

Dynamic Organizational Changes: The period saw significant structural shifts in the mining sector, with a sharp reduction in operational mines and coal production. Despite these changes, high-risk areas persist and, in some cases, have intensified.

Explosion Hazard Trends: The number of workplaces in explosive dust atmospheres decreased overall, correlating strongly with declining production. However, the rising share of zone 20 (high-risk areas) workplaces indicates persistent challenges in mitigating hazards in these critical zones.

Dust Exposure and MAC Compliance: The IMAC index showed no definitive trend, underscoring variability in safety practices and workplace conditions. This variability suggests that factors beyond production levels significantly impact dust exposure risks.

Methane Hazard Dynamics: An increasing trend in the IMC index, despite lower production levels, aligns with a rise in methane content in coal. This indicates that geological and operational factors, rather than production alone, play a significant role in methane hazard exposure.

Future Recommendations

Safety Measures for High-Risk Zones: Given the increasing proportion of zone 20 workplaces, targeted safety interventions, such as improved ventilation and advanced explosion suppression systems and dust suppression systems, should be prioritized for high-risk zones.

Enhanced Dust Monitoring and Control: The variability in IMAC trends suggests a need for standardized dust control protocols across all plants. Adoption of real-time dust monitoring technology and stricter enforcement of dust suppression measures could help mitigate risks.

Methane Hazard Mitigation: The correlation between methane content and IMC index calls for tailored strategies, such as pre-drainage of methane from coal seams and advanced gas detection systems.

Continuous Data Analysis and Index Development: Refining existing hazard indices, such as an IMC, to include additional variables (e.g., geological factors, equipment performance) can improve their predictive value. Establishing automated systems to monitor and analyze safety data in real time would enhance proactive risk management.

Training and Awareness: Regular training programs on hazard recognition and mitigation should be conducted for workers and supervisors. Emphasis on high-risk zones and methane hazards can reduce human error and enhance safety compliance.

Policy and Regulation Alignment: Updating safety regulations to reflect the latest technological advancements and emerging risks is essential. Collaboration between government bodies, industry leaders, and research institutions can ensure regulations are robust and relevant.

These recommendations aim to bolster safety practices and adapt to the evolving risks in coal preparation plants, ensuring worker protection and operational sustainability in the Polish hard coal industry.

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